Appetite for Change

Food system options for nitrogen, environment & health

2nd European Nitrogen Assessment
Special Report on Nitrogen & Food

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About the Task Force on Reactive Nitrogen (TFRN)

The TFRN was established by the Executive Body of the United Nations Economic Commission for Europe (UNECE) Convention on Long-range Transboundary Air Pollution (CLRTAP) with the "*long-term goal of developing technical and scientific information, and options which can be used for strategy development across the UNECE to encourage coordination of air pollution policies on nitrogen in the context of the nitrogen cycle and which may be used by other bodies outside the Convention in consideration of other control measures*." The Task Force conducts its work through the contribution of several Expert Panels, with the present report prepared by the Expert Panel on Nitrogen and Food (EPNF).

Special Reports of the European Nitrogen Assessment (ENA) highlight key challenges and opportunities for action on nitrogen which may be used by the UNECE and other bodies. The first ENA Special Report "Nitrogen on the Table" was published in 2015 and is available from https://www.clrtap-tfrn.org/content/epnf.

About this publication

The present ENA Special Report has been prepared and peer reviewed by a scientifically independent process as a contribution at the work of the Task Force on Reactive Nitrogen. The views and conclusions expressed are those of the authors, and do not necessarily reflect policies of the contributing organizations.

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Front Cover Image: Illustration of a sustainable visionary food system. © Catharina Latka.

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Foreword

This report, 'Appetite for Change', comes at a timely moment for the Air Convention. In December 2022 the 42nd session of the Executive Body of the UNECE Convention on Long-range Transboundary Air Pollution—to use the convention's full name—adopted its review of the amended Gothenburg Protocol to Abate Acidification, Eutrophication and Ground-level Ozone. It means that Parties to the convention now have the main body of evidence they need to consider 'what next' for international air pollution control.

From the Gothenburg Protocol review, it is evident that huge progress has been made in reducing air pollution in the UNECE region. A particular success has been the abatement of sulphur dioxide emissions, which has seen the problem of acidification in Europe substantially reduced compared with the 1980s. However, new issues have emerged, as air pollution is still shortening lives as a consequence of fine particulate matter, nitrogen oxides and ozone concentrations, while ecosystems continue to be threatened by air pollution driven 'eutrophication', where too much nutrient input is changing species composition. At the same time, air pollution emissions are interacting with climate change.

One of the key realisations from the work of the convention is how human alteration of the nitrogen cycle is affecting all of these issues. In the 'European Nitrogen Assessment', published in 2011 under the lead of the UNECE Task Force on Reactive Nitrogen, a clear message emerged of how nitrogen links these issues, and how sustainable management of nitrogen could help air quality with multiple simultaneous co-benefits for environment, climate and economy.

While special attention has been given in the Air Convention to reducing nitrogen oxides (NO_x) emissions from combustion sources, it is now recognized that NO_x is also emitted by agricultural soils and manures, demonstrating how the nitrogen cycle is interconnected. The role of agriculture is even bigger when it comes to ammonia (NH_3) emissions, which are dominated in the UNECE region by livestock housing, manure management and fertilizer-related practices. This has challenged the convention to give much more thought to the role of the food system in contributing to air pollution. Mitigation of agricultural air pollution would offer the opportunity to improve human and ecosystem health by reducing NO_x and NH_3 emissions, alongside the co-benefits for climate, water quality and the economy.

One of the clear messages of the Gothenburg Protocol review is that the approach taken for ammonia needs to be updated, especially in the context of the need for integrated sustainable nitrogen management. This can be illustrated by Annex IX to the Gothenburg Protocol, which was left without an update in the amended protocol of 2012. Its measures focus entirely on technical actions in agricultural production, with little consideration in the Gothenburg Protocol of actions related to food demand.

In 2015, the Task Force on Reactive Nitrogen launched the milestone report 'Nitrogen on the Table: The influence of food choices on nitrogen emissions and the European environment' prepared by its Expert Panel on Nitrogen and Food. The report clearly illustrated how many citizens in the UNECE are eating much more meat and dairy than is needed for a healthy diet. The report showed that a demitarian approach, halving meat and dairy intake across Europe (with a corresponding increase of other foods), could fully meet dietary needs. At the same time, this scenario estimated a 43% reduction in NH_3 emissions, with similar reductions in nitrous oxide emissions and greenhouse gas emissions, as well as nitrogen losses to water and total nitrogen losses from the food system. It is an amount comparable to what might be achieved by an ambitous package of technical measures in agriculture, demonstrating the need to consider both production and consumption-oriented approaches.

The big question emerging from 'Nitrogen on the Table' is how to foster such changes in consumption patterns, especially given that diet is such a sensitive topic. Indeed, the same conclusion has also been reached by the present Gothenburg Protocol review: whether the focus is on transport, energy or food choices, actions to address sustainable consumption patterns need to be part of the conversation on future air pollution control.

It is this that brings us back to the present report 'Appetite for Change'. At its heart, the report emphasizes how the nitrogen cycle, food system, environment and health are inextricably interlinked. As such, it emphasizes how the future policy landscape needs to be equally interlinked. This is illustrated by the recent agreement in December 2022 of the Kunming-Montreal Global Biodiversity Framework (CBD/COP/15/L.25), where Target 7 looks to reduce pollution from excess nutrients (including nitrogen) by at least 50% by 2030. If such a target is to be achieved, the experts of the Expert Panel on Nitrogen and Food (EPNF) are clear that actions will need to address both technical efficiency and consumption choices, considering agricultural production, food consumption and food waste together. The challenge is to find ways that build this 'appetite for change'. The present report presents the main ingredients and a suggested recipe to navigate the necessary sustainability transition, but further efforts are needed to build capacity and find the most attractive pathways for each situation.

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Preface

The Task Force on Reactive Nitrogen operates under the Working Group on Strategies and Review of the United Nations Economic Commission for Europe (UNECE) Convention on Long-range Transboundary Air Pollution ('the Geneva Air Convention'). The long-term goal of TFRN is to develop "*technical and scientific information*" and to provide "*options, which can be used for strategy development across the UNECE to encourage coordination of air pollution policies on nitrogen in the context of the nitrogen cycle and which may be used by other bodies outside the Convention in consideration of other control measures.*" (TFRN, 2021a).

The Expert Panel on Nitrogen and Food (EPNF) is a group of scientists that provide scientific underpinning to the Task Force on Reactive Nitrogen (TFRN) on questions that address the 'food system' in its entire relevance for the nitrogen cycle and the reduction of reactive nitrogen emissions.

The Expert Panel on Nitrogen and Food was established in 2010 "*to create a better understanding of the relationship between human diets and the impact of the N-cycle on the environment*" (TFRN, 2010). The first Special Report of the European Nitrogen Assessment was published under the title 'Nitrogen on the Table' (Westhoek *et al.*, 2015). The Special Report was a milestone in the field of nitrogen research: for the first time, the effect of the reduction of nitrogen pollution through changed demand (dietary change) was assessed at the European scale considering relevance for *both* environment and health.

Since that time, the findings of 'Nitrogen on the Table' and its underlying scientific papers (Leip *et al.*, 2014a; Westhoek *et al.*, 2014) have been reconfirmed and refined by other publications (Clark *et al.*, 2019; Godfray *et al.*, 2018; Springmann *et al.*, 2016, 2018a). Today, together with the important development of a global planetary health diet by the EAT-Lancet Commission (Willett *et al.*, 2019), the need for a systemic approach that combines—amongst others—the health and nitrogen dimensions, is now widely recognized (European Commission, 2020a; Rockström *et al.*, 2020).

'Appetite for Change' in practice

In this setting, the UNECE Working Group on Strategies and Review decided to develop the work of the EPNF and deepen the 'systemic aspects' in relation to nitrogen, food and health, and to nitrogen emission targets. The following questions were agreed as a focus for the work (UNECE, 2015):

1. How far could a combination of improved farm level technical measures and shifts in consumption go to improving the Nitrogen Use Efficiency (NUE) of the overall food system of Europe? What do the incentives need to be in order to realize this NUE improvement?
2. What is the relative potential of dietary changes and food waste reduction to reduce nitrogen air pollution and other environmental threats?
3. What are the health effects of a range of dietary patterns that generate less nitrogen pollution (i.e., positive and negative)? Potential health effects include those from air pollution and those that are nutrition related. Is it possible to identify particular dietary patterns that achieve health-environmental synergies?
4. To what extent can a stronger link between the scientific evidence on environment and health strengthen the case for controlling nitrogen pollution and optimizing diets to meet human health goals?

To approach these questions, collaboration among the Expert Panel crossed various disciplines and promoted a platform for debate and mutual learning. The present report and its underlying scientific publications that were generated in support of the report (see list at TFRN, 2021b) is the result of the co-operation of nitrogen experts and other scientists from various fields: agronomy, environmental impact research, health and nutrition, economy, and policy science.

Many (but not all) of the papers underlying this European Nitrogen Assessment Special Report are published in a Special Issue in the journal *Global Food Security*: 'Managing nutrients: the key to achieve sustainable food systems for healthy diets'(Leip *et al.*, 2021b), published under Open Access copyright. (CC BY 4.0, https://creativecommons.org/licenses/by/4.0/). The respective chapters or sections are adapted to the format, length and focus of this report. However, some tables, figure, or text passages from the articles have been used.

Structure of the report

This report has three main parts:

Part A – Food systems today: A health and nitrogen perspective.

Part B – Food systems à la carte: Elaborating a recipe for sustainable food systems.

Part C – Serving sustainable food systems: Gathering around the table and sharing our plates.

Part A describes the current situation in today's food systems with its complexities, problems, as well as glimmers of hope. Part B looks at the elements that could help to improve food system outcomes on the environment and/or health. We examine the options from farm to societal levels, including food-loss and waste, novel foods, Food-based dietary guidelines and demand-oriented policies.

'Nitrogen' is always the underlying topic, sometimes directly, such as in the chapter on improving nitrogen use efficiencies, and sometimes indirectly, for example when examining the extent to which pollution is already integrated into demand-oriented policies.

Part C examines possible solutions from a systemic level: What makes a sustainable food system sustainable? What are the options for governance of the food system? Finally, we summarize the findings of the previous chapters, especially in relation to the question: How far can a combination of farm level, food waste, and dietary measures go towards achieving a sustainable environment with healthy people?

Research on sustainability research must be sustainable itself

Researchers are part of the food system, not only as researchers, but also as consumers. Our work focuses on scientific evidence about the current status of nitrogen and food. It explores options available to food system actors, policy makers and society. The consequence is that we need to live our ambitions and contribute to the transformation of food systems and nitrogen management.

To address this, the group of scientists who have worked on this the report have aimed to work sustainably, with particular attention to the way we hold and organize our meetings. Firstly, every alternate meeting since 2015 was held virtually. Secondly, physical meetings were organized in 'hybrid' format, allowing participants to actively engage through remote connection. Such e-meetings have become universal since the COVID-19 pandemic. The approach taken by EPNF has prepared the way, as well as provided lessons for successful hybrid meetings in a post-COVID future.

Thirdly, special attention was given to eating healthy and sustainably. This has been followed up in the Cercedilla Manifesto, published by Sanz-Cobeña *et al.* (2020) which raises awareness of the EPNF initiative (OpenPetition, 2020; TFRN, 2021b).

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Executive Summary

Key messages

- Leakage of reactive nitrogen (N_r) from food systems threatens the environment and human health by causing air, water and soil pollution, while contributing to climate change and biodiversity loss. Nitrogen use efficiency (NUE) of the EU food system was only 18% in 2015. Most of the remaining 82% was wasted by loss to the environment contributing to these environmental and health threats.
- A combination of dietary change and technical measures across the food chain can halve nitrogen waste (as the sum of all nitrogen losses) and contribute to reaching the targets set in UNEP's Colombo Declaration, the EU Farm to Fork Strategy and the Kunming-Montreal Global Biodiversity Framework.
- A transition towards plant-based diets will reduce nitrogen inputs and increase the NUE of the food system, since plant-based foods have higher NUE than animal-based foods. Diets that are predominantly plant-based correlate with lower nitrogen footprints, lower greenhouse gas emissions and positive health outcomes compared with current diets in the EU.
- Among 144 scenarios investigated, a combination of halved meat and dairy consumption (demitarian) with improved farm and food chain management, and reduction of excess energy and protein intake achieves 49% reduction in nitrogen losses with the highest score for net societal benefit.
- Full exclusion of meat and dairy products from human diet combined with ambitious technical measures could reduce the need for virgin nitrogen inputs by 73% and achieve a food system NUE of close to 50%. Taking these factors together, such a change could reduce nitrogen waste by up to 84%. However, this scenario did not offer net societal benefit when the environmental benefits were offset against the stringency of actions needed.
- At farm level, there is scope for significant improvement in NUE using available technologies. Values of farm-level NUE of up to 92% for arable systems, 80% for granivores, 61% for ruminant meat production, and 55% for dairy production can be achieved.
- Only about 55% of the nitrogen in commodities leaving the farm-gate suitable as human food is actually used for human consumption. This leaves considerable scope to improve the NUE of the whole food system by reducing food waste and improving wastewater treatment, with an emphasis on nutrient recovery opportunities.
- Agroecological approaches, urban and high-technology food production systems (e.g., vertical or indoor farms) may support a transition towards plant-based diets and sustainable food systems. Investing in legumes, novel and future foods offer opportunities for consumers to reduce the consumption of animal-based foods, with multiple environmental benefits.
- A range of policies addressing consumer food choices is available for public authorities to support dietary change towards lower nitrogen footprint diets. Policy makers are encouraged to combine policy instruments in coherent policy packages to reduce nitrogen inputs in the food system, increase NUEs and monitor their effectiveness, as well as possible adverse side-effects.
- Bottom-up approaches to sustainable food systems are increasingly emerging at local and regional level and require ambitious strategies to facilitate a transition towards a plant-based food system, including novel foods and new food production technologies.
- The unprecedented rise of energy, fertilizer and food prices since 2021 underlines the need to address the vulnerability of the food system. A transition towards plant-based diets requires less land and mineral fertilizers, thus reducing energy dependency and increasing resilience to food and energy crises.
- This report adds evidence on the need and actions to transform the food system based on a systems approach. Encouraging more plant-based diets can promote human health and a healthier planet.

Reduce use of nitrogen to bring benefits for health, nature and climate

The previous report 'Nitrogen on the Table' prepared by the Expert Panel on Nitrogen and Food (EPNF) highlighted that high levels of reactive nitrogen emissions are linked to intensive livestock production and a high share of animal products in the human diet. Losses of reactive nitrogen to the environment have pushed the global nitrogen cycle out of its planetary safe operating space and has detrimental effects on all life on Earth. The nitrogen use efficiency (NUE) in the EU food system has been estimated to be 18% revealing the urgency in addressing this issue [1; **the number indicates the chapter of this report where evidence is presented**].

In the second half of the last century, investments, innovations, import tariffs and agricultural subsidies incentivized agricultural productivity and food production, which increased the availability of affordable but also energy-dense food. This resulted in important changes in the European diets including an increased consumption of animal-based foods and processed foods high in salt, sugar and saturated fatty acids. Such dietary transition had unintended consequences across the food system and public health in the EU. The prevalence of overweight and obesity has more than doubled in Europe within the last 50 years and diet-related diseases are now a leading cause for premature mortality. In addition, a large share of arable land of the EU (40%) is now used to produce animal feed. Producing animal-based foods relies heavily on imports of crop product for animal feed (oil seeds), and production and import of fertilizers, making the current food system vulnerable to energy and food crises.

Reducing nitrogen (N) use requires policy capacity for governing the food system, recognizing the importance of integrative and interconnected policies that address nitrogen use based more on a systems approach, than on separate measures. This report 'Appetite for Change' extends the scope of nitrogen policy assessment by providing additional tools and policy-making approaches for food system governance. It explores the opportunities for reducing nitrogen losses from food production and consumption from a systems perspective, including the links to nutrition and public health.

1. **Leakage of reactive nitrogen from food systems threatens the environment and human health. Nitrogen use efficiency of the EU food system was only 18% in 2015 [1]**

   Losses of reactive nitrogen (N_r) to the environment have pushed the global nitrogen cycle out of its planetary safe operating space and is considered one of the key global risks to all major environmental threats that humanity is facing today. It is regarded as a main cause for losses of biodiversity and natural resources. It is also causing several forms of air pollution and climate change. Around 2015, the EU agri-food system used 20 Tg of virgin (new) N to deliver less than 2.5 Tg N in food and 1.2 Tg N in non-food products to consumers, yielding a nitrogen use efficiency of the food system (NUE_{FS}) of 18%. Of the N loss, 10.9 Tg N is emitted to the environment as N_r and 3.2 Tg N as N_2 and 3 Tg N is solid waste or lost outside the EU linked to feed imports [1].

2. **Plant-based diets correlate with lower nitrogen footprints and positive health outcomes [2]**

   Increasing sustainability of the livestock sector and reducing consumption of animal-based food products is crucial for improving the sustainability of the EU food systems and public health [1, 2]. Overweight and obesity affect almost 60% of adults and nearly one in three children in the WHO European Region.

   Today, unhealthy diets are a major risk factor for non-communicable diseases (NCDs) in the European Region. Diets with a lower nitrogen footprint, e.g., plant-based diets including vegetarian or the Mediterranean diet, are often healthier and can improve public health and reduce the burden on health care systems (i.e., by prevention and behavioural measures to reduce numbers of hospitalized in-patients). Such dietary patterns are associated with improved body weight, lower blood pressure and chronic disease prevention compared with omnivorous diets high in red and processed meat. In addition, excess nitrates in drinking water and nitrogen air-born pollutants can increase the risk of NCDs, including cancer, thyroid disease, and cardiovascular disease.

   Global excess mortality due to air pollution from $PM_{2.5}$ and tropospheric ozone is 8.8 million per year. In some regions more than 90% of the $PM_{2.5}$ concentrations can be attributed to agricultural sources and about one third to emission of N_r. Moreover, the link between $PM_{2.5}$ exposure and increased mortality risk from COVID-19 further underscores the risk of leaving nitrogen pollution unchecked [2]. The livestock sector is also a major source of emissions of methane and N_2O, which are strong greenhouse gases. The livestock sector might be linked to antimicrobial resistance, as well as the emergence of new zoonotic disease. Dairy farming, meat processing and slaughtering are regarded as high-risk jobs [1,2].

Agreed targets to halve nitrogen waste are possible to reach with a shift in diets towards more plant-based foods

3. The most feasible strategies to reduce nitrogen losses in agriculture by 50% will combine diet change towards plant-based diets with intermediate ambitions of farm level and food chain measures [10]

Scenario analysis of the European food system and environmental impacts shows that relying on technical solutions will clearly not be enough for reaching political nitrogen-targets. Successful strategies will need to address a mix of interventions targeting different food system stages. Diet change towards plant-based diets is a key condition for succeeding with a 50% reduction. Specifically, combinations of interventions are needed, in tandem with policy evaluations of their effectiveness, to improve nitrogen (N) management in agriculture, reduce food waste, explore ways to recover N from organic residues, reduce the share of animal products in diets and enable a shift to a balanced and healthy diet. By combining ambitious changes in diet, food chain and residue management, and farm level practices, an increase of the nitrogen use efficiency (NUE) to almost 50% and a reduction of nitrogen waste by 84% is achievable. Additionally, a rising demand for land to produce energy crops and nature conservation cannot be met without decreased land demand for meat production.

4. Dietary changes reduces the socio-economic cost of achieving ambitious nitrogen reduction targets [10]

The scenario analysis showed that focused action within single stages was not sufficient to meet the 50% reduction target. The maximum reduction in N loss achievable with improved N management at farm level only was 37%. In the case of improved nitrogen management in food processing, retail and sewage treatment, the maximum reduction in wasteful nitrogen losses was 17%.

By contrast, of a total of 144 scenarios combining changes in different parts of the agri-food system, it is shown that a wide range of outcomes are achievable using a mix of measures, ranging from a reduction in nitrogen loss from 0% to 84% (Figure ES.1). Of these, 12 scenarios were selected that delivered between 49% to 51% reduction (Figure ES.1) for more detailed analysis in Chapter 10.

Of the 12 selected scenarios, we here illustrate four example scenarios that achieve around 50% reduction in wasteful nitrogen losses and compare these with the baseline scenario and the maximum ambition scenario (Table ES.1). These examples show how contrasting scenarios provide alternative pathways to halve nitrogen waste from EU agriculture and satisfy critical environmental loads and levels of N. The example scenarios reflect contrasting assumptions on improvement of farm N management, waste N management and change of diet. These examples illustrate different strategies to halve nitrogen waste:

Scenario O41 represents a broad approach with somewhat improved farm and food management, slightly reduced energy and N intake and demitarian diet (i.e., half meat and dairy compared with EU average). This represents a healthy diet approach that fully meets dietary needs. This moderate combination of changes achieves halving of nitrogen waste with the highest overall score for net societal benefit (overall score).

Scenario O45 focuses on highly improved farm practices with improved food management, while retaining current energy and nitrogen intake and dietary mix. This extreme combination, putting all the effort on farmers but none on consumers, scored lowest for net societal benefit of the example scenarios.

Scenario O48 combines medium ambition for improved farming with somewhat improved food management, somewhat reduced energy intake (avoiding excess) and a vegetarian dietary mix. The approach was found to have an intermediate score for net societal benefit.

Scenario O51 represents a polarized option, where neither farming nor food management are improved, and the reduction in nitrogen waste is achieved entirely by a reduction in energy intake, combined with a vegan diet across Europe. This scored similarly to O48 but significantly better than O45.

Scenario O144 is the most ambitious of all 144 scenarios considered, achieving an 84% reduction in total nitrogen waste (sum of all nitrogen losses). This offers strong environmental benefits, contributing towards a positive societal score, but this is offset with substantial negatives associated with the ambitious changes. As a net result, the net societal score of this scenario is no better than the current baseline.

Overall, these scenarios show how there are different pathways to reducing nitrogen pollution impacts. The target to 'halve nitrogen waste' can be most acceptably met by a broad range of actions that combine improved farming practice, improved food management (including food processing, retail and sewage treatment), avoiding excess energy and protein intake, and adopting a demitarian approach that halves meat and dairy intake compared with the baseline European situation.

The Nitrogen use efficiencies achieved in these calculations are lower than those reported in the previous report 'Nitrogen on the Table' prepared by the Expert Panel on Nitrogen and Food (EPNF) with NUEs of up to 47% for a demitarian diet. The reason for this difference are the scope and system boundaries which differ between the two studies. While here no assumptions were made on the use of the land not required any more for feed production, the 'Nitrogen on the Table' report assumed that the land was (partly) used for cereal production for export which increases the NUE of EU agriculture.

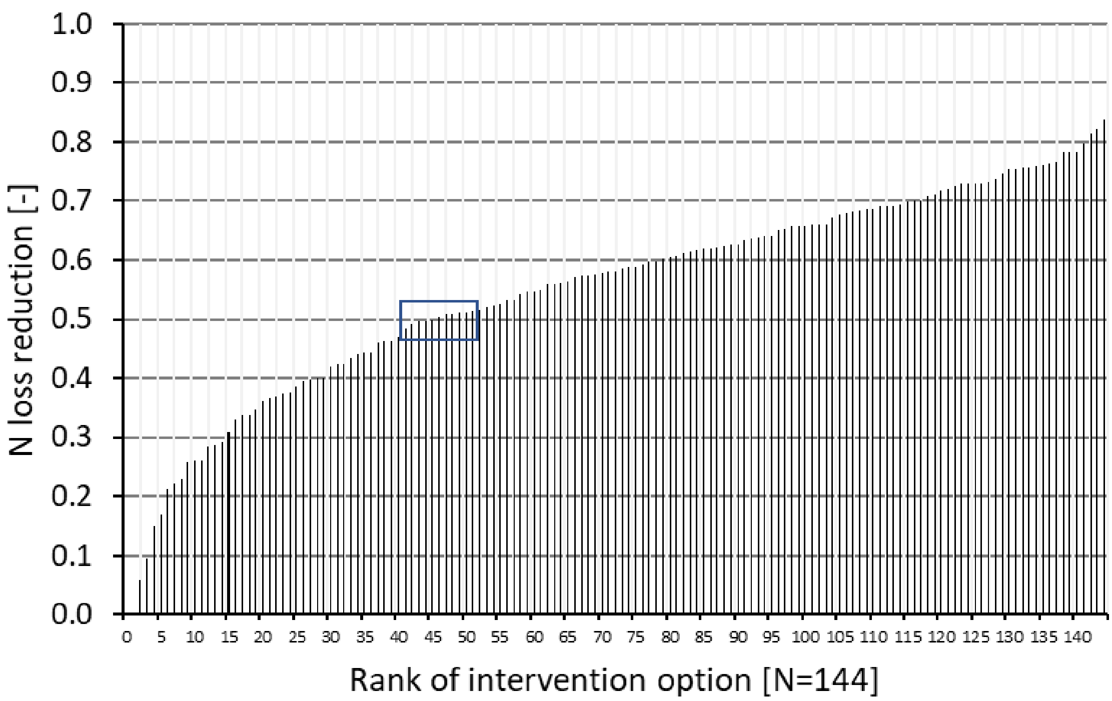

Figure ES.1. *Relative reduction of nitrogen (N) losses in 144 intervention options and selection of 12 intervention options (blue box: O41–O52) with a N loss reduction between 49 and 51%. Source: Leip et al. (2022), reproduced here under CC BY 4.0, https://creativecommons.org/licenses/by/4.0/.*

Table ES.1. *Results of the baseline for 2014-2015 with four example scenarios that deliver around 50% reduction in wasteful nitrogen losses to the environment as compared with the baseline, plus the scenario reaching highest reduction of wasteful nitrogen losses. Source: Leip et al. (2022), under CC BY 4.0, https://creativecommons.org/licenses/by/4.0/.*

Scenario option						Effects on N cycle and implementation				
Example scenario	**Farm level Ambition**	**Food chain Ambition**	**Healthier energy intake *% reduction***	**Healthier protein intake *% reduction***	**Diet**	**Virgin nitrogen Tg N yr^{-1} *% reduction***	**Nitrogen losses Tg N yr^{-1} *% reduction***	**NUE food system**	**Implementation costs score**	**Overall score for net societal benefit $^{\$}$**
Baseline	Baseline	Baseline	*0%*	*0%*	Default	16.0 *0%*	12.4 *0%*	19%	0	0
O41	Low	Intermediate	*13%*	*20%*	Demitarian	9.4 *41%*	6.4 *49%*	27%	0.1	0.8
O45	High	Improved	*0%*	*0%*	Default	10.0 *37%*	6.2 *50%*	32%	-2.8	-0.6
O48	Medium	Intermediate	*13%*	*0%*	Vegetarian	9.7 *40%*	6.1 *51%*	32%	-1.0	0.4
O51	Baseline	Baseline	*13%*	*0%*	Vegan	9.5 *41%*	6.0 *51%*	32%	0.0	0.5
O144	High	Improved	*25%*	*40%*	Vegan	4.3 *73%*	2.0 *84%*	47%	-2.8	0.0

$^{\$}$The overall score for net societal benefit is calculated from the private and public cost of the implementation of measures to decrease nitrogen (N) losses in agriculture and waste management, the public benefits of improved healthy life expectancy and reduced public health cost due to healthier diets and reduced exposure to pollutants; the public benefits of increased biodiversity and ecosystem services; and the public cost for overcoming socio-cultural barriers for adoption of alternative diets. NUE = nitrogen use efficiency.

Sustainable food systems could profit from a mix of traditional and novel plant-based foods

5. **Increasing the share of legumes in food production and consumption needs to be part of a food system policy [2]**

   In Europe, protein intake is almost double the recommended amounts. Consumption of processed and red meats are more than three times the quantity recommended by the EAT Lancet Commission in all EU countries. Only 1.5% of the EU arable land area is used to cultivate legumes compared with 14.5% worldwide. Legumes can fix parts of their nitrogen requirements through symbiosis with nitrogen-fixing microorganisms in their root nodules. Consequently, they have substantially higher nitrogen uptake efficiencies. The nitrogen footprint from soy, peas, chickpeas and lentils is estimated to be almost one order of magnitude lower than that of any other food group. In addition, legumes are a sustainable alternative to animal protein sources in line with dietary guidelines. Legumes are rich in protein, complex carbohydrates, dietary fibre and various micronutrients such as phytochemicals, and they are associated with positive health outcomes. Increased consumption of legumes consumption is a key measure that will positively impact on the share of legumes cultivated in the EU [2].

Figure ES.2. *Illustration of key elements to be considered in future sustainable and healthy diets [3]. © Catharina Latka.*

6. **A shift to lower animal-based foods consumption can be achieved in many ways to reach all people [2]**

   Agroecological approaches aim to reconcile nutrition, ecosystem health and social welfare, combined with dietary change. Agroecology uses traditional practices and maximizes the contribution of ecosystem to food production. It also integrates new knowledge and technologies but minimizes reliance on external inputs. In a visionary food system, advanced technologies and widespread dietary changes can lay the foundation for other paths to a sustainable future food system if acceptance-, technology-, and energy-related obstacles can be overcome [3]. A shift towards urban, high-technology food production systems, for example vertical or indoor farms, promises sustainability improvements with improved nutrient- and water-use-efficiencies and reduced agricultural land requirements, and the supply of urban areas with close-by and seasonally independent produced plant-based food. In addition, novel and future foods such as from cellular agriculture (cultured meat and precision fermentation) will contribute to sustainable visionary food systems. High-energy requirements and the need for further technological breakthroughs remain as continuing challenges [3].

7. **Future foods offer opportunities for substituting unsustainable high consumption of animal-based foods [5]**

   Farmed insects, farmed seafood, microorganisms (e.g., microalgae and fungi) and so-called ‘cultured meat’ all have a major role to play in the future food system. These have the potential to supply valuable nutrients to human diets including protein and a diverse array of minerals, vitamins and fatty acids using less land resources and lower greenhouse gas emissions compared with conventional animal-based food. While many future foods are already in the market, their major adoption will require overcoming technological, economic, legislative and socio-cultural barriers. As such, recognizing and understanding the potential of future foods in providing environmental and nutritional benefits can encourage opportunities and innovations across the food system to address the overconsumption of conventional animal-based foods in the EU.

Strengthening food systems governance

8. **Combining policy instruments can better support a transition towards more plant-based diets [2, 6, 7]**

   Taxes and subsidies, which alter consumer prices, are powerful market-based instruments. Combining taxes on food with high environmental impact or that is typically overconsumed from a health perspective with subsidies to healthy, low impact food can reduce the regressive effect of these instruments. Behavioural policies support both consumers' active and conscious choice (learning and information approaches about plant-based diets) and 'nudge' people into making healthier and more sustainable food choices more or less consciously (e.g., changing the position of food items on supermarket shelves or reducing food portions). Food reformulation and innovation could increase the availability and access to more sustainable food products. Sustainable public procurement could support an increased offer of healthier and more sustainable food options and meals in public institutions. Food-based dietary guidelines (FBDGs) already support the development of national food and nutrition policies and could integrate sustainability goals to better align food and environmental policies. Effective strategies to food system governance must integrate a combination of such measures and target environmental, social and economic objectives at all food system stages. A coherent combination of different demand-oriented measures, together with supply-oriented is likely to be more effective in increasing demand for lower nitrogen footprint diets.

9. **Strengthening governments' coordination and operational capacities can support more integrated solutions [8]**

   Although most nitrogen emissions occur at the farm level, it does not mean that policies have to first target farmers [1,2]. The shape of the European food environment is asymmetric and largely controlled by food and feed industry and retail, influencing consumers and primary producers. Nitrogen reduction options remain un-tapped if these asymmetries in food supply chains are ignored. There are major obstacles to consumers wishing to make sustainable healthy choices and farmers wishing to shift to less intensive farming. Many problems linked to food systems are not yet addressed in food system action-plans [1]. Coordination between government actors at administrative and jurisdictional levels and sectors is crucial to address trade-offs and set priorities. Critical evaluations (reflexivity) of practices, policies and behaviours must be the basis for policy debates and policy-making, supported by monitoring systems and platforms to drive innovation and critical thinking of system dynamics.

10. **Strengthening governments' anticipatory capacity is essential for imagining a future food system that can address trade-offs and anticipate risks and unknowns [8]**

    National governance structures can help guide a common direction for change by investing in anticipatory capacity. Anticipation includes approaches of organisations and institutions to manage their future goals and govern future surprises. Anticipation requires resources for conducting future-oriented tools, such as scenario planning and foresights, and abilities for integrating different types of knowledge in governance processes. In addition, future vision-building needs to involve participatory processes that empower citizens and helps stakeholders build a shared vision. A broad agreement is of great importance to support an effective food system transformation. Systemic approaches at regional or city level are emerging as a relevant opportunity to address food systems worldwide, as for example the Milan Urban Food Policy Pact engaging more than 200 cities.

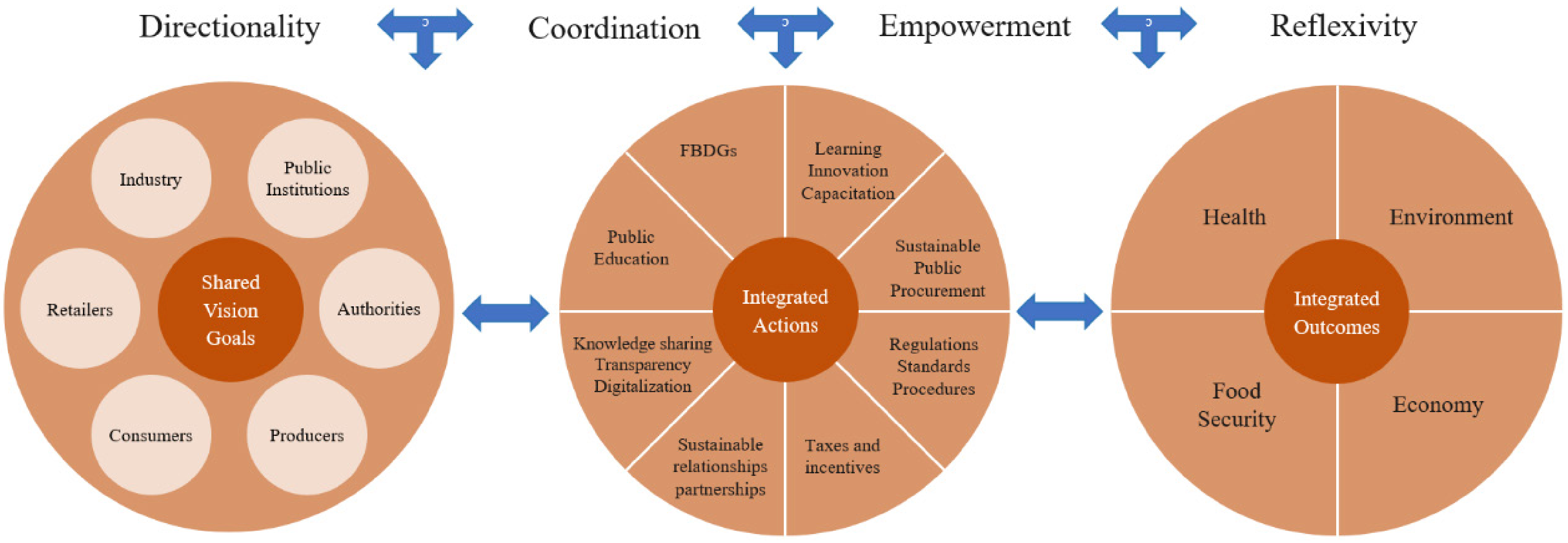

Figure ES.3. *Core principles for planning a food system transformation, resulting in a shared vision, integrated actions and outcomes. FBDGs = Food-based dietary guidelines. Source: created for this report by the authors.*

Set-up a food system monitoring framework along all sustainability dimensions to identify and manage trade-offs

11. **Food systems' sustainability can be measured against four societal goals:**

    1) Adequate, safe, healthy and affordable diets for all;

    2) A clean and healthy planet;

    3) Economically thriving food systems, supportive of the common good; and

    4) Just, ethical and equitable food systems [9].

    A food system monitoring framework must capture all sustainability aspects and consider all people, including those in the future. A growing number of food systems metrics is available to build up capacity for system thinking and reduce policy incoherence between food system challenges. Such metrics can help to find important leverages increasing one or several dimensions of sustainability. Indicators that capture social equity and gender consideration in the food system are lacking, as well as indicators that measure the socio-economic impact of food system policies on other parts of the world.

12. **Applying tools to quantify food system sustainability scores is important for identifying trade-offs and co-benefits in policy-making and requires policy targets for all sustainability objectives [9]**

    Science-based sustainability metrics offer a transparent approach to support decision makers to take better stock of current trade-offs. These include trade-offs between sustainable food production and affordable food prices; the risks of using manure on arable land for recirculation of antibiotics and hormones in the food cycle; or the need to reduce consumption of livestock products and rural development goals. Sustainability metrics must be accompanied by science-based targets to assess policy progress towards endorsed sustainability objectives. By providing a science-based, yet policy-oriented perspective on food system sustainability, sustainability metrics are useful to inform policy dialogues and negotiations, since these provide technical and less value-based judgements to where the trade-offs and positive synergies occur.

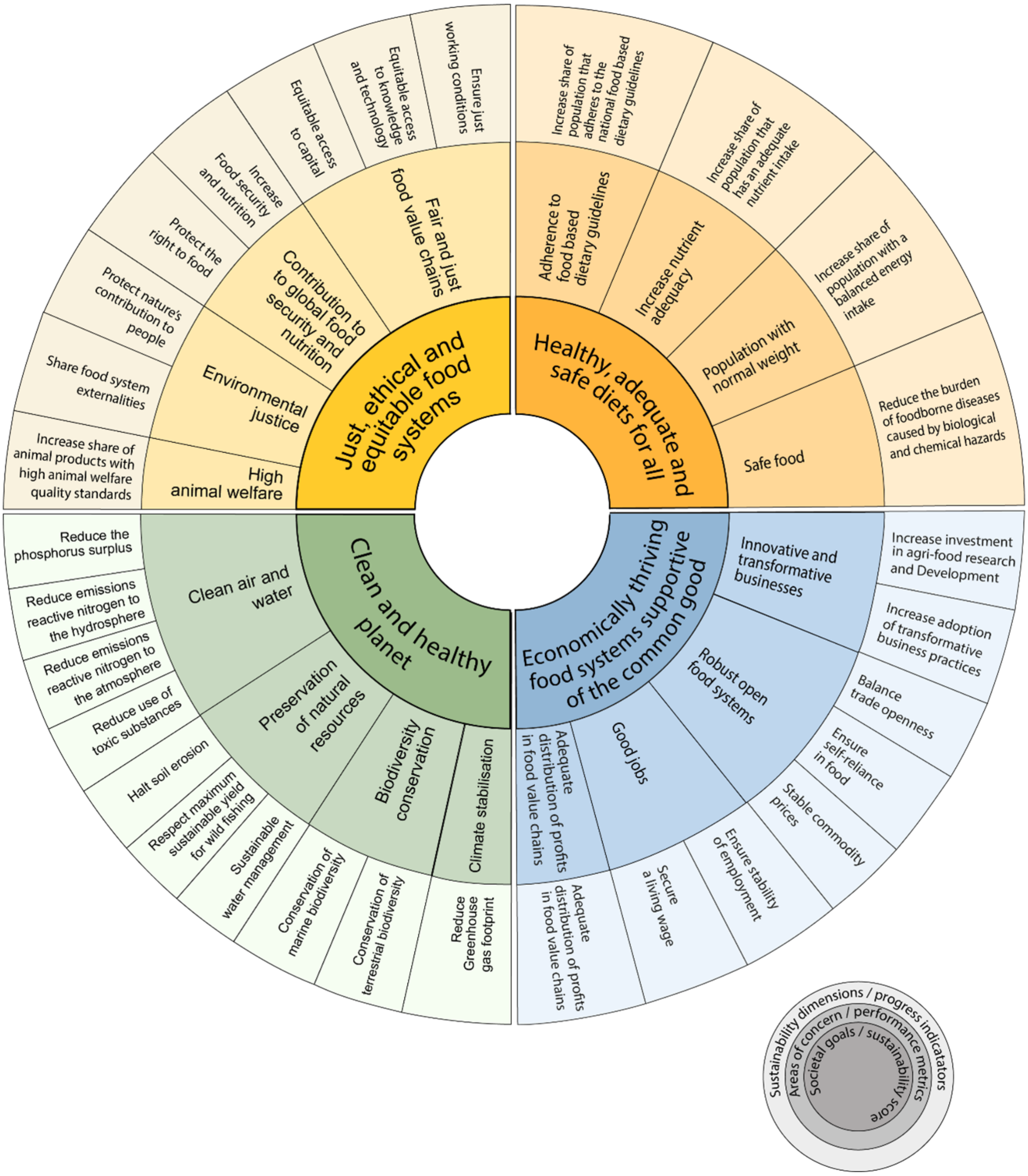

Figure ES.4. *Illustration of how societal goals (centre) link to areas of concern and performance metrics (intermediate ring) and sustainability dimensions, with associated progress indicators (outer ring). Adapted from Hebinck et al. (2021), under CC BY 4.0, https://creativecommons.org/licenses/by/4.0/.*

Increase nitrogen use efficiencies on the farm and in waste/residue management systems

13. **There is scope for significant improvement in the nitrogen use efficiency (NUE) of all production systems with available technologies. Nitrogen use efficiency can be achieved of up to 92% for arable systems, 80% for granivores, 61% for ruminant meat production and 55% for dairy production [4]**

A modelling exercise showed that nitrogen use efficiency (NUE) at the farm level was similar to or higher in Southern than Northern Europe. The NUE of arable production systems is higher than that of livestock production systems and this is likely to also be true in the future, even with the development of new feeds, foods and technologies. Modelling high ambition implementation of current available technologies, arable systems reached the maximum technical NUEs (82% and 92%) followed by granivores (i.e., pig and poultry, 71% and 80%), ruminant meat production on constrained land (beef, sheep, extensive, 45% and 61%), dairy production on unconstrained land (intensive, 53% and 55%) and ruminant meat production on unconstrained land (50% and 36%). However, these values ignore possible impact on other policy areas such as animal welfare. Unconstrained granivore systems offer the greatest possibilities to increase in NUE, while the optimization potential for NUE is lowest in ruminant meat systems with less productive land, as their NUE is already quite high.

14. **There is considerable scope to improve food system NUE by reducing food waste and improving wastewater treatment [1]**

Of the food sold by EU farmers only about 55% is consumed by humans. If the EU met the objective of SDG 12.3 to halve food waste generation by 2030, emissions of reactive nitrogen after the farm gate would decrease by about 50%, while the amount of valorized nitrogen would increase by 9%. Achieving such targets would greatly improve the NUE in the food system. There is potential for reducing post-farm gate reactive nitrogen emissions by more than 45% when fully implementing current EU legislation on food-waste and improving wastewater treatment, which are together currently responsible for more than 60% of emissions.

This improvement would require: 1) an increase of the share of tertiary wastewater treatment to remove chemical pollutants such as drugs, 2) a reduction of food waste generation, and 3) a decrease of the quantity of incinerated and landfilled food waste (combined with an increase in compost production and use). More homogenous food waste makes their valorization easier in the food processing stage as compared to the consumption stage and would reduce the risks of introducing chemical components in the food system (such as microplastics).

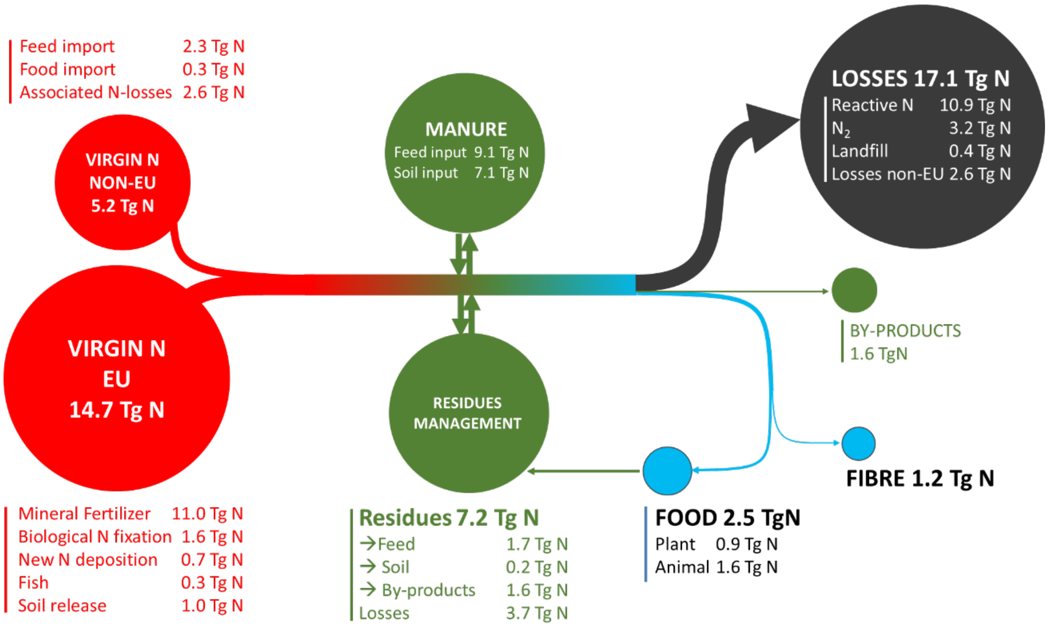

***Figure ES.5**. Summary of nitrogen flows in the EU food system around 2015. Around 85% of virgin (newly fixed) nitrogen associated with the EU food system is wasted as losses to the environment [1]. Source: adapted from Leip et al. (2022), under CC BY 4.0, https://creativecommons.org/licenses/by/4.0/.*

Time for action towards sustainable food systems

15. A transition towards plant-based diets leads to a reduction in edible biomass fed to animals, and can promote more resilient and energy efficient food systems

The present geopolitical situation has revealed the vulnerability of the global food system to energy conflicts. It also demonstrates how future crises will keep threatening food security and the progress on climate change mitigation if society does not act systemically. A transition towards more plant-based diets not only helps achieving environmental and health targets. It is also an essential solution to reduce the food production dependency on energy inputs, promoting food systems that are more resilient to future conflicts and shocks. Energy and food connect three threats that need to be tackled at the same time with highest urgency in the current global crisis:

(1) The threat to democracy and security.
(2) The threat to global food security.
(3) The threat to our living environment by climate change, biodiversity loss, and environmental degradation.

A range of policies addressing consumer food choices are available for public authorities to provide incentives for dietary change towards lower nitrogen footprint diets [6, 7]. In addition, energy savings in food systems need to be pursued, among others, by increasing nitrogen use efficiency and substituting mineral fertilizers with organic fertilizers. For instance, producing more energy-efficient animal feed and animal-based food is possible through the integration of agroecological or agroforestry principles, especially when the development of novel foods with lower nitrogen footprint is promoted.

To support dietary changes towards healthy, environmentally friendly produced food, consumer-oriented instruments are available for public authorities, civil society or private actors. Two examples include policies that encourage the food industry to reformulate processed food products reducing the contents of unhealthy ingredients and public food procurement to increase availability of more sustainable options for the public.

So far there has been little implementation of taxes and subsidies that address the environmental impact of foods. A combination of coherent policies can promote healthier and more sustainable food environments empowering consumers towards sustainable food choices.

A priority is to update and implement effectively national food-based dietary guidelines (FBDGs) that include sustainability aspects to help consumers make healthier and sustainable food choices. These are promising instruments that can guide coherent national policies, institutions, and the public towards healthy diets from sustainable food systems.

This report adds evidence for the need and the benefit of food system transformation to a sustainable agri-food system providing healthy diets for people while caring for the planet.

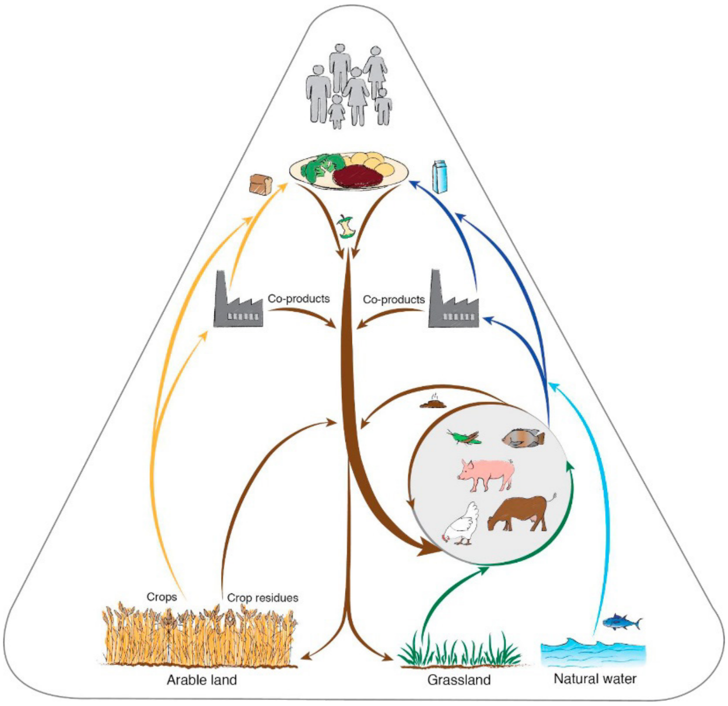

Figure ES.6. *Illustration of a sustainable agri-food system providing healthy diets for people while caring for the planet. A reduced share of meat and dairy in Europe is envisaged as allowing livestock to be primarily fed from food-waste and residues/co-products that are not directly edible for humans. Source: Van Zanten et al. (2019), reproduced here under CC BY-NC-ND 4.0, https://creativecommons.org/licenses/by-nc-nd/4.0/.*

Part A

Food systems today: A health and nitrogen perspective

Chapter 1. Nitrogen and food systems

Adrian Leip, Roberta Alessandrini, Nicholas J. Hutchings and Hans J.M. van Grinsven

- Food is vital for human health and wellbeing, while an appropriate supply of reactive nitrogen is essential for food production.
- Leakage of reactive nitrogen from food systems threatens the environment and human health. Nitrogen use efficiency of the EU food system was only 18% in 2015.
- Solutions to reduce nitrogen pollution from the food system will make the food system more resilient and efficient, and help to provide healthy diets for all. Capitalizing on synergies between different policies is crucial for achieving food system sustainability.
- Considering the role of nitrogen, 'sustainable food systems' can be defined as those that use nitrogen efficiently throughout the food system, without compromising planetary and human health, while also respecting ethical and cultural standards.
- Increasing sustainability of the livestock sector and reducing consumption of animal-based food are crucial for improving sustainability of the EU food systems.
- Holistic and integrated food system policies are needed to keep nitrogen within a 'safe operating space'. A food systems strategy that considers ambitious reduction targets for nitrogen pollution will deliver multiple environmental and health co-benefits.
- **Key policy message: There are significant interconnected challenges to achieve sustainable nitrogen management and a sustainable food system. To find the most powerful leverages, policies need to be food-system based and holistic.**

1.1 Introduction

Plants need an appropriate supply of reactive nitrogen (N_r) to grow. With an increasing global human population and increased per capita intake, inputs of N_r into agriculture have increased in the last decades to produce more food for humans and more livestock feed (Heffer and Prud'homme, 2016).

The mobility of N_r that enables its uptake by plants also means it can easily be lost to the environment. As a consequence, agricultural activities are intrinsically linked to the use and loss of reactive nitrogen, including both intended and unintended nitrogen flows (Galloway *et al.*, 2003; Sutton *et al.*, 2011a, 2011b,). Examples of intended use of N_r are the use of fertilizers on crops to increase yields, the cultivation of crops that increase rates of biological nitrogen fixation, and the feeding of animals with fodder crops and protein rich feed (FAO, 2018a; Sutton *et al.*, 2013). Unintended losses of N_r occur throughout the food system, for example from management and application of manure or from grazing animals. The application of mineral nitrogen fertilizer and organic manures also leads to losses of N_r, both to the atmosphere and to ground and surface waters.

Food is the most prominent human need (Creutzig *et al.*, 2022; Raworth, 2017). Food systems increase the risk of exceedance of several of the 'planetary boundaries', which represent high-level estimates of sustainability limits for different global threats (Rockström *et al.*, 2020). At the same time, nitrogen losses contribute to multiple global and local threats to environmental and human health. Nitrogen transformations happen in a so-called 'cascade' of intended uses and unintended losses that are intertwined with other global biogeochemical cycles with numerous feedback loops (Fowler *et al.*, 2013; Galloway *et al.*, 2003). For example, nitrous oxide (N_2O) is a powerful greenhouse gas for which managed soil is the main source of emission to the atmosphere. Agriculture, including both cultivation of arable crops and livestock rearing, is the main source of ammonia (NH_3) emissions to air that contribute to terrestrial acidification, eutrophication of natural and semi-natural ecosystems, and the formation of harmful air-borne fine particulate matter ($PM_{2.5}$) pollution. Aquatic pollution from agriculture as nitrate (NO_3^-) and other organic nitrogen forms pollute drinking water supplies, fresh waters and coastal waters. The resulting 'eutrophication' of fresh and marine waters refers to the way that additional nutrients lead to increased growth of undesirable organisms such as algae, the turn-over of which can ultimately deplete oxygen levels and kill aquatic organisms. Achieving net negative greenhouse gas emissions, reversing biodiversity loss in terrestrial and aquatic ecosystems, and reducing nitrogen pollution have been suggested to be the most urgent global environmental challenges the world faces today (Ripple *et al.*, 2019; Rockström *et al.*, 2020).

Concerning impacts on human health, emissions of ammonia and nitrogen oxides (NO_x) are precursors for air pollutants harmful for humans. NH_3 and NO_x react together, or with SO_x, to form aerosols. Together with direct emissions of particulate matter, they are causing health problems such as cardiovascular and respiratory diseases. Further, NO_x is a precursor for ground level ozone, which also causes respiratory diseases (Townsend *et al.*, 2003). Air pollution ranks among the four main risk factors for global attributable deaths (GBD 2019 Risk Factors Collaborators, 2020), a substantial fraction of which is due to nitrogen pollution. There are clearly identified health consequences of nitrates and nitrites in drinking water and food, although some positive effects have also beenben identified (Kalaycloğlu and Erim, 2019; Schullehner *et al.*, 2018; Zhang *et al.*, 2019) (see Chapter 2).

Nitrogen is one of the chief ingredients for food and life. It is the essential building block that characterizes amino acids and proteins as compared with carbohydrate, but also chlorophyll, haemoglobin and DNA. At the same time, nitrogen is a major nutrient that is affected by food system actors' behaviours. **Considering the role of nitrogen, 'sustainable food systems' can be defined as those that use nitrogen efficiently throughout the food system, without compromising planetary and human health (see Chapter 2), while also respecting ethical and cultural standards.** Chapter 3 explains how a range of food system types meet this definition of a sustainable food system. The present chapter introduces the concepts of sustainable food systems, and the role that nitrogen plays in them.

1.2 Sustainable food systems

- Sustainable food systems guarantee the availability, affordability, accessibility and safety of food for all through robust food value chains; they thrive economically, while contributing to a healthy diet and a just, ethical and equitable society.
- The nitrogen-food system complex can be analysed by looking at material and governance perspectives of food system spheres. A food system strategy with a nitrogen lens and ambitious pollution reduction targets will deliver multiple environmental and health co-benefits.

According to the UN High-Level Panel on Food Security (HLPE, 2017), a food system "*[..] gathers all the elements (environment, people, inputs, processes, infrastructures, institutions, etc.) and activities that relate to the production, processing, distribution, preparation and consumption of food, and the output of these activities, including socio-economic and environmental outcomes*."

Sustainable food systems ought to encompass environmental, social/cultural and economic sustainability dimensions, including four core objectives:

(1) to provide enough, adequate, affordable, safe and healthy diets for all;

(2) to contribute to a clean and healthy planet;

(3) to be economically thriving and supportive of the common good; and

(4) to contribute to just, ethical and equitable societies (Hebinck *et al.*, 2021; Zurek *et al.*, 2018) (See Chapter 9).

Sustainable food systems contribute to global food security and nutrition in all their dimensions. They ensure that "*sustainable healthy diets*" (FAO and WHO, 2019) needed for optimal nutrition are available, affordable, acceptable, desired, safe and of adequate quantity and quality, while at the same time conforming with the beliefs, culture and tradition of individuals (HLPE, 2020).

Regarding the relevance of nitrogen in food systems, two perspectives are pertinent: the material perspective and the governance perspective.

The ‘material perspective’ looks at material stocks, flows, transformations and biophysical impacts that are present in food systems following the stages of food value chains. The ‘governance perspective’ on food systems shows how relative control and power over resources and core functions are distributed across actors in the food system.

Food system spheres (Box 1.1) allow the analysis of complex food systems, and the interactions between their elements and with the external world. These elements can be food system actors, food system pools (c.f. UNECE, 2010), or food system functions (see glossary in Leip *et al.*, 2021a). A description of food system spheres and their functions in a food system is provided in Box 1.1. Interactions between food system ‘spheres’ are illustrated in Figure 1.1. From a material perspective, spheres can be interpreted as nitrogen ‘pools’, with nitrogen flowing between the spheres (Figure 1.1a). From a governance perspective, spheres can be interpreted as ‘centres of power’, with arrows indicating strength of the influence they are exerting (Figure 1.1b).

Box 1.1. *Food system spheres in food systems. Adapted from Leip et al. (2021a).*

- **Environment:** delivers natural resources and raw materials (land, water, fossil fuels, etc.) and receives waste materials (organic and non-organic wastes, and chemical wastes/pollutants).
- **Primary food production:** produces plant, animal, and microbial products that are partly or fully destined for human nutrition. The primary food production sphere includes all industries producing inputs required for food production, such as fertilizers, agro-chemicals and machinery.
- **Food processing, marketing and distribution:** includes all functions that use primary food commodities and convert them to food products until they are sold from retail outlets. Food that the producer consumes or sells directly to the consumer is not channelled across food processing and distribution sphere.
- **Food preparation and consumption:** includes food preparation and ingestion as well as any transportation and storage in households or food services.
- **Residue management:** residues include food losses and ‘wastes’ as food residues, as long as they are still in a form that allows them to be valued within or outside the food system (e.g,. as recycled nutrients or to produce any other product). Residue management also includes management of non-organic residues (e.g., plastics, glass) that can be reused or recycled.
- **Policy-making:** including regional, national and international governments, conventions, and regulatory institutions.
- **Other actors:** including civil society, research and innovations, media and education, and public or private advisory systems.

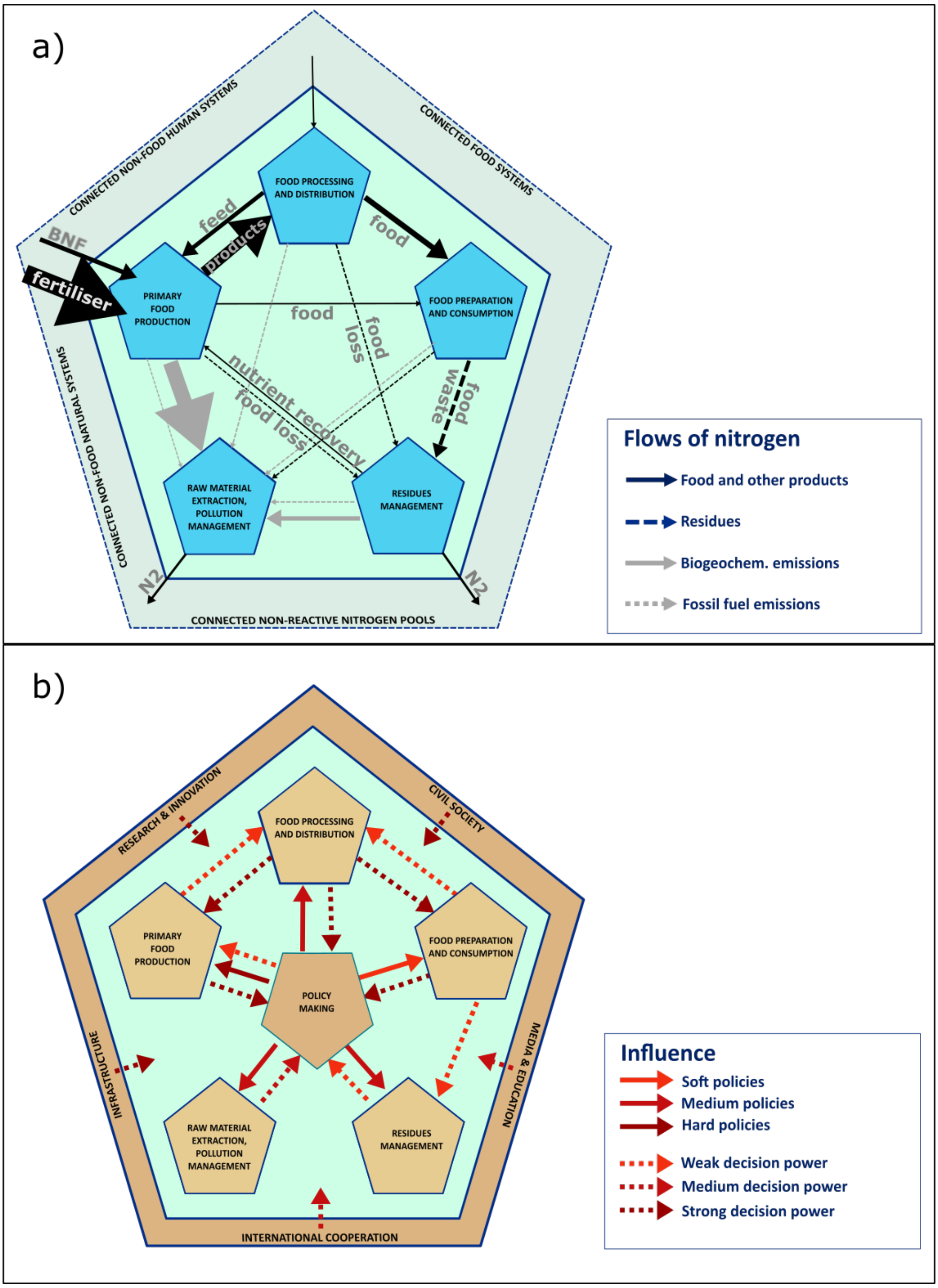

Figure 1.1. *Comparison of a 'material flow perspective' and a 'governance perspective' of food systems. Source: adapted from Leip et al., (2021a), under CY BY 4.0, https://creativecommons.org/licenses/by/4.0/.*
a) The material perspective is illustrated by nitrogen flows between the five food system spheres (blue pentagons) and across the food system boundaries (e.g., a food system from a different country or region where some functions are carried out by the same actors) and non-food systems. Widths of arrows are proportional to the nitrogen flow rate as estimated for the EU food system (Corrado et al., 2020; Leip et al., 2014, 2015), with minimum arrow size corresponding to 1 Mt N yr^{-1}. Black arrows: intended flows; grey arrows: unintended emissions of reactive nitrogen from biogeochemical processes or fossil fuel. BNF: biological nitrogen fixation.
b) The governance perspective shows food system spheres (orange pentagons), with governance actors indicated with red arrows, using solid lines for governmental regulations and policies (Latka et al., 2020; Temme et al., 2020), and dotted lines for other influences (decision-making power). Influences are also exerted from other relevant elements of social setting indicated in the outer orange pentagon (Leip et al., 2021a).

1.3 A new nitrogen budget for the EU food system

- A nitrogen (N) budget for the EU agri-food system has been calculated here for around 2015. In 2015, the EU used 19 Tg of virgin (new) N and 1 Tg N of soil N to deliver 2.5 Tg N in food to consumers and 1.2 Tg N in non-food products, yielding a food-system nitrogen use efficiency (NUE) of 18%. By including the food system output of 1.6 Tg N of by-product for pet-food and biorefineries the NUE increases to 27%.
- The EU food system wasted 17 Tg N per year, 85% of them inside the EU and 15% outside of the EU. About 78% of N losses was reactive N pollution; 22% was wasted by reconversion to N_2 or solid waste.
- Nitrogen use efficiencies depend on system boundaries. The conventional food system NUE does not account for N losses occurring in agriculture outside the EU for feed and food imports. Assuming a NUE of 50% these losses amount to 2.6 Tg N; ignoring them would increase the NUE of the EU food system to 21% when only considering main products, or 31% if by-products are also taken into account.
- The NUEs of EU crop, livestock and total agriculture in 2015 were estimated at 63%, 16% and 37%, respectively, considering virgin N requirements for imported feed.
- The conventional NUE of 21% excluding and 31% including by-products for 2015 is consistent with the NUE of 25% for 2004 as in the 2015 'Nitrogen on the Table' report. Our reported NUEs use updated data and have been corrected for N flows associated with non-food crops (1.2 Tg N), soil N losses, and consider re-deposition of agricultural losses. As a result, the total N loss estimated from agriculture is 17.1 Tg N as compared to the 13.3 Tg estimate for 2004.
- Expressed as lost fertilizer value, using a nominal price of €1 per kg N, the nitrogen losses wasted from the EU food system amount to a value of €17 billion annually. With the Common Agricultural Policy (CAP) costing member states c. €56 billion in 2015, the nitrogen loss is equivalent to almost one third of EU agricultural expenditure. The societal cost of pollution caused by the nitrogen loss is in the order of €100 billion.
- With current food choices, the livestock sector is the most N inefficient part of the food system. Therefore, only efforts to develop a holistic and integrated food system policy will succeed in keeping nitrogen within its safe operating space.

Increased crop yields per hectare are one pathway to meet current, and still increasing, demands of food, feed, fibre and (bio)fuels, but require the continuous addition of newly fixed or 'virgin nitrogen' to agricultural land. This increases the risk of losses to the environment. The utilization of added N is incomplete, with the nitrogen use efficiency (NUE, here defined as the nitrogen reaching the product as a percentage of the nitrogen input) tending to decrease with increasing N inputs per hectare (cf. Leip *et al.*, 2019). Not all N_r added to the soil reaches the crop roots, due to gaseous losses, and not all the N_r taken up by crops is partitioned to harvestable parts. A proportion remains in the soil as crop residues and because agricultural soils are in open connection to air and water, a part of this residual N_r is lost to the environment. The leakiness of the crop-soil ecosystem means that if crop yields are to be maintained, these losses need to be replaced by adding virgin N_r. The losses are substantial, with agriculture accounting for > 90% of EU ammonia emissions and the majority of N_r losses to the hydrosphere (Leip *et al.*, 2015), while energy consumption leads to the majority of nitrogen oxide (NO_x) emissions (Sutton *et al.*, 2013).

A new nitrogen budget for the EU agri-food system and its four subsystems was estimated for around 2015 (Leip *et al.*, 2022): (1) agriculture; (2) food processing and distribution (referred to as the 'food chain' and including the handling of by-product for recycling and other uses); (3) food consumption (including food services); and (4) management and treatment of residues/wastes from subsystems (2) and (3). The main inputs for the agriculture subsystem (1) were Eurostat data for the gross nutrient balance[1] for the year 2014, while N flows in 2011 by Corrado *et al.* (2020) were used for the three other subsystems.

[1] *Meta data: https://ec.europa.eu/eurostat/cache/metadata/en/aei_pr_gnb_esms.htm; data extraction http://appsso.eurostat.ec.europa.eu/nui/show.do?dataset=aei_pr_gnb&lang=en. Last update 24.02.20, extracted on 04.09.20.*

We estimate that more than 19 Tg of virgin N was needed to feed the population of the EU (Figure 1.2), plus 1.0 Tg released from soil reservoirs. An estimated 5.2 Tg N of this input came from outside the EU half of this embedded in imported feed and food and the other half in N inputs needed to grow the underlying crops. Feeding the EU population causes a total loss of N to the environment of more than 17 Tg N, of which 2.6 Tg N occur outside of the EU. About three quarters of N losses were in reactive forms (mainly nitrate and ammonia).

The total N loss from EU agriculture in 2015 was 13.2 Tg N—similar to the value of 13.3 Tg N estimated for 2004 by Westhoek *et al.* (2015; Fig. 5.7) in the first TFRN Special Report 'Nitrogen on the Table'.

The N budget for agricultural land in 2000 compiled for the 'European Nitrogen Assessment' (Leip *et al.*, 2011; Sutton *et al.*, 2011a) had a negative N balance of 2.6 Tg N implying soil depletion, which would be in accordance with decreasing trends in nitrogen fertilizer use, which is higher than our estimate of 1 Tg N yr^{-1}.

In the 2015 N budget for the EU agri-food system (including consumption), the total N input of 20 Tg N was transferred to supply 2.5 Tg N yr^{-1} in food (which remained in the system), and a delivery of 2.8 Tg N of non-food products and residues for use outside the food system. 10.9 Tg N was lost in the EU to the environment as N_r and 3.2 Tg N denitrified to N_2, 0.4 Tg N was landfilled, and 2.6 Tg N was lost to the environment outside the EU.

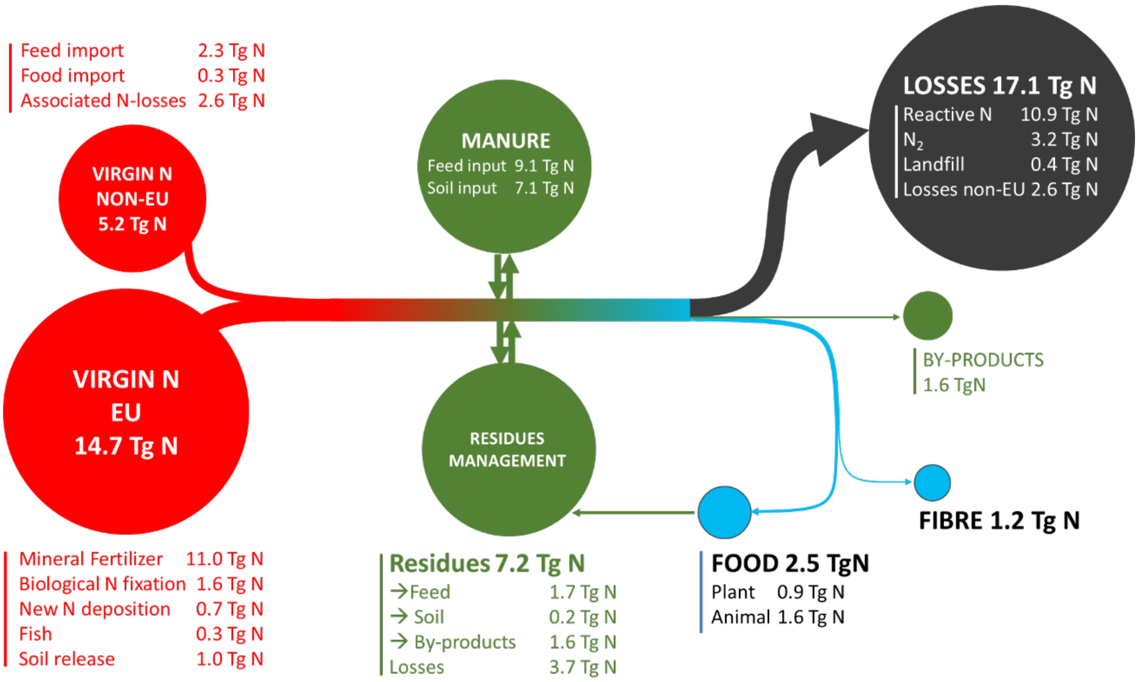

Figure 1.2. *Consolidated nitrogen (N) budget for the agri-food system of the European Union around 2015, based mainly on data from Eurostat, Corrado et al. (2020) and system definitions by Westhoek et al. (2015). Quantities are reported in Tg. Source: adapted from Leip et al. (2022), under CC BY 4.0, https://creativecommons.org/licenses/by/4.0/.*

Food system: The NUE of the overall food system uses 18.9 Tg N of virgin N plus 1.0 Tg N of N released from soils to provide 3.7 Tg N in food and fibre resulting in a NUE of 18%. The NUE increases to 21% if embedded losses of food and feed imports are ignored, which is conventionally done. Quemada *et al.* (2020) is one of the few studies to include virgin N for imported feed in NUE for benchmarking dairy systems across Europe. Results showed that this corrected 'real' system NUE was similar for dairy systems in France, Ireland, Denmark and the Netherlands, while the conventional NUE was not. Taking into account N in by-products for other uses (e.g., in pet-food or biorefineries[2]) increases NUE to 27% (with non-EU emissions) or 31% ignoring them. While NUE is a widely used and informative performance indicator for policy support, its value depends on system boundaries and what are considered N inputs and useful outputs. Therefore, caution is needed when comparing NUEs from different studies for different systems (EU Nitrogen Expert Panel *et al.*, 2015).

[2] *Refineries convert biomass to energy and other beneficial by-products.*

Crop system: Nitrogen (N) input from virgin and recycled N to agricultural land in the EU to feed the EU population in 2015 was 22.9 Tg N. This amount includes inputs for the extraction of 1.2 Tg N in non-food crops. The N removal in crops to feed the EU population, directly and indirectly (including grass and forages), was 14.5 Tg N, resulting in a nitrogen use efficiency (NUE) of the EU agricultural land of 63% (as net output in crops over total inputs). Virgin N inputs for food amount to 13.4 Tg N (synthetic fertilizer, biological fixation and N deposition from NO_x formed by combustion of fossil fuel) and constitute 58% of total N inputs to agricultural land for food. The remaining 42% are recycled N inputs of 9.5 Tg N (with manure N as the largest proportion, and smaller contributions by N released from soils, re-deposited ammonia and other organic fertilizers).

Animals: EU livestock uses 13.1 Tg N in feed (9.1 Tg from feed produced in the EU and 2.3 Tg from imported feed, with large contributions by cakes of soy from Latin America and maize from Ukraine) and an additional 1.7 Tg N in by-products of the food chain and food consumption subsystems, to deliver 2.5 Tg N in animal products to the food chain. This results in a NUE for livestock at 19%, which reflects the low feed conversion efficiencies in animal production as compared to crop production. When recyclable N residues in applied or deposited manure of 7.1 Tg N are also included as useful outputs, the NUE increases to 73%, however this does not account for additional losses on soils due to inadequate use of the nutrients (Leip *et al.*, 2019).

Agricultural system: For calculation of the NUE for total EU agriculture, N in crop and animal products are considered in the numerator of NUE (7.8 Tg N), giving a NUE of 37% considering virgin N of 21.0 Tg N as mineral fertilizer, imported feed including 2.3 Tg N of virgin N losses caused by imported feeds, biological N fixation, and non-agricultural N deposition. The NUE increases to 41% if 1.1 Tg N_r losses that are assumed to re-deposit on agricultural fields are included in in- and output[3].

These various definitions and outcomes illustrate possible confusion raised by using NUE as a performance indicator and may hide underlying discussions on what is considered a useful product in food production, and the justness of externalizing inefficient and potential polluting steps in food production. Commonly, an increase in the NUE of agriculture over time is observed in high income countries (Zhang *et al.*, 2015) and reflects the combined effect of environmental policy, which tends to decrease the use of synthetic fertilizer, and of improved nutrient and crop management.

Food chain: The N_r in the food, either produced in the EU or imported, is processed, retailed and finally consumed in food services or at home. Reactive nitrogen emissions from food-processing and distribution are small (0.8 Tg N) and most N is recycled to agricultural production as organic fertilizers (here 0.2 Tg N) or animal feed (1.7 Tg N). Households and food services waste 1.2 Tg N. A substantial part (1.6 Tg N) is recycled for other uses, e.g., pet-food, garden compost, or biorefineries. From the gross input of 7.2 Tg N that enters the food chain, 2.5 Tg N are consumed, giving a NUE of 35%, while 3.5 Tg N leave the food system as by-products. Taking into account food and by-products gives a NUE of 84%.

Table 1.1 summarizes the nitrogen use efficiencies (NUEs) for the agri-food system of the European Union in 2015 and underlying subsystems according to the data shown in Figure 1.2.

Table 1.1. *Nitrogen use efficiencies (NUE) for different parts of the agri-food system of the European Union in 2015 and underlying subsystems.*

	NUEc	**NUEv**	**NUEvr**
Crops	63%	**63%**	
Animals	19%	**16%**	73%
All agriculture (crops and livestock)	42%	**37%**	41%
Processing & distribution		35%	**84%**
Food system	21%	18%	**27%**

NUEc is the 'conventional' NUE not accounting for embedded emissions of food and feed imports; NUEv considers these losses where relevant (agriculture, food system); NUEvr also considers by-products for the livestock system (manure) or the food system (pet-food, other uses). Calculations as explained in the text. The values we consider as

[3] *This is then added to both in- and output and the formula becomes: NUE = (7.8+1.8)/(17.5+4.9+1.8)=0.40.*

the most 'correct' are marked in bold: NUEv for agricultural (sub)systems and NUEvr for the food chain/system. Source: Leip et al. (2022), under CC BY 4.0, https://creativecommons.org/licenses/by/4.0/.

1.4 Economic impact

The total food system N losses to the environment in the EU in 2015 thus was estimated at 14.5 Tg N as N_r (10.9), N_2 (3.2) or landfilled (0.4). The societal cost of N pollution by ammonia and nitrate from agriculture in the EU27 in 2008 was estimated at 61–215 billion €. Using the marginal damage costs as derived by (Van Grinsven *et al.*, 2018), the N_r loss in 2015 would represent a societal pollution cost in the order of €100 billion. While the 3.2 Tg N loss as unreactive N_2 does not cause pollution, it represents a waste of valuable N_r resources and also contributes to low N use efficiency, ultimately requiring more N_r inputs that end up increasing total N_r pollution. The total N loss 17.1 Tg N represents a fertilizer value of about €17 billion using fertilizer prices around 2015. Though some N loss is inevitable, and zero emission productive agriculture is not feasible, there are substantial mitigation potentials (see Chapter 4).

With current food choices, the livestock sector is the most N inefficient part of the food system. Therefore, the largest potential to increase N efficiency given the current N demand of the current agri-food system lies in the livestock sector, by improved breeding and feeding and improved manure management, processing and recycling, or through different food choices. The potential to reduce N loss in wastewater treatment is also significant as it is responsible for about a fifth of N emissions. A major challenge to increase the NUE of the EU food system is to further prevent N_r and N_2 losses from treatment (incineration and anaerobic digestion) of human wastes and reuse the N, e.g., as fertilizer. The 3.3 Tg N loss represents a virtual fertilizer value of €3 billion, but costs and legislative issues associated with recycling N from human are not to be underestimated.

1.5 Significance of animal-based food for environment and health

- The high demand for animal-based food contributes significantly to the unsustainability of the current food system across Europe and in many other parts of the world.
- Reducing animal-based food consumption and production could improve human health.

During the past century, the production of and demand for animal-based food has increased substantially in Europe and many other world regions (Chapter 2). A large body of evidence indicates that animal-based food production, in particular ruminant meat, comes at a high environmental cost, as producing animal-based food requires more land and water, and emits more greenhouse gases and reactive nitrogen than most plant-based food (Leip *et al.*, 2015, 2014a; Poore and Nemecek, 2018).

Animal-based food production systems also have a range of direct and indirect implications on human health (Figure 1.3). An increased availability of animal-based food can impact nutritional outcomes—both positively and negatively—according to the context (FAO, 2015). For poor and vulnerable people in most low-income countries, where dietary diversity is low, and for population groups with higher nutrient requirements, such as infants and women of reproductive age, small quantities of animal-based foods can improve the nutritional adequacy of their diets, providing essential micronutrients, such as iron and zinc, and protein (FAO, 2015). On the other hand, in high-income countries, diets are varied, and animal-based food consumption is well above the recommended intakes to prevent micronutrient nutrient deficiencies (Mensink *et al.*, 2013).

Meat is also one of the most important dietary sources of salt and saturated fat. These are well-established risk factors for cardiovascular disease, which is the top cause of mortality in the EU (Eurostat, 2020a). In addition, excessive red and processed meat consumption has been linked to an increased risk of colorectal cancer (Bouvard *et al.*, 2015).

Animal-based food production, and in particular ruminant meat, can have detrimental impacts on human health in several other ways. Figure 1.3 summarizes some of these indirect impacts. Livestock production systems result in increased water and air pollution from wasted nitrogen compounds (Westhoek *et al.*, 2015). In the past excess nitrates in drinking water were primarily linked to an increase in the risk of blue baby syndrome (i.e., methemoglobinemia), but currently increases of colorectal cancer, thyroid disease, and neural tube defects (Fossen Johnson, 2019; Ward *et al.*, 2018) are considered far more important causes of increased morbidity and mortality in Europe (Van Grinsven *et al.*, 2018; Schullehner *et al.*, 2018). Nitrogen air pollutants such as NH_3 and NO_x are precursors of tropospheric ozone and fine airborne particular matter (>10 µ), which can have long-term negative impacts on respiratory health and increase the risk of cardiovascular disease and some cancers (Landrigan *et al.*, 2018; Lelieveld *et al.*, 2020).

In addition to the pollution effects, the excessive use of antibiotics in the livestock sector has been identified as potentially one of the major key drivers of antimicrobial resistance (Tang *et al.*, 2017). Currently, available antibiotics are becoming gradually ineffective in treating infections such as pneumonia, tuberculosis, gonorrhoea, and salmonellosis in humans (WHO, 2020). Increasing demand for animal protein and unsustainable livestock intensification has also been identified as a key driver for the emergence of new zoonotic disease (United Nations Environment Programme and International Livestock Research Institute, 2020).

Dairy farming, meat processing, and slaughtering are regarded as high-risk jobs as they involve physically hard and repetitive work at a high pace and with a high risk of injury and disability (Douphrate *et al.*, 2013; Hansen, 2018). Statistics from the UK indicate that an employee in the slaughtering sector is three times more likely to become injured than the average person at work (Hansen, 2018). Those working in animal farming are also more likely to develop mental health disorders, e.g., perpetration-induced-traumatic stress, than the average person at work; symptoms can include depression, paranoia, panic, and dissociation (Taylor *et al.*, 2013; Victor and Barnard, 2016). Recent data indicate that those working in slaughterhouses and meat packing facilities were also more likely to develop Covid-19 (Marchant-Forde & Boyle, 2020; Taylor *et al.*, 2020).

Policies aimed at reducing animal-based food production and consumption, while increasing other production and employment opportunities, could therefore have multiple benefits for animal and human health. This also makes a strong connection to the idea of 'one health', which is a way of looking at the connection between human, animal and plant health and their shared environment (Patterson *et al.*, 2020).

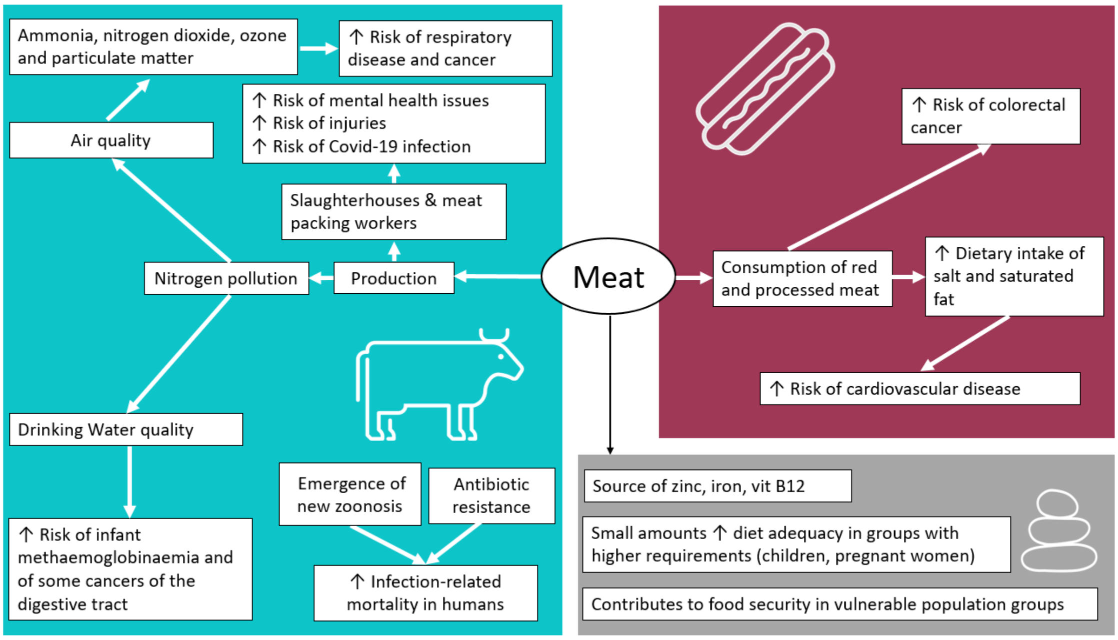

Figure 1.3. *Relationship of nitrogen to other health effects of meat production and consumption. Source: created for this report by the authors.*

1.6 Imbalances of power in the global food system and their consequences

- There are major imbalances of power in the food system which can constrain the ease with which food system actors are able to adopt sustainable practices. Nitrogen reduction options remain untapped if such imbalances (or 'asymmetries') in food supply chains are ignored.
- Although most nitrogen emissions occur at the farm scale, it does not mean policies have to target farmers first. There are major opportunities to reduce emissions by increasing engagement about nitrogen with citizens, and the food commodity, processing and retail sectors.
- Nitrogen pollution is affected by many policies, and nitrogen policy impacts on others. It is important to consider the wider consequence of more sustainable nitrogen use.

Most of the nitrogen losses from the food system occur at the farm scale, and as a result current European food system policies for the environment mainly target primary producers (Kanter *et al.*, 2020a; cf. Chapter 2). However, primary producers typically have relatively little influence on the structure and management of the entire food system (European Comission, 2020b; Jackson *et al.*, 2021; Leip *et al.*, 2021a). The shape of the European food environment is largely controlled by the food commodity, processing and retail spheres, which are dominated by relatively few large companies. These companies influence consumer demand, but are also able to exert a strong influence on agricultural producers (Fałkowski *et al.*, 2017).

This imbalance of power in the food system (sometimes termed 'asymmetry of power') between many small producers and a smaller number of large companies has major consequences for nitrogen and other pollution threats. In particular, it reduces the extent to which consumers are currently confronted with the environmental, health and social costs of food production at the point of sale (Jackson *et al.*, 2021). At the same time, farmers are not encouraged to invest in environmental measures, as they are unable to recoup the investment through higher prices for their products (Eigenraam *et al.*, 2020; The Economics of Ecosystems and Biodiversity (TEEB), 2018). A notable exception is organic farming, where farmers may achieve a higher price through 'package marketing' of a certified label. However, in general, there are major obstacles to consumers wishing to make sustainable healthy choices. Healthy and sustainable food is generally more expensive, more difficult to access, and adequate and transparent information is mostly missing (Clapp, 2019; FAO *et al.*, 2020; Folke *et al.*, 2019; European Comission, 2020b, 2020; Howard, 2016; Penne and Goedemé, 2020; Temme *et al.*, 2020).

Data on the proportion of disposable income spent on food (Figure 1.4) show that the proportion of income spent on food is smallest in the countries with the highest per capita disposable income and vice versa. If the long-term trend for the EU population to increase in wealth continues (Eurostat, 2020b), the price of food is likely to become less important for many citizens (Latka *et al.*, 2020). Environment and other sustainability aspects may increase in importance, in addition to food safety, which is recognized as the most important factor determining food choices (Eurobarometer, 2020). However, in poorer countries (Figure 1.4) or for poorer citizens in rich countries (DEFRA, 2021), food accounts for a substantial proportion of household expenditure, leaving them vulnerable to economic shocks, such as the current energy crisis. Data show an exacerbation of inequalities and an increased risk for global food security, pointing to the need to prioritize social protection systems and policies making food systems more "*effective, inclusive, resilient and nutritious*" (Carducci *et al.*, 2021).

Losses of reactive nitrogen from food systems are of concern primarily for their environmental impact (Sutton *et al.*, 2019a; UNEP, 2019). In parallel, many other policy areas are connected to food systems and have the potential to impact on the losses of reactive nitrogen. There is concern about the role of food production on a wide suite of environmental issues, such as climate change (and the impact that climate change will have on agricultural production) and loss of biodiversity via habitat destruction, pesticide and herbicide use. Other concerns include the decline in rural population across Europe and the role of food system practices on human health and safety, including the working conditions of migrant workers and animal welfare issues. Many of those issues are in the focus of food system policies (see e.g., the EU Farm to Fork Strategy, European Commission, 2020a). Therefore, paradoxically, the most effective measures to reduce nitrogen pollution might be developed in a sector other than the environment.

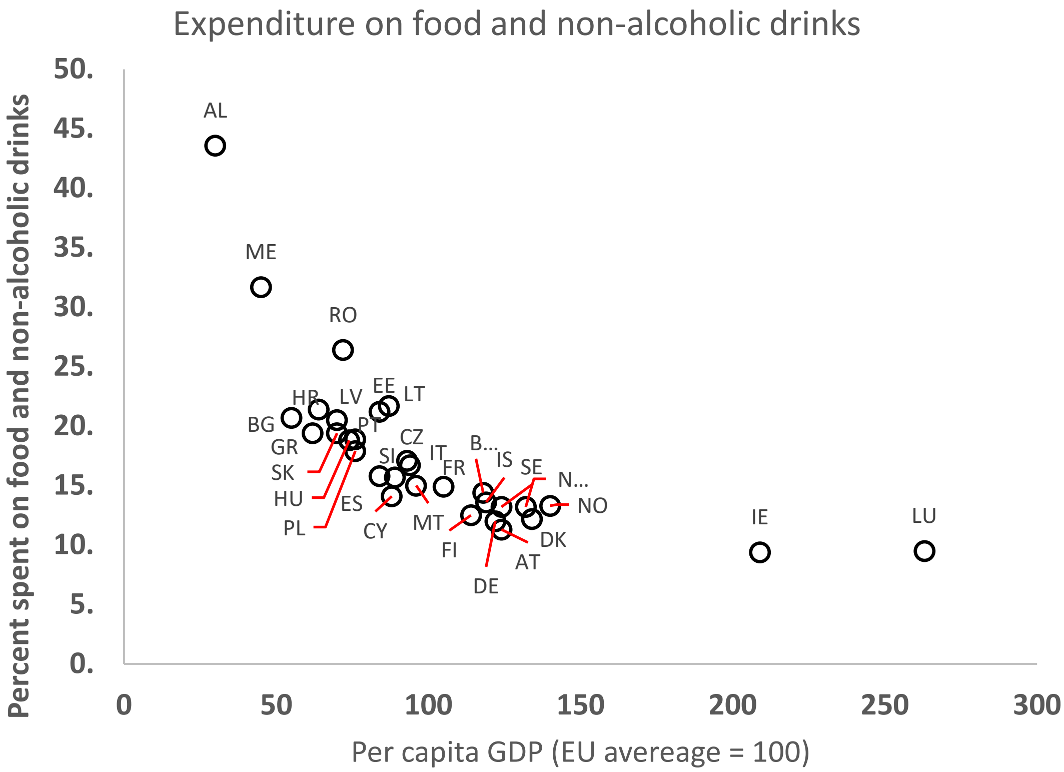

Figure 1.4. *Expenditure on food in 2020. Source: Eurostat https://ec.europa.eu/eurostat/web/products-datasets/-/TEC00134 (data extracted on 11/09/2022). Country codes ISO 3166-1 alpha-2. Figure created for this report by the authors.*

1.7 Conclusions

Nitrogen and food systems are unthinkable without each other—for better or worse. This means that solving problems related to nitrogen pollution goes hand-in-hand with the need to make food system more sustainable (Metson *et al.*, 2021).

Transforming the food system will require acknowledgement of the shared responsibility of all food system spheres (Swinburn, 2008). It will similarly require a realignment of the power structure within food systems (Leip *et al.*, 2021a). There is a need to reconsider food as a common good rather than just a commodity (European Comission, 2020b; Jackson *et al.*, 2021). The power to make decisions concerning the European food system has increasingly been concentrated in relatively few large 'players', and there is a need for a redistribution of this power, to permit a remodelling of the European food system to increase its economic and environmental sustainability for both its human actors and the environment.

In the process of food system transformation, much can be learned from the comprehensive and holistic approaches needed to tackle the cascading complexity of nitrogen losses and to develop sustainable nitrogen management (Metson et al., 2021; Sutton *et al.*, 2019a; UNEP, 2019). Therefore, such a remodelling needs to acknowledge the role of reactive nitrogen in the production of food and the threats to human and planetary health.

Considering the food system nitrogen budget of the EU, addressing the high consumption of animal-based food is one key for finding solutions. Production and consumption of animal-based food in Europe has the lowest efficiency and makes the highest contribution to nitrogen pollution. At the same time, a high intake of these foods, particularly red and processed meat, is associated with public health threats. Reducing the consumption of animal-based food would reduce reactive nitrogen pollution and help achieve healthier diets. Nitrogen flows in the European food system have changed dramatically over the last 70 years, but the reduction of high N inputs at the end of the 20th century has stagnated in the past decade. Similarly dramatic changes are needed now, if the needs of the human population and those of the planet are to be balanced.

Box 1.2. *Research needs related to nitrogen and food systems.*

- The potential of policy instruments aimed at improving food environments and/or targeting food and retail companies in improving access of consumers to healthier diets and farmers to more sustainable and profitable production practices must be better understood and quantified.
- Analyses on the feedbacks between food systems and intersecting non-food systems are required to identify synergies and trade-offs.
- Understanding the behavioural patterns behind decisions made by both consumers and producers is crucial for helping develop integrated approaches for improving nitrogen management, including social and environmental food system outcomes.
- Better quantification of food system nitrogen flows is needed to reduce uncertainties, especially regarding retention/depletion of N in soils, as well as estimation of N content in food commodities, processed foods and food residues.

Chapter 2. Nitrogen in the food system: health and environment implications

Roberta Alessandrini, David R. Kanter, Benjamin L. Bodirsky, Ivanka Puigdueta and Alberto Sanz-Cobeña

- Nitrogen's dual role as an essential nutrient and major pollutant in the European food system has important health and environmental implications for European society and the ecosystem services on which it relies.
- The main dietary risk factor directly associated with high nitrogen use and loss levels is high red meat consumption. Addressing it could help improve nitrogen management and reduce nitrogen losses.
- Plant-based diets correlate with lower nitrogen footprints and positive health outcomes.
- Increasing the share of legumes in food production and consumption needs to be part of a food system policy.
- **Key policy message: Nutrition sensitive agricultural and food policies are needed to promote healthy and sustainable diets. Such diets should be rich in plant-based foods and low in animal-based food, especially red and processed meat.**

2.1 Introduction

The 'synergy of pandemics'—the simultaneous occurrence of obesity, undernutrition and climate change—affects most people worldwide, shares similar societal drivers and requires collaborative solutions (Swinburn *et al.*, 2019). A similar 'syndemic' arguably exists with regards to protein undernutrition, protein overconsumption, and nitrogen (N) pollution. Also in this case, the three problems affect people globally, are interlinked in a complex way, share similar drivers, and require collaborative solutions at different scales and with the participation of several actors (e.g., farmers, consumers, policy makers, see Chapter 1). Undernutrition, due to a lack of protein, is a risk factor for large population groups in low-income countries. In the European Union (EU), protein malnutrition is prevalent in the elderly (Leij-Halfwerk *et al.*, 2019). At the same time, overconsumption, especially of animal-based and highly-processed food, is a phenomenon that can be observed in most middle and high-income countries across the world (Bodirsky *et al.*, 2019) and poses a severe health risk in the EU. Nitrogen pollution causes severe health threats, ranging from air pollution in the form of ammonia (NH_3), oxides of N (NO_x), $PM_{2.5}$, tropospheric ozone formation, stratospheric ozone depletion, global warming and water pollution—which are also driven by individual dietary choices and food-waste habits (Sutton *et al.* 2011a).

Undernutrition, overconsumption, and different forms of reactive N pollution have long been analysed in separated academic silos, associated with siloed policy actions (Sutton *et al.* 2021a). However, food consumption choices are critical to all three health risks. Therefore, when policies are designed, they should use synergies and manage trade-offs (OECD, 2021). Only recently, dietary guidelines have started to consider the environmental impacts of food groups, in addition to the traditional consideration of how consuming certain food groups have health effects (see Chapter 6). Some of these emerging environmental guidelines include the dietary recommendations from Brazil, China, Sweden, Canada, and the Eat Lancet diet (FAO, Food-based dietary guidelines database; Willett *et al.*, 2019).

In this chapter, we highlight how dietary choices and environmental pollution are interlinked. For this purpose, we will first give an overview of how European diets have changed as part of the global nutrition transition. Next, we introduce the direct health impacts of N pollution, especially how its contributions to air and water pollution and climate change and stratospheric ozone depletion can exacerbate a range of mortality and morbidity risks across all age groups. We then assess the environmental and health impacts of the most nitrogen-relevant dietary choices, both negative (e.g., red meat) and positive (e.g., nitrogen-fixing legumes). Ultimately, addressing these challenges is a multi-objective optimization problem that requires a more coherent and systemic approach to nitrogen policy than currently is in place anywhere in the world (see Box 2.1).

Box 2.1. *The need for a systemic approach to nitrogen policy.*

The dominant driver of nitrogen (N) pollution is the oversupply of synthetic fertilizer and manure to agricultural lands. Consequently, the central policy strategy that has been adopted across most countries to address it is to try to change farmer behaviour, either by imposing rules such as N application limits or incentivising the adoption of new practices and technologies via various financial support mechanisms (Oenema *et al.*, 2011; Kanter *et al.*, 2020). However, these types of policies are extremely challenging to legislate and implement for a variety of reasons: N pollution is diffuse, spread across millions of farms and hundreds of millions of hectares, making it very difficult to monitor and enforce rules and regulations; N is an essential resource and many countries, including EU member states, often prioritize food security over environmental concerns. Moreover, farmers are a very powerful political force, often carving out legal exceptions for their activities, making it hard to craft effective policy measures that can lead to meaningful reductions in N pollution (Ruhl, 2000).

This approach to N pollution policy ignores that farmers are part of a large and complex agri-food system made up of a number of actors up- and downstream of the farm, whose choices, products, and expectations significantly shape their decision-making. Focusing policy interventions on these non-farmer actors—that are also more limited in number, facilitating implementation (Sutton *et al.*, 2013)—could therefore significantly influence farm-level nutrient management decisions. These non-farmer actors include multinational food and beverage companies, fertilizer production companies, wastewater treatment facilities and municipal food procurement officials.

One example of such an approach is a proposal to impose product or design standards on the fertilizer industry, akin to the fuel efficiency standards imposed on automobile manufacturers, to drive innovation and farmer uptake of more environmentally efficient fertilizers (Kanter and Searchinger, 2018). Using the US corn sector as a case study, the authors estimated that such an approach could generate economic benefits for farmers (higher income from the increase in corn yields offsetting the higher fertilizer costs); the fertilizer industry (increased sales of patent-protected alternatives); and the environment (avoided nitrogen pollution), with net economic benefits of $5-8 billion by 2030. A version of this proposal is already in effect in India, where a 2015 policy requires fertilizer manufacturers to coat all domestically sold urea with neem, a natural coating substance that delays N release throughout the growing season (Kanter and Searchinger, 2018). This policy targets the 30 urea-producing production facilities in India, instead of its 120 million farmers, making it an easier task for implementation and enforcement—while also generating an important co-benefit: cutting off a supply line of highly subsidized urea for industrial uses.

2.2 European diets within the global nutrition transition

- The current 'nutrition transition' is an ongoing shift of global diets from inadequate plant-based diets towards affluent diets with high shares of processed and animal-based foods. Europe has already undergone the transition during the 20th century.
- Affluent diets result in a health risk profile dominated by non-communicable diseases. Globally, the prevalence of overweight (including obesity) has increased by more than 400% in absolute numbers, increasing from 400 million (12%) in 1965 to 2 billion (29%) in 2010. The share of individuals with a healthy body weight decreased through the nutrition transition globally and in Europe.
- In 1965 in Europe, 5% of the population was underweight while 29% was overweight. By 2010, <2% of the European population was underweight, whereas 54% was overweight (including obese). Obesity prevalence increased from 6% to 20% over the same period. Overall, the share of the population with healthy body weight decreased from 66% to 44%.
- Affluent diets with high household food-waste rates, overconsumption, and high intakes of animal-based foods are among the biggest causes of nitrogen pollution and multiple other environmental problems. With its high population density and affluent diets, Europe is still a hotspot of nitrogen pollution, despite considerable improvements in nitrogen use efficiency.

The global 'nutrition transition' describes how dietary patterns are shifting worldwide from scarce and unprocessed plant-based diets with a high share of coarse grains and pulses towards affluent diets high in sugar, fat, and animal-based foods (Bodirsky *et al.*, 2020; Popkin, 2004). Suboptimal diets are usually accompanied by maternal and neonatal undernutrition-related diseases, increased risk for infectious diseases, and higher prevalence of underweight and stunting. In contrast, affluent diets increase the risk of non-communicable disease (NCD) and lead to a higher prevalence of overweight and obesity (Abbafati *et al.*, 2020). The nutrition transition has been occurring in different world regions at different speeds, and it usually correlates with economic development (Bodirsky *et al.*, 2020). The data show that at no point in the nutrition transition do healthy dietary patterns become widely adopted.

For example, fruit and vegetable consumption has been continuously low and suboptimal throughout the transition in most countries. Moreover, the share of individuals with a healthy body weight usually declines, rather than increases, when countries advance economically (Bodirsky *et al.*, 2020). In total global numbers, overweight (including obesity) has increased by more than 400% between 1965 and 2010, increasing from 0.4 billion (12%) in 1965 to 2 billion (29%) in 2010 (Bodirsky *et al.*2020). Underweight has increased in absolute numbers from 0.5 billion to 0.7 billion during the same period, but decreased as a share of the world population from 15% to 10% (Bodirsky *et al.*, 2020). The population share with healthy body weight declined from 73% to 61% in the same period (Bodirsky *et al.*, 2020).

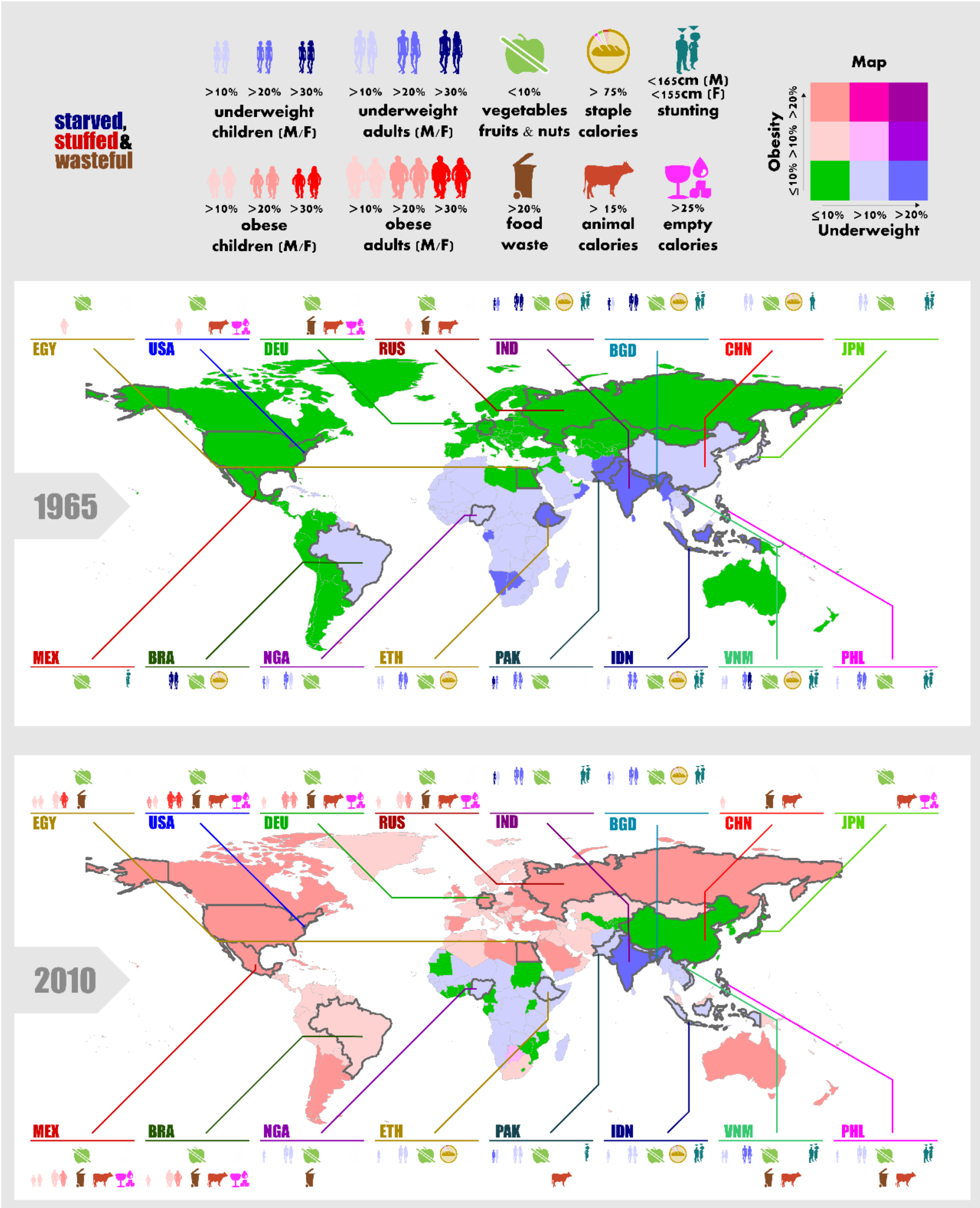

Figure 2.1. The global nutrition transition. The map colours show the prevalence of underweight and obesity in the population. For the 16 most populous countries, symbols indicate further details on anthropometrics, dietary composition and food-waste. Country abbreviations are ISO3-country codes. Based on data reported by FAOSTAT, NCD-Risk (Bentham et al., 2016; NCD Risk Factor Collaboration, 2017) and complemented with model estimates for missing data. Source and further details of the approach: see Bodirsky et al. (2020), figure reproduced with permission from the authors.

European diets began to become affluent in the 1960s, and the share of processed and animal-based foods started to increase. In 1965, 19 million (5%) people were underweight for the EU 28 (including the United Kingdom) (Bodirsky *et al.*, 2020). Nowadays, less than 7 million people (<2%) are considered underweight in the EU 28, representing a decrease by two thirds between 1965 and 2010. By contrast, the number of overweight people has roughly doubled from 125 million people (29%) in 1965 to 275 million people (54%) in 2010 (Bodirsky *et al.*, 2020). This has been accompanied by an even more dramatic increase in the number of individuals affected by obesity, which increased from 25 million (6%) in 1965 to 100 million (20%) in 2010 (Bodirsky *et al.*, 2020). The share of individuals with a healthy body weight decreased in this period from 284 million (66%) to 223 million (44%).

The nutrition transition is also associated with a higher environmental footprint of diets, as an increased food demand requires more resources to produce food, causing emissions and environmental degradation. Given that European diets have already transitioned towards affluent diets, the European consumers' environmental footprint is very high compared to that of low-income countries (Galloway *et al.*, 2014). While the strongest driver for global food demand remains population growth, high food waste and increasing body weight—both connected to affluent diets—also determine an increase of food demand per capita (Bodirsky *et al.*, 2020). Even more importantly, the shift from plant-based to resource-intensive animal-based foods strongly increases environmental footprints for several indicators, including nitrogen (Leip *et al.*, 2014).

Nitrogen pollution from agricultural production has thus strongly increased over the last decades. Nitrogen surplus from global croplands (the amount of organic and synthetic N fertilized that has not been taken up by the crops) has more than quadrupled between 1965 and 2009, increasing from 19 Tg to 88 Tg (Lassaletta *et al.*, 2014). In Europe, the surplus of reactive nitrogen actually decreased during this period from 6.3 to 5.7 Tg despite increasing harvest due to improved N use efficiencies (Lassaletta *et al.*, 2014). However, Europe remains one of the hotspots of N pollution (Figure 2.2) where N surpluses from agriculture are estimated to exceed the safe regional thresholds of the planetary boundaries (Gerten *et al.*, 2020). These hotspots emerge where population density is high, diets are affluent, or low N fertilizer efficiency prevails or co-occur.

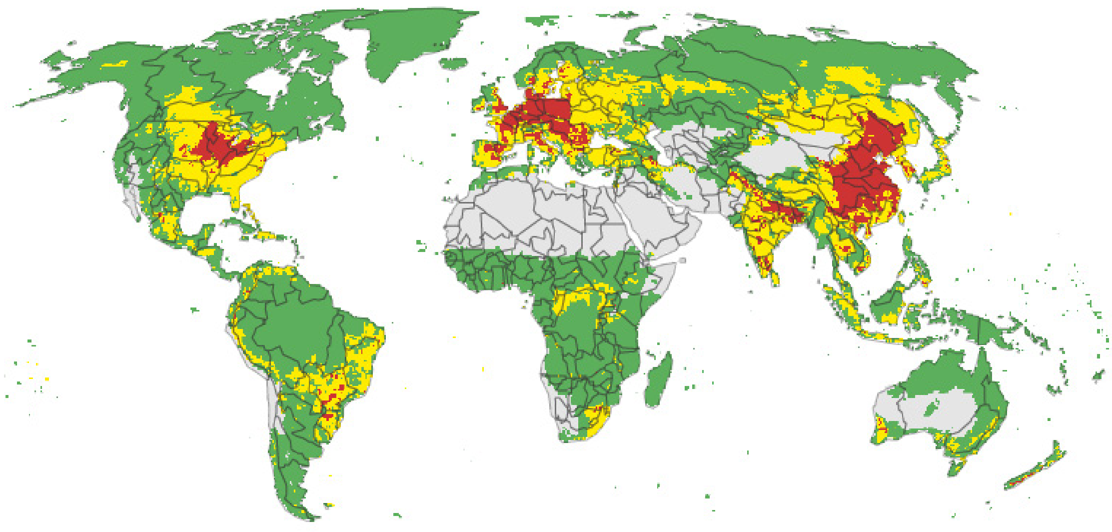

Figure 2.2. *Agricultural nitrogen pollution in 2005 compared to the regional threshold of the planetary boundary for nitrogen. Yellow zones indicate increased risk; red zones indicate a high risk of the transgression of the boundary. Source and further details of the approach, see Gerten et al. (2020), figure reproduced with permission from the authors.*

2.3 Environmental and health impacts of nitrogen in the European food system

- Nitrogen-related air pollution, water pollution, global warming and ozone depletion are directly connected to human health.
- Reducing nitrogen pollution in all its forms can have public health benefits.

Nitrogen pollution poses a substantial threat to the environment and human health (Sutton *et al.* 2011a, b). Losses occur throughout the food system—its dominant source—from fertilizer production to wastewater treatment. Yet, the most dominant loss of nitrogen occurs after applying synthetic fertilizer and manure to agricultural lands (Sutton *et al.* 2013). Nitrogen losses result in a multitude of impacts, from air and water pollution to climate change, stratospheric ozone depletion, and biodiversity loss (see Figure 2.3). These impacts are substantially worse for certain food products than others, ranging from processed and unprocessed red meat (high nitrogen footprint) to nitrogen-fixing vegetables (low nitrogen footprint) (Leip *et al.*, 2014; Poore and Nemecek, 2018). Nitrogen pollution affects human health both directly and indirectly. Direct effects of nitrogen on health result from its contribution to environmental degradation, including from fine particulate matter air pollution and from nitrate in drinking water. Indirect effects of nitrogen on human health result from the consequences of its use in the food system, increasing food production (with benefits for health) or products that have adverse effects on health when consumed in excess. This section details these effects and the linkages between them.

The unique chemistry of nitrogen, which is associated with multiple forms lost to the environment, means that it poses a multitude of threats to the environment and human health—the scale varies depending on the food item, agronomic practices, climate, and other factors (Sutton *et al.* 2013). One way to elucidate this is by following a nitrogen atom on its journey through the nitrogen cascade: once nitrogen fertilizer is applied to agricultural soils, around 10% is often lost as nitrogen oxides (NO_x) or ammonia (NH_3) (IPCC, 2019a)—both critical components of air pollution as central precursors to forming tropospheric ozone (O_3) and fine particulate matter ($PM_{2.5}$), respectively. Tropospheric ozone and $PM_{2.5}$ have been identified as the leading cause of premature mortality worldwide due to how they can cause and exacerbate a range of cardiovascular and respiratory diseases, from heart disease to lung cancer (Lelieveld *et al.*, 2020). Overall, global excess mortality due to air pollution from tropospheric ozone and $PM_{2.5}$ is 8.8 million/year, with an average loss in life expectancy of almost three years, an impact greater than tobacco smoking, HIV/AIDS, and all forms of violence (Lelieveld *et al.*, 2020).

Moreover, the emerging link between $PM_{2.5}$ exposure and increased mortality risk from COVID-19 further underscores the risk of leaving nitrogen pollution unchecked (Wu *et al.*, 2020). From an environmental perspective, nitrogen pollution's role in worsening air quality results from several pathways as follows:

- Nitrogen oxides contribute to 'acid rain', forming nitric acid (HNO_3) which can disrupt the healthy functioning of aquatic and terrestrial ecosystems. The acidification effect can be exacerbated when deposited ammonia (NH_3) is oxidized to nitrate in soils.
- Ammonia is the major alkali in the atmosphere and can contribute to an 'alkaline air' effect causing toxic damage to sensitive vegetation (Sutton *et al.* 2020). This effect occurs on plant surfaces and is distinct from the later potential for soil acidification.
- Reaction between HNO_3 and NH_3 forms ammonium nitrate and $PM_{2.5}$, increasing the burden of airborne particulate matter, which adversely affects human health (Wu *et al.*, 2016).
- Reaction of NO_x emissions (including those resulting from agricultural soils) with volatile organic compounds leads to the formation of tropospheric ozone that reduces crop yields by around 10% (Shindell, 2016).
- Deposition of NH_3 and NO_x emissions to land affects the biodiversity of terrestrial and fresh water systems through 'eutrophication', which increases levels of nutrient availability and subsequently threatens biodiversity by affecting the competitive balance between species (Sutton *et al.* 2011a).

Nitrogen oxides and ammonia can subsequently be oxidized and deposited into waterways as nitrate, or nitrate can directly leach from fertilized areas to groundwater (Sutton *et al.* 2011a). Despite ambitious water policies in the EU such as the 1991 EU Nitrates Directive and the 2000 Water Framework Directive, success was moderate: approximately half of European water monitoring stations show no substantial change in nitrate contamination (Grizzetti *et al.*, 2021), and over 25% measure increasing nitrogen concentrations (Musacchio *et al.*, 2020). As a result, tap water needs to be treated expensively to avoid harmful concentrations in drinking water (50 mg/L according to the WHO, 2007). A recent meta-analysis found strong evidence linking high nitrate concentrations with methemoglobinemia (also known as blue baby syndrome, due to poorly oxygenated blood), and to colorectal cancer, thyroid disease and neural tube defects (Ward *et al.*, 2018). Another study found that nitrate exposure experienced from birth until three years of age is associated with decreased height in adulthood (Zaveri *et al.*, 2019).

Nitrate can subsequently be denitrified and emitted to the atmosphere as N_2, which is a major waste of reactive nitrogen resources. As an intermediary in this step, a fraction is emitted as nitrous oxide (N_2O), which is the third most abundantly emitted greenhouse gas. Globally, N_2O is responsible for approximately 6% of global greenhouse gas emissions (in terms of carbon equivalents) and is the largest remaining threat to the stratospheric ozone layer (IPCC, 2014). Climate change has and will have a multitude of impacts on human health, both direct (e.g., the effects of severe weather events and extreme heat on human wellbeing) and indirect (e.g., the health impacts of forced migration and civil conflict) that have been analysed extensively for Europe and elsewhere (Crimmins *et al.*, 2016; Paci, 2014).

Depletion of the ozone layer increases the amount of harmful ultraviolet radiation that reaches the Earth's surface. This increases incidences of melanomas and eye cataracts and has deleterious effects on terrestrial and aquatic ecosystems and agricultural systems by inflicting damage at the cellular level (US Environmental Protection Agency, 2020).

2.4 Dietary choices and their impact on nitrogen pollution and health

- Addressing major dietary risk factors such as diets low in vegetables and diets high in processed and unprocessed red meat could reduce nitrogen pollution while improving human health.
- Processed and red meat have both the highest environmental impact, as well as the largest adverse health outcomes, while legumes, fruit and vegetables have very low or low environmental impacts and positive health outcomes.
- Legumes have low nitrogen footprints and are also regarded as healthy substitutes for animal-based proteins.
- Some fruit and vegetable production systems have high nitrogen losses; investment in sustainable production systems is therefore crucial to manage trade-offs, as dietary recommendations advise towards an increased consumption of fruits and vegetables.

Another way to view the environmental and human health impacts of nitrogen pollution is through the lens of some food groups consumed throughout Europe and the world. Several recent studies found a correlation between the environmental and human health impacts of different foods (Clark *et al.*, 2019). This pattern is especially true for nitrogen (Leip *et al.*, 2014). The following subsections assess the environmental and human health impacts of several foodstuffs from a nitrogen perspective. The combined health and environmental impacts of some food groups are shown in Figure 2.3 (Clark *et al.*, 2019). The radar plot shows that processed and unprocessed red meat have a combined high environmental impact and, at the same time, have negative impacts on human health as their consumption increases the risk of developing multiple diseases. Figure 2.3 shows that dairy products have a high environmental impact, but do not substantially increase the risk of the diseases considered. On the other hand, fruit and vegetables have a relatively low environmental impact, and their consumption decreases morbidity and mortality risks.

The environmental impacts considered (shown on the right of the radar plot, Figure 2.3) were acidification, eutrophication, land use, greenhouse gas emissions, and scarcity-weighted water use. Acidification and eutrophication are two forms of nutrient pollution that can be considered good indicators of nitrogen pollution. The higher acidification potential for vegetables reflects the more intensive use of fertilizer for their production. However, compared to the animal-based food examined, vegetables have a lower acidification potential.

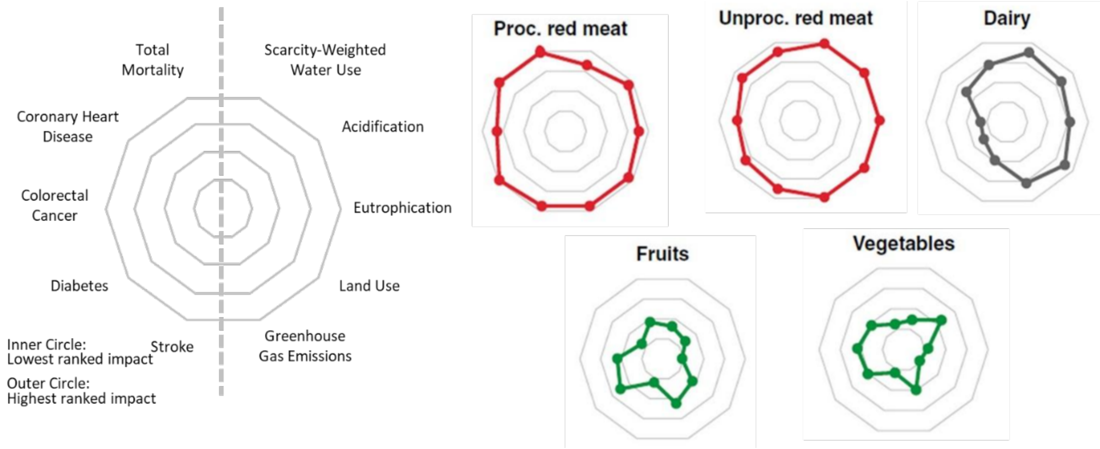

Figure 2.3. *Radar plots of health and environmental impacts per serving of food consumed per day, adapted from Clark et al. (2019), under CC BY 4.0, https://creativecommons.org/licenses/by/4.0/. The figure includes most of the food groups with the highest and lowest nitrogen footprints in Europe as reported by Leip et al. (2014). The health impacts are reported as the relative risk of disease resulting from consuming an additional daily serving (1 serving more than the cohort average) of the selected food groups. The diseases considered (shown at the left of the radar plot) were coronary heart disease, colorectal cancer, type 2 diabetes, and stroke. The analysis also considered the overall risk of mortality for each additional daily serving of food consumed. The environmental impact data has been extracted from several Life Cycle Assessments meta-analyses referenced in Clark et al. (2019). The radar plots show the combined performance for five environmental impact indicators (right of the plot) and five health impact indicators (left of the plot). Data are plotted on a rank order axis such that the food group with the lowest mean impact for a given health or environmental indicator (lowest is the best for health or environmental outcome) has a value of 1 (innermost circle), and the food group with the highest mean impact for a given indicator has a value of 15 (outermost circle). A food group with low mean impacts for the ten outcomes would have a small circular radar plot (shown in green), and one with high impact for the ten outcomes would have a large circular radar plot (shown in red).*

2.4.1 Red meat, processed meat, and dairy

Environmental impacts

Animal-based food products, particularly beef and dairy, have the highest nitrogen footprints of any agricultural product across various national food system types—from Austria to Tanzania (Leip *et al.*,2014; Pierer *et al.*, 2014; Hutton *et al.*, 2017). At the global level, the livestock sector has been estimated to account for a third of global nitrogen emissions (across all sectors, not just agriculture), and current production levels of livestock alone exceed planetary boundaries for nitrogen (Uwizeye *et al.*, 2020). Indeed, dairy and red meat production, in particular, are prime examples of how N impacts can arise and ripple throughout the food system:

- First, the production of livestock feed requires N inputs—ranging from high levels for N intensive crops such as corn, and lower levels for leguminous crops such as soy—and can also drive land-use change, including deforestation, which can result in substantial N losses.
- Nitrogen can subsequently be lost in the processing and trading of feed to the livestock facilities that need it (Uwizeye *et al.*, 2020).
- The feed is usually inefficiently converted into animal protein, with lowest conversion rates in beef systems, where on average, 3% of the feed consumed is transformed into animal protein, and highest for poultry meat (22%) and eggs (31%) (Shepon *et al.*, 2016; Smil *et al.*, 2002). This compares with an average value of 19% estimated for Europe (Chapter 1).
- The nitrogen that is not converted to food is excreted as manure, either directly on pastures or in stables. Manure in stables is collected and stored, with substantial ammonia losses depending on the management system (IPCC, 2019b), and then applied to croplands and pastures, where it may be lost by volatilization, denitrification, leaching, or run-off.

With the rise of large-scale industrialized livestock systems, manure disposal has become increasingly concentrated, reducing its uptake by crops (Sutton *et al.* 2011a). Also, the production of animal and crop products has become increasingly specialized and separated, making it economically impractical to reuse manure N efficiently as an N input (Sutton *et al.*, 2013). A small, yet non-negligible amount of N is also lost once meat or dairy products are further processed, packaged and traded (e.g., as slaughter waste). Finally, a portion is wasted after it is purchased by the consumer (see Chapter 1).

Health impacts

Meat, dairy, and other animal-based foods provide protein and important micronutrients such as iron, zinc, calcium, and B group vitamins. Ensuring an adequate intake of these nutrients is particularly important in low-income countries, where diets are based mainly on cereals, dietary diversity is low, and micronutrient deficiencies are widespread (Food Systems Dashboard, 2020). In Europe, modest amounts of animal-based food contribute to protein and micronutrient intake, particularly in children, pregnant women, and the elderly. The nutrition transition over the last 50-70 years has led the European population to increase its protein intake from animal-based food (Westhoek *et al.*, 2011). Dietary surveys have estimated that protein intake in Europe is almost double the recommended amounts (European Commission, 2020c).

Although the health impacts of high protein intakes remain an open research question, some observational studies show that consuming plant-based protein instead of animal protein might be associated with reduced mortality (Naghshi *et al.*, 2020; Song *et al.*, 2016). Excessive red meat and processed meat consumption have been shown to have a negative health impact (Bouvard *et al.*, 2015). In 2015, the International Agency for Research on Cancer classified red meat as probably carcinogenic and processed red meat as carcinogenic because their excessive consumption is associated with an increased risk of colorectal cancer (Bouvard *et al.*, 2015). According to the World Health Organization, processed meat refers to meat that has been transformed through processes that enhance flavour or improve preservation (e.g., salting, curing, fermentation and smoking). Most processed meat products are based on pork or beef, but processed meat may also contain other red meats, poultry, offal, or meat by-products such as blood. The term red meat refers to all mammalian muscle meat, including beef, veal, pork, lamb, mutton, horse, and goat. It has been estimated that a 50 g portion of processed meat eaten daily increases the risk of colorectal cancer by about 18%. For red meat (if the association to colorectal cancer were proven to be causal), evidence suggests that the risk of colorectal cancer could increase by 17% for every 100g of red meat eaten daily (Chan *et al.*, 2011). In addition, processed meat is also one of the most important contributors to dietary salt (sodium). Salt raises blood pressure, an important risk factor for cardiovascular disease which is a leading cause of death and disability in Europe and globally (Bhat *et al.*, 2020; He *et al.*, 2020). Finally, meat is one of the most important contributors of saturated fat, which raises LDL cholesterol. The latter is the third most important risk factor for cardiovascular morbidity and mortality globally (Roth *et al.* 2020).

In 2017, the Global Burden of Disease Study (GBD) estimated that red and processed meats global intake was 18% and 90% greater than the optimal intake, respectively (GBD 2017 Diet Collaborators *et al.*, 2019), where optimal intake for red meat was defined as less than 23 g/day and for processed meat less than 2 g/day. In Europe, processed meat consumption for Member States spans from 17 g/day in Portugal to 48 g/day in Poland, while red meat intake spans from 24 g/day in Hungary to 90 g/day in Sweden (The Global Dietary database, 2016). According to the optimal intake values provided by the GBD study, the average intakes in the Member States are well above the GBD optimal intakes for red and processed meat for all the EU Member States. The Eat Lancet diet, which provided the first targets for healthy diets and environmentally sustainable food production within planetary boundaries recommends a much lower red meat intake—14 g/day of red meat: 7 g as beef and lamb and 7 g as pork—but it does not provide any recommendation for processed meat intake (Willett *et al.*, 2019).

Milk and dairy products are major components of traditional Western diets. In Europe, the consumption of milk and other dairy products have traditionally been higher than in other world regions (EFSA, 2020), although attitudes towards meat and dairy consumption are changing rapidly (Box 2.2), albeit significant barriers have to be overcome (Box 2.3). Dietary recommendations typically include dairy products to meet calcium requirements and reduce the risk of bone fractures (Willett and Ludwig 2020). However, in recent years, the importance of milk in human diets has been questioned in the light of the ‘calcium paradox’ according to which the risk of fractures is higher in populations with high milk intake (Willett and Ludwig 2020). Milk and dairy are also sources of lactose, a sugar that cannot be fully digested by two-thirds of the world population (Storhaug, *et al.*2017). Milk consumption varies across European countries; in northern countries such as Iceland and Sweden, milk consumption is around 450 g/day per day. In Italy and France, it is around 150 g/day (The Global Dietary Database, 2016). The Eat Lancet diet recommends a 250 g/day of milk or derivative equivalent (e.g., cheese) (Willett *et al.*, 2019). Calcium can also be obtained through drinking water and plant-based foods such as kale, broccoli, tofu, nuts, beans, fortified orange juice and some dairy alternatives (Böhmer *et al.*, 2000; Koeder & Perez-Cueto, 2022; Michael & Somani, 2022). Dairy alternatives such as soy, oat, almond, and rice milk—often fortified with calcium and vitamin B12—are becoming popular choices in Europe (Euromonitor International, 2020) (Box 2.2).

Box 2.2. *The rise of the 'less meat' movement in Europe.*

Data suggest that in Europe, per capita meat consumption is plateauing or beginning to decline (Godfray *et al.*, 2018). This may be due to the meat market being saturated in these regions and social norms around meat consumption slowly starting to change. Apart from India, in which around a third of the population is vegetarian, vegetarians and vegans in high-income regions such as Europe have always been a very small fraction, ranging from 1–3% of the population (Friends of the Earth Europe, 2014). Research conducted in high-income countries showed that the number of people who try to cut down their meat consumption, often called 'flexitarians', or 'part-time vegetarians' has increased substantially in the last years (De Gavelle *et al.*, 2019; Neff *et al.*, 2018). Such an approach is closely linked to the 'demitarian' (i.e., half meat intake) narrative developed as part of the European Nitrogen Assessment process (International Nitrogen Initiative, 2009; Webster, 2014). Health and environmental impacts and concern about animal welfare appear to be the main motivations behind the trend to reduce meat intake, with young women being the leading socio-demographic group driving the change (Neff *et al.*, 2018). Campaigns promoting part-time vegetarianism such as 'Meatless Monday'' and 'Veganuary' have gradually gained the support of institutions such as universities and are currently playing an important role in changing social norms (Milford and Kildal, 2019). The development and the increased availability of plant-based dairy and meat are also important drivers of the 'less meat' movement in high-income settings (Alae-Carew *et al.*, 2022) (see Chapter 5). These issues have been further taken forward by the TFRN Expert Panel on Nitrogen and Food, resulting in the Cercedilla Manifesto (Sanz-Cobeña *et al.*, 2020). The initiatives by researchers, such as the Barsac Declaration and Cercedilla Manifesto, hold the prospect to seed ideas with media and the public as a basis to inform societal change.

Box 2.3. *Beliefs that cloud the 'less meat' debate.*

Livestock systems in the EU have experienced major changes in the last decades, leading to the multiplication of meat and dairy production by factors of 5 and 2.5, respectively, since 1961 (FAO, 2020). Despite the scientific evidence about the need to limit the consumption of animal-based products for environmental and health reasons (The Global Dietary Database 2016*,* Bouvard *et al.*, 2015; Poore and Nemecek, 2018; IPBES, 2019; FAO and WHO, 2019; Smith *et al.*, 2019; Westhoek *et al.*, 2014), national governments and institutions are failing to inform citizens transparently about the characteristics of healthy and sustainable diets. Moreover, most demand-oriented food policies are exclusively oriented towards the limitation of overweight and obesity rates, leaving out other health and environmental challenges related to food consumption (Temme *et al.*, 2020) (see Chapter 7). At the same time, self-perception on the amount of animal-based food consumed diverges from official statistics.

Meat consumption in Europe increased by 63% since 1961 (FAO, Livestock Primary 1961-2018). In countries such as Portugal or Spain, the yearly per capita meat supply—excluding fish—increased five times as much in this period, increasing from 20 kg to around 100 kg per person (FAOSTAT, 2022). However, according to the results from a survey conducted in Spain, consumers perceive having an annual meat consumption of about 26 kg per person (Hernández-Jiménez *et al.*, 2018).

Although information alone does not necessarily lead to behavioural change (Bianchi *et al.*, 2018; Cadario and Chandon, 2018), some evidence suggests that the provision of information can be effective in certain situations (Thorndike *et al.*, 2014), whereas the lack of knowledge can be a barrier for action (Gifford, 2011). According to the Eurobarometer, 81% of EU citizens claim that local traditions and knowledge are important determinants of their food choices; more than nine out of ten EU citizens claim that rural areas are important or very important for them (European Commission, 2022a). These data suggest that EU citizens have a strong desire to maintain traditional food systems and support rural areas through their food purchases. Other data show that EU citizens seem to prefer extensive livestock systems over intensive ones (Busch and Spiller, 2018). The reality is that, for most EU citizens and most products, it is impossible to access information regarding the type of farming practices used to produce meat and dairy, as animal welfare and environmental statements on labels are not mandatory. Indeed, more than 70% of EU livestock is raised on large or very large farms, and half of EU livestock units are raised in only 1% all the EU farms (Eurostat, 2020, 2018b). A trend towards such intensification in a few large farms has coincided with a decline in the number of small and medium-sized farms, and the loss of one-third of agricultural jobs between 2003 and 2018 (Schuh *et al*, 2019). Such differences between actual practice and the beliefs of European consumers point to the need for broader dissemination of reliable information to inform consumer choices.

2.4.2 Nitrogen-fixing legumes

Environmental impacts

In Europe, 1.5% of the arable land area is used to cultivate legumes compared with 14.5% worldwide (Watson *et al.*, 2017). Legumes include soy, peas, chickpeas, lentils and peanuts; and are an increasingly important component of crop rotations, including as cover crops during the off-season, to maintain and bolster soil health by returning more organic N to soils, thereby aiding soil organic matter generation. As legumes can fix parts of their nitrogen requirements through symbiosis with nitrogen-fixing microorganisms in their root nodules, they have less need for additional fertilizer nitrogen. By producing reactive nitrogen slowly, in accordance with plant needs, a generally larger fraction of the reactive N input is harvested as compared with addition of mineral fertilizers (Lassaletta *et al.*, 2014; Smil *et al.*, 2002). Consequently, legumes have a low nitrogen footprint—almost an order of magnitude lower than any other food group (Martinez *et al.*, 2019).

If a portion of the plant protein produced by legumes was to replace animal protein in human diets—an important dietary risk minimization strategy—it could substantially contribute to the reduction of N pollution flows (Westhoek *et al.*, 2015). Furthermore, compared with animal-based food, dry legumes can be stored for years, thereby substantially reducing the risk of food loss and waste.

It should be noted that legume cultivation is not necessarily entirely free of risks from nitrogen pollution. Nitrogen in crop residues; the use of legumes as 'green manures', where a legume is subsequently ploughed into the soil to improve soil organic carbon and nitrogen content; or nitrogen in failed legumes (e.g., due to drought, wind or rain damage); undergo mineralization and risk being lost to the environment. Further research is needed to quantify the nitrogen losses from different legume-based systems. Legumes in grass mixes have been proposed as a greenhouse gas (GHG) mitigation option but growing legumes as livestock feed instead of human food is still associated with substantial nitrogen pollution.

Health Impacts

Legumes are rich in protein, complex carbohydrates, dietary fibre, various micronutrients and phytochemicals, and their consumption is associated with positive health outcomes (Afshin *et al.*, 2014). In observational studies, legumes consumption has been associated with a lower risk of cardiovascular disease (Afshin *et al.*, 2014; Bernstein *et al.*, 2010). In dietary trials, consumption of legumes has been shown to be effective in reducing blood pressure and LDL cholesterol (Bazzano *et al.*, 2011; Jayalath *et al.*, 2014). On the other hand, poorly cooked or unprocessed legumes also contain some compounds that inhibit the absorption of important micronutrients such as iron and zinc (Schlemmer *et al.*, 2009). In addition, legumes also contain some complex carbohydrates that in some individuals can cause gastrointestinal discomfort (Winham and Hutchins, 2011). Nonetheless, evidence shows that the health benefits of eating these foods outweigh any potential negative nutritional effects (Schlemmer *et al.*, 2009; Winham and Hutchins, 2011).

In many regions in Africa, Asia and the Caribbean, legumes are an inexpensive food group of major nutritional importance (especially as a protein source), as together with cereals, they constitute a staple diet (Willett *et al.*, 2019). In Europe, the consumption of legumes has been stable in the past decades, but intake levels differ according to the country. In Europe, the average daily legume intake spans from around 5 g/day in Norway to 30 g/day in the UK and Greece (Global Dietary Database, 2016). The Eat Lancet diet recommends a direct legume intake of 50 g/day and 50 g of 'soy foods' (i.e., processed foods based on soya bean) (Willet *et al.*, 2019).

While the consumption of legumes remains suboptimal and well below dietary guidelines in Europe, the development and sale of legume-based products increased by 39% between 2014 and 2017 (Hamann *et al.*, 2019). The most popular legume-based category is plant-based meat replacers (ING Research, 2020) (Chapter 5). Although in 2019, plant-based meat replacers held only 1% of the entire meat market share, projections show that in the next decade, their market share could increase to up to 10% of the global meat market (Barclays Investment Bank, 2019).

2.4.3 Fruit and vegetables

Environmental impacts

Fruit and vegetables have important health benefits and low environmental impacts (Figure 2.4). However, it is not clear if increasing fruit, vegetable, nut, and seed production would reduce N pollution flows, at least under current production practices. Nitrogen footprint studies come to relatively low nitrogen footprints when measuring the N pollution per kg wet matter (Pierer *et al.*, 2014). By contrast, when calculating the nitrogen footprint on a dry matter basis, such as per kg protein, then fruits and vegetables have a high footprint due to their very low protein content (Pierer *et al.*, 2014). If measured against their overall nutritious value (including dietary benefits of nutrients and fibre), then the nitrogen footprint of fruits and vegetables would again be relatively low due to their high micronutrient density and fibre content. Nitrogen impacts also vary due to the enormous variety of fruits and vegetables and their management methods. Indeed, regions such as the Central Valley in California and many parts of China have some of the highest N application rates in the world, applying often more than double the rates for growing fruits, vegetables, nuts and seeds, as compared to major cereals such as wheat, corn and rice (Tomich *et al.*, 2015; Zhang *et al.*, 2013). Consequently, an ambition to increase fruit and vegetable consumption should be complemented with improved N management practices tailored to individual crops (TFRN, 2020). The high value-added and management intensity of horticultural systems may facilitate the adoption of efficient technologies such as drip fertigation or sensors. While it is recognized that fruits and vegetables have a more variable nitrogen footprint than legumes, they still have considerably lower nitrogen and environmental footprints than animal-based products (Leip *et al.*, 2014; Poore and Nemecek, 2018).

Health Impacts

Suboptimal fruit and vegetables intake is currently a leading dietary risk factor globally and in all European sub-regions. The leading food and health organisations recommend consuming at least 400 g of fruit and vegetables daily to lower cardiovascular disease risk, type 2 diabetes, obesity, and some cancers (European Commission, 2020d). As fruit and vegetables are a source of micronutrients and minerals, adequate intakes are crucial for alleviating several micronutrient deficiencies in less developed settings. Fruit and vegetables also provide dietary fibre, a dietary component which has many health benefits; from the benefits for gastrointestinal health; to the risk reduction of non-communicable diseases such as cardiovascular diseases, type 2 diabetes and colorectal cancer; as well as a reduced risk of weight gain (European Commission, 2020d). Evidence shows that in low and middle-income countries, less than a quarter of the population consumes the recommended 400 g of fruit and vegetables per day (equivalent to five portions) (Hall *et al.*, 2009). In the European Union, only 14% of EU adults consume the recommended 400 g/day. However, the daily consumption of fruit and vegetables differs widely between the EU Member States, with those not eating fruit and vegetables on a daily basis ranging from almost two-thirds of the population in Romania (65.1%) to slightly over 15% in Belgium. On the other hand, the share of those eating at least 5 portions daily varies from a third in the United Kingdom (33.1%) to less than 5% in both Romania (3.5%) and Bulgaria (4.4%) (Eurostat, 2018a). Evidence for the EU suggests that fruit and vegetable consumption is reduced in low socio-economic status groups (de Irala *et al.*, 2000). This is often due to the high cost of fruits and vegetables relative to other foods and the wider availability of unhealthy food options that are high in salt, sugar, saturated fat and calories (Food Systems Dashboard, 2020).

2.5 Conclusions

Nitrogen has a complex yet essential role in food systems. It is both a core input for agricultural production and a major pollutant. With multiple environmental and health impacts, it is especially important to assess the consequences of current diets and agricultural practices. This chapter shows how animal-based foods are associated with adverse environmental and human health impacts. Overall, healthy diets correlate with low nitrogen footprints and positive health outcomes. Reducing consumption of animal-based foods (especially red meat) and replacing with plant-based foods (especially legumes as protein substitutes) may support the transition towards healthy and sustainable diets. We have identified a trade-off between increasing the consumption of certain fruits and vegetables and reducing nitrogen pollution, as such plant-based foods are often highly fertilized. However, we find that the health benefits of increased fruits and vegetable consumption would outweigh their contribution to N pollution, though additional research is needed to provide additional information on the cost-benefit relationship.

Nevertheless, a shift from meat and dairy proteins to plant-based proteins, combined with an increase of fruit, vegetables and legume consumption, will lead to an overall decrease of N pollution and provide health benefits. Possible additional N losses from intensively managed vegetables are expected to be substantially smaller than the decrease in N pollution resulting from livestock production given the latter's scale and supply chain effects. Such dietary shifts must be accompanied by efforts to reduce nitrogen pollution from intensive plant-based production, e.g., through efficient fertigation and other measures. Managing these potential trade-offs and synergies and other key indicators of sustainable development (e.g., labour rights and animal welfare, see Chapter 1) will be a central challenge of a transformation towards a sustainable European food system.

Box 2.4. *Research needs related to health and environment implications of nitrogen in the food system.*

- Accurate and regionally-specific research to develop the nitrogen footprints of different foods.
- More research about the health implications of consuming plant-based alternative products and the barriers to widespread adoption.

Chapter 3. Food system archetypes

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- A shift to lower animal-based foods consumption can be achieved in many ways to reach all people.
- Sustainable food systems can vary significantly in concept, scales and technologies, but they have in common the potential to deliver healthy and sustainable diets.
- Food system archetypes can be defined as characteristic examples or 'models' of typical situations. They can guide a future policy vision of sustainable food systems.
- Food systems are constant changing. Past transitions have often pushed them into unsustainability. Three food system archetypes are described in detail: the Mediterranean, Agroecological and 'Visionary' food systems. These can serve as models for the design of sustainable food systems.
- **Key policy message: A sustainable food system can vary significantly in concept, scales and technologies. Sustainable food system policies are able to combine traditional knowledge with the latest research findings, and find context-specific optimum solutions to serve all people.**

3.1 Introduction

Food systems are constantly changing: how food is produced and processed, and what people consume in Europe today is different than it was in previous decades (Infante-Amate *et al*., 2018; Kim *et al*., 2018). Dominant food systems, mainly in high-income countries, are mostly delocalized and highly industrialized in the whole food chain, from production to distribution and waste management, with positive, but also significant negative consequences for socio-environmental sustainability aspects (see Chapters 1, 2, 4 and 9). To explore how alternative sustainable food systems can look, we here describe three food systems that, with their specificities and challenges, we take as characteristic example model systems (or 'archetypes') of sustainability: Mediterranean, Agroecological and 'Visionary' food systems (Anderson, 2019; Winiwarter *et al.*, 2014). The reason behind this selection systems is the nature of the archetypes. They are different but complementary, presenting elements that can be used as models for designing sustainable food systems as described in Chapter 1. They are not the only solutions towards sustainable food systems, but these three archetypes present characteristics and principles that can be useful in the design and implementation of future national or regional food policies towards the delivery of healthy and sustainable diets.

The **first archetype—Mediterranean**—is inspired by a food agroecosystem that no longer exists but proved to be environmentally and socially sustainable.

The **second archetype—Agroecological**—combines traditional and modern knowledges, carefully combining elements to achieve a healthy equilibrium between food production, environmental protection, and social equity.

The **last archetype—Visionary**—describes a situation that at present can only be discerned, and that uses modern and future technologies, together with the potential for cultural change, to provide healthy food products reducing environmental costs.

3.2 Mediterranean food system linked to the Mediterranean diet

- The Mediterranean food system is a traditional food system favoured by Mediterranean agro-climatic conditions, but potentially implementable in other regions worldwide.
- The Mediterranean food system involves commonly extensive, low-input farming, based on traditional knowledge and using predominantly indigenous breeds and local crop varieties.
- The Mediterranean food system is little practiced in its region of origin these days, as intensive meat and dairy production have increased over the past half century. The present reflection identifies the characsteristics of this past system, which could also be of benefit for the future.

Food systems in Mediterranean countries have suffered a deep transformation from the sustainable and healthy patterns that were predominant in the region until the mid-1960s and known as the so-called traditional Mediterranean diet (Figure 3.1) (Capone *et al.*, 2018; Hidalgo-Mora *et al.*, 2020; Trichopoulou *et al.*, 2014). Such transformation is evident throughout the whole food chain, from production to consumption, leading to the erosion of a cultural heritage that maintained a sustainable balance between land and resource use, ecosystem conservation and healthy nutritional status.

Until the 1960s, agricultural systems in the Mediterranean basin were characterized by the circularity of their material flows, with low dependence on external inputs and low environmental impact (Kim *et al.*, 2018; González de Molina *et al.*, 2020). Such characteristics, as well as the recognized health benefits of the Mediterranean diet and its alignment with socio-cultural values (Serra-Majem *et al.*, 2009; Sofi *et al.*, 2008), make the traditional food systems in the Mediterranean basin a model to be revived in the region, and with the potential to inspire similar sustainable models in other parts of the world (CIHEAM and FAO, 2015; Dernini *et al.*, 2016; Hidalgo-Mora *et al.*, 2020; Trichopoulou *et al.*, 2014). Although the traditional Mediterranean diet—and the inherent food production systems sustaining it—are originally shaped by the Mediterranean climate, the basis of this dietary pattern could be translated to other regions where access to its main food pillars (e.g., legumes, fruits, nuts, whole grains and unsaturated oils) can be easily achieved (Chou *et al.*, 2022; Darabi *et al.*, 2022; Gupta *et al.*, 2022; Hidalgo-Mora et al., 2020; Russo *et al.*, 2021). This is the case for initiatives already seen in (for example) India, Costa Rica, Iran and Taiwan (Hidalgo-Mora *et al.*, 2020).

3.2.1 Food production

The Mediterranean food system is a traditional system, with different regional patterns, favoured by Mediterranean agro-climatic conditions, the availability of local breeds and crop varieties, and the incorporation of crops from other cultures as a consequence of the evolution of international relations and oversea expeditions (Hidalgo-Mora *et al.*, 2020). It is a production system low in external input and labour-intensive, that spread throughout the Mediterranean basin becoming generalized in most areas of southern European and North African countries (see Table 3.1).

The traditional Mediterranean food system dominated until the 1960s, when most of the food consumed was produced locally. In animal production, livestock systems were commonly extensive, based on traditional knowledge, and dominated by indigenous breeds, especially small ruminants, often in agro-silvo-pastoral systems. Multicropping and associated crops were common in the traditional Mediterranean agriculture. Today´s Mediterranean landscape diversity is declining, being substituted by forest areas or by single-crop monocultures (e.g., olives) (Agnoletti and Emanuelli, 2016). Production systems are highly supported by irrigation, largely expanded as a response to an increasing frequency of drought and certain areas becoming arid. However, before the expansion of mechanized irrigation and massive use of external inputs, traditional crop managements were adapted to Mediterranean aridity (e.g., herbaceous crops grew under extensive rotations, a high presence of nitrogen (N) fixing crops and fallow periods to allow nutrients in the soil being naturally restored).

The Mediterranean dietary pattern has recently received increased attention due to its potential to reduce human pressure on the environment (Burlingame and Dernini, 2011; CIHEAM and FAO, 2015; Dernini *et al.*, 2016). The revival of the traditional food systems in the Mediterranean basin could increase agricultural resilience against climate change-related threats (e.g., desertification, droughts, soil erosion, extreme weather events, etc.), and contribute to reversing environmental degradation and resources depletion (e.g., soil erosion, water scarcity and pollution) (Aguilera *et al.*, 2020; Capone *et al.*, 2018; López-Sánchez *et al.*, 2016). Returning to locally-based production systems with reduced resource use, together with a reduction in livestock production, could increase food security in the Mediterranean region (Dernini *et al.*, 2016). Nevertheless, recovering certain agricultural practices of traditional Mediterranean landscapes (such as multi cropping, terraces, etc.) would have higher economic costs since it would be more labour-intensive. Recovering such practices might only be possible with public-oriented policy to subsidize this kind of production.

Given that the Mediterranean diet is composed of a large variety of agricultural products, mainly originating from plants and already present in most parts of the world, the Mediterranean diet could also easily be incorporated into food systems outside the Mediterranean region, with a potential reduction of the environmental impacts associated to food production (Hidalgo-Mora *et al.*, 2020).

3.2.2 Food processing and distribution

Traditional Mediterranean food systems were characterized by a low level of processing and distribution through short supply channels, used local and seasonal products, and led to almost zero food-waste. Most Mediterranean fruits and vegetables were consumed fresh and, in some cases, preserved by natural preservation means (e.g., water bath and sun drying for vegetables and fruits, salt for both animal-based and plant-based foods, smoke for animal-based foods). Since the last quarter of the 20th century, these foods have been subject to further processing in the form of juices, sauces and other products, and thanks to refrigeration and other techniques, consumers began to have access to a greater variety of commodities. Wine and oil were processed by similar procedures as today, but since the 1990s, these systems have become increasingly mechanized and accompanied by chemical processes, such as those for oil extraction or commercial wine production. As a consequence, such products were consumed more frequently. A modern Mediterranean food system could recover the beneficial traits of its traditional model (e.g., the predominance of fresh product consumption) while incorporating the advantages of modern processing.

Another characteristic of traditional Mediterranean food systems is their relatively low energy consumption. The energy requirements for food processing in a typical Mediterranean food system, such as that present in Spain in 1960, was $8.5 * 10^5$ kJ cap^{-1} year^{-1}. For comparison, more recently, the energy used by the 2010 food system in Spain today was $2.6 *10^6$ kJ cap^{-1} year^{-1} (Infante-Amate *et al.*, 2018). In relation to distribution, a traditional Mediterranean food system relies on an important share of the population living in rural areas thus supporting the consolidation of short supply chains between producers and consumers. Current rural depopulation in the Mediterranean region and worldwide can be an obstacle to the implementation of Mediterranean-type food systems (Young *et al.*, 2022). Food strategies focusing on urban and peri-urban agriculture and reinforcing short food supply chains could help re-establish Mediterranean food systems relying on local food chains under Mediterranean conditions. Yet this would require a reconfiguration of traditional landscapes, most of them abandoned or highly specialized in export-oriented products, which would only be possible with a determined public policy.

3.2.3 Diet

The Mediterranean diet has been followed by low-income rural societies for most of its history (Trichopoulou *et al.*, 2014). Regardless of local variations, the Mediterranean diet is an example of a diet in which biodiversity, local food production, culture, and sustainability are strongly connected.

Dietary patterns in traditional Mediterranean food systems are widely recognized as providing adequate nutrient intake and numerous health benefits including positive mental health outcomes, reduced mortality riskreduced risk of non-communicable diseases such as cancer, cardiovascular disease, Parkinson's disease, Alzheimer's disease, and attention deficit/hyperactivity disorders in children, among others (Darabi *et al.* 2022; Young *et al.*, 2022; Serra-Majem *et al.*, 2009; Sofi *et al.*, 2008).

Due to its reliance on local production, the presence and frequency of different food products within Mediterranean diets vary by country and region. However, Mediterranean diets share a common pattern, being a daily consumption of vegetables, fruits, legumes, nuts, legumes, whole grains, and unsaturated fats such as olive oil; a low (weekly) intake of eggs and dairy products (mainly cheese); moderate but variable consumption of fish (depending on the distance from the sea); a low level of meat consumption (Figure 3.1) (Bach-Faig *et al.*, 2011; Trichopoulou *et al.*, 2014); and almost zero associated food waste.

In general terms, the Mediterranean diet can be defined as a frugal plant-based dietary pattern (Dernini *et al.*, 2016). The large variety of food products that compose the Mediterranean diet, and the possibility to achieve variations in flavour by the use of spices and condiments, make it possible to adapt this dietary pattern to other cultural contexts (Gupta *et al.*, 2022; Russo *et al.*, 2021). The case of India is a successful example of how researchers and health practitioners are adapting the Mediterranean diet to local palates, with the aim of improving citizens' health (Maheshwari, 2016; Trichopoulou *et al.*, 2014), and efforts to incorporate this dietary pattern can also be found in places as distant as Costa Rica, Iran, or Taiwan (Darabi *et al.*, 2022; Gupta et., 2022; Chou *et al.*, 2022).

The principles of the Mediterranean diet are very similar to governmental healthy eating advice in many countries and the so-called 'demitarian' diet or the 'flexitarian' diet (Comité Científico AESAN, 2022; Hidalgo-Mora *et al.*, 2020; Russo *et al.*, 2021; Springmann *et al.*, 2018c). Indeed, it has long been the focus of scientific attention due to its association with a reduction of health risks (Keys *et al.*, 1980; Serra-Majem *et al.*, 2009; Fernández-Barrés *et al.*, 2019).

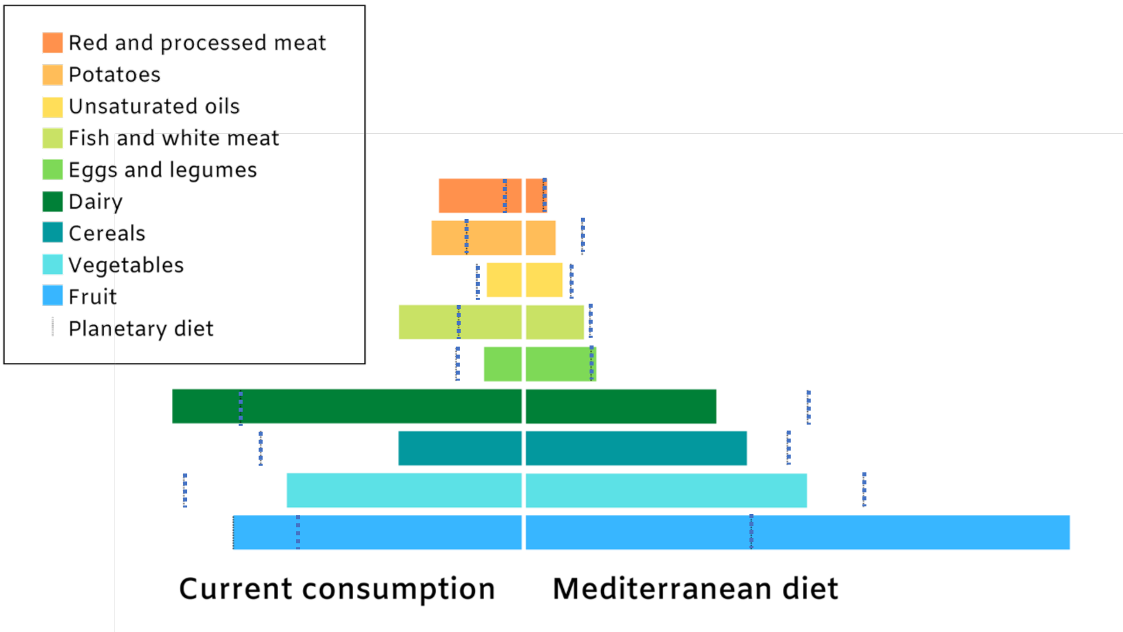

Figure 3.1. *Comparison of Mediterranean diet composition (right) and current per capita food consumption in Spain (left), expressed in kilograms. Dotted lines represent the 'Planetary' diet, as described by Willett et al. (2019). Mediterranean diet data from Blas et al. (2019). Current diet data from MAPA (2023). Source: figure created for this report by the authors.*

3.2.4 Environmental

Environmental scientists are also turning to the Mediterranean diet, focusing on its potential to reduce food consumption pressure on the planet. To date, only exploratory research has addressed its impact on nitrogen footprints (Cruz *et al.*, 2018). Due to the limited intake of meat and dairy and the high consumption of regional/indigenous products, it can be assumed that the Mediterranean diet's impact is comparable to a flexitarian diet, for which per capita nitrogen waste has been estimated to be half that of an average EU diet (Sanz-Cobena *et al.*, 2020; Willett *et al.*, 2019). Similarly, Martinez *et al.* (2019) have shown that pesco-vegetarian and semi-vegetarian diets, assumed to be almost equivalent to the Mediterranean diet, led to a reduction in the amount of N released by 17% and 15%, respectively, compared with non-vegetarian diets. Some authors have also highlighted the potential of demitarian diets to mitigate per capita greenhouse gas (GHG) emissions by about 30%, as compared to the diet projected for high-income societies for the year 2050 (Poore and Nemecek, 2018; Tilman and Clark, 2014; Weber and Matthews, 2008). Specifically addressing the Mediterranean diet, Sáez-Almendros *et al.* (2013) estimated that if these dietary patterns were recovered by the Spanish population, GHG emissions from the agri-food system could decrease by more than 70%, land use by up to 58%, energy consumption by up to 52%, and water consumption by up to 33% in Spain.

The adaptation of consumption patterns to Mediterranean diet principles could reduce food insecurity and improve the possibilities of healthy feeding a growing population within the planetary boundaries (Capone *et al.*, 2018; CIHEAM and FAO, 2015; Rockström *et al.*, 2009). An institutional framework such as the Farm to Fork strategy, which includes objectives such as extending the area under organic farming up to 25% of total agricultural land in the EU by 2030, could catalyse the re-adoption of the former production systems in the Mediterranean and other regions (European Commission, 2020a). This would result in a significant contribution by organic farming and a huge potential for its expansion aligned with Mediterranean principles and technologies, leading to lower external inputs and extensive livestock systems with a strong linkage to the territory.

Large-scale adoption of Mediterranean diets would require an increase in fruit and vegetable production at local and global scales, as the current supply would not be enough either in many Mediterranean countries or in others where Mediterranean-type food systems could be successfully implemented (Siegel *et al.*, 2014). The barriers to expanding a Mediterranean diet are not only economic, as in the case of production and processing, but also cultural, since it would require a dramatic change in dietary habits.

3.3 Agroecological food system

- Agroecology is a farming system that aims to reconcile nutrition, ecosystem health and social welfare.
- Agroecology maximizes the contribution of ecosystems to food production, while minimizing reliance on external synthetic inputs. It aims at shortening the supply chain, bringing producers and consumers closer.
- Agroecology is not only about tradition, thus it should incorporate new technologies and knowledge, for example in the field of biotechnology and agronomy.

3.3.1 Food production

The agroecology concept was defined a century ago (Klages, 1928) and has been historically implemented by smallholders in many regions of Latin America, Asia and Sub-Saharian Africa. It has gained momentum in the past two decades, not only in research but also in the broader policy arena (HLPE, 2019), as an approach to address environmental and socio-economic challenges caused by industrial and conventional food systems.

Originally resulting from the fusion of two scientific disciplines, agronomy and ecology; agroecology is now conceived in general terms as a science, a set of practices and a social movement (Wezel *et al.*, 2009). It is based on the enhancement of natural processes (soil fertility, natural pest control, N fixation and uptake, etc.) functional to crop production and livestock raising. Through an appropriate set of practices (e.g., diversified rotation, intercropping, green manuring, reduced and no tillage, presence of landscape elements, crop-livestock integration), it aims to maintain agroecosystems' productivity and self-sustaining capacity, as well as increasing their resilience. The result is a system that secures production, and at the same time maintains and guarantees, a high environmental quality, while minimizing resource depletion. Through time, the interdisciplinary nature of agroecology became more and more evident and while the focus moved from the agroecosystem level to the *food* system level, social and economic aspects became increasingly important.

Though the term agroecology encompasses different perspectives and disciplinary foci, there is wide acceptance of its general requirements:

- reliance on ecological processes as opposed to purchased inputs;
- equitable, environment-friendly, locally adapted and controlled practices; and
- systemic approaches embracing management of interactions among components, rather than focusing only on specific technologies (HLPE, 2019).

Accordingly, agroecology conceptualizes agro-ecosystems as complex socio-ecological systems and critically engages with socio-economic issues affecting them (Altieri and Toledo, 2011; Gliessman, 2014;

Méndez *et al.*, 2016; Wezel *et al.*, 2009). This entails the adoption of a system thinking approach that acknowledges the interlinkages of the different constitutive elements of the food system, from production in the field, to transport and diets, institutions and governance.

At the farm level, the transition to agroecology may include farm re-design where the overall biological efficiency is improved and biodiversity is preserved or enhanced. Five milestones need to be considered in order to move towards agroecological farming systems:

1. Increased crop diversity (spatial and temporal).
2. Appropriate soil management (e.g., low soil disturbance, permanent soil cover).
3. Integrated management of crops and livestock.
4. Presence of semi-natural features.
5. Minimized use of chemical inputs, with nutrients mostly produced on the farm.

In particular, **managing nutrients** based on agroecological principles makes use of a variety of farming practices to optimize N use and uptake and decrease reliance on mineral N. These include applying fertilizers at different times and in varying quantities to match crop demand (split fertilization); selection of crops with traits that enhance rhizosphere activities and foster the development of beneficial soil microorganisms; inclusion of leguminous in crop rotation or in intercropping; crop-livestock integration; and green manuring through crop residues and compost.

The successful application of these practices requires good knowledge of the conditions and characteristics of the local agroecosystems. Education and capacity building are therefore key since agroecology is knowledge intensive rather than input intensive.

3.3.2 Food processing and distribution

Agroecology is an evolving concept, which is now extending **from the farm to the food system** (Figure 3.2.) through a transdisciplinary approach, that includes all the ecological, sociocultural, technological, economic and political dimensions of food systems, from production to consumption (HLPE, 2019, Barrios *et al.*, 2020). Gliessman (2014) identifies the two steps characterizing the transition to agroecological food systems: re-establishing a more direct connection between producers and consumers; and building a new global food system based on participation, localness, fairness and justice.

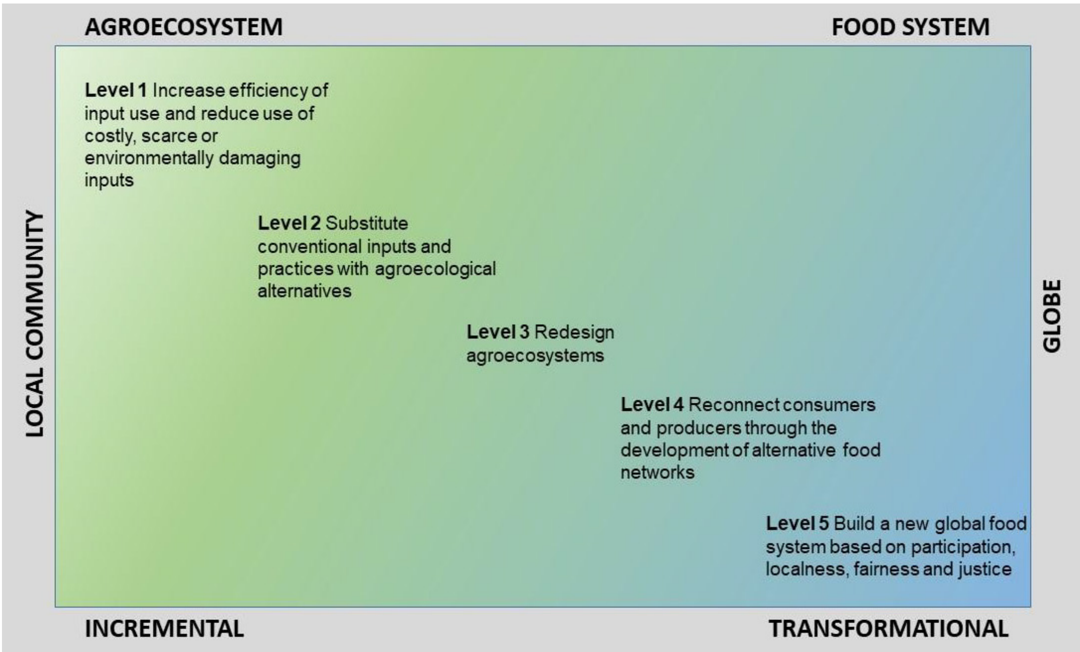

Figure 3.2. *Levels of transition to Sustainable Food Systems according to the agroecological paradigm. Source: adapted from Gliessman (2014); HLPE (2019).*

Therefore, agroecology promotes diversification of farming activities and services besides crop production and livestock raising, such as on-farm food processing (FAO, 2018). Agroecology also emphasizes the enhancement of local food systems, where significant shares of food supply and inputs are available at community level and products are processed locally (FAO, 2018). Local food systems also have less need for industrial processing than required when production and consumption are distant in space and time (e.g., drying, freezing, addition of preservatives) (Gliessman, 2014). More broadly, agroecology promotes the establishment of alternative food networks, where food producers and consumers are more strongly connected, knowledge is exchanged and co-created, and information on how the food is produced and consumed is shared in an open and transparent way. The interaction between farmers and consumers can be more or less direct and take different forms, from direct selling to community supported agriculture, box schemes or international fair trade. In all cases the overarching goal is to promote a *shorter* (not necessarily just *local*) supply chain which would allow producers to receive a higher share of the value generated within it (HLPE, 2019).

3.3.3 Diets

The agroecology paradigm promotes changes in the food system aimed at also reducing per capita environmental footprints, and fostering healthier diets and lifestyles. This entails increasing the share of local varieties and seasonal food in individual diets to reduce ecological costs associated with processing, packaging, transportation and storage. Poux and Aubert (2018) show that an agroecology scenario for Europe is possible and, under the conditions that the demand for food in 2050 can be met through a widespread adoption of a highly diversified, more plant-based, and therefore less agriculturally intensive diet. Agroecology further advocates focusing on the overall nutritional properties of foods instead of caloric content only. This means reducing the quantity of cheap but often highly processed foods rich in saturated fats, salt and/or sugar; and building food systems based on local identity, culture and dietary diversity (HLPE, 2019).

3.4 Visionary food systems

- Visonary food systems are those that look to advanced technologies and widespread dietary changes to lay the foundation for a sustainable future food system.
- To make such a vision come true, acceptance-, technology-, and energy-related obstacles need to be overcome. Further research in these domains is needed to show the way.
- The components of such visionary food systems need to be selected locally according to context, guided by improving the sustainability performance of the prevalent local setting.

In the coming decades, continued population growth and urbanization are projected to further add to today's food system challenges. It is expected that demand for nutritious food that contributes to healthy diets will rise, while the consequences of unsustainable production may become increasingly overwhelming. Food production patterns and food consumption habits need to change so that planetary boundaries can be respected (Gerten *et al.*, 2020).

Sustainable niche food systems already exist today. Combining increased production of novel foods, technological advances like vertical farming and dietary change look to substantial reductions in agricultural land requirements, nitrogen pollution and methane emissions (Winiwarter *et al.*, 2014). Developing coherent and shared visions of sustainable food systems is important to manage such related sustainability concerns (Halbe and Adamowski, 2019). A sustainable, visionary food system could be driven by the expansion of such promising production approaches and consumption habits. Advanced and innovative technologies are critical to produce food with less pressure on the environment (Herrero *et al.*, 2020). This, however, largely depends on the availability of clean energy. Such visionary systems are principally independent of location, but some might be particularly suited for areas of high population density.

3.4.1 Food production

Food production in a sustainable, visionary food system will need to reduce substantially the share of conventional livestock production systems. As described in Chapter 5, novel food products such as farmed insects or cultured meat may become promising protein alternatives to improve the sustainability and circularity of food production. Future foods could reduce the food-related nitrogen footprint and land requirements compared to conventional vertebrate livestock-based food systems (Pali-Schöll *et al.*, 2019; Tuomisto, 2019). Besides shifting to the production of novel animal-based foods, technological advancements will likely also enter the crop production chain, for example in the form of smart agricultural technologies and robotics (Boursianis *et al.*, 2020), or vertical ('indoor') farming. As a closed system, vertical plant cultivation is nutrient- and water-use-efficient and reduces agricultural land requirements (Benke and Tomkins, 2017; Tuomisto, 2019). A shift towards urban, high-technology food production systems and away from established agricultural production sites promises sustainability improvements. However, high-energy requirements and still missing technological breakthroughs remain challenges of these potential developments (Kobayashi *et al.*, 2022). In addition, improvements in its profitability, related policies and consumer acceptance are critical to mainstream vertical farming (Van Delden *et al.*, 2021). Moreover, such a food system transformation would require potential landscape, labour market and sectorial changes that need to be tackled early on by anticipatory policy-making to avoid an unfair distribution of resulting costs and benefits (Benke and Tomkins, 2017; Kalantari *et al.*, 2018).

3.4.2 Food processing and distribution

Despite the technological push in food systems, increasing consumer demand for a great variety of unprocessed or minimally processed food products could reduce the need for food processing in the future. A growing desire for regional production and short supply chains furthers urban farming concepts including community gardens and farms (Doernberg *et al.*, 2016; Schmutz *et al.*, 2018; Kirby *et al.*, 2021; Puigdueta *et al.*, 2021). Types of urban agriculture are manifold and they have a wide range of environmental impacts, stressing the need for further research (Dorr *et al.*, 2021).

Vertical farming in urban areas could supply a growing market for plant-based foods with locally produced crops, independent of the season, which reduces the need for storage and allows crop-breeding to focus on other qualities like taste. Such a high-investment solution will be especially relevant and cost-effective in megacities, where food demand of a large and densely living urban population with high purchasing power exceeds the food conventionally supplied by the locally available agricultural land (Beacham *et al.*, 2019). Technological advancements in the distribution and storage of food may furthermore contribute to reducing food-waste (e.g., by advanced packaging) or endow consumers to trace their products through the supply chain in order to enable more informed consumption choices (e.g., Poyatos-Racionero *et al.*, 2018; Bumblauskas *et al.*, 2020).

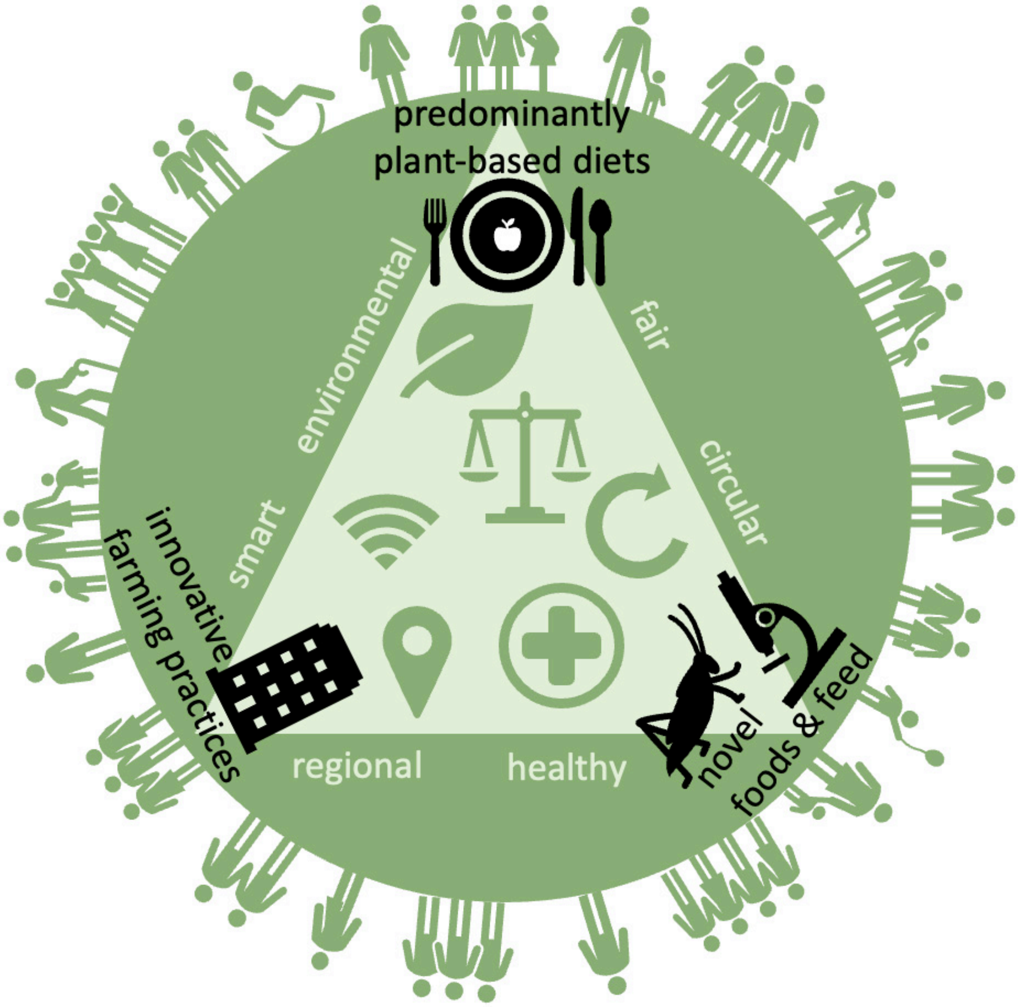

Figure 3.3. *A sustainable visionary food system could encompass innovative farming practices including urban and vertical farming, the production of novel foods, and predominantly plant-based diets. © Catharina Latka.*

3.4.3 Diets

Plant-based foods play a major role in diets linked to any sustainable food system for health-related and environmental concerns (Sabaté and Soret, 2014). A trend among certain consumer segments towards increasingly plant-based diets steered by environmental, animal welfare and health considerations has already induced an increasing range of vegan food products in the market (Curtain and Grafenauer, 2019; Janssen *et al.*, 2016). A predominantly plant-based diet is related to a low environmental impact (Castañé and Antón, 2017; Chai *et al.*, 2019) and can be nutritious, if balanced, well-planned and supervized (Costa Leite *et al.*, 2020); it can also be more affordable in upper-middle and high-income countries (Springmann *et al.*, 2021).

It may be asked whether a complete abolishment of animal farming is a desirable future? At a population level, this would require a substantial and non-trivial behavioural change and could increase the risk of nutrition deficiencies in cases of unbalanced food choices or limited access to healthy diets (FAO *et al.*, 2020, p. 98). Furthermore, fruits, vegetables and plant-based protein rich-foods are typically among the highest cost food items (FAO *et al.*, 2020, p. 116). Globally, diets with overall adequate nutrient supply cost more (at least by factor 2.66) than diets that only meet adequate energy levels (Bai *et al.*, 2020). In addition, healthy diets are currently not accessible for a significant share of the population (Penne and Goedemé, 2020). It should be added that ruminant meat can make a valuable contribution to sustainable food supply where the animals graze on marginal areas accessible to ruminants but not to crop production (Van Zanten *et al.*, 2016).

A combination of plant-based food choices, future foods and livestock fed on either food leftovers or grass could facilitate a balanced nutrient intake, while reducing the negative environmental impacts related to food choices. However, the potential efficiency gains also need to be considered in relation to possible market feedbacks, such as where increased efficiency reduces price and thereby tends to increase total flows (Parodi *et al.*, 2018; Van Hal *et al.*, 2019; Latka *et al.*, 2022). The role of novel foods in the future food system will furthermore depend on consumers' acceptance of emerging agri-food technologies (Siegrist and Hartmann, 2020). Nevertheless, further technological advancements, increased data availability and improved scientific evidence may enable consumers to follow a healthy, individualized and affordable diet, adapted to personal needs (Bock *et al.*, 2014; Herrero *et al.*, 2021).

3.5 Conclusions

The three food system archetypes described above have been conceived here as models containing elements, principles and technologies potentially usable in the design of sustainable food systems. These three archetypes are different in their elements, such as area of influence, food production (e.g., use of external inputs, labour intensity, use of technology, etc.), food supply chains and type of diet (Table 3.1). However, their characteristics are complementary and thus suitable to satisfy the common objective of shaping sustainable food systems through bottom-up or top-down actions.

Table 3.1. *Main characteristics of the three food system archetypes addressed in this chapter.*

		Mediterranean	Agroecology	Visionary
Area of influence		Regional (Mediterranean)	Global (Rural/peri-urban)	Global (Urban)
Food production	**Traditional knowledge**	High	High	Low
	High-tech	Medium	Medium	High
	Labour-intensive	High/Medium	High	Low
	Role of livestock	Medium	High	Low
	External energy inputs	Medium	Medium	High
	External material inputs	Low/Medium	Medium	Medium
Food chain		Region	Local to Global	Local
Diet		Demitarian	Demitarian	Plant-based
Nitrogen Use Efficiency		High	High	High

Box 3.1. *Research needs related to food system archetypes.*

- Research to recover knowledge of traditional sustainable food systems, generalize to other regional settings, and combine with high-tech knowledge.
- Regional cost-benefit analyses need to assess the potential of scaling up and combining key elements of sustainable food system archetypes.

Part B

Food systems à la carte: Elaborating a recipe for sustainable food systems

Chapter 4. The scope to improve nitrogen use efficiency of European food systems

Barbara Amon, Hannah H. E. van Zanten, Alberto Sanz-Cobeña, Cláudia Marques-dos-Santos, Sara Corrado, Carla Caldeira, Adrian Leip and Nicholas J. Hutchings

- At farm level, there is scope for significant improvement in nitrogen use efficiency (NUE) using available technologies. Values of farm-level NUE of up to 92% for arable systems, 80% for granivores, 61% for ruminant meat production, and 55% for dairy production can be achieved. Future food systems require optimized NUE through conventional and precision on-farm technologies, a close link between crop and livestock production, a reduction in food waste and improved used of by-products.
- The NUE of arable production systems is higher than that of livestock production systems and this is likely to also be true in the future, even with the development of new feeds, foods and technologies.
- Granivore systems offer the greatest possibilities to increase NUE, while the optimization potential for NUE is lowest in ruminant meat systems with less productive land, as their NUE is close to achievable limits.
- Livestock production can increase the total food production by up-cycling non-edible food from the whole food system and there is scope for increasing this utilization.
- Future technologies, including precision and digital farming, have the potential to improve NUE beyond the currently available level.
- **Key policy message: There is an urgent need, and a wealth of opportunities, for increasing European agricultural NUE, with arable systems having both a higher NUE and more potential for improvement than livestock systems. Livestock feed should be mainly restricted to non-edible biomass, rather than using what could be human food as animal feed.**

4.1 Introduction

This chapter deals with the options to improve nitrogen use efficiency (NUE) at the farm level. Nitrogen use efficiency is a key indicator for enhancing environmental sustainability that is applicable at multiple scales, from individual field to the entire economy. The NUE of an agricultural production system can thus be seen as indicating the balance between benefits and costs of primary food, feed and fibre production.

The impact of food trade needs to be considered in estimating NUE at the scale of the food system, as it is estimated that globally 10% of the total reactive nitrogen (N_r) inputs are due to outsourced food/feed production. Moreover, almost all the N_r inputs are from countries where there are issues of environmental pollution associated with low NUE. At the consumption level, an average of 30% food waste is generated globally, reducing food system NUE even more (Liu *et al.*, 2016). Improved NUE of crop and livestock production systems can and must play a crucial role in future food systems, but the required environmental benefits can only be achieved if production and consumption are addressed simultaneously.

Today's global food systems have major impacts on the environment (see Chapter 2). They are responsible for about a third of all human-induced greenhouse gases, one third of global terrestrial acidification, and the majority of global eutrophication; furthermore, crop and animal production cover 40% of the world's ice- and desert-free land (Crippa *et al.*, 2021; Bajželj *et al.*, 2014; Crist *et al.*, 2017; Foley *et al.*, 2011; Godfray *et al.*, 2010; Popp *et al.*, 2014; Springmann *et al.*, 2018a; Van Zanten *et al.*, 2019; Willett *et al.*, 2019).

Considering the scale of present impacts, it is evident that current food systems need to be rethought to feed the world's growing population, while safeguarding the environment (FAO, 2011; Poore and Nemecek, 2018). Researchers have proposed three main pathways to reduce the environmental impact of food production, especially with regards to nitrogen (Springmann *et al.*, 2018a):

1. The **production pathway** that aims to reduce N_r losses into the environment from the food production.
2. The **consumption pathway** by changing food consumption patterns towards products that are associated with lower N_r losses.
3. The **circular or regenerative pathway**, which seeks to improve the NUE of the food system, by more effectively utilizing residues/wastes and by-products.

A food system can be considered to consist of five main components: primary production (agriculture: cropping and livestock), food processing, food retail, consumption, and waste/residue management. There is a flow of nitrogen (N) from primary production through food processing, to food retail, and then to consumption; but within each component, there is a loss of N to the environment and the partitioning of N to waste products (see Chapter 1). The N lost to the environment can either be in the form of N_2 or N_r (e.g., ammonia NH_3, nitrous oxide N_2O, nitric oxide NO, nitrate NO_3^-). Although only the release of reactive nitrogen leads to environmental degradation, both losses of reactive nitrogen and N_2 represent the waste of a valuable resource. This potential is already to some extent utilized in current food systems (see Chapter 3). The minimal N losses correspond to the highest nitrogen use efficiency (NUE).

Although an efficient food system is not necessarily an environmentally sustainable one, a high NUE is a precondition for the system to be considered sustainable and the NUE indicator is a valuable tool to assess the potential of the system to become sustainable in such terms (i.e., minimizing environmental degradation). The NUE of a food system is a direct indicator of its resource use efficiency and an indirect indicator of its impact on the environment (Erisman *et al.*, 2018; Lassaletta *et al.*, 2014). Since capturing nitrogen for use in food production always requires resources of energy, time and cost, in these terms, increasing NUE will always be an advantage. Nitrogen use efficiency may be applied to different steps of the food system, and its increase has the potential to contribute to sustainable intensification (EU Nitrogen Expert Panel *et al.*, 2015; Garnett *et al.* 2015a). In contrast, the environmental impact depends on the form in which nitrogen is lost, e.g., N_2 has no direct environmental impact whereas N_2O is a powerful greenhouse gas. A range of traditional measures and technologies are already available and have been for many years. The implementation rate of these measures and technologies has yet to reach its maximum potential (Amon *et al.*, 2014). In addition, novel technologies are needed to meet the requirements for food and fibre of an increasing global human population (Herrero *et al.*, 2020).

This chapter focuses on measures to increase on-farm NUE (including technological options), the role of crops and livestock, NUE in the whole food system, and closes with an outlook to future technologies.

4.2 Measures to increase on-farm nitrogen use efficiency

- A modelling exercise showed that farm-level nitrogen use efficiency (NUE) in southern Europe was similar to or higher than in northern Europe.
- Arable systems reached the maximum technical NUEs (82% and 92% for northern and southern Europe, respectively) followed by granivores (71% and 80%), ruminant meat production on constrained land (45% and 61%), dairy production on unconstrained land (53% and 55%), and ruminant meat production on unconstrained land (50% and 36%).
- Unconstrained granivore systems (e.g., pig and poultry) offer the greatest possibilities for increasing NUE, while the optimization potential for NUE is lowest in constrained ruminant meat systems (e.g., cattle and sheep).
- Nitrogen use efficiency can be used as an indicator of the temporal trend in the costs and benefits of existing agricultural production systems and as part of the sustainability assessment of livestock production systems.

Current agricultural systems include interactions between land dedicated to the production of different commodities (e.g., cereal production for livestock feed) and a substantial recycling of nitrogen (e.g., as livestock manure). An assessment of the NUE of primary agricultural production needs to use system boundaries that include newly fixed nitrogen input to the production system until it is either exported for food processing or lost the environment (Figure 4.1). As noted by Erisman *et al.* (2018), the only truly new inputs of N (virgin N) are via fertilizers, biological N fixation and N fixed during combustion (e.g., in power generation, transport). Nearly all virgin N inputs enter the food system via agriculture (a small proportion is input via fishing).

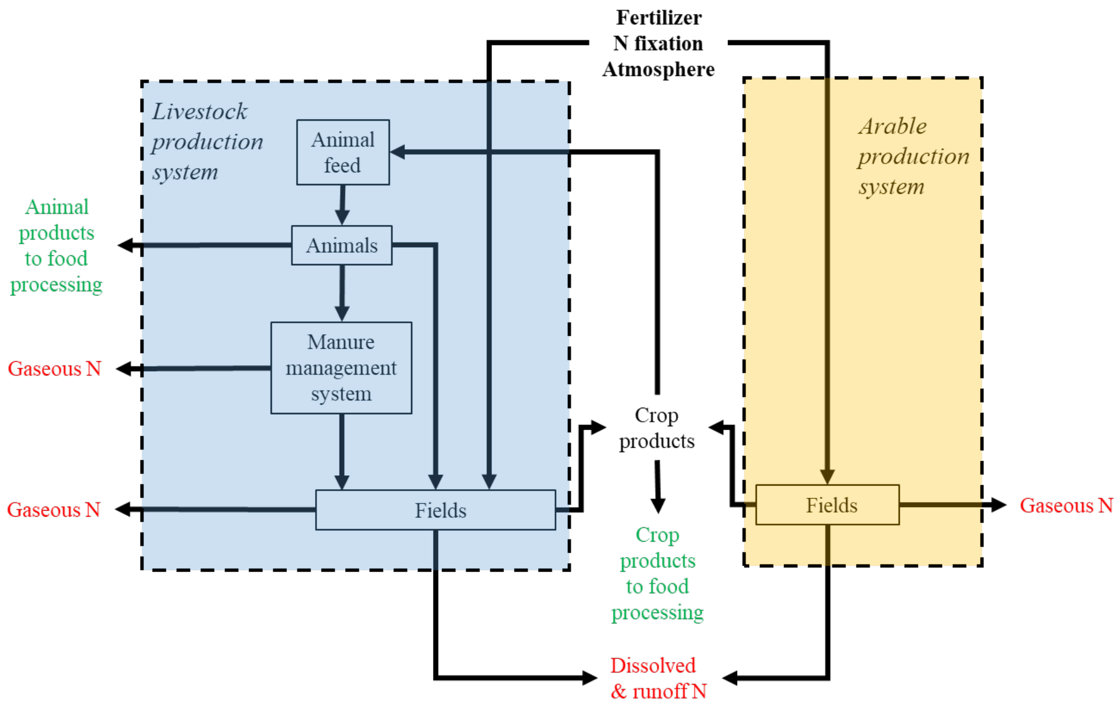

Figure 4.1. *Nitrogen (N) flows in the livestock and arable production systems (red = undesirable flows, green = desirable flows). Adapted from Hutchings et al. (2020), under CC BY-NC-ND 4.0, https://creativecommons.org/licenses/by-nc-nd/4.0/.*

The proportion of virgin N recovered in crop production is always greater than in animal production, since all animal production relies on the consumption of plant material and this process introduces additional inefficiencies. However, a certain level of animal production can increase the supply of protein in raw products for processing into food, by the conversion into products edible to humans of inedible crop production (e.g., grass) and by-products and wastes from later components of the food system (Fairlie, 2010). Increasing the contribution of animals beyond this point can lead to a reduction in both the supply of protein raw products for processing into food and the overall NUE of agriculture.

The varying biological and technical limitations on the NUE of different virgin N - crop - animal combinations create difficulties when assessing the scope for increasing the NUE of agriculture by other means than changing the balance between plant- and animal-based products. Godinot *et al.* (2015) suggested evaluating performance of a given production system against the maximum attainable efficiency of that system. However, estimating the maximum attainable NUE is a non-trivial task, partly because there are a range of measures to reduce N losses from different components of the farming system (animals, manure management, fields), some of which are mutually exclusive, and partly because reductions in N losses from one component can lead to increases in another (i.e., pollution swapping).

Hutchings *et al.* (2020) defined five production systems: ruminant meat on marginal land and on productive land, ruminant meat, dairy cattle, granivore meat and arable production. Two geographic regions were considered: northern and southern Europe. Currently, available measures to improve NUE were identified and allocated to Low, Medium and High ambition groups, with Low equating to the current situation in Europe for production systems that are broadly following good agricultural practice. If all available measures are implemented, the maximum technical NUEs for northern and southern Europe, respectively, would reach 82% and 92% for arable systems, 71% and 80% for granivores, 45% and 61% for ruminant meat production on constrained land, 53% and 55% for dairy production on unconstrained land, and 50% and 36% for ruminant meat production on unconstrained land. The greatest increase in NUE with the progressive implementation of higher ambition measures was found in unconstrained granivore systems (pig and poultry) and the least was in constrained ruminant meat systems (cattle and sheep). This reflected the lower initial NUE of granivore systems and the larger number of measures applicable to confined livestock systems, with the reverse situation applying to the ruminant meat production on constrained land. In general, increasing NUE requires gaining more control over the nitrogen flows. Some measures, such as an increased used of livestock confinement, will impact other policy areas (e.g., animal welfare).

There remains scope for increasing the NUE of all European primary food production systems using methods and technologies that are currently available. In addition, a range of novel feeds, foods and technologies are becoming available that have the potential to increase the food system NUE beyond the maximum values discussed here (see Chapters 3 and 5). These may reduce the differences in NUE between the arable and livestock production systems but are unlikely to remove them completely. In addition, NUE is only one of the indicators of sustainability, and other indicators relating to aspects of the environmental and human impacts of food systems also need to be taken into consideration when assessing the overall sustainability of different food production systems (Chapter 9).

4.3 The role of crops and livestock in a circular food system: the potential of recycling

- Currently, a large share of EU arable land—about 40% —is used to produce animal feed. Arable crop products should be processed for direct human consumption, rather than as animal feed.
- To maximize the effectiveness of utilization, by-products of food production should be recycled to the closest upstream component of the food system.
- Up-cycling wastes, by-products and crop residues from the food system back to agriculture reduces the land area required to satisfy the nutritional demand of the human population.

The nitrogen use efficiency (NUE) of livestock production strongly depends on the way livestock is kept and crops are produced. An increasing number of studies stresses the importance of a radical redesign of our food systems. Recently, a transition of the current more linear food system towards a more circular food system has gained attention. For instance, some authors have explored the role of the soil, crops and farm animals in a circular food system with high NUE and low nutrient losses (Van Zanten *et al.*, 2019; De Boer *et al.*, 2018; Erisman *et al.*, 2018). They concluded that to minimize the use of external inputs, arable land should be used primarily to produce foods from plant biomass that fulfil the nutritional requirements of humans. Currently, a large share of EU arable land—about 40%—is used to produce animal feed. No matter how efficiently animal-based food is produced, using arable land to produce feed for its production will always be less efficient than using it directly as food (Foley *et al.*, 2011; Godfray *et al.*, 2010).

Crops can contribute to the food system in several ways: directly by providing plant-based-food and indirectly by providing crop residues left over from harvesting of food crops, as cover crops, and as co-products from industrial food processing. Crop residues, cover crops and by-products can contribute to the food system as they contain carbon and valuable nutrients which makes them important as a source of energy or protein, micronutrients or structural material. Crop residues can also be used to maintain or improve soil structure and health, fertilize crops and co-products can be used to feed animals. Cover crops promote soil fertility, balance soil water availability and may also be used as feed. The choice of future crops for food production and their rotations should thus be based on maximizing the direct use of the crops including their co-products and by-products first, and only then maximizing their indirect use.

By adopting the approach described above, arable land will be used primarily for production of food crops, rather than feed, so that livestock can contribute to nutrition supply without using arable land (Figure 4.2). **Farm animals** would then not consume human-edible biomass, such as grains, but convert biomass that humans cannot or do not want to eat (i.e., low-opportunity-cost) into valuable food, manure and other ecosystem services. This includes biomass from grassland and scrubs, crop residues, by-products and unavoidable food waste in the food system. Ideally, these materials should be recycled to the closest upstream component of the food system that is safely feasible (e.g., food waste used as animal feed not biogas feedstock). By converting these leftover streams, livestock recycle nutrients back into the food system and the competition for land for feed or food is minimized.

Although recent studies have shown that farm animals can play a role in a circular food system, it is currently not known how much food could be derived from farm animals fed solely with low-opportunity-cost feeds. This will depend on the quantity and quality of by-products and grass resources available for animals, the type of animals, and how efficiently farm animals utilize these feeds.

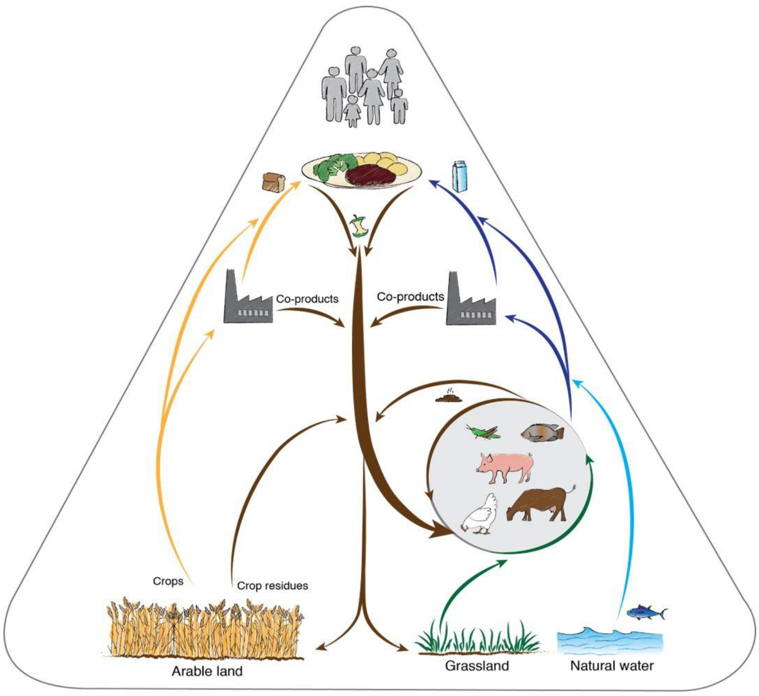

Figure 4.2. *The biophysical concept of circularity: arable land is primarily used for food production; biomass unsuitable for direct human consumption is recycled as animal feed; by-products and manure are used to maintain soil fertility. In this way, nutrients are recycled and animals contribute to a circular food system, while sustainably feeding the future population. Source: Van Zanten et al., (2019), reproduced here under CC BY-NC-ND 4.0, https://creativecommons.org/licenses/by-nc-nd/4.0/.*

4.4 Nitrogen use efficiency and the potential of avoiding food waste

- In the EU, about 55% of the nitrogen leaving the farm gate ends up in the food consumed by humans, while the remaining percentageis embedded in food waste and by-products generated along the food chain.
- If the EU met the objective of the Sustainable Development Goal 12.3 to halve food waste generation by 2030, emissions of reactive nitrogen (N_r) beyond the farm gate would decrease by about 50% while the amount of valorized (i.e., utilized) nitrogen would increase by 9%.
- In the EU, 27% of the nitrogen entering the processing stage is emitted as reactive nitrogen, 19% is emitted as molecular nitrogen (N_2) and 54% is valorized, i.e., it re-enters the food chain or other productive chains.
- There is a considerable potential for reducing emissions of N_r by more than 45% when fully implementing current EU legislation on waste and improving wastewater treatment. This improvement would require: 1) an increase of the share of tertiary wastewater treatment, 2) a reduction of food waste generation, and 3) a decrease of the quantity of incinerated and landfilled food waste.

Of the nitrogen entering the food system, only about 55% ends up in the food consumed by humans, while the remaining percentage is embedded respectively in food waste and by-products generated along the food chain. Food waste represents 30 to 40% of the food produced worldwide, with 14 to 20% of the food lost between harvesting and the retail sector (FAO, 2013a)[4]. At EU level, 20% of the food produced is wasted, being primarily food waste generated during the consumption stage (46%)—almost as much as the amounts generated during the primary production (25%) and processing and manufacturing stages (24%) combined (Caldeira *et al.*, 2019; Sanchez Lopez *et al.*, 2020). Reducing food waste along the food supply chain represents an environmental advantage, including the reduction of reactive nitrogen (N_r) losses. To assess nitrogen quantities in the environment and highlight conditions of inefficient use of nitrogen, Corrado *et al.* (2020) used literature and statistical sources to perform a comprehensive analysis of nitrogen flows along the post farm gate EU food chain, and the potential for reducing the identified inefficiencies was investigated using scenarios.

Corrado *et al.* (2020) highlighted that about half of the nitrogen that enters the post-farm gate food chain is currently utilized either re-entering or remaining in the food system in different forms, such as animal feed, compost or digestate, or entering other supply chains, e.g., biorefineries producing cosmetics. In 2011, the food processing stage was a responsible for the generation of 31 Mt of food waste and 97 Mt of by-products. These quantities highlight that the processing stage has a relatively high nitrogen utilization rate, since the homogeneity of the discarded food fraction makes recycling easier. On the contrary, 60 Mt of food waste were generated at consumption and no by-products were produced (Caldeira *et al.*, 2019).

Wastewater treatment was found to be responsible for more than 60% of non-agricultural reactive nitrogen emissions, hence it should be targeted for improvement. There is potential for the application of innovative wastewater treatment systems which retain N that would otherwise be lost and convert it into a quality fertilizer product (Herrero *et al.*, 2020).

Corrado *et al.* (2020) highlighted a potential to reduce non-agricultural reactive nitrogen emissions. Three scenarios were investigated besides the baseline:

1. **Improved Scenario**, considering an improvement in food waste reduction and wastewater treatment coherent with EU goals;
2. **Advanced Scenario**, considering that a share of wastewater is treated with alternative techniques to harvest reactive nitrogen directly from urine and wastewater; and

[4] *See also UN (2020) International Day of Awareness on Food Loss and Waste Reduction, 29th September.* https://www.un.org/en/observances/end-food-waste-day

3. **Combined Scenario,** combining the measures considered in the Improved and Advanced Scenarios (Figure 4.3).

In the three scenarios analysed there is a considerable reduction of reactive nitrogen emissions compared to the baseline, reaching 70%, in the Combined Scenario. However, technological barriers (e.g., the use of innovative systems for nitrogen recovery) or legislative barriers, (e.g., for the use of wastewater treatment sludge in agriculture) may be encountered.

Regarding N_2 emissions, a reduction is observed for the Advanced and Combined Scenarios, whereas an increase of about 30% is observed for the Improved Scenario due to an increase of tertiary wastewater treatment, which converts reactive nitrogen in N_2. This N_2 then needs to be transformed in a reactive form before being 're-filled' in the food system. This highlights that tertiary wastewater treatment has the advantage of reducing the environmental pressures due to reactive nitrogen emissions compared to primary and secondary wastewater treatments, however, it does not contribute to the closure of the nitrogen circle. In order to close the nitrogen cycle, N_r recovery approaches are needed.

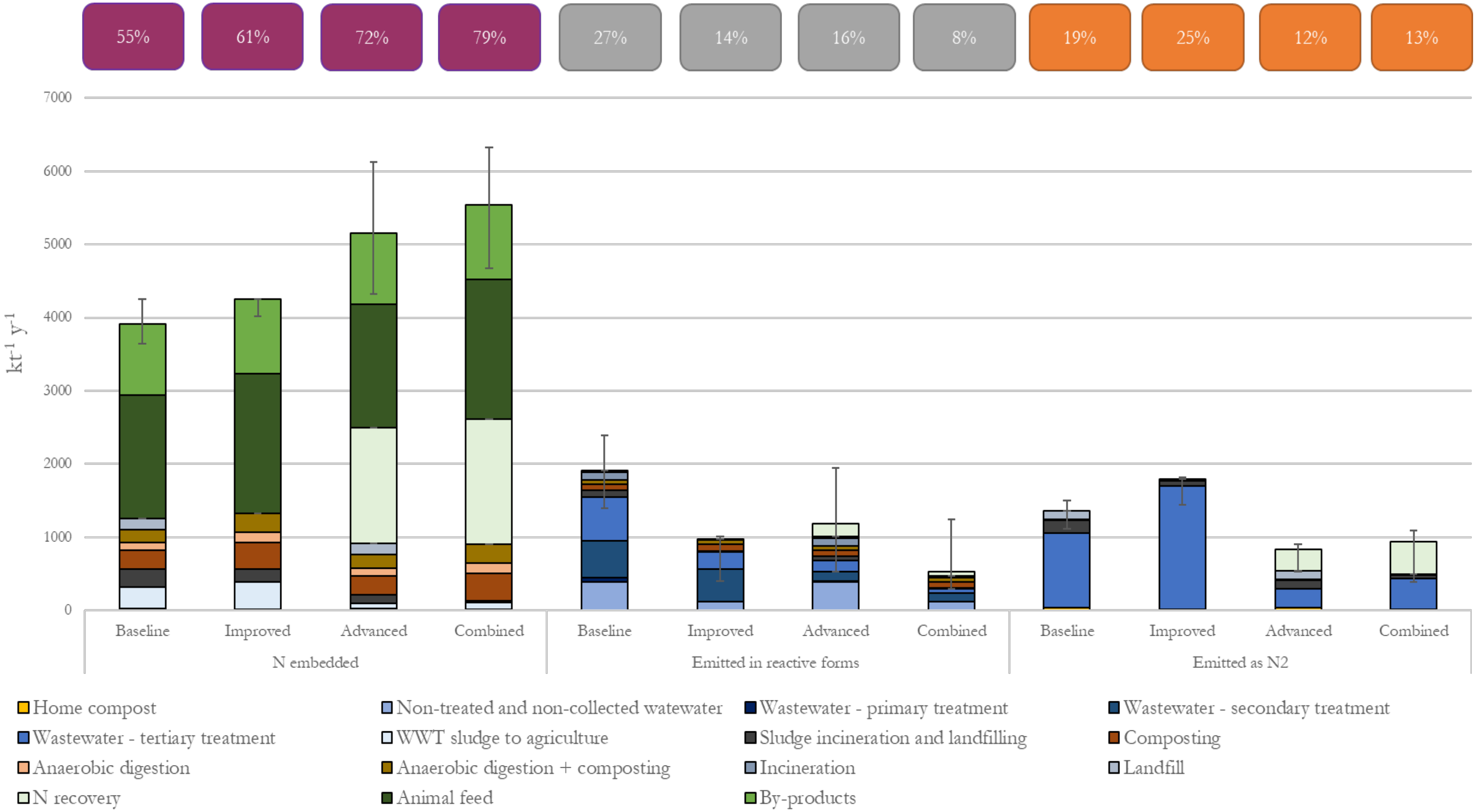

Figure 4.3. *Nitrogen (N) embedded and emitted either as reactive nitrogen or molecular nitrogen (N_2). Percentages in the boxes give the average share of N embedded, N_r and N_2 in the total N. Error bars correspond to the average minimum and maximum results from the sensitivity analysis. Source: Corrado et al. (2020), reproduced here under CC BY 4.0, https://creativecommons.org/licenses/by/4.0/.*

4.5 Future technologies

- Future technologies will have the potential to further improve nitrogen use efficiency (NUE) along the food chain.
- Future technologies should include regenerative resources, technologies that prevent losses and technologies for reuse/recycling materials and energy.
- Precision and digital farming technologies are promising options towards more sustainable food systems with increased NUE.

The previous sections show that nitrogen use efficiency (NUE) in the food system can be improved by minimizing waste in the first place and recycling recourses at the highest utility level. Future technologies to improve NUE along the food chain are required to meet the growing demand for food, feed and fibre. These include the use of regenerative resources, the development of technologies that prevent losses and leakage of natural resources, and the use of technologies to reuse/recycle resources inevitably lost (Sutton et al., 2022). Herrero *et al.* (2020), Van Zanten *et al.* (2018) and Parodi *et al.* (2018) considered a range of future technologies and their technological readiness level.

Some promising technologies target current farming systems. The efficient conversion of low-opportunity-cost feeds into food for humans requires additional livestock breeding, since modern livestock are bred to be highly productive on high-quality feeds and are probably less suited to utilize co-products and food waste. The biological treatment of straw with fungi can significantly improve the nutritional value for ruminants, and generally improve the quality of low-cost feeds (Khan *et al.*, 2015). Progress in precision and digital farming technologies including sensors, drones, robots, big data and artificial intelligence, can allow farming operations to better account for variations in production capacity, thereby increasing resource use efficiency. There appears to be a substantial potential for biorefinery to process fibrous plant material such as grass into protein and fibre. The protein is highly suitable for pigs or poultry, where it can replace imported soya, or may even be processed directly into food suitable for humans. The fibre and some remaining protein can be used as a cattle feed. The industrial production of proteins by bacteria, yeast, fungi or algae from low-opportunity-cost materials has a large potential for replacing conventional animal feeds and for use directly as food, thereby reducing the cropland area required to support food production (Pikaar *et al.*, 2018). Nitrogen recovery and reuse from different waste sources, including wastewater and sludge can also contribute towards improving NUE and polluted ecosytems. Outside current farming systems, technological developments offer the potential to up-scale the production of underexploited protein sources such as insects, seaweed and mussels, either as animal feed or for direct use by humans. Finally, there is considerable attention being given to the production of plant-based meat substitutes, and both meat and milk that is cultured from plant-based substrates, all of which has the potential to avoid the inefficiencies associated with livestock production.

4.6 Conclusions

Improvement in the nitrogen use efficiency (NUE) of crop and livestock production systems can and must play a crucial role in future food systems. However, the required environmental benefits can only be achieved if production and consumption are addressed simultaneously. At the farm level, livestock systems are less efficient than arable systems and have a lower maximum technically achievable NUE. The NUE of ruminant livestock compares more favourably with non-ruminant livestock when the comparison is made at the system scale. The scope for improvement is less for grazing livestock systems, partly because they are already much more efficient than other livestock systems and partly because there are fewer technical opportunities for increasing NUE than in other livestock systems. When considering the currently available technologies to improve the NUE of the production of livestock products, a high ambition requires having considerable control over the N flows, which consequently means having livestock housed and using advanced manure processing technologies.

Even when applying high ambition measures, the current food system and the currently available technologies are unlikely to be able to simultaneously meet the food demands of a growing population while also reducing the environmental impacts of agricultural production. A fundamental change is required. Both on the technological side and along the whole food supply chain, it is necessary to include the increase of NUE in all of its links.

If existing sustainability goals are to be achieved (such as a long-term goal to avoid air pollution effects), the currently practiced linear model of extract-produce-consume-discard must be transformed into a circular food system. This should be built on regenerative resources and use these natural resources efficiently and with low emissions to produce nutritious food. To develop these renewed circular food systems, analysis should not only consider increasing the efficiency per kg of product produced (including through increasing NUE), but on increasing the number of people to be nourished per unit of natural resource used. This provides a foundation for sustainable production and consumption of food for a growing world population (Mottet *et al.*, 2017; Van Zanten *et al.*, 2018).

Box 4.1. *Research needs related to improvement of nitrogen use efficiency in European food systems.*

- Digital and precision farming technologies must be further developed to improve nitrogen use efficiency (NUE) in crop and livestock production. Such technologies include: sensor technologies, data accessibility, data networks and communication, artificial intelligence, integration into decision support systems that take account of variabilities in time and space, robotics, and autonomous driving.
- Improved logistics and technologies are required to increase the utilization of food residues and by-products along the whole supply chain, and to use the nutrients as feed or fertilizer.
- Innovative technologies should be developed to recover nitrogen from wastewater and other waste/residue streams, including polluted ecosystems, to return it for the production of food and fibres.

Chapter 5. Future foods as alternatives to conventional animal-based foods

Alejandro Parodi, Roberta Alessandrini and Hannah H. E. van Zanten

- Future foods have the potential to supply valuable nutrients to human diets in a land-efficient way and with lower greenhouse gas emissions compared with conventional animal-based foods.
- Many future foods are already commercialized, but their major adoption will require overcoming technological, economic, legislative and socio-cultural barriers, and elucidation of their true impact on greenhouse emissions and nitrogen.
- Only when overconsumption of conventional animal-based foods in the EU is addressed, could future foods truly provide environmental and nutritional benefits.
- **Key policy message: Future foods offer opportunities for substituting unsustainable high consumption of animal-based foods; but to reap their nutritional and environmental potential, certain regulatory barriers need to be removed or reduced.**

5.1 Introduction

Farmed insects, farmed seafood, microorganisms such as microalgae and fungi, as well as so called 'cultured meat', all have potential to play a major role in the future food system (FAO, 2013b; Parodi *et al.*, 2018). While some of these foods are already commercialized and consumed in different parts of the world (e.g., algae) (FAO, 2020a), others are still in the development phase (e.g., cultured meat). The major adoption of these alternative foods (here termed 'future foods') will not only depend on their tastiness and capacity to supply essential nutrients with low environmental impact, but also on overcoming different technological, economic, legislative and socio-cultural barriers. This chapter provides insights into the nutritional and environmental features of these future foods and discusses the main factors that will ultimately determine their adoption in global diets.

5.2 Nutritional profile of future foods

- Future foods contain high levels of protein and a diverse array of minerals, vitamins and fatty acids crucial for human nutrition.

Thanks to their nutritional content and versatility, future foods could be key for ensuring adequate nutrition for the next generations, both as main foods and food ingredients. These foods not only contain equal or larger amounts of protein, minerals, vitamins and fatty acids than most conventional animal-based foods (Figure 5.1), but also offer great potential for the design of nutritionally-customized foods (Ben-Arye and Levenberg, 2019). For instance, laboratory-grown meat, made from laboratory-grown muscle and fat cells could be mixed with nutrients produced by microorganisms to obtain foods with specific nutrient profiles (Post, 2012). Similarly, different levels of fat, protein and omega-3 fatty acids can be obtained from fly larvae depending on the diet used to feed them (Barragan-Fonseca *et al.*, 2019; Oonincx *et al.*, 2020).

Even though evidence suggests that the consumption of some of these foods can help to ameliorate nutrient deficiencies (Li *et al.*, 2012; Nakano *et al.*, 2010; Watanabe, 2007), the extent to which these nutrients can be absorbed by the human body is only known for a small number of foods and nutrients, and not always with positive outcomes. For instance, while insects contain iron levels generally higher than conventional animal-based foods (Figure 5.1), the iron absorption for humans has been found to be low (<3%) (Mwangi *et al.*, 2022). To fully exploit the nutritional potential of future foods, the bioavailability of nutrients and the design of processes to improve it, are crucial topics that should be on the research agenda.

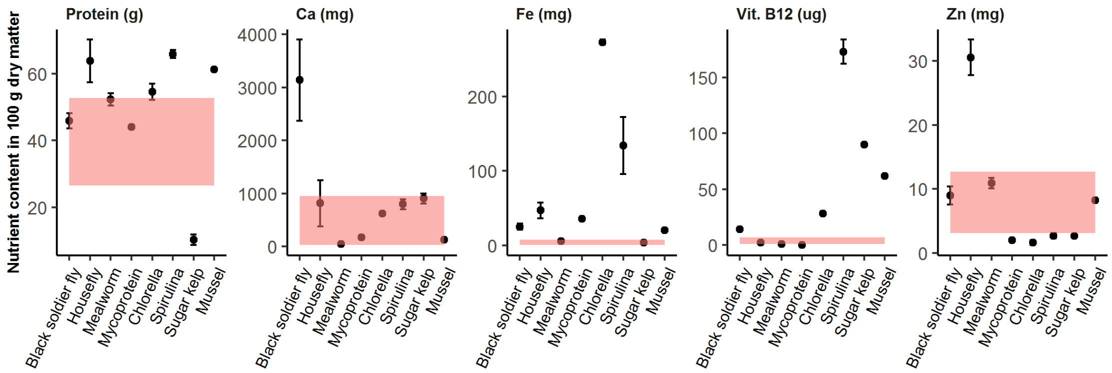

Figure 5.1. *Nutrient content of a range of future foods per 100 grams of dry matter (mean ± std. error). The nutrient amounts found in conventional animal-based foods (i.e., milk, egg, pork, beef and chicken) are within the red shaded area. Source: Parodi et al. (2018), figure created for this report by the authors.*

5.3 Environmental benefits

- The production of future foods requires less land and could potentially result in less nitrogen and greenhouse gas emissions than livestock production.
- Environmental impacts on other impact categories such as nitrogen pollution and biodiversity loss should be further assessed and quantified.

Future foods are land-efficient alternatives to conventional animal-based foods (Parodi *et al.*, 2018). Their land-use benefits originate from:

1. the use of organic side streams as feedstock (e.g., insects fed on food waste (Alexander *et al.*, 2017));
2. the dispensability of feed inputs of certain foods (e.g., mussels (Wijsman *et al.*, 2018)); and
3. the fact that their production can take place on lands not suitable for crop production (e.g., microalgae (Zhang *et al.*, 2012)) or in the ocean (e.g., mussels and other seafood, and seaweed).

Even though spatial conflicts in coastal areas might limit seafood production in some parts, globally, the areas suitable for seafood farming are vast (Gentry *et al.*, 2017).

The intensity of greenhouse gas (GHG) emissions during the production of most future foods were found to be similar to those of eggs and milk, the conventional animal-based foods with the lowest emissions (Table 5.1). However, the processes involved in GHG production differ. For conventional animal-based foods, most of the GHG emissions are associated with feed production, manure management and enteric methane emissions from ruminants (Gerber *et al.*, 2013); while the GHG emissions of future foods are mainly linked to energy-intensive processes such as drying (e.g., microalgae and insects, Salomone *et al.*, 2017), cell cultivation (Tuomisto and Teixeira de Mattos, 2011), steam production and maintenance of the fermentation process (e.g., mycoprotein, Finnigan *et al.*, 2010). For this reason, the shift towards renewable energies could potentially bring larger GHG emission reductions related to the production of future foods than from conventional animal-based foods.

There is evidence to support that some of these foods could also improve nitrogon use efficiency (NUE) along the food system (although the impacts of these foods on the N cycle have not been as thoroughly assessed as those on GHG emissions and land use). For instance, the production of manure-fed and food waste-fed insect larvae for feed applications, could not only potentially increase the NUE in the feed chain (i.e., as less conventional animal feeds will be needed), but also reduce the associated N losses from manure, as during insect rearing, ammonia-N can be incorporated in their body mass (Parodi *et al.*, 2022), with lower emissions compared with livestock (Oonincx *et al*., 2010). Ammonia emissions from insect rearing systems are a known environmental concern, for which well established mitigation measures are available (Bittman *et al*., 2014; Sutton *et al*., 2022). In addition, aquatic future foods such as seaweed and farmed mussels could help to reduce excess nutrients in coastal waters (Aubin *et al.*, 2018). Thus, the positive and negative effects of future foods production on the N cycle should be systematically assessed and quantified. The same is the case for other impact categories such as biodiversity loss.

If future foods are widely adopted, trade-offs are expected to occur. For instance, insect leakages from production facilities could potentially affect natural ecosystems and local biodiversity (Berggren *et al.*, 2019; Tomberlin and van Huis, 2020), and the extraction of wild mussels from natural beds to provide seeds for mussel farms could threaten natural populations and disrupt ecosystem functioning (Piñeiro-Corbeira *et al.*, 2018). Therefore, to avoid undesired trade-offs additional research on more impact categories (e.g., N and phosphorus eutrophication, biodiversity loss) is highly needed.

Table 5.1. *Greehouse gas GHG) emissions and land use (mean ± std. error) to satisfy the daily protein requirements of one person (50 g). Source: Parodi et al. (2018), table created for this report by the authors.*

Food	GHG emissions (kg CO_2 eq)	Land use (m^2)
Black soldier fly	0.74 ± 0.12	1.87 ± 0.3
Housefly	0.13 ± 0.02	0.0029 ± 0.0003
Mealworm	0.61 ± 0.03	3.63 ± 0.57
Mycoprotein	1.07 ± 0.34	2.41
Chlorella	6.40 ± 1.53	0.39 ± 0.05
Spirulina	5.64 ± 1.12	0.24 ± 0.03
Sugar kelp	0.93 ± 0.12	0
Cultured meat	1.54 ± 0.18	0.73 ± 0.14
Mussel	0.59 ± 0.04	0.26 ± 0.13
Beef	12.01 ± 0.39	20.31 ± 1.08
Chicken	2.70 ± 0.15	4.52 ± 0.28
Egg	1.42 ± 0.09	2.95 ± 0.18
Milk	2.91 ± 0.10	4.64 ± 0.27
Pork	4.20 ± 0.20	4.71 ± 0.19

5.4 Barriers to the adoption of future foods

- Dietary, biotechnological, economic, legislative and socio-cultural barriers need to be overcome to stimulate the adoption of future foods on a large scale.

To stimulate the adoption of future foods in the transition towards sustainable food systems, various barriers need to be overcome:

Dietary barriers – Currently, in general, conventional animal-based foods are overconsumed in the EU (Van Zanten *et al.*, 2018). If consumption of conventional animal-based foods is not reduced, the environmental and health benefits that future foods could bring as alternatives to conventional animal-based foods will not be tangible as overconsumption is still unsustainable and unhealthy. Therefore, to fully benefit from future foods, it is key to tackle overconsumption of conventional animal-based foods first, and then introduce future foods as alternatives.

Biotechnological barriers – Of all foods, cultured meat is the one facing the biggest technical barriers. Even though developments in the field of tissue engineering have made it possible to envision laboratory-grown meat as a potential food source, its large-scale implementation is constrained by technical challenges. These challenges include the efficient expansion of animal cells and the design and implementation of structures needed for cell proliferation. The development of animal-free inputs (growth media and scaffolds) (see Ben-Arye and Levenberg, 2019; Stephens *et al.*, 2018) used to be an important technological barrier which has recently been overcome (Ben-Arge *et al.*, 2020). For other foods, biotechnological challenges include reducing seaweed susceptibility to diseases (Cottier-Cook *et al.*, 2016; Michèle *et al.*, 2019) and guaranteeing the safety of waste-fed insects to be used as food or feed (see Box 5.1 to explore how safety concerns about mycoprotein were overcome).

Economic barriers – For most future foods, production still takes place at a relatively small scale and therefore producers cannot benefit from the economies of scale (Draaisma *et al.*, 2013; Han *et al.*, 2017; Kim *et al.*, 2019; Vigani *et al.*, 2015). In addition, factors such as initial capital investment (FAO, 2013c; Vigani *et al.*, 2015), dependence on energy and fuel prices (Lourguioui *et al.*, 2017), and expensive inputs (e.g., highly refined glucose syrup for mycoprotein (Whittaker *et al.*, 2020), contribute to high production costs.

Legislative barriers – Changes in EU legislation, such as the approval of the use of insect-derived protein in feed for aquaculture and livestock (European Commission, 2017) helped to boost insect production in the EU. However, there are still strict regulations on which organic waste/residue streams can be fed to insects (IPIFF, 2022) that are constraining the growth of the sector. Other legal barriers include the strict and complex novel food regulation (Belluco *et al.*, 2017; Michèle *et al.*, 2019; Vigani *et al.*, 2015) and the authorization permits required to start farming activities in the ocean (Leinemann and Mabilia, 2019; Roberts and Upham, 2012).

Socio-cultural barriers – To succeed, the future foods which are not yet widely consumed globally, need to become accepted by the average consumer. Food appearance (Elzerman *et al.*, 2011), education (Birch *et al.*, 2019), food familiarity (Tan and House, 2018), ethics (Laestadius, 2015), religion, culture (Hamdan *et al.*, 2018) and taste are some of the identified factors ruling the acceptance and rejection of foods. For instance, in a Dutch study 30% of the participants liked the taste of an insect product, 30% did not like the taste, and 39% were ambivalent (House, 2016). Consumer studies on cultured meat show that most consumers are willing to try cultured meat, but only a small portion would choose it over conventional animal-based foods (Bryant and Barnett, 2018).

Box 5.1. *Overcoming safety concerns about future foods – the mycoprotein case.*

Mycoprotein, commercialized as the vegetarian food product ‘Quorn’ is obtained by farming the fungi *Fusarium venenatum* in large bioreactors. This Mycoprotein-based food is a good example of how food processing technology can help to overcome safety concerns. Naturally occurring compounds (i.e., mycotoxins) present in the fungi genus *Fusarium* are known to be detrimental for human health. By ensuring specific culture conditions during the industrial production of mycoprotein and by performing regular checks (Wiebe, 2004), the production of naturally-occurring mycotoxins (Desjardins, 2007) are avoided. In addition, heating is used to reduce the nucleic acids levels in mycoprotein to avoid physiological complications (i.e., gout and kidney stones) known to occur in humans when excessive levels of nitrogen-containing compounds (i.e., nucleic acids) are consumed (Whittaker *et al.*, 2020).

Box 5.2. *Plant-based meat replacers.*

Contrary to cultured meat, plant-based meat replacers (PSMR) are mixtures of plant foods reproducing the taste, texture and the full look and feel of popular processed animal-based foods such as sausages, burgers and nuggets (Lagally *et al.*, 2015). Unlike future foods which come from foods not traditionally consumed by the EU population, PSMR are foods that have been on the market for a long time (e.g., soya mince and chunks), but that have recently been improved through novel processing techniques. Plant-based meat replacers are increasingly popular among younger generations and flexitarians (MSU, 2019). Although currently these foods hold only 1% of the market share of the entire meat sector, projections show that in the next decade their market share could increase up to 10% (Barclays Investment Bank, 2019). Nutritionally, PSMR can be as high in salt as their animal-based equivalent but contain lower levels of saturated fat and energy density, and have higher dietary fibre (Alessandrini *et al.*, 2021; Bryant, 2022). Considering that crucial micronutrients contained in conventional animal-based foods such as vitamin B12, zinc and iron are not always present in all PSMR (as not all products are fortified), it is key to guarantee the consumption of these nutrients either via fortification of PSMR or dietary diversification. As the main ingredients of PSMR are usually legumes and grains, the overall environmental impact of PSMR is expected to be lower than their animal-based equivalent (World Economic Forum, 2019).

5.5 Discussion and conclusions

Future foods could contribute to healthy and sustainable diets as they have the potential to supply valuable nutrients to human diets in a land-efficient way and with lower greenhouse gas (GHG) emissions compared to conventional animal-based foods. However, their potential to transform the food system is context specific. In regions like the EU where there is a high intake of nutrients associated with high levels of consumption of conventional animal-based foods, future foods will only bring environmental benefits if met with a reduction in the consumption of conventional animal-based foods. Instead, in regions where nutrient deficiencies exist, future foods could bring immediate benefits by supplying essential nutrients with low environmental pressure.

For the faster adoption of future foods, the existing framework on circular food systems (De Boer & Van Ittersum, *et al.*, 2018) could be useful. Circularity principles, such as prioritizing the consumption of primary biomass for human consumption (e.g., adding further variety to legumes and vegetables by introducing seaweed or algae) or using animals to recycle nutrients in the food system (e.g., insects fed on food residues), are in line with how future foods are envisioned.

Box 5.3. *Research needs related to future foods as alternatives to conventional animal-based foods.*

- Quantification of the bioavailability and digestibility of nutrients in future foods.
- Quantitative assessment of the environmental effects of future foods such as nitrogen and phosphorus pollution and biodiversity loss.
- Development of technologies to guarantee the safety of future foods when biomass streams are used for their production.
- Development of food processing methods designed to deal with the functionality, consistency and taste of new ingredients.
- Implementation of consumer studies on acceptability of future foods.

Chapter 6. Sustainability-minded food-based dietary guidelines as a tool to promote human and planetary health

João Costa Leite, Stefan Storcksdieck genannt Bonsmann, Elisabeth H.M. Temme and Jan Wollgast

- Environmental goals related to dietary choices including nitrogen emissions are often neglected in current national food-based dietary guidelines (FBDGs).
- Sustainability-minded FBDGs are much-needed instruments to guide national policies, institutions and the public towards healthy diets that are socio-culturally, economically and environmentally sustainable.
- The development of sustainability-minded FBDGs at a national scale can demonstrate how healthy diets that respect planet boundaries can be achieved in practice in various ways differing by country, population group and personal preferences.
- For sustainability-minded FBDGs to become effective for supporting a dietary shift, the public needs to know that adhering to them is feasible and be aware and convinced that it is key in a sustainable food system for healthy people and planet.
- The adoption of FBDGs require strong leadership and commitment by governments in achieving dietary targets
- **Key policy message: The extension of current FBDGs into sustainability-minded FBDGs is crucial for achieving healthy and sustainable diets.**

6.1 Introduction

Current food systems have a major impact on the environment (see Chapters 1 and 2) and shifting to predominantly plant-based healthy diets is seen as a necessary condition for a successful transition to healthy people and planet (see Chapters 3 and 5) (European Commission, 2020a; Willett *et al.*, 2019). A coordinated policy approach that acts on multiple levels of the food system is thus needed to guide an effective transition towards sustainability (see Chapters 7, 8 and 9). Importantly, defining dietary targets for sustainable food systems and healthy diets rely on agreements regarding food values in society (see Chapters 8 and 9) (Costa Leite *et al.*, 2020). One way for countries to develop such shared dietary targets is through the development of national food-based dietary guidelines (FBDGs).

Food-based dietary guidelines are "*science-based policy recommendations in the form of guidelines for healthy eating […] primarily intended for consumer information and education*" (EFSA Panel on Dietetic Products, Nutrition, and Allergies, 2010) and important governmental tools widely adopted by countries to provide advice on healthy diets and support the development of national food and nutrition policies (Gonzalez Fischer and Garnett, 2016).

The fact that all EU countries have their own national FBDGs underlines the cultural diversity of food choices and stresses the importance of a bottom-up approach (European Commission, 2022b). Presently, recommendations typically include following a varied, mainly plant-based diet with plenty of fruits and vegetables; water as the beverage of choice; and reducing the intake of red and processed meat, sugars, fat and salt. The European Food Safety Authority (EFSA) notes that FBDGs should be "*consistent with other public policies that have an impact on food availability and be integrated with other policies related to health promotion*" (EFSA Panel on Dietetic Products, Nutrition, and Allergies, 2010).

Present FBDGs provide guidance for a nutritionally adequate diet that promotes optimal physical and mental development and prevents non-communicable diseases. However, current policies, such as the European Green Deal and Farm to Fork Strategy, aim further, to change course towards healthy and sustainable food systems (European Commission, 2020a). Recently, the analysis of the implications of FBDGs in relation to environmental impacts including nitrogen (N) has highlighted the importance of aligning these guidelines with broader sustainability aspects (Springmann *et al.*, 2020). Therefore, this chapter explores, with a European lens, to what extent current FBDGs already address sustainability aspects. It then addresses how sustainability-minded FBDGs could become an effective tool for much-needed progress towards healthy and sustainable diets.

6.2 Sustainability aspects in food-based dietary guidelines (FBDGs)

- Sustainability requires further and more comprehensive attention in food-based dietary guidelines (FBDGs).

Globally, the adoption of principles of sustainable healthy diets in dietary guidelines have been mainly focused on health outcomes and less frequently consider environmental and socio-cultural aspects (Martini *et al.*, 2021). In the EU, the EFSA opinion on establishing FBDGs does not mention any environmental or other sustainability considerations, but instead focuses on the development of FBDGs from nutrient requirements, food intake data, and information about diet-disease relationships (EFSA Panel on Dietetic Products, Nutrition, and Allergies, 2010).

Likewise, many national FBDGs in Europe are not explicitly sustainability-minded. Still, according to an analysis of the FBDG overview provided by the European Commission, 23 out of the 32[5] FBDGs consider sustainability in a broad sense through their recommendation to consume local and seasonal products (European Commission, 2022b). However, only 11 FBDGs[6] expressly considered sustainability, mostly from an environmental perspective. While this is an increase compared to the two FBDGs[7] from Europe noted in the 2016 report 'Plates, pyramid, planet' (Gonzalez Fischer and Garnett, 2016), it shows the substantial room and need for including sustainability in all its facets.

Beyond emphasising local, seasonal produce, the existing sustainability-minded FBDGs in Europe recommend behaviours such as substituting animal-based with plant-based foods (such as pulses, legumes and nuts); choosing fish from sustainable sources; and reducing food waste and packaging. Other advice concerns lower environmental impact choices within product groups, for example, choosing poultry instead of red meat; cereal grains other than rice; tap water instead of bottled water; and sturdy vegetables (e.g., roots, tubers) and other fibre-rich options rather than more perishable produce (e.g., leafy vegetables). Where the thinking behind these sustainability-minded recommendations is laid out[8], aspects such as greenhouse gas emissions, climate change, production efficiency, environmental pollution, food transport practices and animal welfare feature less prominently. Furthermore, the importance of social and economic sustainability is given little attention.

Importantly, aspects such as nitrogen and phosphorus cycling, soil health or lifecycle assessment are spelled out less often. Of note, the new FBDGs by the Belgian Superior Health Council (2019) highlight the issue of natural disasters, war and migration resulting from climate change (Belgian Superior Health Council, 2019). Together with Sweden and Germany, respectively, they refer to vegetarianism/veganism, sustainability food labelling and fair trade.

Overall, efforts to introduce sustainability criteria are increasing in national FBDGs across Europe, but these are still limited to certain aspects and do not fully reflect the systemic outcomes of dietary choices in the food system. Considering the complex interdependencies that result in challenging environmental, social and economic implications from unsustainable food systems, pathways to explore and improve existing FBDGs need to address healthy diets and the food system as a whole.

[5] *EU-27 plus UK, Switzerland, Iceland, and Norway (NB: Flanders and Wallonia have separate FBDGs, hence the total number of 32 FBDGs for 31 countries).*
[6] *Belgium (national & Flanders), Denmark, Germany, Estonia, Finland, Sweden, UK, Iceland, Norway, Switzerland*
[7] *Germany and Sweden.*
[8] *Concerns FBDGs and scientific background reports with a sustainability chapter (BE, DE, EE, FR, NL, FI, SE, UK).*

6.3 Approaches to turning FBDGs into sustainability-minded FBDGs

- Multidimensional criteria and appropriate methodological tools are needed to deal with trade-offs when developing sustainability-minded FBDGs.
- Approaches based on interdisciplinary science to calculate an optimized healthy and sustainable diet need to be combined with a transparent process at national level, engaging relevant stakeholders in defining sustainability-minded FBDGs.

Designing dietary guidelines for the population to achieve sustainable food systems relies on approaches that integrate the different dimensions of healthy and sustainable diets. To address this complexity, linear programming models have been used to calculate an optimized diet under a set of constraints (Donati *et al.*, 2016; Gazan *et al.*, 2018; Huang *et al.*, 2012; Macdiarmid *et al.*, 2012; Perignon *et al.*, 2019). These mathematical models seek to reconcile constraints based on sustainability metrics (e.g., greenhouse gas emissions reduction, water footprint) with constraints related to healthy and feasible nutrition (e.g., dietary reference values, minimum cost of diets, minimum deviation from current national dietary intakes). The resulting recommended dietary shifts typically include an increase in plant-based foods and a decrease in animal-based foods, in particular red meat, as well as avoiding overconsumption of foods rich in energy, sugar, salt and fat (Hendrie *et al.*, 2016; Vieux *et al.*, 2018).

Nevertheless, caution is needed when selecting such constraints. For instance, overvaluing environmental outcomes could result in meat and dairy replacements with foods high in sugar, salt and fats, which would not be appropriate for health promotion (Macdiarmid *et al.*, 2012; Clark *et al.*, 2022). Diets that are otherwise nutritionally adequate are not necessarily environmentally protective or economically viable (Vieux *et al.*, 2018). Importantly, ignoring current food habits of populations in diet optimization could generate dietary patterns that are unacceptable or not achievable for many populations (e.g., complete exclusion of meat and dairy or with limited amounts of highly processed foods). Such dietary patterns could require additional efforts to shape individuals' perspectives regarding alternative sustainable food choices (Donati *et al.*, 2016).

More recently, alternative approaches using mathematical optimization models have been proposed to overcome the aforementioned limitations and better align modelled diets with actual food consumption patterns. One such approach is 'data envelopment analysis', where observed diets are benchmarked based on reported intakes (Kanellopoulos *et al.*, 2020). Alternative modelled diets are then calculated as linear combinations of food items consumed in the population. While this method provides a more realistic solution, as it resembles current diets in the population, a potential limitation is that the health and sustainability value of modelled diets relies on the quality of such diets.

Diet optimization relies on integrated and comprehensive data availability to ensure adequate and robust metrics are applied. While information on all sustainability parameters will not be easily accessed or derived, national data may allow the particularities of a given country's food system performance to be captured (e.g., local foods, geographical variability) (Donati *et al.*, 2016). Greenhouse gas (GHG) emissions including nitrogen emissions data from life-cycle analysis studies, which are often integrated in diet modelling, may serve as a proxy for other environmental indicators such as land use and eutrophication (Chaudhary and Krishna, 2019; Vieux *et al.*, 2018).

Other environmental concerns including biodiversity loss (e.g., fish consumption) also need to be appropriately considered. Importantly, addressing cultural acceptability and food security issues may rely on collective discussions focused on societal values towards healthy diets and sustainable food systems. Engaging experts and stakeholders including policy makers, food system actors and civil society in an effective and transparent way will be critical to achieve a shared agreement, ensure appropriate decisions and thus improve diet optimization outcomes (Brink *et al.*, 2019; Drewnowski, 2020).

As the original WHO/FAO framework recommendations to develop dietary guidance are limited to public health goals, a new set of recommendations to update FBDGs is needed to help the implementation of dietary guidelines for sustainable food systems (FAO and WHO, 1998, 2019b). The EAT-Lancet global targets provide an opportunity to discuss the environmental boundaries for national food systems, and FBDGs could help translate such global targets into national commitments to achieve sustainable and healthy food choices (Springmann *et al.*, 2020; Willett *et al.*, 2019; Wood *et al.*, 2019). The commitment and leadership of governments is crucial. This includes the development of adequate strategies/plans, budget allocation and the availability of monitoring data to ensure the effective implementation of FBDGs towards dietary targets (Wijesinha-Bettoni *et al.*, 2021).

6.4 Making sustainability-minded food-based dietary guidelines effective for people and the planet

- Updating FDBGs to integrate sustainability goals should be done in a transparent manner involving scientists and citizens, to increase societal buy-in for the shift to healthy sustainable diets.

Recently, the European Commission has put forward a strategy for a transition to a sustainable EU food system (European Commission, 2020a). A shift to healthy, sustainable diets is a necessary element of this transition. A range of science-based targets and tools are becoming available, including the guiding principles for sustainable healthy diets[9] (FAO and WHO, 2019), a reference for a planetary diet and FBDGs that increasingly integrate all dimensions of sustainability (Willett *et al.*, 2019a).

Costa Leite *et al.* (2020) have highlighted a number of policy measures to promote healthy and sustainable food preferences (see Figure 6.1) building on concepts developed by Hawkes *et al.* (2015) for healthy food preferences, including public procurement (Caldeira *et al.*, 2017), economic incentives (Cornelsen *et al.*, 2019) and nutrition labelling (Storcksdieck genannt Bonsmann *et al.*, 2020). However, the health and economic burden from obesity and diet-related diseases in Europe is still high (European Commission, 2022b). Furthermore, it is projected to increase by 2030 if current trends continue (OECD, 2019; World Obesity Federation, 2019), despite repeated efforts to reverse this. Given the scale of adverse effects, it becomes increasingly urgent to find ways to overcome the barriers (Dietz, 2020; Swinburn, 2019) and identify effective ways the shift to healthy and sustainable diets.

[9] *"Sustainable Healthy Diets are dietary patterns that promote all dimensions of individuals' health and wellbeing; have low environmental pressure and impact; are accessible, affordable, safe and equitable; and are culturally acceptable" (FAO and WHO, 2019, page 11).*

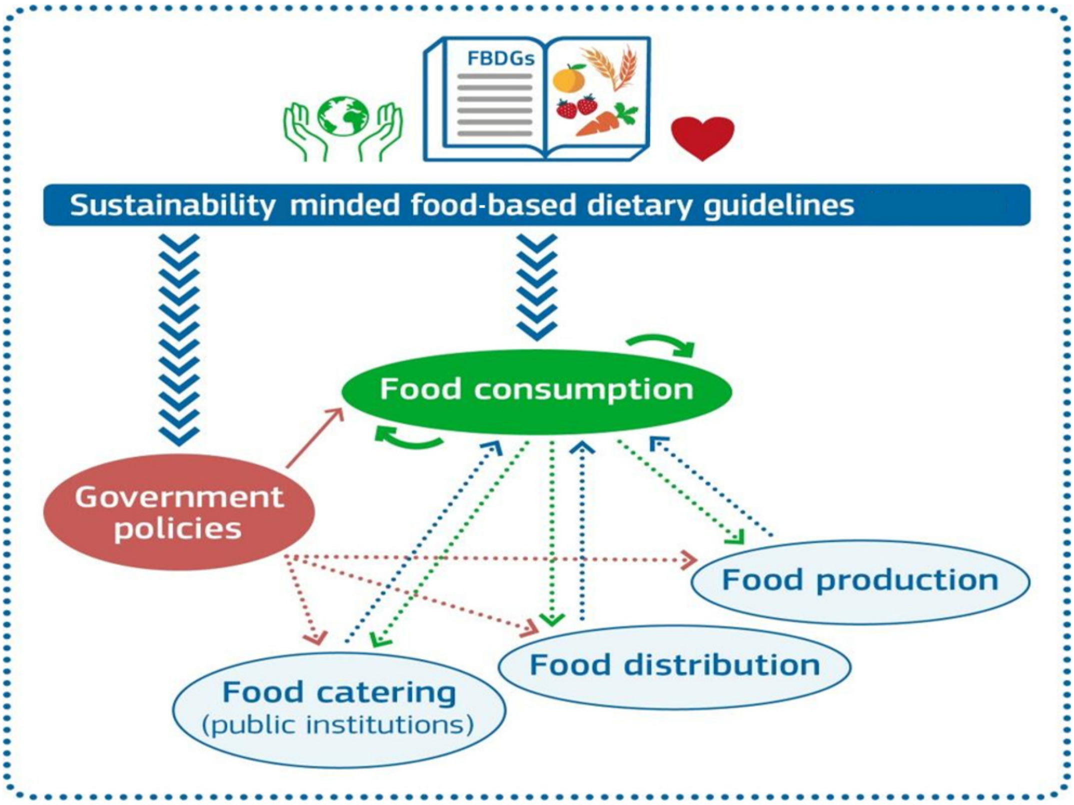

Figure 6.1. Sustainability-minded food-based dietary guidelines (FBDGs) can influence food consumption. Large blue arrows: FBDGs guide individuals and policies towards consuming and promoting healthy sustainable diets. Red arrows: Smart policies, such as incentives, food standards, legislation or fiscal measures promote healthy low footprint consumer food preferences directly (solid line) or indirectly (dotted line). Green arrows: Consumer demand feedbacks to food production, distribution, and catering (dotted line) and peer-influence also nudges other consumers (solid lines) towards healthy low footprint diets. Dotted blue arrows: Food system changes lead to increased availability, ubiquity, and attractiveness of healthy low footprint choices. Source: adapted from Costa Leite et al. (2020), under CC BY 4.0, https://creativecommons.org/licenses/by/4.0/.

Coercive policies to steer consumption towards health and sustainability, such as taxes or legal restrictions, are effective to some extent (Martin-Saborido *et al.*, 2016; Springmann *et al.*, 2018b), yet rather unpopular in European societies (see Chapter 7). This might in part be because the impact of current diets on health and the environment and the need to adhere to dietary guidance is not sufficiently understood or accepted. It may also be that many individuals already perceive their own diet as healthy and sustainable (European Commission, 2020e). Hence, strong policy measures that affect people's dietary choices in the name of public and planetary health are rejected as unduly interfering with personal choice.

With science and international agreements requiring a transition to sustainable food systems, the indispensable updating of FBDGs could be done in a transparent and inclusive manner with the support of public dialogues. Scientists and relevant stakeholders need to be part of the debate, such as through committees with a high-level governmental mandate and appropriate reporting obligations. Local policies are also emerging across the globe as transformative pathways to improve urban food systems and may be great opportunities to link national guidelines towards healthy and sustainable diets.

Strong governance (see Chapter 8) and political commitment in following suit with policies (e.g., public procurement, rules for responsible marketing and consumer information) (see Chapter 7), it is possible to support more sustainable food environments and make sustainable food choices easier for consumers. In addition, the active participation by citizens in this transition may support other efforts across the food system and society. For example, in order to achieve more rapid and wider changes towards decarbonisation, Otto *et al.* (2019) explored the potential of social tipping dynamics that can activate contagious processes of rapidly spreading technologies, behaviours, social norms and structural reorganisation. Initiators for such change include politicians, financial investors, popular citizens, writers, educators, media etc.; with lifestyle choices, values and norms eventually spreading from minorities to majorities in populations.

Food-based dietary guidelines are primarily intended for consumer information and policy development. Finding ways for wider participation in updating national FBDGs to integrate all aspects of sustainability can serve two purposes:

1. a better understanding of diet-health-environment relations and agreement with targets in FBDGs, which can
2. influence policy-making and consumer information for better adherence to healthy, sustainable diets.

These elements can foster a transition to a sustainable food system through food as an essential and tangible aspect of life, which can spill over to other societal aspects equally important towards living within planetary limits (Randers *et al.*, 2018).

6.5 Conclusions

This chapter has highlighted the key sustainability considerations, scientific methodologies and societal approaches for updating and making food-based dietary guidelines (FBDGs) effective in transitioning to sustainable diets and food systems. In so doing, the authors hope to inspire action by governments to update national FBDGs to include sustainability aspects.

Healthy diets that respect planetary boundaries and the cultural contexts are possible using available approaches. Adherence to sustainability-minded FBDGs in dietary practice can and will differ by country, population group and personal differences. Developing such guidelines upon a governmental mandate by relevant scientists and stakeholders, transparently and engaging in public debate can be an opportunity to show that shifting to healthy and sustainable diets is feasible, needs to engage everyone and is pivotal for a sustainable food system. The outcome would be a win-win for people and the planet.

Box 6.1. *Research needs for sustainability-minded food-based dietary guidelines (FBDGs).*

- Improve understanding of food/nutrition/health literacy and its relation to people adhering to FBDGs, and support policies/political parties towards sustainable food systems in different national contexts.
- Development and implementation of adequate methodological approaches to deal with sustainability trade-offs and diet optimization in developing FBDGs.
- Development of adequate methods to develop sustainability-minded FBDGs taking into account the most sustainable and healthy diets currently consumed in the population (benchmark approach) to avoid unfeasible diets.

Chapter 7. Consumer-oriented food policies for healthy and environmentally sustainable diets

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- To support dietary changes towards healthy, environmentally friendly produced food, a range of consumer-oriented instruments (administrative, information, market and behavioural) are available. However, taxes and subsidies have hardly been implemented.
- Implemented demand-oriented instruments largely focus on healthy food consumption and not yet on environmental sustainability, nor the combination of these two aspects.
- Although several policy instruments have been identified as effective, some require large-scale and long-term assessments.
- Power asymmetries in the food system and political tensions between domains and actors may have impeded political willingness to implement policy instruments for more plant-based diets; this requires further research.
- Food policies should be more coherent, taking into account both health and environmental factors, and combining different demand-oriented instruments; while also considering complementary supply-oriented policies to increase positive and reduce negative impacts.
- **Key policy message: A mix and better coherence of policies aimed at both provision of and demand for food, including implementation of demand-oriented policies (that have been shown to be effective in scientific literature or small-scale implementations) will promote health and sustainable diets in populations.**

7.1 Introduction

Among the various strategies to reduce nitrogen (N) losses, as well as greenhouse gas (GHG) emissions from agriculture, a change of diets towards low emission foods is considered to have a large positive impact (Poore and Nemecek, 2018; Westhoek *et al.*, 2014), while similary contributing to food security (Smith *et al.*, 2013). Diets with foods associated with low emission levels are often healthier than those with foods high in emissions. Examples include plant-based foods, such as legumes as compared with red and processed meat, or tap water compared with sugar-sweetened beverages (Van De Kamp *et al.*, 2018; Clark *et al.*, 2019; see also Chapter 2). Overconsumption, particularly of foods high in energy, fat, sugar and/or salt, causes both health problems and avoidable emissions of pollutants (Hendrie *et al.*, 2016). Hence, there are gains for both human and planetary health from changes in food choices. This chapter looks at policy interventions that can increase demand for healthier and more environmentally sustainable diets, presenting examples of implemented policies and discussing their effectiveness based on scientific evidence.

7.2 Types of policy instruments

- Informative, administrative, behavioural and market-based instruments can be implemented to steer the dietary choices of consumers.
- Most consumer-oriented food policies focus on public health and a lower consumption of energy-dense, (micro)nutrient-poor foods and drinks, and higher vegetable and fruit consumption.

Instruments available to stimulate dietary change can be categorized as either administrative, informative, market-based or behavioural. So far, most policies related to food demand are implemented to steer consumers towards nutritious foods that contribute to healthy diets, but there is a potential for alignment with environmental outcomes (Temme *et al.*, 2020).

7.2.1 Administrative policies

Administrative policies aim to monitor, prohibit or mandate behaviour. Examples are policies that encourage (mostly via voluntary agreements) the food industry to reformulate (i.e., change the recipes of) processed food products to reduce the contents of unhealthy ingredients of food (e.g., salt content). Recently, the European Commission has implemented a policy regulation by setting a maximum limit for industrially processed trans-fatty acids (TFA) in foods of 2 g/100 g of fat, with a transition period until April 2021 (European Commission, 2019). Theoretically it should be possible to implement similar agreements or regulations encouraging the industry to reformulate processed food products to reduce the amount of ingredients with a high environmental impact. This would require the use of environmental indicators (e.g., GHG emissions), or nutritional indicators specific for animal-based (e.g., saturated fatty acid, animal protein contents or % meat) or plant-based (e.g., plant protein content, fibre or % vegetables) foods.

Other examples of administrative policy instruments are public food procurement, through which it is possible to increase servings of healthier and more sustainable food options or meals, such as in public canteens. The EU has a set of voluntary green public procurement criteria for food and food services (EU, 2019), but these focus on environmental sustainability, and do not incorporate aspects of healthy diets. There are also examples of municipalities, schools and universities in various countries that have implemented measures to reduce the carbon footprint from food with, for instance, meat free days in canteens or compulsory provision of vegetarian alternatives (Lombardini and Lankoski, 2013; Milford and Kildal, 2019, Lassen *et al.*, 2021; Morris and Kershaw, 2021).

Lastly, public authorities can implement administrative policies which involve restrictions on advertisements for specific products like alcoholic beverages, or in certain domains or time frames such as restrictions on marketing unhealthy foods during children's television programmes.

7.2.2 Informative policies

Informative instruments are commonly applied by governments to promote healthy diets. Food-based dietary guidelines (FBDGs) developed by national health authorities usually recommend a certain intake of fruits and vegetables, and in some countries, they also recommend a maximum amount of meat consumption (Brink *et al.*, 2019; Cashman and Hayes, 2017; Public Health England, 2016). Moreover, FBDGs that explicitly recommend more sustainable food choices have been published in several countries (Mazac *et al*. 2021). Besides informing and creating awareness about healthy and sustainable diets, FBDGs can serve as input for policy development, for example in setting public procurement criteria and stimulating food and recipe (re)formulation by the food industry (see also Chapter 6 on sustainability-minded FBDGs).

Many countries run national information campaigns to promote the consumption of nutritious foods that contribute to healthy diets, for instance by using posters or advertisements on television or the internet. Campaigns for increased consumption of fruits and vegetables are most prevalent (Hyseni *et al.*, 2017). In addition, informative measures can be implemented as part of school curricula, where public authorities can decide to focus on sustainability as well as on the health aspects of food choices (FAO, 2019a).

Although with some limitations and room for improvement, labels on food products from third party certification schemes, such as Keyhole (https://www.livsmedelsverket.se/en/food-and-content/labelling/nyckelhalet) or Nutriscore (https://www.santepubliquefrance.fr/determinants-de-sante/nutrition-et-activite-physique/articles/nutri-score), exist in many countries to create awareness among consumers and facilitate healthier food choices, as well as to stimulate the food industry to reformulate food products (Galloway *et al.*, 2014; Hyland *et al.*, 2017; Leach *et al.*, 2016; Garnett *et al.*, 2015b). Likewise, certification and labelling systems for organic and fairtrade products, in common use in most EU countries, make it possible for consumers to recognize food produced following specific environmental or ethical standards. Examples for environmental impact labels include the Norwegian food company Orkla Foods which has created its own private labelling system for climate friendly food products (https://www.toro.no/klodemerket/), or the Oatly company (https://www.oatly.com) which labels its products with their carbon footprints. However, so far there are no such labelling systems administered by public authorities or third-party certification organisations. While private and public environmental food labelling initiatives have faced quantification and traceability limitations in the past, increasing data availability and novel tracking approaches will likely facilitate similar attempts in the future (Astill *et al.*, 2019).

7.2.3 Market-based policies

Price is an important determinant of food choice, thus, taxes and subsidies which alter consumer prices are powerful market-based instruments to discourage or encourage consumption of certain foods (also see Box 7.2). Several countries have implemented taxes on sugar-sweetened beverages (SSB) to discourage their consumption (Teng *et al.*, 2019), e.g., Mexico (Colchero *et al.*, 2017), Estonia, the UK, and the Republic of Ireland (Backholer *et al.*, 2018).

Another nutrition-motivated food tax example is from Denmark, where in 2011–2013 a tax of 2.14 Euro/kg was implemented for foods with a saturated fat content of more than 2.3 g/100 g, which was later repealed (Smed *et al.*, 2016). Taxes specifically targeting foods associated with a large environmental impact have not been implemented in any country so far. However, several studies have modelled their food system consequences (e.g., Moberg *et al.*, 2021, Springmann *et al.*, 2017; Gren *et al.*, 2021). It may be added that price subsidies to encourage healthy food choices are rarely found, possibly because they represent a considerable burden for the state budget (Mazzocchi, 2017). This points to a differential where substantial subsidies support farming across the EU (through the Common Agricultural Policy), while no subsidies directly support healthy food choices.

7.2.4 Behavioural policies

Behavioural policies can ‘nudge’ people into making healthier and more sustainable food choices more or less consciously, such as by changing the position of food items in supermarket shelves or cafeterias so that healthy and sustainable foods are more visible and accessible (Bucher *et al.*, 2016). Other examples are the provision of smaller food portions or smaller plates in self-service buffets (Hollands *et al.*, 2015), or making more sustainable options, such as vegetarian meals, the default menu at organized dinners (Boztas, 2019, Sanz-Cobena *et al.*, 2020). Digital interventions with the use of applications is another example of nudging (Rose *et al.*, 2017). Nudges are attractive instruments for policy makers because they can be cost effective (Benartzi *et al.*, 2017) and rarely involve elements of force. However, implementing nudges may require collaboration with (or the implementing of regulations affecting) the private sector, such as supermarkets or restaurants.

Box 7.1. *Case studies of policy instruments indirectly affecting demand.*

There are policy instruments that cannot be strictly classified as demand-oriented policies, which nevertheless influence consumer choices. Here we consider two case studies.

Case 1: Policies for meat and dairy substitutes

There is presently a strong growth in sales of dairy and meat substitutes or 'analogues'. These can ease the transition from animal to plant-based diets, particularly for consumers with strong preferences for the taste and texture of animal-based food (see Chapter 5). Available policy instruments to speed up this growth are subsidies to public research and innovation projects developing new processing methods for more attractive and affordable vegetarian food products. However, policies that make the marketing of these products more cumbersome, such as restrictions regarding the use of words like 'milk', 'cheese' or 'yoghurt' (EU 1308/2013 (CMO), 2013), can hinder consumers from easily identifying plant-based alternatives to familiar animal-based food. This may lead to a slower growth path and hinder innovation of plant-based food (Leialohilani and de Boer, 2020; Domke, 2018).

Case 2: Policies to support urban agriculture

An increased interest for urban gardening and community supported agriculture (CSA) is relevant, as it has been found that consumers who participate in such activities increase their consumption of locally produced fresh fruits and vegetables (Puigdueta *et al., 2021*; Rossi *et al.*, 2017). The UN Food and Agricultural Organization (FAO) has identified short food supply chains in urban and peri-urban areas as a priority to for health and environmental benefits, including preservation of food producing soil (FAO, 2020b). Relevant policy measures to promote these agricultural activities could be the provision of public land for allotments and community gardens, and agricultural subsidies to CSA fruit and vegetable farms.

7.3 Effectiveness of instruments

- Not all available policy instruments have been implemented yet, and impact assessments are scarce, particularly in large-scale and long-term studies.
- Effectiveness studies give mixed results, but all instruments are, in at least some studies, found to be effective in steering healthy and sustainable food choices.
- Combinations of demand-oriented instruments promise increased effectiveness, for instance implementing informative policies together with market-based policies.
- Demand-oriented policies can complement potential supply-oriented policies by counteracting the risk of achieved domestic emissions reductions being offset by increased imports.
- Combining taxes on food that has a high environmental impact or that is typically overconsumed from a health perspective while subsidies to healthy, low impact food can reduce the regressive effect of market-based instruments.

While there is a wide repertoire of policy instruments to steer consumer diets, there is not always sufficient evidence available on the effectiveness of those instruments. Few policy instruments address health and sustainability objectives jointly (Temme *et al.*, 2020). Not all instrument types have actually been implemented at population level and even for those that have, impact assessments are difficult to conduct and are rarely done. In these cases, *ex-ante* assessments can indicate the projected effects of a policy, for instance food taxes and subsidies.

Reviews have assessed the effectiveness of different food policy types in achieving a population-level consumption change with corresponding nutrition implications (Latka *et al.*, 2021). A review by Mazzocchi (2017) on national health and nutrition policies reveals that **information** campaigns are most prevalent, but school food interventions, labelling and advertising bans are also increasingly implemented, which lays the basis for *ex-post* effectiveness analyses. Studies on the effectiveness of information campaigns and dietary guidelines have shown mixed results. Some find them to be strongly effective in terms of raising awareness and significantly stimulating healthier eating patterns (Mazzocchi, 2017), while others conclude that they have a limited overall direct effectiveness (Mozaffarian *et al.*, 2018).

Hyseni *et al.* (2017) found that price interventions and product reformulations appear to be effective in changing energy and nutrient intakes, and they outperform food labelling or food provision and marketing restrictions. Multi-component interventions that combine various policy types (e.g., information with price-based measures) are considered especially successful in changing consumption behaviour (Hyseni *et al.*, 2017; Mazzocchi, 2017).

Thow *et al.* (2014) find that **taxing** foods high in fat, sugar or salt and **subsidizing** foods like fruits and vegetables shows a consistent desired effect on food intakes in terms of obesity and chronic disease prevention. Nutrition-targeted taxes, for instance on sugar-sweetened beverages (SSB), have been found to be effective in influencing consumption choices (Mazzocchi, 2017). The review by Teng *et al.* (2019) of implemented taxes on SSB revealed that the equivalent of a 10% SSB tax was associated with an average decline in beverage purchases and intake of 10%.

Healthy and sustainable diets are not always affordable for all people (FAO *et al.*, 2020). It is possible to combine the implementation of taxes on food that has a high environmental impact or that is typically overconsumed from a health perspective, with subsidies to healthy, low impact food. This might reduce regressive effects so that the generally stronger impact of taxes on low-income households can be partly alleviated. Such an approach could also help avoid unintended substitution effects as an incentive is set to replace unhealthy with healthier food options. This can enable consumers to change towards a healthy and sustainable diet without necessarily creating additional cost (Broeks *et al.*, 2020; Doro and Réquillart, 2020; García-Muros *et al.*, 2017; Springmann *et al.*, 2017; Garnett *et al.*, 2015b).

Box 7.2. *Case study of how market-based instruments have been found to be effective.*

Taxation and subsidization are market-based interventions that can resolve market failures and are simulated in various food tax modelling studies. Most of these studies focus on tax implications (mainly on red and processed meat or sugar-sweetened beverages) for nutrition and health (e.g., Veerman *et al.*, 2016; Springmann *et al.*, 2018b). Latka *et al.* (2021) assess the scope of required price interventions in order to achieve EU dietary recommendations applying three economic models. Their findings suggest that specific taxes and subsidies for different food groups are potentially effective in reaching nutrition and environmental sustainability improvements (Figure 7.1).

However, considerable tax levels are required to achieve the targeted consumption shifts in the models. Due to changes in preferences and substitution behaviour towards predominantly plant-based diets, it is likely that in reality less drastic price incentives would be needed. Awareness arising from the policy due to a signalling effect may also increase the consumer response beyond what is captured in modelling analyses, which typically do not reflect changes in preferences arising from such pricing policies (Mazzocchi, 2017). Recent research findings emphasize the effectiveness of food taxes and suggest that environmental and health benefits can be maximized by a combined carbon and health tax policy (Faccioli *et al.*, 2022).

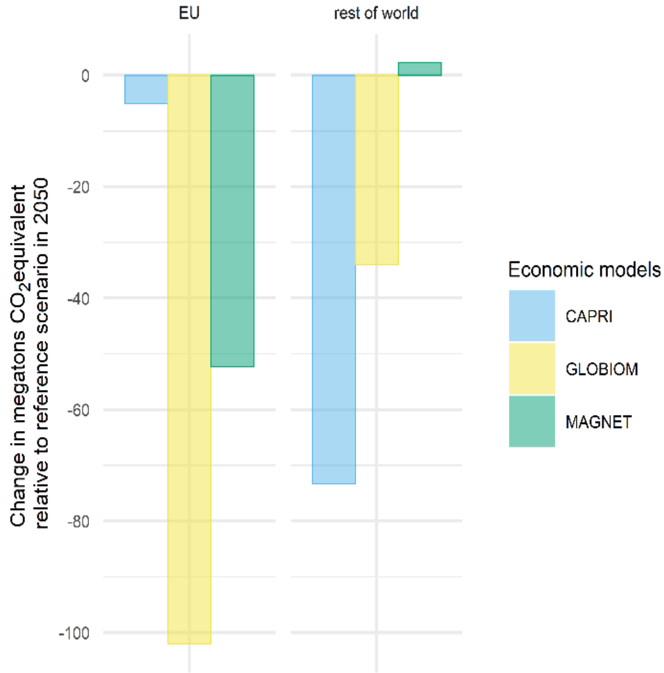

Figure 7.1. *Simulated change in greenhouse gas (GHG) emissions related to agricultural production by implementing health motivated food taxes on red/processed meat and sugar, and subsidies for fruits and vegetables, at EU level compared with the 2050 business-as-usual reference situation (including a continuation of existing agricultural policies). The reduction of GHG emissions is either mainly the result of reduced agricultural production within the EU (GLOBIOM, MAGNET), or in trading partner countries (CAPRI), depending on how sensitive trade variables adjust in the models in response to the EU-level demand change. (Further differences in resulting impacts are due to divergencies in the modelling systems). Source: adapted from Latka et al. (2021), under CC BY-NC-ND 4.0, https://creativecommons.org/licenses/by-nc-nd/4.0/.*

Some of the non-price interventions, such as **information-based, administrative** and **behavioural interventions** reveal promising effects, but their effectiveness at a large scale is difficult to measure, and long-term impacts are rarely investigated (e.g., Garnett *et al.* (2015b), Hyseni *et al.* (2017); Morren *et al.*, 2021).

There are many examples of behavioural interventions such as nudges which have shown to increase healthier food and/or beverage choices (Arno and Thomas, 2016; Bucher *et al.*, 2016; Wilson *et al.*, 2016). Yet few studies assess nudging interventions for encouraging sustainable choices (Vandenbroele *et al.*, 2019), particularly in terms of reduced meat consumption (Taufik *et al.*, 2019; Vellinga *et al.*, 2022; Reinders *et al.*, 2020). Still, existing evidence shows that nudges targeting portion sizes and the visibility of products in the market, or changing the sensory properties of plant-based meat analogues, are promising in reducing meat demand (Bianchi *et al.*, 2018b; Coucke *et al.*, 2019). A combined behavioural and administrative intervention study found that increasing the proportion of vegetarian meals offered in the English University of Cambridge increased total vegetarian meal sales significantly, especially for consumers who had not chosen the vegetarian option previously (Garnett *et al.*, 2019).

Little is known about the effectiveness of combinations of various policy types implemented at the same time. Pricing policies are estimated to be effective in steering food choices, but taxes can also be perceived to restrict people's food choice opportunities (Latka *et al.*, 2021). Thus, combining these with non-price interventions such as information campaigns might be helpful in order to increase awareness and social acceptability. For example, if accompanied by a campaign providing the necessary information and justification to achieve a preference change, they could possibly have a stronger effect (Hyseni *et al.*, 2017; Mazzocchi, 2017). Likewise, nudges have been found to be effective in the short term and in experimental contexts, but their aim is often to make people impulsively and unconsciously choose healthier and sustainable food options (Bucher *et al.*, 2016). Therefore, the awareness of consumers about sustainable and healthy diets, might be low unless combined with such information policies (Garnett *et* *al.*, 2015b). In a recent randomized controlled trial performed in a three-dimensional supermarket, a mixed policy of pricing and nudging led to 36% less meat purchases (Vellinga *et al.*, 2022).

The environmental impacts resulting from demand-oriented policies can depend on whether or not there is a simultaneous implementation of supply-oriented policies, such as restrictions on livestock density, reduced subsidies for animal production, or limits on manure application (see Chapter 4). Demand-oriented food policies that aim at reducing the intake of animal-based products may improve public health, but if production (which causes most of the environmental burden) is not subject to restrictions, domestic surplus production might be exported instead of reduced, which weakens the potential for sustainability improvements within the same region (Latka *et al.*, 2021). On the other hand, a focus on supply-oriented measures alone may reduce domestic production of animal-based products, but without changes in demand it may just lead to increased imports, increasing production in third countries with potentially weaker environmental and labour regulations, while leaving domestic diets unchanged (see Chapter 8).

7.4 Discussion and conclusions

In order to move consumer demand towards healthy and sustainable diets, a range of policy instruments exist. Several of these, particularly information campaigns, have already been implemented with the aim of improving public health through dietary change. However, to date there are few policies explicitly addressing the environmental sustainability of diets, except for some FBDGs, and a few examples of increased plant-based foods in public procurement.

Positive effects of food demand policy instruments have been found in many studies, but for some the effectiveness is unclear, particularly as many measures have never been implemented at large scale or are difficult to evaluate, and few have been assessed in the long term.

This chapter has focused largely on public policy measures targeting consumers. However, food production and marketing are mainly managed by private sector actors who are usually not primarily motivated by health or sustainability concerns (Global Panel on Agriculture and Food Systems for Nutrition, 2020). The success of policies for healthier and more sustainable food demand depends to a large degree on these commercial actors, who presently run far more marketing campaigns for unhealthy than healthy food on television (Batada *et al.*, 2008), supermarket circulars (Charlton *et al.*, 2015) and social media (Potvin Kent *et al.*, 2019). Furthermore, consumer-oriented measures aiming for a reduced consumption of food with a high environmental impact are met with resistance from the agricultural sector, for instance the livestock industry (see Chapter 1 on asymmetries in the global food system). Industry actors use lobbying activities and their own marketing campaigns to deter consumers from moving towards more plant-based food (Bogueva *et al.*, 2017; Sievert *et al.*, 2021; Sievert *et al.*, 2022; Lazarus *et al.* 2021). While the private sector consists of powerful stakeholders with strong commercial interests, consumers are a mostly unorganized interest group with highly heterogenous interests (Treich, 2018); and for a large segment of consumers, policies for changing dietary habits will not be popular (Malek *et al.*, 2019; Michielsen and van der Horst 2022). The economic and political power of groups in favour of policy measures for more sustainable diets is seemingly weaker than the power of those who are against such measures. This could explain why there seems to be little political willingness to implement measures for reduced meat consumption (Dagevos and Voordouw, 2013; Laestadius *et al.*, 2016; Swinburn *et al.*, 2019).

The Global Panel on Agriculture and Food Systems for Nutrition (2020) calls for stronger political leadership to solve these food system challenges. They recommend that the public and private sectors work together, and that the private sector spells out "*specific, measurable responsibilities for improving diet quality and sustainability of food systems*". In some cases, actors in the private sectors can also be a key driving force for a transition towards healthy and sustainable diets. Consumers with preferences for plant-based food constitute an increasing market segment, which is valuable to industry, retail and restaurants. The measures these sectors apply to gain shares in this market, such as product development and marketing strategies, can play an important role in creating consumer awareness and facilitating a transition to sustainable and healthy diets, and thereby increase the total size of this market. Policy makers can contribute towards increasing these activities by, as already mentioned, supporting relevant research and development from which this industry may benefit, or by engaging in partnerships or alliances with the industry to promote healthy and sustainable diets, such as the 'Green Protein Alliance' in the Netherlands (Drewnowski *et al.*, 2018).

The **policy implications** from this are as follows:

1. Policy makers should vastly increase their efforts to accelerate a transition towards sustainable and healthy diets, given that few such policies have presently been implemented (Global Panel on Agriculture and Food Systems for Nutrition, 2020).
2. Policy makers need to take into account more actively that these policies present win-win solutions, as they are not only beneficial for public health, but also for the environment.
3. There is a need for more policy coherence and collaboration between public authorities working in different sectors, and a bundling of various instruments into policy packages (Fesenfeld *et al.*, 2020). Actions need to be taken at local, national and global levels (Swinburn *et al.*, 2019).
4. Policies should be elaborated addressing the entire food system comprehensively, which also includes the agriculture sector and food industries (Kugelberg *et al.*, 2021). Just as agricultural policies ought to take health and environmental aspects into account, health and environmental policies should not overlook consequences for agricultural production, farmers and rural development.
5. Trade-offs must also be acknowledged, not just win-wins. Particularly in rural areas where other employment opportunities are scarce, the social costs of decreased food demand can be very large, and the pressure on politicians to not implement such policies is potentially strong. Policies for sustainable and healthy diets therefore need to address demand- and supply-related questions simultaneously and ensure that policy solutions are implemented to prevent negative consequences for the agricultural sector, such as subsidies for conversion to plant-based agricultural production, or payments for ecosystem services.

Research needs focus on the effect of demand-oriented policies for sustainable diets, including long term effects and the effect of new types of interventions, for instance those involving digital platforms (Rose *et al.*, 2017). In particular, there is a need to understand the different policies more comprehensively and how their interaction can reinforce dietary change, instead of just looking at their singular effects. As combined policy types targeting both health and environmental sustainability have not yet been implemented, the joint effect is yet unclear. It is worthwhile to explore the effectiveness of policy packages to change food consumption patterns. An appropriate and comprehensive set of indicators on the health, environmental and societal impacts of foods may help design future policies.

Building confidence in science is also essential to obtain science-led policies, and the Global Panel on Agriculture and Food Systems for Nutrition (2020) recommends to "*increase the legitimacy of scientific advice through transparency in a rigorous synthesis and assessment process*".

Furthermore, the political tensions around the topic have to some extent been subject to research, although this is probably an important explanation for the limited implementation of the wide range of available policies targeting healthy diets and environmentally sustainable food systems.

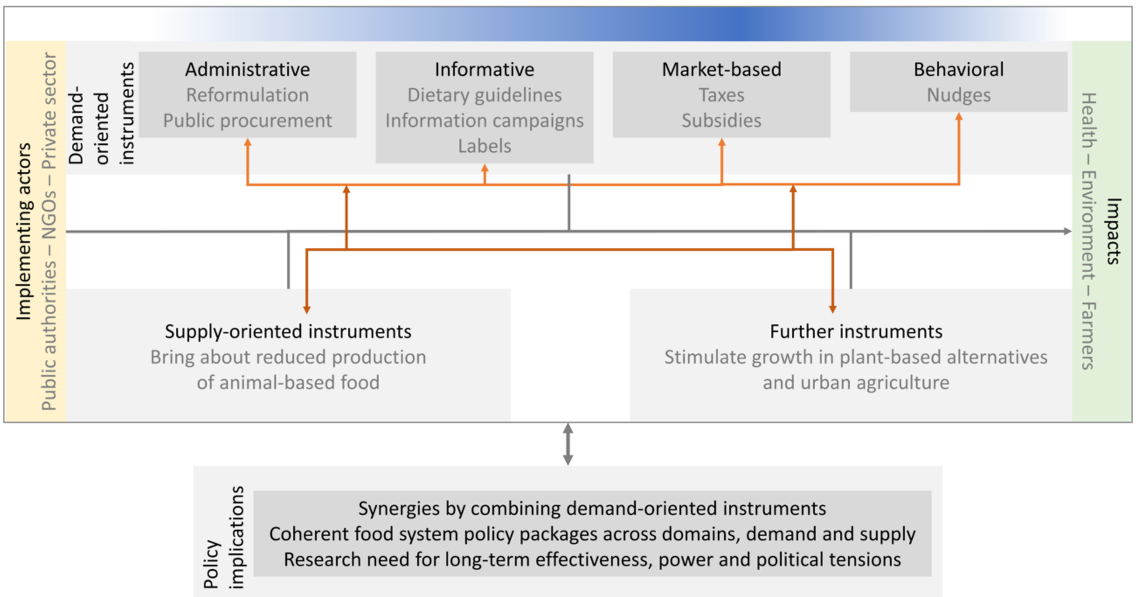

***Figure** 7.2. Policy implementation is subject to different actors. A combination of different demand-oriented measures, together with supply-oriented, and further instruments is likely effective if coherently considering all relevant impact domains. Source: created for this report by the authors.*

Box 7.3. *Research needs related to consumer-oriented food policies for healthy and sustainable diets.*

- The development, implementation and effectiveness of demand-oriented policies for healthy and sustainable diets needs more research.
- More large-scale and long-term studies in this policy area are needed, and collaboration between policy makers and researchers for setting up sound scientific impact assessments of implemented programmes would be an advantage.
- The joint effects of policies targeting both health and environmental sustainability and how they can reinforce dietary change need to be explored.
- There is a need for the development of appropriate and comprehensive standardized indicators for measuring combined health and sustainability of different food items.
- There is a need to better understand the political tensions around policies for nutrition-related health and sustainability in the food system.

Part C

Serving sustainable food systems: Gathering around the table and sharing our plates

Chapter 8. Governing a transition towards a sustainable food system

Susanna Kugelberg, João Costa Leite, Alberto Sanz-Cobeña and Ivanka Puigdueta

- Policy makers need to approach the food system as a complex and dynamic system.
- Strengthening food system governance requires a system approach and the inclusion of stakeholders in the process of building a transformative shared vision.
- Strengthening directionality, coordination, empowerment and reflexivity can support goverments towards more integrated and systemic solutions.
- Strengthening governments' anticipatory capacity is essential for imagining a future food system that can address trade-offs and anticipate risks and unknowns.
- **Key policy message: To achieve a more sustainable food system, governments need to increase their policy capacity for governing a food system transition.**

8.1 Introduction

Concerns regarding the increasing burden of chronic disease, malnutrition, hunger, as well as environmental degradation and greenhouse gas (GHG) emissions, can be linked back to the malfunctioning of the global food system. Transforming food systems is an emerging priority on the agenda across policy, societal and research communities (European Comission, 2020a; HLPE, 2017; IPES Food, 2019; UNSCN, 2017). Importantly, it is now recognized how managing the complexity of food systems will be crucial to deliver all the Sustainable Development Goals (SDGs) (Von Braun et al., 2021). Even if there are different ideas and lines of research about what a sustainable food system is, the scientific community agrees that the food system is an important leverage for action on a range of issues: environment, public health, employment, trade and equity (Béné *et al.*, 2019a; European Commission, 2020a).

Despite a growing momentum for a transition towards sustainable food systems, governments face enormous challenges to shift current governance approaches for a number of reasons. Policy-making is influenced by past policies and governance systems and policies can be 'locked-in' by the current regime, resistant to change. There are several mechanisms that act on food policy-making processes. These include:

- institutional norms and culture;
- level of competencies and learning about sustainable food approaches within the public and private sector;
- availability of technological and social innovations; and
- international trade agreements and regulations;

all of which can limit governments actions on the national arena (Hospes and Brons, 2016; Parsons, 2018, SAPEA, 2020).

Thus, for governments to achieve more sustainable food systems, they will need to improve their capacity (resources and abilities) to deal with the complexity of interdependencies within food systems—which include environment, human health, economic and social dimensions—through a more *systemic* approach (Caron *et al.*, 2018; Rockström *et al.*, 2020). A food system approach aims to align the objectives of food production, processing, distribution and consumption to a sustainable and healthy diet (Willett *et al.*, 2019). Moreover, it emphasizes the need to go beyond a view of food systems as linear and 'single focused' to comprehend food systems as dynamic and interlinked, and to acknowledge multiple outcomes and feedbacks of the system (Ericksen, 2008). A food system approach has wide implications for governance, and should be accompanied by a holistic, participatory, and above all reflexive*,* governance framework (Galli *et al.*, 2020).

To further disentangle this issue related to governance, this chapter shows how four concepts from transition theory, namely **directionality**, **coordination**, **empowerment** and **reflexivity,** can help policy makers to build capacity in the governance of a sustainable food system.

8.2 Key principles of food system governance

- A transition towards a sustainable food system is a huge challenge and requires that food system actors work together and towards the same goals.
- Governing a transition needs to be underpinned by a system thinking approach and democratic values.
- The four principles of food system governance presented here can increase the capacity of policy makers in the governance of a sustainable food system and enable transparency, legitimacy and accountability.

As highlighted in Box 8.1, a growing research body emphasizes that more attention needs to be given to rethinking governance structures and policy-making processes from a systems approach, to take better account of the multi-causality of the food system and the dynamics between drivers, outcomes and feedbacks (Gillard *et al.*, 2016; Ingram, 2011; Preiser *et al.*, 2018). A system perspective has important implications for governing a sustainable food system and requires more participatory, collaborative and reflexive structures (Hospes and Brons, 2016).

Box 8.1. *Systems thinking and food systems governance.*

Systems thinking is increasingly applied to develop structural solutions, and functions as a conceptual learning approach to deal with the structure and behaviour of the food system (Ingram, 2011). Systems thinking can be valuable to decision makers in demonstrating the complexity of interconnections between the multiple actors in the food system and improve decision making processes. Importantly, it helps identify entry points for action, known as leverage points, to drive transformation of the food system more effectively (Meadows, 1999).

By adopting systems thinking, governance can play a key role in impacting key leverage points for change, i.e., changing the vision, mindsets and values in society towards a sustainable food system, defining overarching goals and a clear direction for action, and investing in system structures and information flows to alter feedbacks and redesign the food system (Abson *et al.*, 2017).

Recent advances on the international policy agenda indicate a global ambition to achieve healthy diets and sustainable food systems, but this requires deep changes in the prevailing paradigm that guides global and national policy-making (European Commission, 2020a; FAO, 2018b; IPES Food, 2019). Enabling nutritious and healthy food for all and promoting sustainable agricultural production, while also mitigating climate change and building resilient food systems, is a huge challenge for country specific actions that also need to integrate the diversity and richness of a country's food system, culture and food preferences (Caron *et al.*, 2018).

National governments will need to bring the vision of sustainable food systems down to the heart and functioning of working societies, engaging with multiple actors and promoting intersectoral partnerships for an inclusive approach. Achieving an agreed shared vision towards national food systems is a collective and learning endeavour that reflects an accountable governance posture towards more flexible, collaborative and intersectoral transformative approaches.

The four principles of directionality, coordination, empowerment and reflexivity based on transition and innovation studies can provide practical guidance to governments on how to govern a transition towards a sustainable food system, as shown below.

Principle 1: Directionality – agreement of shared goals

Planning any type of system transition at policy sector level, whether it be related to the energy or food system, needs to be guided by a set of strategic and shared goals, i.e., the principle of directionality. With weak agreement of vision and strategy, it is very difficult to navigate a transition (Weber and Rohracher, 2012).

A strategic and shared vision of a future food system can be achieved from an inclusive stakeholder engagement process and guided by research assessments and evaluations. It is important that there is transparency of the exact parameters, adjustments and trade-offs when developing policy frameworks (Kugelberg *et al.*, 2021; see also Chapter 9). When deciding priorities, policy makers are therefore advised to commission multiple assessments and research, e.g., impact assessments or participatory scenario planning, to better understand the range and extent of trade-offs and synergies. These scientific assessments need to inform the policy agenda-setting process and guide Green Paper development and consultations with diverse stakeholder groups (Kugelberg *et al.*, 2021).

Principle 2: Coordination – effective working together across linked actors and actions

A food system is situated in a specific food system context and a transition needs to be planned and negotiated with diverse food system actors (Weitz *et al.*, 2018). Changes are required everywhere and ideally should be reinforced by multiple policies, e.g., sustainable intensification in agriculture; technological innovation, social and gender protection policies; and by various economic, administrative, informative and legislative measures to incentivize in sustainable behaviours and growth (see Chapter 7). Hence, the principle of coordination is both about coordinating policy mixes and actors. Coordination between actors can be done by establishing linkages between and across administrative and jurisdictional levels and sectors. Policy makers at national and local levels can establish collaborative food hubs, research centres, networks and platforms, e.g., inter-ministerial committees, food system networks and policy councils to provide platforms for learning and action on food system sustainability (Kugelberg *et al.*, 2021).

Principle 3: Empowerment – enabling actors to make a difference

Empowering citizens is a crucial part of successful transition management (Hölscher *et al.* 2017). Governments can empower citizens to take on new roles that are a better match for attaining sustainability targets. In the governance of sustainable food systems, governments can provide strong incentives for consumers and other societal groups, to change current behaviours, roles and services. A sustainable food system is an urgent and a collective responsibility, where the public sector has an important role to lead a transition towards sustainability. The issue at stake is to incentivize changes at consumption and demand level, by facilitating empowerment processes (Avelino, 2009; Weber and Rohracher, 2012).

Principle 4: Reflexivity – learning from experience

A transition towards a sustainable food system will have to allow for more critical evaluations of current practices, policies and behaviours. The principle of reflexivity calls for a more prominent use of policy evaluations and wide stakeholder deliberations to inform policy-making, such as building up robust monitoring; reliable metrics and tools on food system drivers and outcomes; and establishing platforms to drive experimentation, innovation and possibilities for learning (Kugelberg *et al.*, 2021; Müller and Riegler, 2014; Sol *et al.*, 2018). Policy evaluations and assessments from independent organizations are important for increasing reflexivity (Hildén *et al.*, 2014). However, these should also feed into policy-making processes at national or local level for more effective policy frameworks. Reflexivity fosters accountability as it involves active oversight by a number of actors on agreed food system outcomes and public goods.

8.3 A governance framework

- The application of system thinking can support more holistic and integrated solutions.
- Policy makers can increase transparency and accountability by adhering to the four principles of food system governance in the policy-making process.
- Examples at national level in Finland and at city level in Spain highlight the capacity (resources and abilities) of public organizations to govern food system transitions.

Recognizing that a food system relies on complex and hard-to-change interdependencies is relevant for initiating dialogues to address food system issues. Importantly, considering the systems' dynamic behaviour, actors need resources and skills for negotiating multiple trade-offs between goals and values at different levels (such as national, regional, local). To support governance, public sector organisations can invest in standardized monitoring and adequate evaluation using multicriteria indicators. Societies that are resistant to a systems approach may face increasing barriers to explore new opportunities, behaviours and relationships that align the social, environmental and economic dimensions towards sustainability. Thus, the integration of systems thinking with the four principles (directionality, coordination, demand articulation and reflexivity) may help support a more effective food systems governance (Figure 8.1).

While governments often neglect the power of a shared vision to lead substantial systems changes, innovative governance approaches that invest in engaging stakeholders towards a shared vision are of great importance to achieve an agreed direction towards a sustainable food system. Importantly, systemic approaches at **regional or city level** have been an opportunity to integrate the community and intersectoral partnerships in effective dialogues regarding a transformative food system. Effectively, local food policy is emerging as a relevant opportunity to address food systems worldwide. For instance, the Milan Urban Food Policy Pact has now engaged more than 200 cities in developing more integrated urban food policies towards sustainable food systems (MUFPP, 2016). The FAO, in collaboration with the RUAF Foundation (Global Partnership on Sustainable Urban Agriculture and Food Systems), have developed a city region food system programme to assist local governments in designing and monitoring food policies based on systems approaches (Candel, 2020; FAO, 2019b; MUFPP, 2016). Local initiatives also provide an opportunity to increase accountability towards sustainable eating across local institutions and communities, serving as an approach to achieve healthier food choices, protect environmentally friendly and locally produced foods and promote more sustainable relationships and shared values.

National governance structures can help guide and articulate such initiatives at all geographical scales, providing a direction for change. In the long-term, public education that promotes systems thinking may be critical in shaping future generations' vision for human systems, including sustainable views and behaviours related to food (Abson *et al.*, 2017; Senge *et al.*, 2007; Wegener *et al.*, 2018, 2013). The development of food-based dietary guidelines for sustainable foods systems (see Chapter 6) can help shape dietary choices serving as a guide for more integrative policies that influence consumer awareness and more sustainable food environments (Costa Leite *et al.*, 2020).

Integrative approaches that address the food system rules (such as trade rules, taxes, incentives, public procurement) can support a transformative systems design. Importantly, a more transparent and trustful flow of information across the food system is essential to facilitate new feedback loops and sustainable behaviours. This not only requires more integrated data and knowledge production but also making the consumers more aware of the food system outcomes. For instance, the health and environmental costs of dietary choices need to be more visible and clearer to all consumers to create pressure for change.

Investing in technological and social innovation such as digitalization can also inspire transformative sustainable connections and partnerships that shape the food system behaviour towards sustainable diets. In this context, the EU Farm to Fork Strategy includes actions that aim to increase transparency and empower consumers to make informed sustainable food choices (European Commission, 2020a).

Box 8.2. *National Governance in sustainable food systems: Case study of Finland (Kugelberg et al., 2021).*

In 2017, Finland adopted a new food policy, addressing the whole food chain, Food2030. To strengthen **directionality** for the future Finnish food system, the vision-building process was agreed by the use of a highly iterative consultation approach, a range of expert studies, research and working groups; which resulted in building wide support for Food2030 across political boundaries (Kugelberg *et al.*, 2021).

The range of policy, tools and measures that form the Finnish governance approach to implementing the vision, objectives and priorities of Food2030, includes measures designed to enable information flow, e.g., multi-media campaigns, standards and guidelines (organic and local public procurement and food-based dietary guidelines); to stimulate a demand for organic and local foods. They also include system rules, such as direct funding, certifications, network and support schemes to support responsible production.

Conversely, potential critical barriers to a transition of the Finnish food system include a rather weak monitoring framework, with mostly qualitative and descriptive indicators. Hence, measures and tools to reinforce **reflexivity** have not yet been confidently integrated into the governance approach.

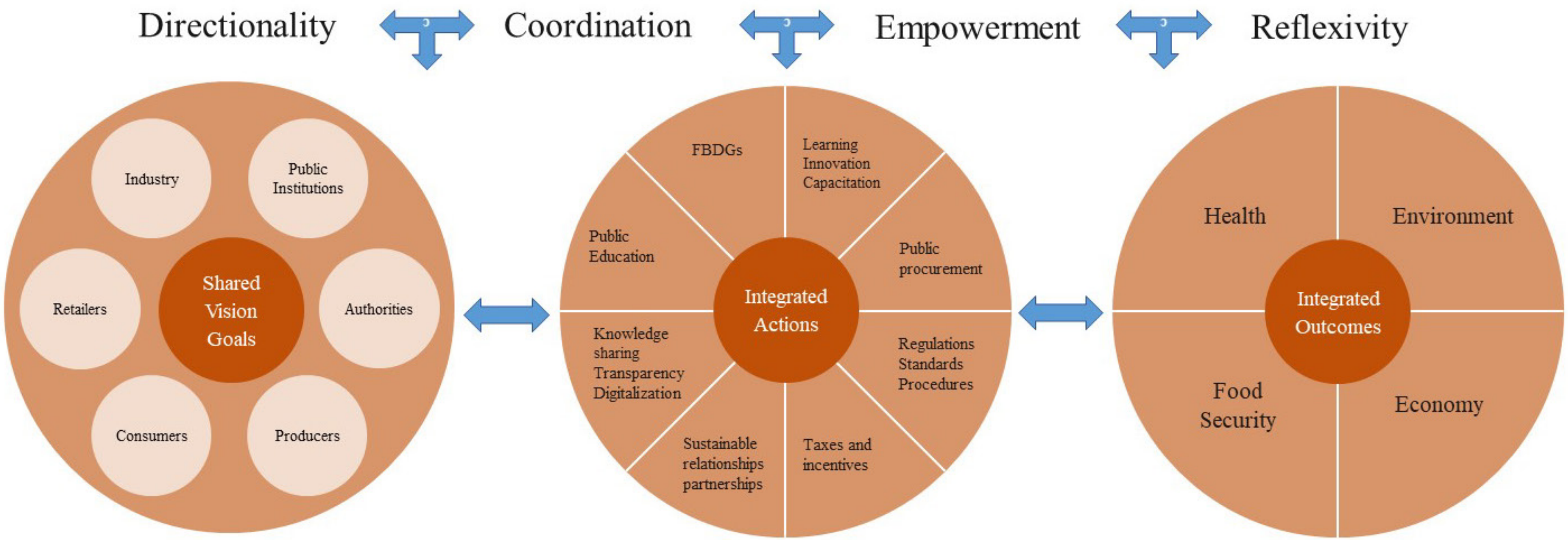

Figure 8.1. *Applying directionality, coordination, empowerment and reflexivity in policy-making processes for food systems governance can enable a shared policy vision between actors, integrated actions and outcomes increasing the potential for sustainable performance. FBDGs = Food-based dietary guidelines. Source: created for this report by the authors.*

While there is a great urgency to improve national food systems, it is important to highlight that a national food system crosses jurisdictional and administrative boundaries (SAPEA, 2020). As governments rule within well-defined jurisdictions, national food systems sit within an overwhelming complex and interconnected **global food system** supporting the goals of the international food trades and economic growth. Thus, agreeing at a global level on a planetary sustainable food system that shapes international arrangements, commitments and regulations will have an effect on countries' abilities and efforts to achieve food security, public health, environmental protection and economic justice.

Box 8.3. *Local Governance in sustainable food systems: Case study of Madrid. Photograph: 'Esta es una plaza' by the Madrid Communitarian Urban Garden Group (2020). Source: 'Esta es una plaza' (https://estaesunaplaza.blogspot.com/2022/10/esta-es-una-plaza-un-proyecto-de-exito.html), reproduced here with permission.*

Between the years 2010 and 2019 the city of Madrid made important advances to transform the urban food system. These advances originated from grass-roots movements claiming sustainable food systems and healthy urban spaces, joining transnational initiatives such as Milan Urban Food Policy Pact (MUFPP, 2016) and the European network of cities for agroecology (https://www.ae4eu.eu/european-network-for-agroecological-food-systems/). As a response to this movement, a political willingness grew in the City Council (2015–2019) to support **coordination.** The City Council developed participatory processes that empowered citizens to be part of the agenda-setting, which resulted in a broader political coalition to support food system change.

The resulting food strategy (Simón-Rojo *et al*. 2020; Área de Gobierno de Coordinación Territorial y Cooperación Público-Social, 2018) covered the whole food chain, from production (e.g., collaboration agreement with neighbouring farming areas) to waste management (e.g., communitarian agro-composting project). A new governance approach to food resulted in a transformation of the use of public urban lands, allowing non-profit associations to manage the spaces with environmental, social, educational and cultural goals.

Whereas the City Council set some basic system rules, such as the obligation to adopt agroecological farming practices, it also provided full autonomy to **empower** the social groups that manage these spaces (https://www.vegmadrid.es/huertos-urbanos-en-madrid/). Communitarian urban gardens have proved to be spaces of **reflexive** social learning, gathering people with very different interests and backgrounds, and serving to change habits and habitats towards a more sustainable food system.

8.4 Conclusions

How policy makers should govern a transition towards a sustainable food system represents a major challenge of our time. Applying systems thinking to this question can provide new ways of designing governance structures and offer promising solutions for more effective and systemic policy responses. The four principles of directionality, coordination, empowerment and reflexivity can offer practical guidance for increasing a government's capacity in the governance of a food system transition, while strengthening good governance.

Box 8.4. *Research needs for governance in sustainable food systems.*

- Research on how to operationalize concepts from system thinking and transition theory in policy design.
- More empirical research on food policy processes and what information flows, ideas and norms are influencing policy constructs and narratives.
- More empirical research of what organizational tools, measures and capabilities are at play, to ensure accountability, transparency and legitimacy in food policy-making processes.

Chapter 9. Navigating towards future food systems with a Sustainability Compass

Adrian Leip, Aniek Hebinck and Monika Zurek

- A food system Sustainability Compass shows the direction of necessary change to increase overall sustainability.
- Food system sustainability addresses several universal areas of concern that are grouped into four societal goals:
    1) healthy, adequate and safe diets for all;
    2) a clean and healthy planet;
    3) economically thriving food systems, supportive of the common good; and
    4) just, ethical and equitable food systems.
- **Key policy message: Applying tools to quantify scores for food system sustainability is important for identifying trade-offs and co-benefits in policy-making, and requires policy targets for all sustainability objectives.**

9.1 Introduction

Today's food systems are characterized by a large number of activities and actors, making them quite complex. This complexity leads to diverse outcomes that affect all people. As food provisioning and consumption are interconnected, their set-up shapes diverse dietary patterns, access to, and availability of, food globally. Many activities that make up food systems (food production, processing, retail, waste/residue management, and so on) are a source of employment and livelihood for much of the world's population. Moreover, food systems are a key driving force of global environmental degradation, while at the same time their dependency on changing environmental systems result in severe food security challenges (see Chapters 1 and 2). In other words, there are currently four broad areas of concern with respect to food system outcomes that are intimately linked to the systems configuration and allow food system actors to uphold both ethical values and sustainability in food systems (Oliver *et al.*, 2018).

Navigating towards future food systems that provide food and nutrition security while being environmentally and economically sustainable, as well as fair and just, entails understanding the system's interconnected dynamics, outcomes and their trade-offs. This is especially the case for decision-making processes and the (re-)design of policies, products, or governance options aimed at enhancing the sustainability of food systems (see Chapters 7 and 8). As trade-offs are complex and their magnitude unknown, in most cases win-win solutions will not exist. Nevertheless, decisions need to be made and priorities must be set, requiring negotiations among food system actors about the outcomes societies care about and the potential trade-offs between outcomes that are acceptable (European Commission, 2020a; European Comission, 2020b).

To facilitate and inform the decision-making process for the best possible sustainability outcome, a 'Sustainability Compass' is proposed to help actors navigate between different food system outcomes. This Sustainability Compass shows the context-specific sustainability direction of decision-making across multiple sustainability dimensions. To enable informed and more-conscious decisions, aggregated sustainability scores are based on transparently weighted and scientifically based, quantified individual sustainability indicators. This chapter is based on the paper 'A Sustainability Compass for policy navigation to sustainable food systems' by Hebinck *et al.* (2021), published under Open Access (CC BY 4.0, https://creativecommons.org/licenses/by/4.0/).

9.2 What makes a food system sustainable?

- Food system sustainability is measured against universal areas of concern which comprehensively span all aspects of sustainability for four societal goals: 1) healthy, adequate, and safe diets for all; 2) a clean and healthy planet; 3) economically thriving food systems supportive of the common good; and 4) just, ethical and equitable food systems.

A food system is sustainable when it has positive and equitable outcomes on all aspects of its environmental, social and economic dimensions. It must be sustainable to the people who are directly connected to a food system, but also to those who are indirectly connected to it, living in different places or in the future. Examples of such indirect effects are global trade-impacts on prices, leading to less affordable food commodities, or the exporting of valuable resources, such as water embedded in produce, to another distant food system. To capture the sustainability aspects both *universally* and *comprehensively,* Hebinck *et al.* (2021) have defined four 'societal goals' against which food system sustainability must be measured, each of which covers four 'areas of concern' (see Figure 9.1).

Healthy, adequate and safe diets are the basis of a healthy life and the pre-condition for successful participation in society for each individual. Delivering food and nutrition security is the principal outcome and main *raison d' être* of food systems (Béné *et al.*, 2019a; CFS, 2012; Zurek *et al.*, 2018). Diets of poor quality are the main contributors to the multiple burdens of malnutrition (stunting, wasting, micronutrient deficiencies, overweight, obesity, and nutrition-related non-communicable diseases, NCDs) and the main cause of deaths (GBD 2017 Diet Collaborators, 2019; GBD 2019 Risk Factors Collaborators, 2020; Lindgren *et al.*, 2018). Food must provide an adequate quantity of macro-nutrients (for example energy and protein) and micro-nutrients, but an adequate diet must also contain a balanced proportion of food groups, and sufficient food diversity, as defined in food-based dietary guidelines available for many countries (Costa Leite *et al.*, 2020; Springmann *et al.*, 2020, see Chapter 6). Finally, diets must be safe, avoiding foodborne diseases caused by biological and chemical hazards.

A clean and healthy planet is the foundation for life on earth. Food systems depend on natural resources and the environment, while simultaneously impacting on them by extracting resources; polluting soils, air and water; and contributing to climate change and the loss of biodiversity (Rockström *et al.*, 2020). A key societal goal is therefore the reduction of these damaging impacts and the transformation of food systems to become nature- and climate-positive: in other words, to not use more resources than can be replenished sustainably. Environmental sustainability needs to be assessed at a global scale to capture the impacts along the entire food supply chain. This should be done irrespectively of whether this took place inside or outside the territory for which food system assessment is performed, and across all food system spheres (see Chapter 1). Thus, quantification of indicators needs to be done with suitable life cycle indicators (pressure footprints; FAO, 2018c; Vanham *et al.*, 2019; Vanham and Leip, 2020).

Economically thriving food systems, supportive of the common good make up the backbone of a food system. Economic sustainability entails robustness and openness on a systems-level, while allowing sufficient flexibility and support for individual businesses to innovate and adopt more transformative practices (FOLU *et al.*, 2019; Herrero *et al.*, 2020). This includes economic (value added) and trade (self-sufficiency) indicators, but also institutional factors that govern the economic system. Value chains need to be competitive and thriving, but also require innovative capacity for the mainstreaming of incorporating environmental and social externalities in entrepreneurial activities (Friel *et al.*, 2020). Moreover, food system actors must conduct commerce fairly and provide jobs that are safe, secure, and rewarding with wages that allow for a dignified life. Economically thriving and robust food value chains supporting the common good demand balancing the economic impacts at multiple scales.

Just, ethical and equitable food systems are at the heart of achieving universal goals for sustainable food systems respecting all living things. The global orientation of food supply chains results in the possibility of food system activities carried out in one location to have both positive impacts as well as unexpected consequences in other, possibly distant, locations (Eakin *et al.*, 2017; Wood *et al.*, 2018). Undesirable outcomes of interactions between global food trade, public health and environmental impacts are a major source of food insecurity, and social and environmental injustices (Feldbaum *et al.*, 2010; Folke *et al.*, 2019; Friel *et al.*, 2020; Kummu *et al.*, 2020). Governing value chains towards being fair and just demands addressing concentration of power issues as well as risk management practices that shift the burden to those with less power (TEEB, 2018), while also addressing animal welfare questions in livestock systems. Such ethical considerations have so far received less attention in indicator-based food system assessments due to the lack of direct (and quantitative) indicators (Zurek *et al.*, 2018); however, the Sustainability Compass proposes key areas for concern based on a varied base of work around ethics, justice and equity.

9.3 Assessing food system sustainability

The academic debate on food system sustainability is highly dynamic. Thanks to a growing number of studies that explore food systems, different understandings and metric frameworks have been developed in recent years. This can be explained by a process of convergence around the notion of food systems, which brings previously separate research communities, such as agronomy, nutrition sciences, environmental sciences and agricultural economics, together (Béné *et al.*, 2019b; Stefanovic *et al.*, 2020). This convergence has resulted in an overall shift towards approaches that aim at integrating sciences and therewith increase in their complexity (see Table 9.1).

Such frameworks are extremely policy-relevant. Experience shows that they increasingly aim to address policy-specific queries about the status of the system and what might be levers for change. However, few frameworks are able to identify trade-offs and synergies, and show the impact of policy interventions. This is a shortcoming, as the majority of research on the future of food systems underscores the importance of governance addressing food system trade-offs (Zurek *et al.*, 2020).

Table 9.1. *Review of existing food system frameworks with regard to policy-relevance and indicators. Source: based on Hebinck et al. (2021), under CC BY 4.0, https://creativecommons.org/licenses/by/4.0/.*

				Framework indicators						
Paper	***Year***	***Framework focus***	***Policy relevant output***	**Food economy**	**Climate & environment**	**Food security**	**Nutrition & health**	**Social Welfare**	**Food safety**	**Food waste**
Sustainable Development Goals	2015	Sustainability	Setting policy goals; Assessment individual goals	●	●	●	●	●	●	●
Lukas et al.	2016	Sustainable diets	Nutritional footprint framework and diagram		●		●			
Jones et al.	2016	Sustainable diets	Integrated metrics for Life Cycle Assessment		●		●	●		●
Le Vallée et al.	2017	National food performance	Country-level report card	●	●		●		●	
Chaudhary et al.	2018	Food system sustainability	Sustainability assessment: Show trade-offs & synergies; Identify levers of change		●	●	●	●	●	●
Eme et al.	2019	Sustainable diets	Integrated metrics for Life Cycle Assessment		●		●	●		
Willett et al.	2019	Planetary health diet	Scenarios; Sustainability intervention strategies		●		●			●
Béné et al.	2019	Food system sustainability	Sustainability assessment; Identify levers of change	●	●	●	●	●	●	●
Fanzo et al.	2020	Food system sustainability	Sustainability assessment; Identify levers of change	●	●	●	●	●	●	●
Mayton et al.	2020	Sustainable diets	Sustainability assessment	●	●	●	●	●	●	●
The Sustainability Compass *Hebinck et al.*	2021	Food system sustainability	Sustainability assessment; Identify levers of change; Show trade-offs & synergies; Impact of policy interventions	●	●	●	●	●	●	

The Sustainability Compass presented here (Figure 9.1) builds on the existing frameworks and addresses a number of these shortcomings. The Sustainability Compass differs from existing assessment approaches in its comprehensiveness and transparency and by aiming to identify trade-offs in a policy-relevant manner. Through the calculation of sustainability scores, it provides comprehensive scientific evidence by striking a balance between capturing the complexity of food systems, the usability for policy, and transparency about what can and cannot be measured.

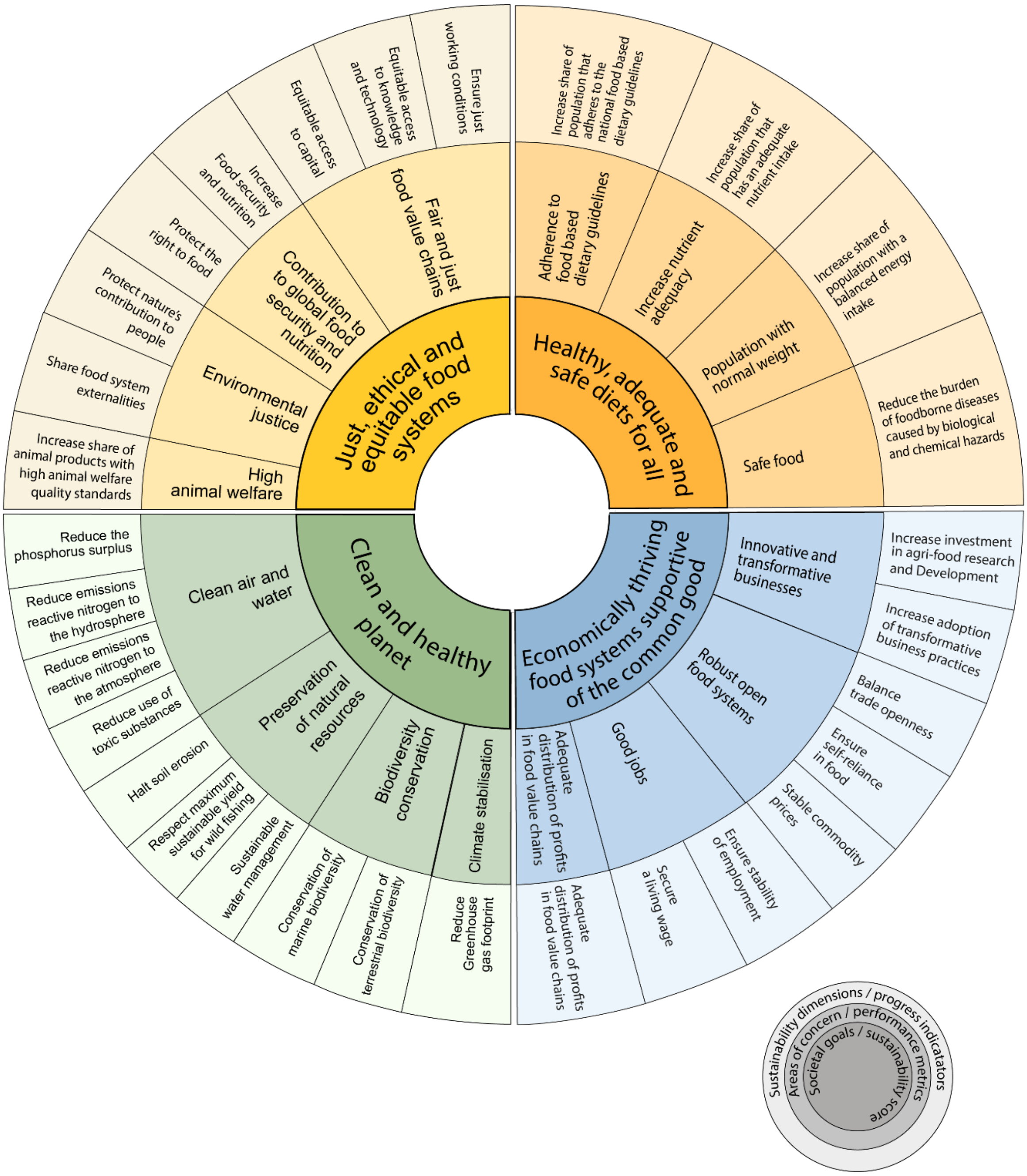

Figure 9.1. The Sustainability Compass for sustainable food systems. Four societal goals (inner ring, measured by a sustainability score) link to sixteen areas of concern (middle ring, measured by performance metrics) and thirty sustainability dimensions (outer ring, measured by progress indicators) that make up the Sustainability Compass. Source: adapted from Hebinck et al., (2021), under CC BY 4.0, https://creativecommons.org/licenses/by/4.0/.

The underlying idea of the Sustainability Compass is that besides the need to assess the current status of a food system, it can also inform if the system moves ‘in the right direction’. This is done by relating existing and/or new policy visions with concrete policy targets. With this step, the Compass aims to translate indicators from the ‘science domain’ to the ‘policy domain’, as it evaluates progress with respect to policy. The use of the ‘distance-to-target’ approach allows further comparison across different sustainability domains.

For the Sustainability Compass to provide actionable insights into progress made as compared to a broader vision, it differentiates between policy targets and visions. Policy visions represent long-term desirable scientific objectives, such as the planetary boundaries or the 1.5-degree target to avoid dangerous climate change. Policy-targets, on the other hand, are often concrete targets to operationalize those visions, negotiated between stakeholders, sectors and policies, and are thus the result of a compromise between science and political/socio-economic constraints.

Calculation of the sustainability scores is organized in a hierarchical manner. These sustainability scores are calculated for each societal goal; first individual variables are aggregated to sustainability status indicators, which are used to calculate progress indicators. The progress indicators are further aggregated to performance metrics and finally to sustainability scores (see Figure 9.2). In this hierarchy, each societal goal has several areas of concerns (e.g., number of good jobs or reduction of greenhouse gas (GHG) emissions), which are measured by the **performance metrics** that capture the performance of a food system or an entity’s actions (e.g., a country, region, or city, but also supra-national entities).

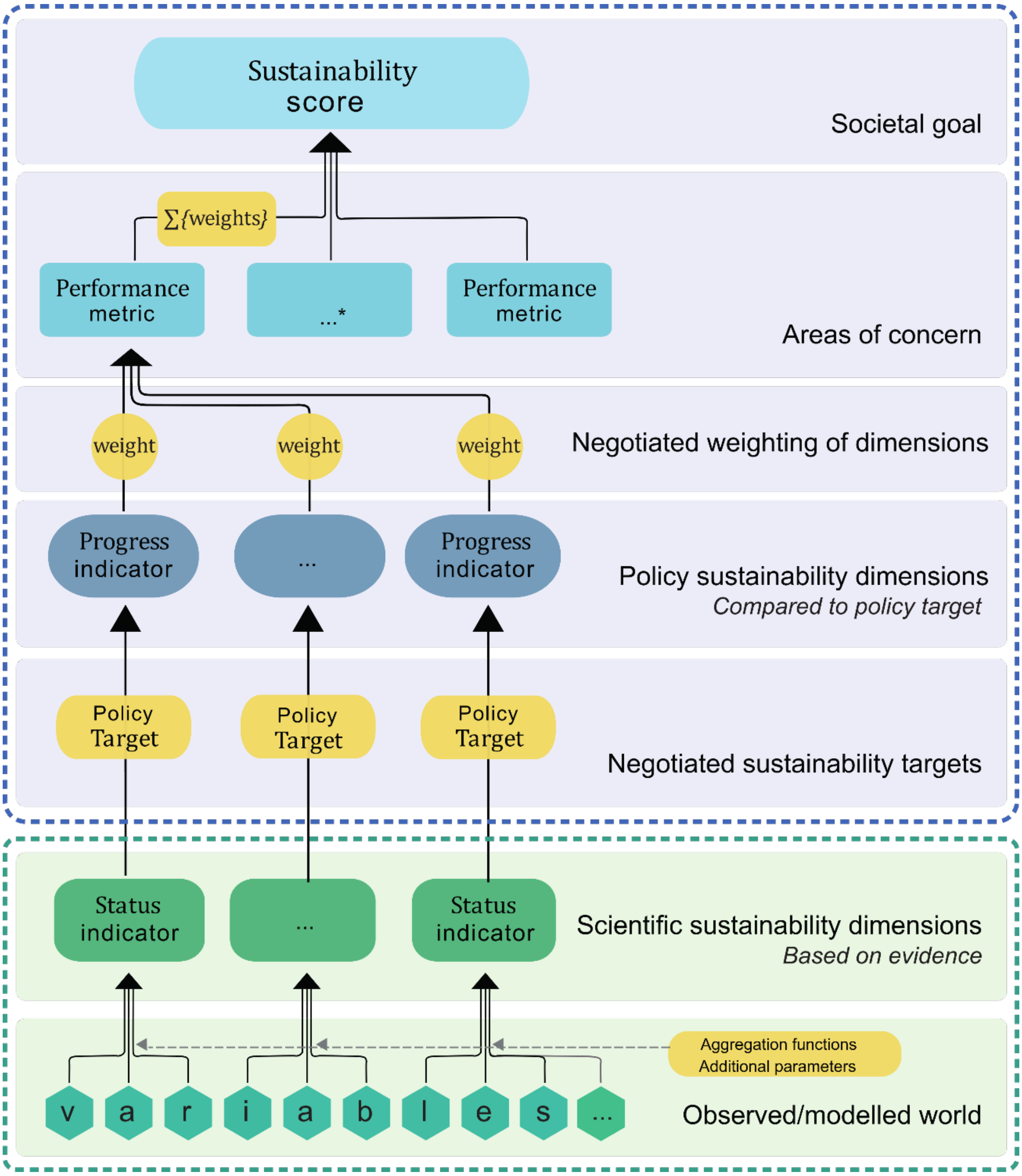

Figure 9.2. *Schematic concept for the hierarchical quantification of sustainability scores and performance metrics from a set of indicators and concrete policy targets and visions. Source: Hebinck et al. (2021), reproduced here under CC BY 4.0,* *https://creativecommons.org/licenses/by/4.0/.*

9.4 Conclusions

Food systems around the world need transformation, but how to best navigate towards change is not straightforward due to the complex and dynamic nature of food systems today. Governance towards sustainability requires that policy- and decision makers across various scales in the food system have access to transparent and comprehensive tools that allow them to make sense of this complexity during the diverse stages of the policy cycle—such as policy design, policy implementation, monitoring and evaluation (Kugelberg *et al.*, 2021; Chapter 8). This requires food system sustainability frameworks to provide an understanding of policy choices, potential trade-offs or impacts across the four societal goals: : 1) healthy, adequate, and safe diets for all; 2) a clean and healthy planet; 3) economically thriving food systems supportive of the common good; and 4) just, ethical and equitable food systems (Zurek *et al.*, 2020). Such a comprehensive and dynamic understanding is vital for negotiation between diverse food system actors on what is sustainable and desirable, and how to govern the food system towards these goals.

The Sustainability Compass offers an approach and a set of metrics that support decision makers to take stock of current food system performance, assess policy aspirations against existing targets, and assess innovation options *ex-ante*. Such a comprehensive, yet policy-oriented, perspective on food system sustainability is also a strong foundation for informed dialogue and negotiations between diverse food system stakeholders. The Sustainability Compass presented here is a step toward more action-oriented frameworks for food system assessments.

Further research to strengthen this approach should focus on several food system assessment challenges. First, there is a continued need for interdisciplinary engagement for development of indicators that capture equity considerations and economic metrics that can go beyond measuring growth alone. Second, quantification of the societal goals demands solid evidence; however, for several sustainability dimensions this is still non-existent. Renewed attention on these missing aspects is vital for the calculation of a comprehensive outlook on food system sustainability. Third, further research should focus on understanding the cross-scale interactions that are inherent to globalized food systems, as they have a paramount role in trade-offs across various societal goals. Regardless of these scientific challenges, the Sustainability Compass presented in this chapter can support decision makers by providing unique and valuable insights for policy-action today to secure sustainability in future food systems but also support a reflexive learning approach to research and policy-making processes (see also chapter 8).

Box 9.1. *Research needs in relation to navigating towards sustainable food systems.*

- Further research and development of indicators, in particular those that capture equity considerations, and use of those indicators in food system assessment models.
- Quantification of targets are crucial for balanced sustainability assessment and need to be based on solid evidence, which is still missing for several sustainability dimensions.
- Further research on system interaction and dynamics is needed to create a better understanding of the dynamics that lead to food system trade-offs, and to develop insights on how to balance sustainability goals equitably.
- Testing and operationalizing the Sustainability Compass in case study contexts with stakeholders to refine the use of indicators and targets in relation to the different areas of concern and sustainability dimensions.
- Implementation in practice of the Sustainability Compass to support a reflexive learning approach to research.

Chapter 10. Reaching nitrogen reduction emissions targets in the European Union

Hans J.M. van Grinsven, Carla Caldeira, Sara Corrado, Nicholas J. Hutchings, Jan Peter Lesschen, Wim de Vries, Henk Westhoek and Adrian Leip

- The Farm to Fork strategy of the European Commission aims to reduce the nitrogen (N) losses from agriculture by 50% by 2030; as regards the food system, this is consistent with the wider ambition of the Colombo Declaration to halve nitrogen waste from all sources by 2030.
- Scenario analysis reveals that a 50% reduction of wasteful N losses is achievable by a wide range of combinations of options that reduce N losses in agriculture; N losses in wastewater treatment; and adopt alternative diets lower in calories, total protein and animal products.
- Halving wasteful nitrogen losses will not only benefit ecosystems and human health but will also address high-cost barriers in agriculture, as well as high socio-cultural barriers to adopt alternative diets.
- The nitrogen use efficiency (NUE) of the EU agri-food system could be increased from the present 18% to a value around 30% solely by change to diets avoiding meat and dairy intake. Combined with ambitious technical measures at farm level and in the food chain, it would be possible to achieve a NUE of the EU food system of close to 50%. Since a more efficient system requires less inputs, such a change would reduce nitrogen waste from the food system by up to 84%.
- Based on expert judgement of these barriers, the most-acceptable interventions combine diet change with intermediate ambitions to reduce N losses in agriculture.
- Key policy message: **Reaching the nitrogen targets will require a comprehensive policy package that in addition to technical innovations at the farm-level, enables social and behavioural innovations across the food system, including dietary shifts, to cut implementation barriers.**

10.1 Introduction

In this chapter, different options to reduce nitrogen waste in the European food system—through intervention at farm level, in the food chain, or through changes in diets—are modelled. Based on the results, the socio-economic costs of the options are analysed with a semi-quantitative approach supported by expert judgement. The chapter is based on the paper of Leip *et al.* (2022).

10.2 Current nitrogen pollution and ambition to halve nitrogen losses

Losses of various nitrogen (N) compounds to air and water have large impacts on both the environment and human health, not only in Europe but also globally (Sutton *et al.*, 2019b; see also Chapters 1 and 2). The nitrogen issue is a global concern because current levels of N pollution lead to multiple severe and acute impacts both on human and ecosystem health. Underlying cause-effect relations are complex because N emissions arise from multiple sources and include multiple mobile, reactive compounds (N_r).

The estimated societal cost of N pollution is dominated by the impact of ammonia on human health and of nitrate on marine ecosystems. For the EU, the total societal cost of N pollution in 2008 was estimated at €75–485 billion, equivalent to 0.6–4.5% of the EU gross domestic product, GDP (Van

Grinsven *et al.*, 2013), with ammonia and nitrate from agriculture contributing an estimated €61–215 billion, equivalent to 0.5 to 1.8% of the GDP (Van Grinsven *et al.* 2018). Similar relative GDP effects by N pollution were found for the US (Sobota *et al.*, 2015) and China (Zhang *et al.*, 2020). The urgency of the N issue has led to the aspiration of halving nitrogen waste globally by 2030 (Colombo Declaration, UNEP, 2019), where nitrogen waste has been defined as the sum of all N losses to air and water, including denitrification to N_2 which is equally a waste of valuable N_r resources; (Sutton *et al.,* 2022). Consistent with this, the EU Farm to Fork Strategy (European Commission, 2020a) aims at reducing nutrient (N and phosphorus) losses from agriculture by 50% by 2030. Equally, in the Kunming-Montreal Global Biodiversity Framework (GBF) the EU and its Member States committed themselves at global level to "*reduce pollution risks and the negative impact of pollution from all sources by 2030, to levels that are not harmful to biodiversity and ecosystem functions and services, considering cumulative effects, including: (a) by reducing excess nutrients lost to the environment by at least half, including through more efficient nutrient cycling and use*"(CBD/COP/DEC/15/4) [10].

Here, we explore options to halve nitrogen waste in the EU agri-food system.

10.2.1 Farm to Fork Strategy and nitrogen

The European Commission has addressed the issue of reducing N losses (i.e., nitrogen waste) in the European Green Deal, notably in the Farm to Fork Strategy (European Commission, 2020a) and in the Biodiversity Strategy (European Commission, 2020f), setting an aspirational target to reduce nutrient losses by at least 50% by 2030, while ensuring that there is no deterioration in soil fertility. The expectation as expressed in the strategy is that this will reduce the use of synthetic fertilizers by at least 20%. This target will have to be addressed by Member States in their National Strategic Plans as included in the new Common Agricultural Policy. Nitrogen losses will also be tackled by stimulating responsible supply chains and by promoting healthy and sustainable diets in various ways.

The view expressed by the European Commission (2020a) is that the market for organic food will continue growing and organic farming needs to be further promoted as it has a positive impact on biodiversity, it creates jobs and attracts young farmers. Therefore, the Farm to Fork Strategy has the further objective to increase the EU's agricultural land under organic farming to at least 25% by 2030. The labelling of organic farming for food products does not allow the use of synthetic N fertilizers, which is expected to reduce virgin N inputs and total N losses, and also has implications for food production.

10.2.2 Boundaries for nitrogen losses in European agriculture

The recent planetary boundary (PB) framework proposes global quantitative precautionary limits for human perturbation of nine critical Earth system processes, one of them being fixation of N (De Vries *et al.*, 2013; Steffen *et al.*, 2015). This framework also generated interest among EU policy makers and was also applied to the EU scale (Lucas *et al.*, 2020; De Vries *et al.*, 2021). Steffen *et al.* (2015) propose a global PB for N of 62–82 Tg yr^{-1}, while the global N fixation in 2010 was 120 Tg yr^{-1} (excluding nitrogen oxides) with a contribution of the EU of about 10%. Current N policies as laid down in the National Emissions Ceilings Directive, Nitrates Directive and Water Framework Directive (EU, 2016; European Commission, 2000, 1991) imply the existence of critical emissions and virgin inputs of reactive N. Conforming to the PB for N will have implications for meeting European climate targets, the economy of the agri-food system and food security.

De Vries *et al.* (2021) used the method developed by De Vries *et al.* (2013) to estimate spatially explicit planetary boundaries for N inputs in the European Union. They quantified critical thresholds of the ecosystem status which would allow avoidance of environmental problems such as acidification of soils due to ammonia deposition, eutrophication of fresh and coastal waters caused by N runoff, and high concentration of nitrates in drinking water; and would restore ecosystems to a healthy state. A model was used to back-calculate corresponding environmental maximum levels of environmental pressures. Critical N inputs were calculated with the INTEGRATOR model (De Vries *et al.*, 2011) by back-calculation from critical ammonia emissions, based on area-weighted mean critical N loads, a critical N concentration in surface water and a critical nitrate concentration in ground water, accounting for local variations in N fluxes and effects. This was done by using close to 40,000 unique soil-slope-climate combinations to capture differences in sensitivity of the receiving ecosystems. The authors further quantified the necessary

[10] https://www.cbd.int/decisions/cop/?m=cop-15

changes in ammonia loss fractions and nitrogen use efficiencies (NUEs) in agriculture to attain actual yield while simultaneously reaching air and water quality goals.

More specifically, De Vries *et al.* (2021) used critical N loads that safeguard against decline in plant species diversity due to eutrophication and soil acidification in sensitive terrestrial ecosystems to calculate critical NH_3 emissions, while correcting for dilution effects from non-agricultural land. A critical N concentration of 2.5 mg N L^{-1} in fresh surface water was used for protection against eutrophication, and a critical concentration of 11.3 mg NO_3-N L^{-1} in N leaching from agricultural land was used as safeguard for drinking water. Critical N runoff rates and critical N leaching were calculated by multiplying the precipitation surplus with the above-mentioned critical N concentrations, in which critical N runoff rates were corrected for dilution effects from non-agricultural land. Unlike the calculation at global scale (De Vries *et al.*, 2013), the calculation by De Vries *et al.* (2021) of critical N inputs for EU agriculture also allowed the possibility to increase N fertilizer inputs in areas where N is limiting crop growth if there are no environmental problems. Details on the calculation approaches are given in De Vries *et al.* (2021).

Results by De Vries *et al.* (2021) showed that the overall required overall reductions in NH_3 losses and N runoff at EU level to prevent exceedance of critical N limits for terrestrial and aquatic ecosystems were calculated at 38% and 49%, respectively; the latter value being close to the mentioned reduction in nutrient losses of 50% by the Farm to Fork strategy (De Vries and Schulte-Uebbing, 2020).

De Vries and Schulte-Uebbing, 2020 concluded that the use of generic, rather than regionally differentiated, reduction targets for N losses and N inputs was, however, was not appropriate. Targeted more ambitious reductions are needed in regional hot spots with N-related environmental and health impacts, while N use can sometimes increase in areas with large yield gaps and low current N inputs. If the NUE stays the same, this required reduction in N losses implies a significant reduction in N inputs, which in turn would imply significant crop yield losses. However, if the current NUE is increased, the N input reduction to protect terrestrial and aquatic ecosystems is less and could be reconciled with current or even target crop production (see Figure 10.1) if the required NUE is attainable. De Vries and Schulte-Uebbing (2020) concluded that in part of the European Union it is impossible to fully protect air and water quality without a reduction in agricultural production (according to the approach they implemented), considering that an NUE of 0.9 is the maximum plausible NUE that farmers can achieve.

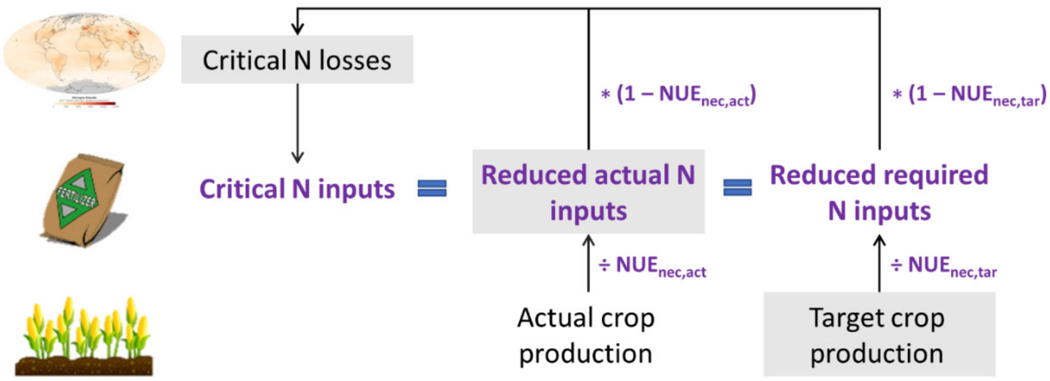

Figure 10.1. *Illustration of required nitrogen use efficiency (NUE) changes to reconcile crop production and environmental targets (act: actual; tar: target). According to this approach, the target crop production is defined at 80% of the water limited production. When the current production exceeds that value, the current production is used in the model. The required NUE increase refers to land application of fertilizer and manure. Critical N losses stands for all N losses to air (ammonia), surface water (total nitrogen) and ground water (nitrate), which were calculated on the basis of critical limits for the relevant N compounds.* NO_x *and* N_2O *were not included as part of the approach. Source: De Vries and Schulte-Uebbing (2019 and 2020). Figure reproduced from De Vries and Schulte-Uebbing (2019) with the permission of Springer Nature.*

10.3 Scenarios of options and ambitions to halve nitrogen losses in the food system

Four domains are distinguished for interventions to reduce N_r losses and to increase the NUE of the agri-food system in accordance with Springmann *et al.* (2018a). Four model scenarios are considered, referred to as Options 1 to 4:

Option 1: Reduce N input and improve management of N in agriculture (primary production). This will increase the NUE in farming systems and reduce N losses from soils producing crops for food and feed, and reduce emissions from livestock housing and manure management.

Option 2: Reduce N emissions from agricultural residues and food waste and from human excreta by improved treatment and management of these residues/wastes.

Option 3: Reduce demand for agricultural production for food by reducing food waste and associated N losses; and increasing reuse of N from the sewage system and the valorization (utilization) of co-products and residues/waste from food processing, retail and consumption.

Option 4: Reduce N need for human consumption by dietary change. This includes reducing energy and protein demand, and the share of animal products by optimizing diets.

10.3.1 Definition and analysis of scenarios

Option 1 was explored by Hutchings *et al.* (2020; see also Chapter 4) for low, medium and high reduction ambitions to increase farm-level NUE (nitrogen use efficiency), distinguishing several technical measures for a set of crop and animal systems, in northern and southern EU. They were termed as follows:

Rfa standing for ambition level of farm-level mitigation (Rfa1, Rfa2, Rfa3) (see Table 10.1).

Hutchings *et al*. (2020) found maximum NUEs of 82% and 92% for arable systems 71% and 80% for granivores and 50% and 36% for ruminant meat production on marginal agricultural land, in each case for northern and southern EU, respectively. Here granivores refer primarily to pig and poultry, while ruminants refer primarily to cattle and sheep. On land unconstrained by soil conditions or topography, they found maximum NUEs of 53% and 55% for dairy production and 46% and 62% for ruminant meat production. For these cases, farm-level NUE refers to the amount of nitrogen in food products produced divided by the nitrogen in inputs to the farm system (fertilizer, biological nitrogen fixation, atmospheric deposition).

Options 2 and 3 were explored by Corrado *et al.* (2020; see also Chapter 4), distinguishing an improved scenario aimed at reducing food waste and a 'combined' scenario that additionally recovers N from wastewater. They were termed as follows:

Rfo standing for ambition level for food waste reduction in food processing and retail (Rfo1, Rfo2).

Corrado *et al.* (2020) estimated that the combination of the effects of the interventions foreseen by the EU legislation for food waste reduction and improvement of wastewater treatments may reduce N_r emissions in processing, distribution and consumption of food up to 50%, while increasing N_2 emissions by 30%. According to the implementation of this scenario, N_2 were increased because the focus included an increase in denitrification-based treatment of wastewater. Alternative scenarios for future research could focus more on the reduction of denitrification (i.e., reducing N_2 emissions) by applying emerging wastewater technologies that recover N_r for reuse (e.g., 'white ammonia'; wastewater to fertilizer technology).

Option 4 was explored by implementing combinations of progressive scenarios for diet change (Table 10.1, see source code at https://github.com/aleip/Ntargets). The subscenarios are termed as follows:

Ren, standing for reduction of energy (Ren1, Ren 2);

Rpr, standing for reduction of protein (Rpr1, Rpr 2);

Rap, standing for reduction of animal products (Rap1, Rap2, Rap3).

Accordingly, seven subscenarios were analysed:

Ren 1: to reduce overconsumption of calories by 1/3 (reduction of overall energy intake in food by 12.5%);

Rap 2: to reduce overconsumption of calories by 2/3 (reduction of overall energy intake in food by 25%);

Rpr 1: to reduce overconsumption of protein by 40% (reduction of total protein intake by 20%);

Rpr 2: to reduce overconsumption of protein by 80% (reduction of total protein intake by 40%);

Rap 1: demitarian diet (halving meat consumption, substitution with 50% crops, 10% seafood and 40% 'novel' foods including insects and plant-based analogues);

Rap 2: vegetarian diet (no meat, but with dairy and eggs, substitution with 50% crops and 50% dairy and eggs);

Rap 3: vegan diet (no animal products, substitution as in demitarian diets).

Current gross intake of energy in the EU exceeds body needs by 35% (Van den Bos Verma *et al.*, 2020) and protein requirements by 70% (Westhoek *et al.*, 2011). The Ren and Rpr subscenarios aim to comply with WHO (2007) recommendations to reduce morbidity and mortality caused by cardio-vascular diseases, diabetes and cancer in relation with overconsumption of energy, red meat and saturated fats and underconsumption of fibres (Westhoek *et al.*, 2014; see also Chapter 2). We assumed that N emissions from livestock operations are reduced proportionally to changes in the consumption of animal protein.

10.3.2 Possible reduction of nitrogen losses across the scenarios

A scenario tool was built and a total of 144 combinations of scenarios was analysed (being a selection of plausible combinations of interventions, see Table 10.1).

Table 10.1. *Ambition levels and targets per food subsystem interventions, yielding 144 scenarios of plausible combinations. Source: Leip et al, 2022, reproduced here under CC BY 4.0, https://creativecommons.org/licenses/by/4.0/.*

Level of ambition	Reduction of farm N losses (Rfa)	Reduction of food system N losses (Rfo)	Reduction of energy intake (Ren)	Reduction of protein intake (Rpr)	Diet (Rap)
0	Baseline	Baseline	0%	0%	Default
1	Low	Intermediate	12.5%	20%	Demitarian
2	Medium	Improved	25.0%	40%	Vegetarian
3	High				Vegan

These scenarios delivered a range of N loss reductions between 6% and 84% (Figure 10.2). From this set of scenario results, 12 combinations were selected that yielded a reduction of N losses of between 49% and 51%, thus meeting ambitions as in the EU Farm to Fork strategy. The purpose of this selection was to see how the ambition to halve nitrogen waste could be achieved using different combinations of measures.

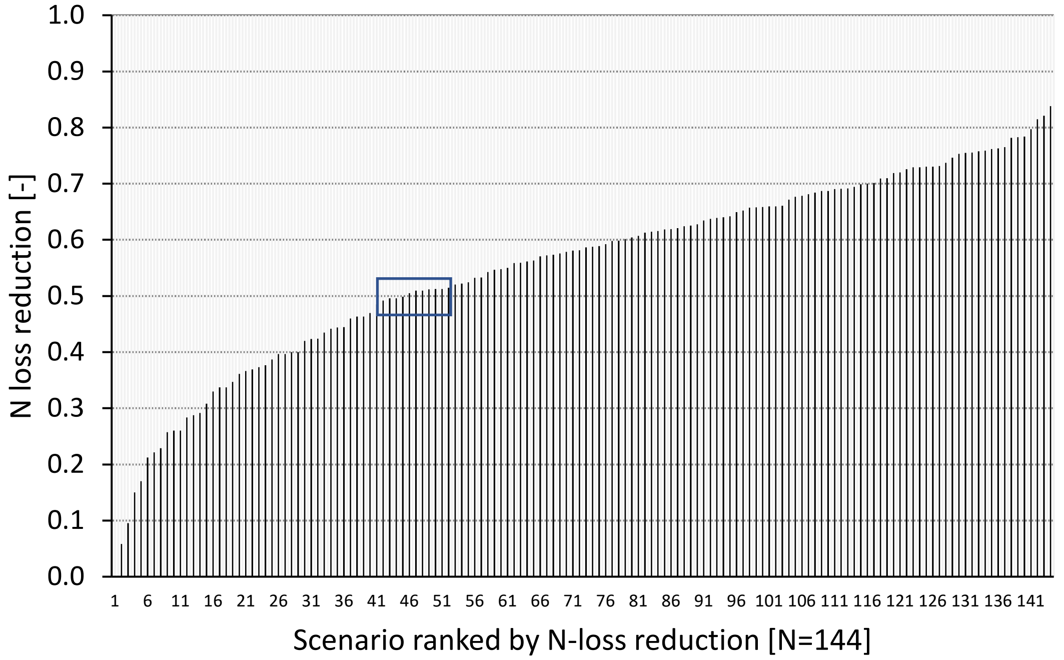

Figure 10.2. *Relative reduction of nitrogen (N) losses in 144 intervention options and selection of 12 intervention options (box: O41–O52) with a N loss reduction between 49 and 51%. These 12 combinations of intervention options represent different combinations of farm-level, food waste, and dietary options. They include combinations of medium level ambitions for all intervention options or combinations with high ambitions for one intervention option combined with lower ambition for the others. For example, with a shift to vegan diets no or low farm level interventions are required to reach a 50% reduction of wasted nitrogen losses; while for high ambition levels at farms, a moderate reduction of protein intake might be sufficient. Source: Leip et al. (2022), reproduced here under CC BY 4.0, https://creativecommons.org/licenses/by/4.0/.*

10.3.3 Tentative societal appreciation of combinations of interventions

Policy decisions about how to transform the EU agri-food system with a high chance of halving N waste and with a low risk of trade-offs, require a comprehensive basic understanding of its functioning and careful consideration of the many biophysical and socio-economic aspects. Science can support the decision-making process by providing a simple, transparent and reproducible set of rules to combine and weigh the most important factors that determine the potential success of a policy option. The most important point is that a transparent approach be taken. Four aspects were considered to evaluate the 12 scenarios identified in Figure 10.2:

1. The private and public cost of the implementation of measures to decrease N losses in (a) agriculture and (b) waste management.
2. The public benefits of improved healthy life expectancy and reduced public health cost due to:
   (a) a lower energy intake, which reduces obesity and related diabetes and cardiovascular problems;
   (b) healthier diet choice, with less red meat, less saturated fats and more fibre; and
   (c) reduced exposure to N related air pollution, with as dominant route for the agri-food system reduced exposure to PM2.5 from NH_3 containing aerosols.
3. The public benefits of increased biodiversity and ecosystem services (e.g., recreation, pollination) from:
   (a) a reduced N load in deposition and runoff; and
   (b) a reduction in land requirement with a decreasing share of animal products in diet.
4. The public cost for overcoming socio-cultural barriers to the adoption of alternative diets (less freedom of choice), distinguishing diets with:
   (a) a lower energy intake;

(b) less protein intake; and
(c) fewer animal products.

Here we propose such a framework of simple rules, partially deriving from the results of previous Cost-Benefit Analysis (CBA) studies, and partly on our expert judgement regarding relative societal weights; and with an appreciation of the barriers to adopt alternative diets. We acknowledge that these aspects do not capture the complex dependence of preferences on contrasting societal perspectives of the agri-food system (Muilwijk *et al.*, 2020).

10.3.4 Evaluation of scenarios than can halve nitrogen losses

For each of the four aspects, scores were assigned by ranking the scenarios according to their level of ambition and assigning weights to aggregate the scores within and across the aspects. Scores and evaluation in this paper were based on expert judgement of the authors but ideally should involve stakeholders. The rules used for scoring (Table 10.2) were as follows (for explanation of acronyms see section 10.3.1):

1. Negative values represent a social cost, positive values represent a benefit.
2. Implementation cost to reduce N emission (Rfa, see section 10.3.1): score 0.5 for low, -1 for medium, -2 for high. The score of 0.5 for low ambition reflects the savings of improved N management, e.g., in the purchase of fertilizer or required measures to reduce emissions of ammonia from manure.
3. Implementation cost of reduction of N losses from food-waste in food processing and retail (Rfo): score 1 for improved and 2 for 'combined'.
4. Health benefits of reduction of energy intake in diet (Ren): score 1 for reduction by 12.5% and 2 for reduction by 25%.
5. The are no clear health risks of protein intake exceeding the WHO (2007) recommendations and therefore benefits of reduction of protein intake (Rpr) were not considered. For reduction of consumption of animal products (Rap) all scenarios were assigned a score of 1. Although there are net health benefits, there are also health risks when moving from the current diet to a vegetarian or vegan diet, e.g., deficiencies of iron, specific proteins and vitamins.
6. The health benefits of improved air and water quality were calculated proportionally to the reduction in N loss, giving a score of 1 for all selected scenarios with a N loss reduction of 50%, and a score around 1.7 for the two scenarios with the highest N loss reduction.
7. Ecosystem benefits of N losses were also assumed proportional to the reduction in N losses but were presumed more sensitive, giving a score of 2 for all selected scenarios with a N loss reduction of 50%, and a score of 3.4 and 3.3 for the two scenarios with the highest N loss reduction.
8. Potential ecosystem benefits of reduced land requirement for diets with less animal products were calculated using a land-footprint calculator (https://themasites.pbl.nl/o/duurzaam-voedsel/): resulting scores are the ratio of land requirement per capita in the current reference and land requirement for the alternative diet; 1.2 for demitarian, 1.65 for vegetarian and 2.0 for vegan. Effects of food waste reduction would only slightly modify these scores.
9. The scores for overcoming societal barriers to adopt demitarian, vegetarian and vegan diets increased from -1 to -2 to -3.

The overall score of the social net benefit was calculated by giving equal weight to the scores for the four aspects: implementation cose, health benefits, ecosystem benefits, and socio-cultural barriers. Scores on costs were assigned negative values; scores on benefits were assigned positive values. Equal weights for the impacts of N_r loss on human health and ecosystems is in line with comparable societal costs for both impacts in 2008 in the EU (Van Grinsven *et al.*, 2018; Van Grinsven *et al.*, 2013). The relative weight for each ambition within the four aspects was differentiated and motivated as follows (Table 10.2):

1. **Implementation cost:** the weight of the score for implementation costs in agriculture was set three times higher than for municipal waste and wastewater, despite the fact that compliance costs to meet the EU wastewater directive (about 50 billion Euro in 2008, European Commission, 2010) are higher than the compliance cost for N related environmental directives for agriculture (about 5 billion Euro, European Commission, 2014). The reasons for this are that (i) only a small

part of the cost to meet the EU wastewater directive is related to N pollution; and (ii) agricultural costs are directly paid by farm households (<2% of total households); while costs for communal waste treatment are paid by all households, in general by taxation.

2. **Health benefits:** the weight of improved health by reducing overconsumption of calories was assumed to be four times the combined effect of low protein and reduced animal products as there are no important health risks of consuming more protein than recommended (18 kg per year, WHO, 2007). The score for reduced morbidity and mortality by reduced N losses (dominated by a reduction of NH_3 containing aerosols) was twice the weight as the weight of low energy diet. Although diet related mortalities in the EU (3% of total mortalities, 14 million in 2017, GBD 2016 Risk Factors Collaborators, 2017) are higher than mortalities from N-related ambient air pollution (3.3 million in 2013, Gu *et al.*, 2021), equal weights were motivated by the absence of choice to prevent exposure to ambient air.

3. **Ecosystem benefits:** the weight of the ecosystem benefits resulting from reduced land requirements was set twice as high as that of reduced N losses. For Western Europe the contribution of N deposition to biodiversity (Mean Species Abundance, MSA) loss in 2015 was >5 times less than from land use change (Schipper *et al.*, 2020); however, the impact of N deposition on biodiversity in remaining natural land is of course much larger.

4. **Socio-cultural barriers** to adopt diets with reduced energy intake and reduced animal products were given equal weight. Barriers for adoption of diets with less protein and with less animal products were merged.

Results of the calculations are shown in Table 10.3 for example scenarios and in Table 10.4 for the full results from the 12 scenarios with a N loss reduction between 49 and 51% (Figure 10.2).

Table 10.2. *Calculation of scores of the societal net benefit of quantified agri-food system options: i) scores of costs (negative sign) and benefits per ambition level and effects of food subsystem intervention; ii) weights per score within each of the four domains (Weighting A); iii) weight for the aggregated score between these domains (Weighting B) as used for evaluation of ambitions and results of food system scenarios that can achieve a 50% reduction of nitrogen (N) losses in the EU. Source: Leip et al. (2022), under CC BY 4.0, https://creativecommons.org/licenses/by/4.0/.*

	Effect scores[#] of options to reduce N loss									
	Implementation cost		Human health			Ecosystem		Socio-cultural barriers		
Ambition[&]	Rfa	Rfo	Ren	Rap	N loss	N loss	Rap	Ren	Rpr	Rap
Baseline	0	0	0	0	0	0	0	0	0	0
1	0.5	-1	1	1	Calc[*]	Calc[*]	1.20	-1	-1	-1
2	-1	-2	2	1	Calc[*]	Calc[*]	1.65	-2	-2	-2
3	-2			1	Calc[*]	Calc[*]	2.00			-3
Weighting A	3	1	2	0.5	1	1	2	1	0	1
Weighting B	1		1			1		1		

[#] *Negative values represent a social cost; positive values represent a benefit.*
[&] *For explanation of acronyms see section 10.3.1*
[*]*Score for effect on human health and ecosystem is function of nitrogen (N) loss. As N loss for selected scenarios giving a 49–51% reduction in N loss, varies in a narrow range (6.0–6.4 Tg N), consequently also the range of scores for health and ecosystem benefits is narrow, 0.97–1.03 and 1.9–2.1, respectively.*

Table 10.3. *Results of the baseline for 2014-2015 with four example scenarios that deliver around 50% reduction in wasteful nitrogen losses to the environment as compared to the baseline, plus the scenario reaching the highest reduction of wasteful nitrogen losses. Values of nitrogen flows (Tg) are specified on an annual basis, the reduction of energy and nitrogen intake and of nitrogen flows are relative to the baseline situation. NUE = nitrogen use efficiency. Source: Leip et al. (2022), under CC BY 4.0, https://creativecommons.org/licenses/by/4.0/.*

Scenario option						**Effects on N cycle and implementation**				
Example scenario	**Farm level** **Ambition**	**Food chain** **Ambition**	**Healthier energy intake** ***% reduction***	**Healthier protein intake** ***% reduction***	**Diet**	**Virgin nitrogen** **Tg N yr^{-1}** ***% reduction***	**Nitrogen losses** **Tg N yr^{-1}** ***% reduction***	**NUE food system**	**Implementation costs score**	**Overall score for net societal benefit $^{\$}$**
Baseline	Baseline	Baseline	*0%*	*0%*	Default	16.0 *0%*	12.4 *0%*	19%	0	0
O41	Low	Intermediate	*13%*	*20%*	Demitarian	9.4 *41%*	6.4 *49%*	27%	0.1	0.8
O45	High	Improved	*0%*	*0%*	Default	10.0 *37%*	6.2 *50%*	32%	-2.8	-0.6
O48	Medium	Intermediate	*13%*	*0%*	Vegetarian	9.7 *40%*	6.1 *51%*	32%	-1.0	0.4
O51	Baseline	Baseline	*13%*	*0%*	Vegan	9.5 *41%*	6.0 *51%*	32%	0.0	0.5
O144	High	Improved	*25%*	*40%*	Vegan	4.3 *73%*	2.0 *84%*	47%	-2.8	0.0

Notes: *Table 10.4 shows full results from the 12 scenarios which met this target, which are themselves selected from 144 scenarios (Figure 10.2).*
$^{\$}$ The overall score for net societal benefit was obtained through a three-step approach as explained above (see Table 10.2): (i) assigning scores for each indicator according to the ambition level; (ii) aggregating scores across the indicators in each of the four issues—Implementation cost, Human Health, Ecosystem, Socio-cultural Barriers; and (iii) aggregating score across the four issues to obtain the overall net benefit score.

Table 10.4. *Evaluation of agri-food-system scenarios for the European Union that can deliver a reduction of nitrogen (N) losses of 49–51% as compared to the current situation (baseline) and the two scenarios (O143, O144) giving the highest N loss reduction.* ***(A)*** *Nitrogen flows and nitrogen efficiencies for food supply (agriculture) and the whole food system.* ***(B)*** *Cost and benefit scores as defined according to Table 10.2. The four scenarios with the highest net benefit score are indicated in darker shade. NUE = nitrogen use efficiency. Source: based on Leip et al. (2022), under CC BY 4.0, https://creativecommons.org/licenses/by/4.0/.*

Scenario	**Farm level Ambition**	**Food chain Ambition**	**Healthier energy intake *% reduction***	**Healthier protein intake *% reduction***	**Diet choice**	**Virgin nitrogen Tg N yr^{-1}**	**Nitrogen intake Tg N yr^{-1}**	**Nitrogen losses Tg N yr^{-1}**	**Nitrogen losses *% reduction***	**NUE agriculture**	**NUE food system**	**Implemen-tation cost score**	**Human health benefit score**	**Ecosystem benefit score**	**Socio-cultural barriers score**	**Overall score for net societal benefit**
									A					**B**		
Baseline	Baseline	Baseline	*0.0%*	*0%*	Default	16.0	3.0	12.4	*0%*	46%	**19%**	0.0	0.0	0.0	0	0.0
O41	Low	Intermediate	*12.5%*	*20%*	Demitarian	9.4	2.4	6.4	*49%*	59%	**27%**	0.1	1.0	1.4	-1	**0.8**
O42	Baseline	Improved	*12.5%*	*20%*	Vegetarian	9.3	2.4	6.3	*49%*	56%	**27%**	-0.5	1.0	1.7	-1.5	0.5
O43	Low	Baseline	*12.5%*	*40%*	Default	8.4	1.8	6.2	*50%*	53%	**22%**	0.4	0.8	0.6	-0.5	**0.7**
O44	Medium	Intermediate	*12.5%*	*20%*	Default	9.3	2.4	6.2	*50%*	60%	**28%**	-1.0	0.8	0.6	-0.5	0.2
O45	High	Improved	*0.0%*	*0%*	Default	10.0	3.0	6.2	*50%*	65%	**32%**	-2.8	0.3	0.7	0	-0.6
O46	High	Baseline	*12.5%*	*20%*	Default	9.0	2.4	6.1	*50%*	66%	**28%**	-2.3	0.9	0.7	-0.5	-0.2
O47	High	Baseline	*12.5%*	*0%*	Vegetarian	9.5	2.8	6.1	*51%*	74%	**32%**	-2.3	1.0	1.8	-1.5	-0.1
O48	Medium	Intermed.	*12.5%*	*0%*	Vegetarian	9.7	2.8	6.1	*51%*	68%	**32%**	-1.0	1.0	1.8	-1.5	0.4
O49	Baseline	Improved	*12.5%*	*20%*	Demitarian	9.1	2.4	6.0	*51%*	58%	**28%**	-0.5	1.0	1.5	-1	0.6
O50	Low	Improved	*12.5%*	*20%*	Vegetarian	9.1	2.4	6.0	*51%*	58%	**28%**	-0.1	1.0	1.8	-1.5	**0.7**
O51	Baseline	Baseline	*12.5%*	*0%*	Vegan	9.5	2.8	6.0	*51%*	74%	**32%**	0.0	0.9	2.0	-2	0.5
O52	Low	Baseline	*12.5%*	*0%*	Vegan	9.5	2.8	6.0	*51%*	75%	**32%**	0.4	0.9	2.0	-2	**0.7**
O143	Medium	Improved	*25.0%*	*40%*	Vegan	4.5	1.8	2.2	*85%*	91%	**47%**	-1.3	1.6	2.5	-2.5	0.5
O144	High	Improved	*25.0%*	*40%*	Vegan	4.3	1.8	2.0	*84%*	87%	**45%**	-2.8	1.6	2.4	-2.5	0.0

10.4 Results and discussion

The 144 Intervention options delivered a range of nitrogen (N) loss reductions up to 84% (Figure 10.2). From this set of intervention option results, 12 combinations were selected that yielded a reduction of N losses between 49% and 51%, thus meeting the ambition of reducing nitogen loss by 50% (i.e., 'halve nitrogen waste') of the EU Farm to Fork strategy (European Commission 2020a) or the Colombo Declaration (UNEP, 2019). Selected results for the baseline scenario, four example scenarios out of the 12 selected conbinations, plus the scenario reaching highest reduction of wasteful nitrogen losses are shown in Table 10.3. More detailed results for all 12 intervention options plus the two scenarios reaching highest reduction of wasteful nitrogen losses are shown in Table 10.4. Table 10.4 indicates for the EU of total virgin N input, dietary intake of N, total N losses and nitrogen use efficiencies (NUEs) for food supply (agriculture) and the total agri-food system (columns A), as well as the costs and benefits, and the overall net benefit score as defined in Table 10.2 (columns B).

There are contrasting scenarios which all could lead to a reduction of N losses by 50% from EU agriculture and satisfy critical environmental loads and levels of N. These scenarios contrast regarding assumptions on improvement of farm N management, waste N management and change of diet. Results show that scenarios that assume a moderate combination of these pathways achieve halving N losses at lower societal costs. The implementation of measures to any one part of the food system was insufficient to halve the N loss, showing that there is no single silver bullet to solve N pollution problems in the EU.

Feasible futures with half of current nitrogen loss

Based on the expert scores and weights used, the intervention options vary significantly in the net benefit score. O41, O43, O50 and O52 would be recommended choices for halving N losses (Table 10.4) and suggest that demitarian, vegetarian and vegan diets could be feasible directions to solve the N problem. Intervention option O45, which could be labelled as the high-tech scenario to reduce N losses by 50% without diet change, yields the lowest overall score. The scenario study suggests that the best overall strategy for the EU to achieve the 50% reduction of N losses would be reducing the virgin N need for the primary production system by combining moderate ambitions for agriculture with intermediate ambitions for diet change and wastewater. This strategy would mean reducing energy and protein demand to WHO (2007) recommendations, combined with reduction of N_r losses from wastewater treatment (and recycling of N-rich waste from the food system and human excreta back to primary production).

Measures in agriculture could focus on ammonia reduction (excretion, storage and application of manure N) in view of its dominant contribution to impacts both on nature and human health, and on measures with low cost and few negative trade-offs like soil compaction and swapping NH_3 losses for losses as N_2O or NO_3. The efficacies of cheaper options to reduce N losses in agriculture, such as the application of nitrification inhibitors and urease inhibitors are often overestimated, and also meet with societal resistance (Li *et al.*, 2018).

These findings are consistent with the conclusions of Springmann *et al.* (2018a) and Muilwijk *et al.* (2020) that no single measure is enough to keep the effects of the food system within planetary boundaries and that a synergistic combination of measures in subsystems is necessary (see also Chapters 7 and 8). The values for the nitrogen use efficiencies are lower than those obtained in Westhoek *et al.* (2014, 2015) with Nitrogen use efficiencies (NUEs) of up to 47% for a demitarian diet. The reason is differences in system boundaries. Higher NUEs were achieved by Westhoek *et al.* (2014, 2015) due to the partial use of land not required for feed production to produce wheat for export. Here no assumptions on the use of this land were made and all numbers refer to a system providing food for the EU population.

Combining higher ambition levels

The maximum N loss reduction achievable with improved N management at farm level only was 37%. N loss reduction with only improved N waste management in food processing, retail and sewage treatment was 17% (Table 10.5). By combining ambitious changes from current diets to a vegan diet throughout EU society with a high-level of ambition at the farm and food chain, an emission reduction up to 84% and a food system NUE of 47% are achievable. A vegan diet alone combined with reduced overconsumption of energy and proteins, can lead to a reduction of N losses between 51% and 69%, at NUEs of 32%. However, an EU wide adoption of a vegan diet seems at the current time not to be a feasible route in the absence of societal support and political will. However, the results emphasize the importance of diet change; a partial adoption of vegan diets to achieve the 50% reduction can save significant implementation costs.

Table 10.5. Evaluation of agri-food-system scenarios for the European Union that can deliver a reduction of nitrogen (N) losses dietary shift to vegan diets at different ambition levels of farm level and food chain N reduction options, as compared to a focus on farm and food chain measures only. NUE = nitrogen use efficiency. Source: based on Leip et al. (2022), under CC BY 4.0, https://creativecommons.org/licenses/by/4.0/.

Scenario	Farm level Ambition	Food chain Ambition	Healthier energy intake % reduction	Healthier protein intake % reduction	Diet choice	Virgin nitrogen Tg N yr^{-1}	Nitrogen intake Tg N yr^{-1}	Nitrogen losses Tg N yr^{-1}	NUE system %	Total N losses % reduction
O23	Baseline	Baseline	*0.0%*	*0%*	Default	11.4	3.0	7.7	28%	*37%*
O5	Baseline	Improved	*0.0%*	*0%*	Default	14.1	3.0	10.3	23%	*17%*
O40	Baseline	Baseline	*12.5%*	*40%*	Default	8.7	1.8	6.6	21%	*47%*
O51	Baseline	Baseline	*12.5%*	*0%*	Vegan	9.5	2.8	6.0	32%	*51%*
O74	Baseline	Baseline	*12.5%*	*20%*	Vegan	8.0	2.4	5.1	32%	*59%*
O111	Baseline	Baseline	*25.0%*	*40%*	Vegan	6.0	1.8	3.8	32%	*69%*
O105	Baseline	Improved	*12.5%*	*20%*	Vegan	7.0	2.4	4.0	37%	*68%*
O123	Baseline	Intermed	*25.0%*	*40%*	Vegan	5.6	1.8	3.3	35%	*73%*
O133	Baseline	Improved	*25.0%*	*40%*	Vegan	5.3	1.8	3.0	37%	*76%*
O140	High	Improved	*12.5%*	*20%*	Vegan	5.7	2.4	2.7	47%	*78%*
O142	High	Intermed	*25.0%*	*40%*	Vegan	4.6	1.8	2.3	44%	*81%*
O144	High	Improved	*25.0%*	*40%*	Vegan	4.3	1.8	2.0	47%	*84%*

Organic agriculture

Our scenario analysis did not include organic agriculture as an option to increase farm level NUE, even though organic agriculture, beside significant benefits for biodiversity objectives, aspires to reduce N_r losses while achieving food sufficiency (Barbieri *et al.*, 2019). The EU Farm to Fork strategy has set an aspirational target of increasing the share of organic agriculture to at least 25% of the EU's agricultural land (European Commission, 2020a). The organic food label does not allow use of synthetic N fertilizer. Instead, organic agriculture relies on biological N fixation and the use of organic fertilizers. Nitrogen surpluses and losses per hectare in organic agriculture tend to be lower than in conventional agriculture (Van Grinsven *et al.*, 2015). On the other hand, organic cultivation tends to have lower yields (Muller *et al.*, 2017), but some practices such as crop diversification have also been shown to increase yields (Beillouin *et al.*, 2020). Therefore, an organic food system might require more land, which could potentially be further increased by animal welfare standards and any ban on chemical pesticides (Muller *et al.*, 2017).

Conversion to organic production implies a major change in crop rotations to include N fixing crops, and additional costs to comply with standards such as animal welfare and the avoidance of pesticides. Poux and Aubert (2018) assessed implications of a conversion to organic for the N budget of agriculture in the EU, that took into account rotation changes to compensate for the absence of N inputs from synthetic N fertilizer and the use of chemical pesticides. They estimated a net N input of 12 Tg N delivering 2.4 Tg of N in food, giving an overall NUE of 20%, which is similar to conventional agriculture.

10.5 Conclusions

With respect to achieving the ambition to reduce nitrogen (N) losses in the EU by 50%, our approach identifies different combination of interventions implemented along the food chain at similar socio-economic costs. From the 144 possible combinations of intervention options, we found that 12 combinations of different technological ambitions at farm level and dietary shifts can achieve a reduction of nitrogen waste close to 50%. Technical measures and management improvement to increase nitrogen use efficiency (NUE) in crop and animal production will be crucial in view of societal barriers and the time needed to adopt substantial diet change.

With one exception, all 12 combinations of interventions delivering a 50% reduction of N loss involve diet change. The only scenario that did not involve dietary change (O45) scored the lowest when considering all costs and benefits (Table 10.3), mainly because of high estimated implementation costs in agriculture. Diet change therefore appears to be a pre-condition for achieving a 50% reduction of nitrogen losses (i.e., nitrogen waste) in EU agriculture in accordance with the EU Farm to Fork Strategy (European Commission, 2020a), the Colombo Declaration (UNEP, 2019), and the Kunming-Montreal Global Biodiversity Framework (UNCBD 2022).

There is no single optimal virgin N input that ensures that targets are met for reduction in wasteful losses (including emissions, leaching etc.), and that the benefits of N use for society clearly exceed the cost of the associated N pollution. To establish what is optimal, policy makers and public need the best available information on the bio-physical and socio-economic implications of these options at a manageable level of complexity; but the evaluation of these implication, and the weighting of partly non-monetizable costs, depends also on political perspectives and preferences.

We have presented a semi-quantitative, simplified way to assess effects of reducing N losses by 50% ('halving nitrogen waste') for human health, ecosystem quality, cost of mitigation and societal resistance. We approximated societal preferences by assigning scores and weights to these effects, which may not necessarily reflect real preferences. Therefore, one way forward would be to organize interactive sessions with stakeholders to discuss assumptions and results to provide alternative scores and weights, but also to verify if the level of complexity is right. Such sessions should also address implications of the food-system changes for other environmental and social aspects than N, like land use, greenhouse gas emissions and water use.

Box 10.1*. Research needs in relation to teaching nitrogen reduction targets in the EU.*

- Improved estimates for the societal (economic and non-economic) costs of measures to improve food system nitrogen use efficiency (NUE) and achieve dietary shift.
- Better understanding of barriers for diet change is crucial to define optimum pathways for reaching environmental and health goals.

Reflections and perspectives

It is not surprising that this report finds that there is an urgent need to accelerate the transition to more sustainable nitrogen management and more sustainable food systems in Europe and globally. For both, the case has been made based on strong scientific evidence that has been accumulated in the last decade. Furthermore, there are signs that the voice has been heard, as the Colombo Declaration on Sustainable Nitrogen Management (UNEP, 2019), the EU Farm to Fork Strategy (European Commission, 2020a), the UN Food Systems Summit[11] held in 2021, as well as the Resolution 5/2 of the 5th UN Environment Assembly (UNEP, 2022) and most recently the Global Biodiversity Framework agreed by COP15 of the UN Convention on Biological Diversity (UNCBD, 2022), demonstrate.

The first European Nitrogen Assessment Special Report on Nitrogen and Food ('Nitrogen on the Table', Westhoek *et al.*, 2015, 2014) studied co-benefits between two major food system outcomes, i.e., health and environmental impacts; they confirmed that it is possible to make diets in industrialized countries healthier, and reduce greenhouse gas emissions and nitrogen losses at the same time. Production and consumption of livestock products—and in particular (red) meat)—continues to take a central role in the debate.

Global nitrogen losses pose a serious threat to environmental sustainability and compromise the ability of the agriculture sector to feed a growing population and the sustainability of western dietary patterns with a high intake of meat in the longer term. Population growth and economic development in high- and middle-income countries have pushed a nutrition transition with a demand for meat and foods high in salt, sugar and fats to acute levels, giving rise to an increasing trend of life-style related chronic diseases. At the same time, poverty in many low-income countries, especially those in sub-Saharan Africa and South Asia, urgently need nitrogen fertilizer to improve agricultural productivity, to ensure access to adequate nutrition and quantities of food for all. This report strengthens the scientific evidence in the worlds of nitrogen and food systems and calls for more ambitious actions to transform the current food system into a sustainable food system that supports a clean planet, moving to sustainable nitrogen management and healthy diets. To be effective and sustainable in the longer term, nitrogen management needs to be dealt with from a food system approach, with responsive governance action across policy sectors and targeting a wider set of food system actors.

- A sustainable food system is essential for achieving nutrition security and healthy diets for all, while also reducing ecological imbalances and contributing to socio-economic welfare.
- Solutions to balance nitrogen flows throughout the food system and reducing nitrogen pollution will make the food system more resilient and efficient; and will also help to provide healthy diets for all.

While nitrogen losses predominantly occur at the farm level, farmers alone are often not in the position to change their practices towards sustainable nitrogen management. More powerful players, such as large, globalized companies throughout food value chains, need to recognize their responsibility and use their influence to keep the global nitrogen cycle within its regional, continental, and planetary boundaries.

Food systems, being complex on their own, are interconnected with other societal systems. They contribute significantly to the health system, to the economic system and to the social tissue in any society. Indeed, this report finds that changes to the food system might be incentivized by policy areas outside the environment/food security domain, with significant benefits for the environment. It is therefore paramount to understand those synergies and develop coordinated pathways. Policy makers must be prepared to mobilize significant transformations in a coordinated manner to meet the interlinked challenges related to nitrogen, sustainable food systems and beyond.

[11] *https://www.un.org/en/food-systems-summit*

- Effective technologies to reduce nitrogen pollution at farm and food chain level already exist.
- Food system archetypes can guide a future policy vision of sustainable food systems.

By using currently available technologies, there is already considerable scope for improving farm level nitrogen use efficiencies (NUEs). This is particularly true for arable systems, which could reach 92%, but high NUE is also achievable for granivores (pig, poultry: 80%) and ruminant (cattle, sheep: 55-61%) meat production. Future technologies, including those in precision and digital farming, have the potential to improve NUE beyond the currently available level. Future foods, such as farmed insects, farmed seafood, microorganisms such as microalgae and fungi, and also the so-called cultured meats; have been shown to have the potential to supply valuable nutrients to human diets in a land-efficient way and with lower greenhouse gas emissions, and likely also with lower nitrogen emissions, as compared with conventional animal-source foods. New models of food production such as visionary food systems and agroecological approaches, as well as the revival of traditional successful food system 'archetypes' can serve as blueprints for sustainable food systems, if 'mixed' and adapted to the local contexts in terms of priority challenges, environmental potentials, and socio-economic setting. Sustainable food systems can vary significantly in concept, scales and technologies, but key ingredients need to be a focus on nutrition sensitive food supply, circularity and avoiding/reducing competition for land.

- Only a combination of technological measures and diet shift will allow ambitious nitrogen emission reduction targets to be reached at acceptable societal costs.
- Integration of health and environmental policies needs to be strengthened to change consumption patterns for a sustainable and healthy diet.

However, just changing the way food is supplied will not be sufficient to reach ambitious targets for nitrogen emission reductions. While comprehensive implementation of current technological solutions can achieve deep cuts in reactive nitrogen (N_r) emissions, some of the most ambitious measures come at high societal costs. Diet shifts towards high shares of plant-based proteins in combination with technological measures help to lower costs and barriers for reaching N_r reduction targets. Reducing excess intake of energy and protein, and replacing meat and dairy with plant-based protein sources, will at the same time generate benefits for public health through reduction of obesity and non-communicable diseases.

Even though the benefit of diets with low shares of animal-source foods are well established, national recommendations on diets generally do not focus on those choosing diets low in animal-source foods. Moreover, important environmental outcomes related to dietary choices including air pollution, nitrogen emissions, soil degradation and biodiversity loss are mostly neglected in current food-based dietary guidelines (FBDGs). Sustainability-minded FBDGs, giving those outcomes more attention and aiming towards sustainable food systems, can prompt engagement and actions towards a shared dietary target by all system actors, including producers, retailers, food services and, last but not least, consumers.

A key consensus identified in this report is that such a shift to sustainable food systems will require new mind-sets, responsible actions from all food system actors, and the revision of regulatory frameworks and policy support. However, the report also highlights gaps in policy mixes, where there is a void of consumption policies directed at both healthy and sustainable diets, using the instruments already available, including administrative, information, market and behavioural policies. So far, not all available policy instruments have been implemented: the focus to date has been on information campaigns, while harder policies such as taxes and subsidies, are less often used. A combination of demand-oriented instruments, e.g., by implementing informative policies together with market-based policies, promises increased effectiveness.

- Consideration of all sustainability dimensions is necessary to ensure food system transformation.
- A holistic and integrated food system needs more innovative governance frameworks.

While this report focuses on avoiding nitrogen losses and promoting healthy diets—key outcomes of sustainable food systems—it also makes clear that sustainability is based on three pillars: social (including nutrition), economy and environment. A transition towards sustainable food systems must recognize the challenges and trade-offs in all sustainability dimensions. Following the 'do no harm' principle, this transition can simultaneously alleviate the path for potential 'losers'. Food interests everybody and if not everybody is heard, the transition will fail.

Therefore, the food system Sustainability Compass needs to show direction on four universal societal sustainability goals: 1) healthy, adequate and safe diets for all; 2) a clean and healthy planet; 3) economically thriving food systems, supportive of the common good; and 4) just, ethical and equitable food systems. Within each goal, indicators need to be quantified for a number of areas of concern. Each of these indicators must be selected according to the specific context, and accompanied with quantified targets, determined in an open and transparent policy process, as the basis to assess trade-offs, monitor progress and provide accountable information.

This report also highlights that in order to achieve a sustainable food system, society needs to go beyond a view of the food system as linear and 'single focused', and to comprehend the food system as dynamic and interlinked. Meeting the challenges requires actions across the food system. Policy makers need to enable a governance structure and framework to work together across these issues.

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'Appetite for Change: Food system options for nitrogen, environment & health'

2nd European Nitrogen Assessment Special Report on Nitrogen & Food

This report assesses the main ingredients needed to navigate the transition towards agreed nitrogen sustainability targets.

Global nitrogen losses pose a serious threat to environmental sustainability and compromise the ability of the agricultural sector to feed a growing population. The first ENA Special Report 'Nitrogen on the Table' showed how encouraging more plant-based diets can promote human health and reduce nitrogen emissions. Building on these foundations, the present report 'Appetite for Change' explores pathways towards sustainable nitrogen and food choices.

This report, prepared by the Expert Panel on Nitrogen and Food of the UNECE Task Force on Reactive Nitrogen, presents the main ingredients and a suggested recipe to navigate the necessary sustainability transition towards agreed nitrogen targets. It shows that a combination of diet change towards plant-based diets and technical measures across the food chain can halve nitrogen waste. It thus sets out a path to reaching targets set in the Colombo Declaration, the EU Farm to Fork Strategy and the Kunming-Montreal Global Biodiversity Framework. Importantly, diet change can reduce pressure on land resources and mineral fertilizers, reduce energy dependency and increase resilience to food and energy crises.

'Appetite for Change' emphasizes how the nitrogen cycle, food system, environment and health are inextricably interlinked. It goes on to identify ambitious and systemic actions to transform the food system. There are great opportunities for reducing nitrogen losses from food production and consumption with co-benefits for nutrition and public health. To be sustainable in the longer term, nitrogen management needs to be based on a systems approach and requires responsive governance action across inter-connected policy sectors, engaging a wide set of food system actors.

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