Global Food Security 35 (2022) 100648

Contents lists available at ScienceDirect

Global Food Security

journal homepage: www.elsevier.com/locate/gfs

Halving nitrogen waste in the European Union food systems requires both dietary shifts and farm level actions

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ARTICLE INFO

Keywords:
Nitrogen budgets
Nitrogen use efficiency
Nitrogen losses
Dietary shift
Diet change
Food systems
Farm to fork

ABSTRACT

The pivotal role of nitrogen to achieve environmental sustainable development goals and transform our food system is recognized in an ambitious nitrogen waste reduction target in the Farm to Fork Strategy of the European Commission. But is this a realistic objective and if so, what are the pathways that lead to success? To answer these questions, we first established, as a baseline, an updated food system nitrogen budget for the EU for the year 2015. The EU used 20 Tg of virgin (new) N to deliver 2.5 Tg N in food and 1.2 Tg N in fibres to consumers, yielding a food-system nitrogen use efficiency (NUE) of 18%. We then built a simple model to combine intervention options that (a) increase farm level nitrogen use efficiencies, (b) reduce food waste increase recycling of waste and improve waste treatment, or (c) achieve a dietary shift towards healthier dietary patterns. The largest potential to increase N efficiency of the current agro-food system was found to lie in the livestock sector. From 144 possible combinations of intervention options analysed, we found that 12 combinations of interventions would reduce nitrogen losses by about 50%, 11 involving diet change. We further carried out an assessment of the societal appreciation of combinations of interventions considering private and public costs of the intervention measures, public benefit through effects on health and increased biodiversity of ecosystems, and public costs for overcoming socio-cultural barriers. Results show that a combination of moderate intervention options achieve halving of N losses at lowest societal costs. We conclude that systemic approaches are paramount to achieve deep nitrogen reduction targets and diet change appears to be an essential condition for success.

1. Introduction

Losses of various nitrogen (N) compounds to air and water have multiple impacts on both the environment and human health (De Vries, 2021), both in Europe (Leip et al., 2015) and globally (Sutton et al., 2019). Underlying cause-effect relations are complex because N emissions arise from multiple sources and include multiple mobile, reactive compounds (Nr). The 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 GDP (Van Grinsven et al., 2013), with ammonia (NH_3) and nitrate from agriculture contributing an estimated €61–215 billion, equivalent to 0.5–1.8% of the GDP (Van Grinsven, 2019). 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 global N waste (defined as the sum of all N losses to air and water) by 2030 (Colombo Declaration, UNEP, 2019).

Several policies have been implemented at the European (EU) level to reduce negative side-effects of excess N, including (i) the National Emission Ceilings Directive (European Commission, 2001) with emission targets for NH_3 and nitrogen oxides (NO_x), (ii) the Habitats

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https://doi.org/10.1016/j.gfs.2022.100648
Received 11 April 2022; Received in revised form 24 July 2022; Accepted 3 August 2022
Available online 28 September 2022

Directive (European Commission, 1992), which indirectly regulates N emissions causing N deposition, (iii) the Nitrates Directive (European Commission, 1991) and the Water Framework Directive (European Commission, 2000) with limits for use of manure N and of N concentrations in waterbodies, and (iv) the Paris Agreement (UN, 2015) with targets for reducing emissions of greenhouse gases, such as N_2O. Furthermore, the European Commission has recently addressed the overall issue of reducing N losses (waste) to air and water in the European Green Deal, notably in the Farm to Fork Strategy, FFS (European Commission, 2020a), and in the Biodiversity Strategy (European Commission, 2020b). These strategies define targets to reduce nutrient losses by at least 50% by 2030, linked to integrated nutrient management actions plans, which also should prevent deterioration of soil fertility. An expectation expressed in the strategies is that this will reduce the use of synthetic N by at least 20%. These targets in the FFS 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 in more indirect ways, amongst others by stimulating responsible supply chains, as well as by promoting healthy and sustainable diets.

The generic targets for overall reductions in N inputs and losses in the FFS are ambitions to reduce N waste but they are linked to the concept of a safe boundary that defines a 'safe operating space' for human disturbance of the N cycle, being derived first at global scale, i.e. a planetary boundary (De Vries et al., 2013; Steffen et al., 2015), and recently also at EU scale (De Vries et al., 2021; Lucas et al., 2020). De Vries et al. (2021) used the method developed by De Vries et al. (2013) to estimate boundaries for N losses and N inputs in the European Union, by aggregating spatially explicit boundaries for N losses and associated N inputs for three environmental thresholds: (i) N deposition onto natural areas to protect terrestrial biodiversity (critical N loads), (ii) N concentration in runoff to surface water (2.5 mg N L^{-1}) to protect aquatic ecosystems, and (iii) nitrate (NO_3^-) concentration in leachate to groundwater (50 mg NO_3^- L^{-1}) to meet the EU drinking water standard. Critical N losses and inputs were calculated with the spatially explicit N balance model INTEGRATOR for close to 40,000 unique soil-slope-climate combinations to capture differences in sensitivity of the receiving ecosystems. Unlike the calculation at global scale (De Vries et al., 2013), the calculation 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 this does not increase environmental risks (De Vries et al., 2021).

Results by De Vries et al. (2021) showed that the overall average required reductions in NH_3 losses and N runoff at EU level to avoid exceedance of critical limits were 38% and 50%, respectively, the latter value being equal to the target mentioned by the 'Farm to Fork' strategy. This implies that overall the FFS targets are adequate to protect the environment in the EU, but more ambitious reductions are needed in regional hot spots with N-related environmental and health impacts (Serra et al., 2019), while N can sometimes increase in areas with large yield gaps and low current N inputs (De Vries et al., 2021).

Assuming that an overall average 50% N loss reduction is sufficient to protect air and water quality in the EU, when properly allocated in space, and that increasing farm NUE alone would not protect the environment everywhere, there is a clear need for an assessment of changes necessary in the whole food chain to halve N waste. Here, we explore options to halve N waste in the EU agri-food system along three routes (i) increasing the NUE in farming systems, reducing N losses from livestock housing, manure management and soils, (ii) reducing food waste, increasing recycling of waste and improving waste treatment and (iii) reducing the N in human consumption by dietary change, with large consequences for crop and livestock production (Billen et al., 2019).

2. Methods

2.1. Building the EU N budget

We calculated N flows for the EU agri-food system around the year 2015 using best available data for EU countries. Data on mineral fertilizer input, biological nitrogen fixation, total N deposition and on processing and export of crops were available from the Gross Nitrogen Balance published by Eurostat (2020). Agricultural NH_3 and NO_x emissions were calculated as average from national GHG inventories (EEA, 2020, 3.6 Tg N yr^{-1}) and the EMEP-CEIP air pollution database (EMEP-CEIP, 2022, 2.9 Tg N yr^{-1}). Other losses of reactive nitrogen from livestock and crop systems, as well as release of N from mineralization of organic cultivated soils, were derived from the European greenhouse gas inventory (EEA, 2020). We used a recycling rate of 35% for NH_3 losses from agricultural sources that is re-deposited on agricultural land, derived from emission-deposition modelling based on EMEP-CEIP and the LOTOS-EUROS model (Manders et al., 2017; Kuenen et al., 2022). N in feed imports was obtained from EU balance sheets for the agricultural market (DG AGRI, 2020). Indirect N fertilizer use embedded in imported feed was estimated assuming a NUE of 0.5, as in Quemada et al., 2020. Input of N for agricultural production from the food processing and residue management was obtained from Corrado et al. (2020) and Caldeira et al. (2021). Dinitrogen (N_2) losses from soils and un-accounted N losses from livestock are the most uncertain N flow and calculated as a residual flow to close the balance. N flows in the food chain (here considered as food processing and distribution), as well as food waste quantities and residues management, were taken from Corrado et al. (2020) and Caldeira et al. (2021). Food intake was based on Caldeira et al. (2019) using N contents from Corrado et al. (2020). We assumed that 20% of household and food service N-supply goes to pet food based on the studies by the Flemish Food Supply Chain Platform for Food Loss (2018), according to which 45% of food waste generated in Flemish households was either composted or fed to pets. Kranert et al. (2012) estimated the fraction of uncollected food waste (including food that is home composted, disposed of via the sewer, and fed to pets) in Germany to be 24% for the households and 11% for food services. The value is also consistent with estimates of human N excretion by Corrado et al. (2020).

We calculated the N balance and NUE for the EU food system, as well as for the underlying sub-systems: crop production, livestock production, agriculture, food chain, food chain including the consumer, and waste management. For each of these sub-systems, relevant flows were classified as 'input', 'output', 'losses', and 'internal flows'. All N loss flows and their classification and data source are given in Table SM1.

2.2. Intervention options and ambitions to halve N losses in the food system

Different options for interventions to reduce Nr losses and to increase the NUE of the agri-food system in accordance with Springmann et al. (2018) were analysed, considering different levels of ambition. A description of the options is presented below and a summary is given in Table 1.

Option 1. Improve management of N in agriculture (primary production), implying a reduction of N input (Reduction N losses in **fa**rm systems, **Rfa).** This will increase the NUE in farming systems, reduce N losses from soils producing crops for food and feed, and reduce emissions from livestock housing and manure management. Hutchings et al. (2020), explored low, medium and high reduction ambitions to increase farm-level NUE, distinguishing several technical measures for a set of crop and animal systems, in northern and southern EU countries. Their results show that maximum technical NUEs of 82% and 92% can be achieved for arable systems, 71% and 80% for granivores, and 50% and 36% for ruminant meat production on marginal agricultural land for northern and southern EU, respectively. On land unconstrained by soil

Table 1
Ambition levels and targets per food sub-system intervention options, yielding 144 plausible combinations.

Level of ambition	Option 1	Option 2	Option 3		
	Reduction N loss farm system (Rfa) (Hutchings et al., 2020)	Reduction N loss food system (Rfo) (Corrado et al., 2020)	Reduction energy in diet (Ren)	Reduction protein in diet (Rpr)	Reduction animal products (Rap)
0	Baseline	Baseline	0%	0%	Default
1	Low	Intermediate	12.5%	20%	Demitarian
2	Medium	Improved	25.0%	40%	Vegetarian
3	High				Vegan

conditions or topography they found maximum technically feasible NUEs of 53% and 55% for dairy production and 46% and 62% for ruminant meat production.

Option 2. Reduction of food waste and improvement of waste treatment (Reduction of N losses in the **fo**od system, **Rfo).** This will reduce N emissions from food systems and from human excreta by improved treatment and management of these wastes; and reduce demand for agricultural production for food by reducing food waste and associated N losses, increasing reuse of N from sewage system and the valorization of co-products and waste from food processing, retail and consumption. Corrado et al. (2020) considered an "improved" scenario aimed at reducing food waste coherently with the SDG 12.3 target and a "combined" scenario that additionally recovers N from wastewater. They estimated that the combination of the effects of the interventions foreseen by the EU legislation for waste reduction and improvement of wastewater treatments may reduce Nr emissions in processing, distribution and consumption of food up to 50% while increasing N_2 emissions by 30%. Here, we considered the "improved" scenario but included also an "intermediate" scenario with less stringent emission reduction ambitions.

Option 3. Dietary change, including **R**eduction of **en**ergy **(Ren)** and **pr**otein **(Rpr) demand,** and the share of **a**nimal **p**roducts **(Rap)**. This will reduce the need of N for human consumption. For this option, three alternatives were considered:

a) to reduce overconsumption of calories by 1/3 (Ren1 - reduction of overall energy intake in food by 12.5%) and by 2/3 (Ren2 - reduction by 25%),
b) to reduce overconsumption of protein by 40% (Rpr1 - reduction of protein intake by 20%) and by 80% (Rpr2, reduction of protein intake by 40%)
c) to reduce consumption of animal products by a shift to a demitarian diet (Rap1 - halving meat consumption, substitution with 50% crops, 10% seafood, and 40% 'novel' foods including insects and plant-based analogues), vegetarian diet (Rap2 - no meat but with dairy and eggs, substitution with 50% crops and 50% dairy and eggs), and vegan diet (Rap3 - no animal products, substitution as in the demitarian diet).

The current gross intake of energy by EU citizens exceeds body energy needs by 35% (van den Bos Verma et al., 2020) and proteins needs by 70% (Westhoek et al., 2011). Options 3a and 3b aim at complying with WHO recommendations to reduce morbidity and mortality by cardio-vascular diseases, diabetes and cancer and its relation with overconsumption of energy, red meat and saturated fats and under-consumption of fibres (Westhoek et al., 2014). We assumed that N emissions from livestock operations are reduced proportionally to the changes in the consumption of animal protein.

Table 1 summarizes the different levels of ambition considered for each intervention option. A tool was built and a total of 144 combinations of options and ambition levels was analysed.

2.3. Societal appreciation of combinations of interventions

Policy decisions about how to transform the EU agro-food system with a high chance of halving N waste and with 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 this decision 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. Four aspects were considered to evaluate the options:

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** resulting from (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 fibres and (c) reduced exposure to N related air pollution, with as dominant route for the agro-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 and pollination) from (a) reduced N in deposition and runoff and (b) reduction in land requirement with decreasing share of animal products in diets.
4. The **public cost for overcoming socio-cultural barriers for adoption of alternative diets** (reducing freedom of diet choice) distinguishing diets with (a) a lower energy intake, (b) lower protein intake and (c) fewer animal products.

Here we propose such a framework of rules, simple and partially deriving from results of previous Cost Benefit Analyses, and partly on our expert judgement regarding relative societal weights and the 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 agro-food system (Muilwijk et al., 2020).

For each of the four aspects, scores were assigned by ranking the intervention options according to their level of ambition and assigning weights to aggregate the scores within and across the aspects. Scores and evaluation were based on the expert judgement of the authors. The rules used for scoring (Table 2) were as follows:

1. Implementation cost to reduce N emission (Rfa): 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. for the purchase of fertilizer or required measures to reduce emissions of NH_3 from manure.

Table 2
Scores of costs (negative sign) and benefits per ambition level (2 or 3) and effects of food subsystem interventions (9), and weights per score within each of the four domains (A), and weights for the aggregated score between these domain (B) as used for evaluation of ambitions and results of food system intervention options that can achieve a 50% reduction of N losses in the EU.

	Effect scores of intervention 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[a]	Calc[a]	1.20	−1	−1	−1
2	−1	−2	2	1	Calc[a]	Calc[a]	1.65	−2	−2	−2
3	−2			1	Calc[a]	Calc[a]	2.00			−3
Weight A	3	1	2	0.5	1	1	2	1	0	1
Weight B	1		1			1		1		

[a] Score for effect on human health and ecosystem is function of N loss. As N loss for selected intervention options 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.

2. Implementation cost of reduction of N losses from waste in food processing and retail (Rfo): score 1 for Intermediate and 2 for Improved.
3. Health benefits of energy intake reduction in diet (Ren): score 1 for reduction by 12.5% and 2 for reduction by 25%
4. The are no clear health risks of protein intake exceeding the WHO recommendation and therefore we assume no health benefits of reduction of protein intake (Rpr). For reduction of consumption of animal products (Rap) all intervention options were assigned a score of 1. Although there are net health benefits, there are also health risks when moving from current diet to demitarian, vegetarian or vegan, e.g. disease related to deficiency of iron and specific proteins and vitamins.
5. Health benefits of improved air and water quality were assumed proportional to the reduction in N loss, giving a score of 1 for all selected intervention options with a N loss reduction of 50%, and a score of 1.7 for the two intervention options with the highest N loss reduction.
6. Ecosystem benefits of N losses were also assumed proportional to the reduction in N losses but twice as sensitive as for humans; the rationale is that ecosystems cannot evade exposure and have less options for remediation. This leads to a score of 2 for all selected intervention options with a N loss reduction of 50%, and a score of 3.3 for the two intervention options with the highest N loss reduction.
7. Potential ecosystem benefits of reduced land requirement for diets with fewer animal products were calculated using a land footprint calculator: resulting scores were 1.2 for demitarian, 1.65 for vegetarian and 2.0 for vegan (https://themasites.pbl.nl/o/duurzaam-voedsel/). Effects of food waste reduction would only slightly modify these scores.
8. The scores for overcoming societal barriers to adopt demitarian, vegetarian and vegan diets were 1, 2 and 3, respectively.

For this assessment of societal acceptability of changes in the agro-food system in the intervention options, the scores on the four aspects were given equal weight, with costs assigned negative values and benefits assigned positive values. Equal weights for impacts of Nr loss for human health and ecosystems is in line with comparable societal costs for both impacts in 2008 in the EU (Van Grinsven, 2018; Van Grinsven et al., 2013). The relative weight per sub-aspect was differentiated and motivated as follows (Table 2):

1. **Implementation cost:** the weight of the score for cost in agriculture was set three times higher than in the waste sector. Although compliance costs to meet the EU waste water directive (about 50 billion euro in 2008 of which a small part is related to N, European Commission, 2010) are higher than compliance cost for N related environmental directives for agriculture (about 5 billion euro and equivalent to 2% of total production cost, European Commission, 2014), agricultural costs were given more weight as these are directly paid by farm households (<2% of total number of households), and costs for communal waste treatment are paid by all households, in general by local taxation. Of course, the weight given to cost bearers principally is subject of political or personal considerations.
2. **Health benefits:** the weight of improved health by reducing overconsumption of calories was assumed twice as high as 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 reduction of NH_3 containing aerosols (Gu et al., 2021) was given the same weight as effects of low energy diet. Although diet related mortalities in the EU (3% of total mortalities, 14 million in 2017, (Gakidou, 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 ecosystem benefits of reduced land requirement was set twice as high as that of reduced N losses. For Western Europe, the contribution of N deposition to biodiversity (expressed as Mean Species Abundance - MSA) loss in 2015 was >5 times less than by land use change (Schipper et al., 2020); however, the impact of N deposition on biodiversity in remaining natural land is much larger (as then reduction of land area no longer causes MSA loss, while fragmentation, disturbance and drought remain).
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 fewer animal products were merged.

3. Results and discussion

3.1. Nitrogen budget of the European agri-food system

We estimated that around 2015 the EU agri-food system produced 2.5 Tg N in food that was eaten by EU citizens, 1.2 Tg N in industrial crops, and 1.6 Tg N used as pet food or in bio-refineries (i.e. to produce non-food products) (Fig. 1). To achieve this, the system required 19 Tg of virgin N, and used an additional 1.0 Tg N released from soil reservoirs. An estimated 5.2 Tg N of this input came from outside the EU, half embedded in imported feed and food and the other half in N inputs needed to grow the underlying crops. The system caused a total loss of N to environment of more than 17.1 Tg N, of which 2.6 Tg N was outside of the EU. About 78% of N losses were in reactive forms (mainly NO_3^- and NH_3).

We compared a selection of N flows in our budget with those in recent publications to detect major discrepancies. When comparing, we should take into consideration that years (2004–2017) and geographical

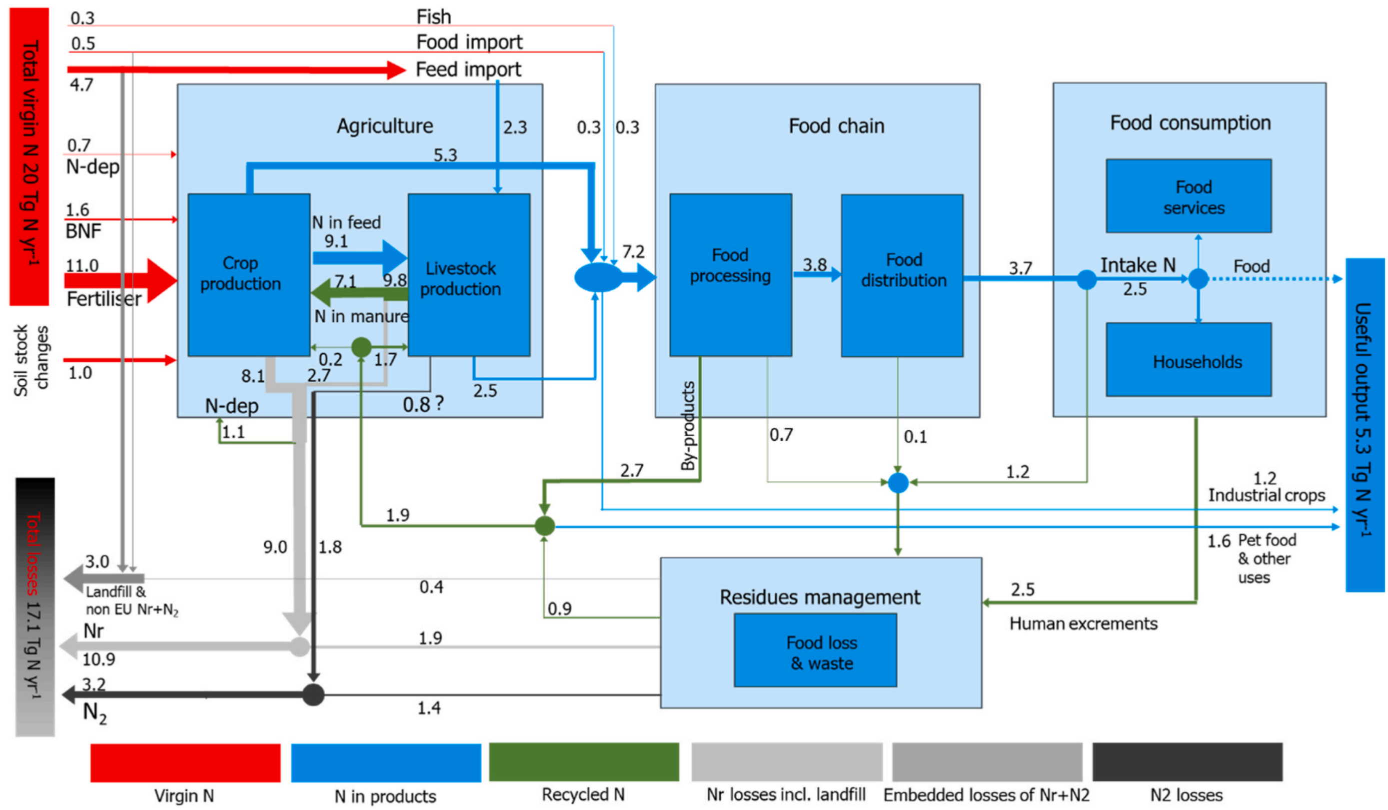

Fig. 1. Consolidated nitrogen budget for the agri-food system of the European Union in 2015 based on data from Eurostat, Corrado et al. (2020) and system definitions by Westhoek et al. (2015). See Table SI1.
Quantities are reported in Tg N yr^{-1} (BNF: biological N fixation).

coverage (EU versus Europe; total agriculture versus arable) differed between studies (Table 3). Discrepancies exceeding 25% were found for manure application, crop and fodder removal and N deposition. Discrepancies in manure application are likely due to cumulative uncertainties in estimates of excretion, gaseous losses and allocation. Discrepancies for crop and fodder removal are due to uncertainties in areas, productivities and N content in harvest. Discrepancies for N deposition on agricultural land are likely due to uncertainties and conceptual issues in the modelling of emission, transport and re-deposition of NH_3 from agricultural sources in heterogeneous landscapes. We obtain internal deposition flows of 1.1 Tg N yr^{-1} and virgin N-deposition of 0.7 Tg N yr^{-1}. The resulting share of recycled versus virgin nitrogen deposition is 60% and 40%, respectively.

3.2. Nitrogen use efficiency of the European agri-food system

Based on the food intake of 2.5 Tg N in households and food services and a total mobilization of 19 Tg N yr^{-1} (virgin N and release from soils), the NUE of the EU food system is 27% when non-food products and by-products are included. N in non-food biomass totals 2.8 Tg and includes materials for construction and textiles, tobacco, pet food, and (bio-) fuels. Accounting only for the EU agro-food system with an input of 19.9 Tg N yr^{-1}, which includes 1 Tg N yr^{-1} soil mineralization, and an output of 3.7 Tg N yr^{-1} in food and fiber, the NUE is 18%. Food consumed by humans, however, is not an 'endpoint' of the food system, since it is all excreted (assuming N retention is nearly zero) and ideally, this could be re-circulated into the production system. We assume that N for pet food and other co-products will eventually be land-filled or dispersed into the environment. However, the EU waste management system is highly inefficient, with only 19% of its input returned to production systems. This does not include the 2.7 Tg N yr^{-1} that we estimated being directly recycled from the processing industry to agriculture or other industries, for use in agriculture mainly as feed, such as cereal brans or oil crop cakes.

EU agriculture (for all uses) outputs 7.8 Tg N yr^{-1} in products and requires a virgin input of 21.0 Tg N yr^{-1}, resulting in a NUE of 37%. This efficiency is to a large degree determined by the 'mix' of crop- and livestock production that are characterized by very different efficiencies. While crop production uses 22.9 Tg N yr^{-1}, 13.4 Tg N of it being virgin N and 9.5 Tg N recycled (including manure from livestock systems), it has a NUE of 63%, which is relatively high compared to other world regions. Livestock systems require 13.1 Tg N yr^{-1} to produce 2.5 Tg N yr^{-1} in products (carcass, milk, and eggs), giving a NUE of 19%. A 2.3 Tg N yr^{-1} of feed N is imported from abroad. Livestock systems also produce 7.1 Tg N yr^{-1} in manure, corrected for an estimated 2.7 Tg N yr^{-1} losses in manure management systems, as well as 0.8 Tg N yr^{-1} unaccounted losses. Those losses might be partly caused by inconsistencies in the data used and partly they might be additional N_2 losses which are difficult to measure and for which no robust methodology exists (IPCC, 2019). If the 7.1 Tg N yr^{-1} in manure is considered a (tradable) co-product, the NUE of the EU livestock system would increase from 19% to 73%. However, even though manure should be used as efficiently as possible and be considered as a 'resource' rather as a 'waste' (Leip et al., 2019; Nowak et al., 2013), it is in rare cases an intended outcome of agricultural activities.

The 'food chain' between farm gate and food consumption takes up 7.2 Tg N yr^{-1} in agricultural commodities in our model and supplies about half of it (3.7 Tg N yr^{-1}) in food products to the consumer and 2.7 Tg N yr^{-1} as by-products, most of it recycled to agriculture, giving an overall NUE of 89%.

3.3. Effect of system boundaries on nitrogen use efficiency estimates

In our estimates of NUE, we included N losses occurring in non-EU

Table 3
The main nitrogen flows (Tg N) as reported in various studies for the past decade for the EU or Europe.

	Data year	Total reactive N input	Feed import	Excretion	Manure application to crops	Manure application	Animal products to Food	Crop on arable land removal	Crop + fodder[a] removal	Crop products to Food	Recycling by-product	N-deposition[b]	Reactive N losses
This paper (EU27)	2015	19.0	2.3	9.8		7.1	2.5	8.1	14.1	4.1	3.6	1.9	5.9
Westhoek et al. (2015); EU27	2004	17.7	2.5	9.7		8.0	2.2	7.4	11.4	2.0	1.0	3.2	6.6
Lassaletta et al. (2016); Europe, cropland	2009		2.4	10.7	3.3			9.3				1.2	6.4
Lesschen et al. (2020) EU	2017	14.8	2.5	10.1		8.3	2.2		13.8	3.8	3.0	3.2	6.3
Bouwman et al. (2017); Beusen et al. (2022); Europe	2010			11.2		10.3		9.5	16.3			3.6	9.1
Einarsson et al. (2021). EU28, cropland	2015	21.1		11.0	4.7	8.7		10.5				1.2	5.7

[a] Fodder including grassland.
[b] Total deposition, composed of 1.1 Tg N yr^{-1} recycled (NH_3) and 0.7 Tg N yr^{-1} virgin (NO_x) deposition.

Table 4
Nitrogen use efficiencies (NUE) for the agri-food system of the European Union in 2015 and underlying subsystems. 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 considers also 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 the 'correct' are marked in bold.

	NUEc	NUEv	NUEvr
Crops	63%	**63%**	66%
Livestock	19%	**16%**	73%
All agriculture (crops and livestock)	42%	**37%**	41%
Processing & distribution		35%	**84%**
Food system	21%	**18%**	27%

countries where imported food and feed is produced. In absence of detailed data, we roughly estimated it, assuming an NUE of 50%. Quemada et al. (2020) also included 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. Ignoring virgin N use outside EU, as is more common, the EU agricultural NUE increases non-negligibly from 37% to 42%. For the total food system NUE the effect is smaller, leading to an increase from 18% to 21% if only considering food, or from 27% to 31% if other uses are also considered.

This shows that despite – or maybe particularly because - NUE is a widely used and informative performance indicator for policy support, it is crucial to clearly define the boundaries applied and what is considered as 'useful outputs'. Therefore caution is needed when comparing NUEs from different studies for different systems (EU Nitrogen Expert Panel, 2015).

Table 4 illustrates the effect of using different system boundaries for the calculation of the NUE. Here, NUEc stands for the 'conventional 'NUE not accounting for embodied N losses of food and feed imports and usually regarding only the 'main' products as output, while NUEv includes 'virtual', thus embedded, losses, and NUEvr considers both embodies Nr losses and systems' co-products (residues) such as manure (livestock) or pet-food (food system). In our N budget, we have not included Nr losses from energy use. However, we do consider that losses of NH_3 from agricultural sources re-deposit on agricultural fields and contribute there as N-input.

There is no one approach to calculating NUE that fits all purposes. While we consider the accounting of embodied N losses as correct for all systems and subsystems considered, this is not the case for recycled outputs. While for agricultural (sub) systems we consider that residual flows as internal flows which should not be used to 'inflate' NUEs; the use of residues of the food system as such is a measure of efficiency and likely substitutes for other materials. However, when looking case-by-case at the products, this view might not be applicable to each of them. For example, if a by-product causes a significantly higher environmental pressure than the product is substitutes (e.g. in case of replacing mineral N fertilizer by manure), it does not seem appropriate to increase the agro-food systems' NUE. Instead, the 'correct' NUE would be calculated based on the difference of the impacts, a method that the LCA community knows as 'system expansion'. Thus, the 'correct' NUE likely lies between NUEv and NUEvr.

3.4. Intervention options reducing nitrogen waste by 50%

The 144 Intervention options delivered a range of N loss reductions between 5% and 85% (Fig. 2). From this set of intervention option results, 12 combinations (O41 to O52) were selected that yielded a reduction of N losses between 49% and 51%, thus meeting the ambition of halving N loss of the EU Farm to Fork strategy. The results for these 12 intervention options for the EU of total virgin N input, amount of

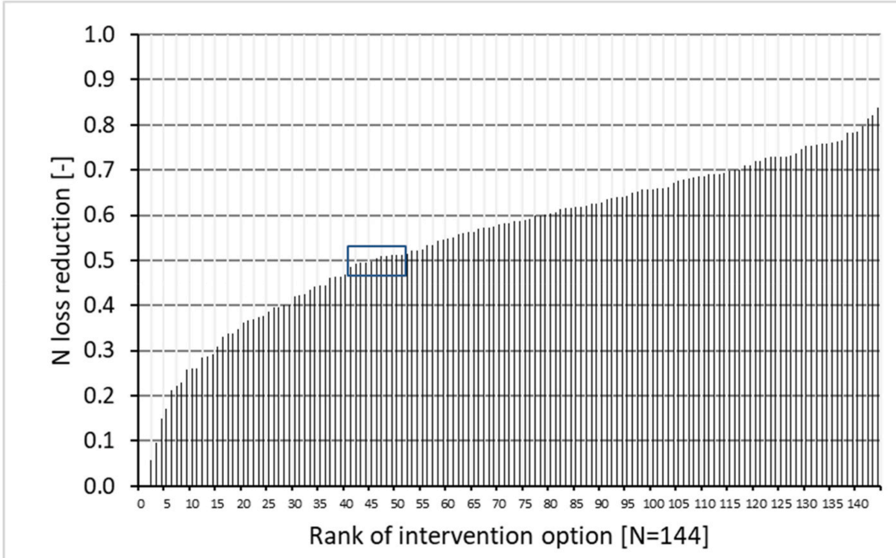

Fig. 2. Relative reduction of N losses in 144 intervention options and selection of 12 intervention options (O41–O52) with a N loss reduction between 0.49 and 0.51.

recycled N, dietary intake of N, farm gate input of N, total N losses and NUEs for food supply (agriculture) and the total agro-food system are shown in Table 5 and compared with the Baseline and the two options with the highest N loss reduction (O143 and O144). The maximum N loss reduction achievable with improved N management at farm level was 37% and with improved N waste management in food processing, retail and sewage treatment 17%.

Results show that interventions that combine moderate ambitions to increase N efficiency via agriculture production, waste management and diet, achieve halving of N losses at lower societal costs than more focused interventions. The implementation of measures to any one part of the food system alone was insufficient to halve the N loss, showing there is no single silver bullet to solve N pollution problems in the EU. There are contrasting intervention options 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 intervention options contrast regarding the focus on improvement of farm N management versus waste N management and change of diet.

Based on the expert scores and weights, intervention options O41, O43, O50 and O52 would be recommended choices for halving N losses (Table 5) and suggest that both demitarian, vegetarian and vegan diets could be feasible directions to solve the N problem. Intervention option O47, which could be labelled as the high-tech option to reduce N losses by 50% without diet change, yields the lowest overall score. The study suggests as overall strategy for the EU to achieve the 50% reduction of N losses to reduce the virgin N need for the primary production system by combining moderate ambitions for agriculture with intermediate ambitions for diet change reducing energy and protein demand to WHO recommendations, combined with reduction of Nr losses from food waste and residues management. This agrees with the conclusion of Springmann et al. (2018) 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.

The overall score of 0.5 for option O143 with a Nloss reduction of 85% is better than 7 of the options that achieve a reduction of Nloss by 50%, but would require a EU wide adoption of a vegan diet, which in the current time is not a feasible route, in absence of societal support and political will. However, it emphasizes the importance of diet change; a partial adoption of vegan diets to achieve the 50% reduction can save a lot of implementation cost.

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

The values of weights in Table 2 are now based on our experience of working on the science-policy interface, both national and for EU, and therefore to some extent arbitrary. The weights are in fact part of a political process and in the future would need to be derived from surveys among stakeholders. In spite of its simplicity and using some provisional weights of aspects in the scoring, this framework can structure and discipline policy discussions and be used to screen sketch designs of contrasting policy options to produce sufficient food with less (N) pollution. The final scoring, however, should be looked at with caution, in view of the many simplifications.

The intervention options that are needed to reduce the overall N losses (waste) of 50% require a very significant increase in the N use efficiency (NUE) to avoid significant reductions in crop yield due to lower N inputs. In this context, we only quantified the impacts of options at EU level while there is spatial variation in the required NUE increase to protect terrestrial and aquatic ecosystems while maintaining crop production. Schulte-Uebbing and de Vries (2021) quantified the necessary NUE changes in EU agriculture to attain current crop yields while simultaneously reaching EU air and water quality goals. Assuming 0.9 as the maximum plausible NUE from soil to crop, they found that in parts of the EU, it is impossible to come everywhere below the three environmental thresholds for N deposition on natural areas, N concentration in runoff to surface water and nitrate concentration in leachate without a production penalty, especially for livestock (Schulte-Uebbing and de Vries, 2021). Therefore, while reducing N losses by 50% seems an appropriate overall EU reduction target to meet environmental goals for air and/or water quality, the required reduction targets are higher in areas with a high N excess and vice versa.

4. Conclusions

A nitrogen budget for the EU agri-food system has been calculated for 2015. The EU used 20 Tg of virgin (new) N to deliver 2.5 Tg N in food and 1.2 Tg N in fibres to consumers, yielding a food-system nitrogen use efficiency (NUE) of 18%. Of the N loss of 17.1 Tg N, 2.6 Tg N are

Table 5
Evaluation of agri-food-system intervention options for the European Union that can deliver a reduction of N losses of 49-51% as compared to 2015 (baseline) and two intervention options giving the highest N loss reduction.
All N flows in TgN/yr; Nvirg = Virgin N which is new N input in farm system from conversion of N_2 to reactive N by biological and chemical N fixation; Nrecy = N reuse in food processing from food system N waste (not including manure); Nintk = N intake by consumers; Nfarm = net N output at farm gate in agricultural products; Nloss = total N loss to air and water from the food systems equal to (Nvirg – Nrecy - Nintk); NUEsup = Nfarm/Nvirg; NUEsys = Nintk/(Nvirg - Nrecy). Increased hue of blue colours for options indicates increasing ambition, increased hue of purple colours indicate magnitude of N flow but with no direct relation to cost or benefits; traffic light colours from green to red indicate the increasing social cost.

Scenario	Rfa	Rfo	Ren	Rpr	Rap	Nvirg-Tg	Nrecy-Tg	Nintk-Tg	Nfarm-Tg
Baseline	Baseline	Baseline	0.0%	0%	Default	16.0	0.7	3.0	7.4
O41	Low	Intermed.	12.5%	20%	Demitar	9.4	0.7	2.4	5.6
O42	Baseline	Improved	12.5%	20%	Vegetar	9.3	0.7	2.4	5.2
O43	Low	Baseline	12.5%	40%	Default	8.4	0.4	1.8	4.5
O44	Medium	Intermed.	12.5%	20%	Default	9.3	0.7	2.4	5.6
O45	High	Improved	0.0%	0%	Default	10.0	0.8	3.0	6.5
O46	High	Baseline	12.5%	20%	Default	9.0	0.5	2.4	5.9
O47	High	Baseline	12.5%	0%	Vegetar	9.5	0.6	2.8	7.1
O48	Medium	Intermed.	12.5%	0%	Vegetar	9.7	0.8	2.8	6.6
O49	Baseline	Improved	12.5%	20%	Demitar	9.1	0.7	2.4	5.2
O50	Low	Improved	12.5%	20%	Vegetar	9.1	0.7	2.4	5.2
O51	Baseline	Baseline	12.5%	0%	Vegan	9.5	0.6	2.8	7.1
O52	Low	Baseline	12.5%	0%	Vegan	9.5	0.6	2.8	7.1
O143	Medium	Improved	25.0%	40%	Vegan	4.5	0.5	1.8	3.9
O144	High	Improved	25.0%	40%	Vegan	4.3	0.5	1.8	3.9

Scenario	Nloss-Tg	Nloss R	NUEsup	NUEsys	Cost	HlthBen	EcosBen	Barriers	Score
Baseline	12.4	0%	46%	19%	0.0	0.0	0.0	0.0	0.0
O41	6.4	49%	59%	27%	-0.1	1.0	1.4	1.0	0.7
O42	6.3	49%	56%	27%	0.5	1.0	1.7	1.5	0.4
O43	6.2	50%	53%	22%	-0.4	0.9	0.6	0.5	0.6
O44	6.2	50%	60%	28%	1.0	0.9	0.6	0.5	0.1
O45	6.2	50%	65%	32%	2.8	0.3	0.7	0.0	-0.6
O46	6.1	50%	66%	28%	2.3	0.9	0.7	0.5	-0.3
O47	6.1	51%	74%	32%	2.3	1.0	1.8	1.5	-0.2
O48	6.1	51%	68%	32%	1.0	1.0	1.8	1.5	0.3
O49	6.0	51%	58%	28%	0.5	1.0	1.5	1.0	0.5
O50	6.0	51%	58%	28%	0.1	1.0	1.8	1.5	0.6
O51	6.0	51%	74%	32%	0.0	0.9	2.0	2.0	0.4
O52	6.0	51%	75%	32%	-0.4	0.9	2.0	2.0	0.6
O143	2.2	85%	91%	47%	1.3	1.9	2.5	2.5	0.5
O144	2.0	84%	87%	45%	2.8	2.0	2.4	2.5	0.0

occurring outside of Europe, associated with imported feed, while from the losses in the EU three quarters are reactive N pollution and one quarter is wasted by reconversion to N_2 or solid waste.

With current food choices, the livestock sector is the most N inefficient part of the food system. The largest potential to increase N efficiency of the current agro-food system therefore lies in the livestock sector, through improved breeding and feeding and improved manure management, processing and recycling, or alternative food choices. With respect to achieving the ambition to reduce 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 medium 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 NUE in crop and animal production will be crucial in view of societal barriers and the time needed to adopt drastic diet change. However, with one exception, all combination of intervention options delivering a reduction of N loss of at least 50% involve diet change which therefore appears to be a pre-condition for achieving substantial reduction of virgin N needs in EU agriculture.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

R source code calculating N reductions for the different option combinations is provided at github.

Acknowledgements

This paper constitutes an output of the Expert Panel of Nitrogen and Food of the Task Force on Reactive Nitrogen under the Working Group on Strategies and Review of the UNECE Convention on Long-range Transboundary Air Pollution. Jan Peter Lesschen acknowledges the funding of the Nutri2Cycle project from the European Union's Horizon 2020 Framework Programme for Research and Innovation under Grant Agreement no 773682. Hans van Grinsven acknowledges the International Nitrogen Management System project (INMS, http://www.inms.international/) funded by the Global Environment Facility (GEF) through the United Nations Environment Programme (UNEP). Martijn Schaap acknowledges the funding of the PINETI-IV project (FKZ 3718 63 2020) from the German Environment Agency (Umweltbundesamt – UBA). Nicholas J. Hutchings acknowledges the funding of the MELS project 'Mitigating greenhouse gas Emissions from Livestock Systems' (grant nr SUSAN/II/MELS/01/2020) within the framework of the Joint Call of ERA-NETs SusAn, FACCE ERA-GAS and ICT-AGRI 2

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.gfs.2022.100648.

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