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The Danish nitrogen footprint: balancing regulation with individual environmental responsibility

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Abstract

Anthropogenic production of reactive nitrogen (N_r) amplifies the negative impact of excess N_r on the environment, causing harm to both ecosystems and human health. N-footprint tools offer a valuable method for predicting N_r emissions, helping to identify leakage points across the entire production chain, from farm to plate. This study estimates the N-footprint of an average Danish individual based on population-based consumption patterns. The results indicate an annual N-footprint of 27.5 kg N cap^{-1} yr^{-1}. Food production and consumption account for 82% of the N-footprint, with agricultural production and consumption at 22.7 Kg N cap^{-1} yr^{-1}. Goods and services constitute 12% of the footprint (3.2 kg N cap^{-1} yr^{-1}), followed by transport at 4% (1.1 kg N cap^{-1} yr^{-1}) and housing at 2% (0.5 kg N cap^{-1} yr^{-1}). Denmark has implemented extensive environmental policies that have successfully mitigated part of the N_r load to the environment. While top–down regulatory frameworks play a crucial role, this study emphasizes the significance of individual agency in shaping consumption patterns and reducing N_r emissions. A holistic approach to N_r management is essential, integrating stringent regulations with community-driven initiatives. The study highlights three key abatement strategies for Denmark: (1) shifting Danish meat and meat derived consumption (71% of the diet) towards more plant-based alternatives, (2) improving nitrogen use efficiency at the farm gate level and (3) reducing waste and enhancing recycling throughout the entire farm-to-plate supply chain. By combining policy-driven measures with individual actions, Denmark can further mitigate the environmental impact of N_r.

1. Introduction

Sustainable development faces a significant challenge in managing reactive nitrogen (N_r) leakage, which threatens the stability of Earth's ecosystems [1, 2]. Effective communication and accurate quantification of N_r sources are essential for informed decision-making. The N-footprint serves as a communication tool that helps measure environmental N_r emissions based on individual consumption patterns. By doing so, it aids in understanding and managing nitrogen's environmental impact [3, 4].

The Haber–Bosch process, introduced in 1908, revolutionized agriculture by enabling the production of synthetic ammonia (NH_3). This breakthrough dramatically increased N_r application in crop and animal feed production [5–7]. By 2020, global N_r fertilizer production peaked at 121.5 Tg [8, 9]. While this expansion has helped meet global food demands, concerns over its environmental impact have grown since the 1950s. By the late 1990s, 85 Tg of N_r was used in agriculture, a figure that exceeded 114 Tg by 2020. By 2010, nearly 48% of the global population relied on synthetic nitrogen fertilizer for sustenance

[5–8, 10]. The increasing use of N_r fertilizers has altered the natural nitrogen cycle, rates and pathways, contributing to soil acidification, water eutrophication, reduced drinking water quality, climate issues, and biodiversity loss [11–13]. These environmental consequences underscore the urgent need for sustainable N_r management.

Governments have responded to N_r pollution with a range of political measures, including regulation (command and control), governmental spending, voluntary initiatives, and market-based instruments. Among these, regulation is the most commonly used tool in environmental policy [14]. However, while top–down regulation has produced both positive and negative outcomes, regulators face limitations, such as high enforcement costs and inflexible policies. Therefore, a multifaceted approach to sustainable development is necessary [14–16].

1.1. The Danish N-footprint

Denmark has made significant progress in reducing N_r pollution through regulatory measures. In 1983, N_r loading, defined as anthropogenic N_r added to a given spatial region, peaked at 143 kg N ha^{-1} per farmed area [17, 18]. By 2020, this figure had decreased to 91 kg N ha^{-1} [19], largely due to Denmark's political water action plans implemented since 1985 to mitigate N_r leaching into the environment [17, 20, 21]. Between 1990 and 2010, N input declined by 34%, primarily due to improved fertilizer application efficiency. This resulted in a reduction in the average N_r surplus from 170 kg N ha^{-1} to below 100 kg N ha^{-1} [18, 22].

While Danish policy has been effective in reducing N_r pollution through regulatory measures, enforcing these policies can be both costly and rigid [15, 18]. As N_r pollution becomes increasingly spatially variable, a more targeted and flexible approach is needed for continued progress [23].

Relying solely on regulation may yield diminishing returns, necessitating alternative strategies for reducing N_r pollution [16, 18, 24]. This paper advocates for a participatory decision-making approach, which empowers individuals to take action in reducing their environmental impact—an idea similarly suggested in Graversgaard [15] and Graversgaard *et al* [25].

Calculating and sharing the Danish N-footprint enables individuals to understand their environmental impact and identify personal strategies for reduction [26]. Individual choices are shaped by societal structures, which influence sustainable behaviour. Recognizing this, Danish authorities have shifted policy implementation to blend top–down governance with bottom–up knowledge generation from local communities. This approach fosters cooperation and enhances policy outcomes [15, 25, 27].

The Danish N-footprint serves as a tool to raise awareness about individual contributions to N_r emissions. Danish consumers are increasingly interested in reducing their environmental footprint [28–30]. Studies indicate a growing shift towards flexitarian diets, reflecting rising awareness of sustainability among the Danish population [28, 29]. Scoping reviews highlight the significance of dietary choices in sustainability, emphasizing the need to reduce heavy meat-based diets [31–33].

The calculation of the Danish N-footprint serves a dual purpose by providing individuals with insight into their personal contributions to nitrogen pollution while also offering policymakers valuable data on how consumption patterns influence the overall N-footprint.

This study aims to calculate the Danish N-footprint using established methodology, analysing individual contributions from four different production sectors. The results will be used to inform the public about sustainable consumption patterns. By comparing the Danish N-footprint with those of other nations, this research will contribute to the discussion on the interplay between policy, regulation, and individual environmental responsibility.

2. N-footprint methodology

The Danish N-footprint study calculates national N_r loss by analysing individual consumption patterns in food, energy, transport, goods and services, to assess potential environmental impact. Results calculated are shown in kg N per capita for each consumption group mentioned. Totals from all sectors are summed to form the national average per capita Danish N-footprint.

2.1. Study area

Denmark, with a population of 5.9 million and 2.6 million households (averaging 2.1 persons per household), is known for its flat, arable land and sandy coasts [34]. Denmark is one of Europe's most agriculturally intensive countries, with over 60% of its 42 930 km^2 dedicated to farming. Denmark's extensive agricultural activity has significantly impacted the country's aquatic environment.

Denmark is recognized for its commitment to environmental sustainability, particularly in renewable energy and organic farming. It has progressively reduced its reliance on coal for electricity, aiming to eliminate it entirely by 2024. From 33% in the early 90s, coal's share in energy production decreased to 4.3% by 2023, averaging a reduction of approximately 58% every five years. Denmark's energy mix comprises oil, natural gas, coal, and renewables, with biomass, wind power, solar energy, and biogas being the primary renewable sources [35].

Table 1. Food categories used in the Danish N footprint, as stipulated from Leach *et al* [4]. Data obtained from FAO website and protein amounts adapted from own data based on food supply data [8, 36–38].

FAO categories	Food consumed	Protein content	Nitrogen content
Animal products	$g\ Cap^{-1}\ d^{-1}$	$g\ Cap^{-1}\ d^{-1}$	$g\ Cap^{-1}\ d^{-1}$
Poultry meat	57.75	8.05	1.29
Pigmeat	53.86	6.48	1.04
Bovine meat	63.30	9.18	1.47
Milk—excluding butter	575.57	19.88	3.18
Eggs	38.03	4.79	0.77
Fish and seafood	0.03	0.01	0.002
Aquatic products, other	0.03	0.01	0.002
Animal fats	16.33	4.27	0.68
Offal's	9.66	1.86	0.30
Meat, other	5.28	1.01	0.16
Mutton & goat meat	2.04	0.39	0.06
Subtotal	821.88	55.03	8.80
FAO categories	Food consumed	Protein content	Nitrogen content
Vegetable products	$g\ Cap^{-1}\ d^{-1}$	$g\ Cap^{-1}\ d^{-1}$	$g\ Cap^{-1}\ d^{-1}$
Alcoholic beverages (barley beer)	129.28	0.006	0.001
Cereals (wheat)	171.11	19.19	3.07
Rice (milled equivalent)	9.44	24.74	3.96
Fruits—excluding wine	111.72	0.11	0.02
Pulses	2.86	1.48	0.24
Starchy roots	111.72	2.36	0.38
Stimulants	0.74	0.04	0.006
Tree nuts	0.55	0.11	0.02
Vegetables	179.52	1.16	0.03
Oil crops	0.08	0.20	3.96
Spices	4.22	24.74	0.006
Sugar & sweeteners	263.54	0.04	0.19
Vegetables oils	0.75	1.16	12.06
Subtotal	996.67	75.35	12.06
Total consumption	1819	130	62.66

The coexistence of Denmark's environmental dedication and its export-oriented agricultural sector provides an intriguing opportunity to explore methods to reduce the N-footprint from both consumer behaviour and agri-food production practices.

2.1.1. Food N-footprint methodology

The food N-footprint is divided into two categories: food production and food consumption. The calculation of the food production N-footprint of Denmark requires the calculation of N contained (N_{cont}) in the food consumed as well as N lost to the environment from agricultural production and waste, known as virtual nitrogen (VN). VN is the portion of N lost to the environment that was not embedded and consumed in the final food product. N_{cont} is the N consumed in the final foodstuff. The two N variables (N_{cont} and VN) are then used to calculate a coefficient ratio called VN factors (VNFs). VNF is the amount of N used to produce a foodstuff divided by the total amount, of N consumed in the final product as shown in equation (1) [36, 37],

$$\mathrm{VNF} = \left(\frac{\text{Virtual Nitrogen (VN)}}{\text{Nitrogen contained in consumed foodstuff } (\mathrm{N_{cont}})} \right). \tag{1}$$

Equation 1. The equation used to calculate VNF for each foodstuff adapted from Galloway *et al* [3].

The second part of the food N-footprint is the calculation of average food consumption data for the Danish population. Food consumption patterns are calculated based on food supply data from the Food and Agricultural Organization of the UN (FAO) [8]. The food categories chosen are emulated from Leach *et al* [4] and are shown in table 1. The two main parameters obtained from the FAO are grams of each foodstuff supplied per day and grams of protein contained in each foodstuff per day. The protein contained in each foodstuff was adapted to Danish equivalents [8, 38–40]. To account for variability, an 11 year average of consumption patterns is chosen for the food supply data. The food supply data used averages from 2010 till 2021. The last step in the food consumption N-footprint calculation is wastewater treatment. The total sewage treatment facility N removal efficiency is set to 60% for Denmark (see section 2.3 and supplementary material 2.2 wastewater management data) [41, 42]. As stated in Leach *et al* [4] 100% of the consumed N is assumed to be excreted, as the average human adult will not accumulate additional N in their muscle mass [43].

2.1.2. Calculation methodology for the VNFs

Danish VNFs are calculated for 27 selected food categories and 5 feed crops for animal production. The 27 food categories are chosen based on the relevance to consumption patterns and size of current production capacity in Denmark [19]. Crops chosen are solely based on crops grown in Denmark and no imports are considered, for further methodological breakdown reference supplementary material sections 1.1 and 1.2. The 27 food categories are then allocated to major food categories as described in Leach *et al* [4]. These food categories are all weighted averages based on Danish consumption patterns per capita as calculated in Leach *et al* [4] using the FAO database [8].

The food categories are: (1) fruits that consist of apples, pears, strawberry, cherries and black current; (2) vegetables that consist of leeks, lettuce, beets, sugar beets, cabbage, carrots, onion; (3) potatoes is used as the average for all root crops; (4) grains consisting of corn, winter wheat, winter barley, oats, rye and winter canola; (5) peas as the average for all legumes; (6) meat production pork, poultry, beef, fish farmed and fish wild caught (7) animal derived products milk and eggs. The animal feed crops used for calculation of meat and animal derived VNF are as follows: (1) rapeseed cake, (2) corn silage, (3) winter wheat, (4) rye, (5) winter barley, (6) grass clover silage, (7) alfalfa, (8) grass. Winter wheat, rye and winter barley are not specifically calculated for feed crop production but are reutilized from the crop production category. VNF is used to estimate the total amount of N_r lost by consuming each foodstuff. The amounts are given as total N_r lost to the environment by consuming 1 kg of dry foodstuff consumed.

2.1.3. Wastewater management data

Nitrogen removal efficiency ranges from 80%–90%, with an average denitrification rate of 50%–60%. About 20% of nitrogen is retained in sludge, and 20% is discharged. The total N_r removal rate for wastewater treatment is set at 60% for this study. These figures highlight Denmark's commitment to effective wastewater treatment and environmental protection (for more information on wastewater management in Denmark, see supplementary materials 2.2).

2.2. Goods and services methodology

The calculation methodology for goods and services is based on an environmentally extended input–output analysis (EEIO). The objective of an EEIO is to evaluate the relationship between economic activity and the downstream effects of economic activity on the environment [44, 45]. Nitrogen (N) accounting using EEIO is used in Leach *et al* [4] and in this paper the same methodology is used. The calculation of results from the EEIO analysis utilizes the database for classification of individual consumption according to purpose (COICOP). In total 40 main categories are calculated for goods and services N-footprint. Table 6 the EEIO divides the economy into main production units and estimates its environmental externalities via a monetary calculation. The EEIO analysis calculates the upstream effect of N_r pollution from consuming a set of products defined in the COICOP database for the year 2005. The objective of the EEIO analysis is to enable the calculation of hidden upstream and indirect environmental impacts associated with a downstream consumption activity. In this study, the total N_r emissions associated with the consumption of a loaf of bread as an example, from production to purchase, is calculated. The EEIO analysis assesses the entire supply chain which includes all emissions generated during production, processing, transportation, and preparation, prior to the final consumption. Utilizing the EEIO analysis, indirect upstream N_r emissions are accounted for from individual consumption patterns. The EEIO analysis is used to capture all upstream consumption N_r emissions, compared to the downstream emissions calculated in the other sections of this manuscript. Additional context can be found in supplementary section S4. For further explanation on how the EEIO is used with N-footprint calculations refer to section 2.3 Energy nitrogen footprint in Leach *et al* [4].

2.3. Transportation N-footprint

The transport component of the N footprint (i.e. the N_r released to the environment from individual transport habits) in the N-footprint calculation, uses average rates of individual or household transport consumption statistics and country-specific emission factors. This methodology involves a bottom–up calculation of the kilometres travelled, multiplied by the specific emission factor per kilometre for each transport unit (see supplementary section S5). Individual transport patterns are derived from the Danish Technical University (DTU) transport investigations. These transport habit investigations are based on yearly surveys on a representative sample of Danish citizens. The report from DTU is a transport habit investigation as shown in table 2 [46, 47].

Table 2. Breakdown of respondents detailing their daily transportational use in Denmark.

Transport	Transportational use by Danes: 2011–2014		
	Respondents	km $Pers^{-1}$ d^{-1}	min $Pers^{-1}$ d^{-1}
Passenger car	75 211	30.1	31.3
Public bus	4224	1.2	3.5
S-train	1660	0.8	1.8
Second train	1650	2.6	3
Metros	386	0.1	0.3
Telebus, flextrafik	170	0.1	0.1
Airplane	45	0.2	0.1
Ferry, harbour bus	43	0	0.1

Table 3. Energy consumption from Danish households from 1990 to 2018. The Danish N-footprint only uses latest statistics from 2019.

Final distribution of energy consumption in households from 1990 to 2018							
Energy consumption (TJ)	1990	2000	2005	2010	2015	2017	2018
Households (total)	185 039	189 270	194 721	191 563	193 252	191 437	190 971
Oil	58 998	35 444	27 617	18 595	11 105	9564	9663
Natural gas	17 877	29 329	29 993	27 761	25 495	24 797	24 284
Coal	830	49	8	28	0	0	0
Renewables	17 434	22 052	33 279	39 444	48 724	49 830	49 505
Electricity	35 696	37 335	37 802	36 717	36 855	35 510	35 228
District heating[a]	52 820	64 466	65 536	68 612	70 644	71 378	71 913
Bygas	1384	594	486	408	429	358	378

[a] District heating = Public heat supply + Public district heating installations.

2.4. Energy N-footprint

Energy consumption is calculated via a top–down methodology. The energy component of the N footprint, i.e. the N_r released to the environment from generating 1 kWh. The energy N-footprint is calculated using average kWh usage rates from household consumption. Emission factors are given in kg/NO_x/kWh and are based on Danish specific emission factors. Energy consumption data for households were taken from official Danish statistics for the year 2018 as given in table 3. In 2018, the households' climate-corrected energy consumption was 190.9 PJ and thus constituted 30.1% of the total final energy consumption in Denmark. Of the 189.1 PJ, 156.5 PJ went to heating and 32.6 PJ to electrical appliances, etc. The energy component in Denmark is calculated based on average household consumption of electricity, average household consumption of space heating (district heating, individual heating: natural gas, oil), average household usage of gas works gas (bygas) and average usage of renewable energy. Additional information on the calculation methodology is shown in supplementary material section S6.

3. Results

3.1. Danish N-footprint results

The overall N-footprint for a Danish individual is 27.5 Kg N cap^{-1} yr^{-1}. Food production accounted for 20.7 kg N cap^{-1} yr^{-1} and food consumption 1.9 kg N cap^{-1} yr^{-1}. Food consumption before correcting for sewage treatment is calculated at 3 kg N cap^{-1} yr^{-1}. The overall contribution of food production and consumption to the Danish N-footprint is 82%. The second biggest N-footprint is goods and services with 3.2 kg N cap^{-1} yr^{-1}. Goods and services contribute 12% to the total Danish N-footprint. Transport utilization by the Danish public contributes 1.1 kg N cap^{-1} yr^{-1}. The transport sector contributes 4% to the Danish N-footprint. Electricity usage calculated for household consumption is 0.5 kg N cap^{-1} yr^{-1}. Electricity usage accounts for 2% of the Danish N-footprint.

3.1.1. Food N-footprint results

Whilst the N-footprint illustrates a high N_r footprint associated with food production. Further distinctions into the categories calculated for the food N-footprint show that all meat products combined contribute 16.1 kg N cap^{-1} yr^{-1} (71% of food N-footprint). The remaining categories that fall under plant production are cereals 2.6 kg N cap^{-1} yr^{-1}, sweeteners-oils and miscellaneous 1.6 kg N cap^{-1} yr^{-1}, vegetables 0.4 kg N cap^{-1} yr^{-1}, fruits 0.04 kg N cap^{-1} yr^{-1}, and pulses 0.03 kg N cap^{-1} yr^{-1}. Plant-based food production is 29% of the N-footprint.

Results shown in table 4 illustrate the nitrogen use efficiency (NUE) calculated for the entire production chain from farm to plate for all food groups averaged. The NUE calculated are all weighted average based on consumption patterns calculated from the FAO [8]. Table 4 categorizes the least efficient production system to the highest based on national statistics. The NUE is solely based on anthropogenic N_r added and

Table 4. Results shown for the weighted average (consumption) for major foodstuffs NUE for anthropogenic N_r calculated from farm to plate production (full chain NUE %).

Foodstuffs calculated	Full chain NUE %
Meat derived production[a]	19%
Fish production[b]	16%
All meat groups—combined[c]	20%
Meat production[d]	15%
Vegetable production	49%
Root production	69%
Cereal production	110%
Fruit production	464%

[a] Meat derived production: the weighted average from milk and egg production NUE.
[b] Fish production: the production chain NUE % is only based on farmed fish averages. No weighted average applied.
[c] All meat groups—combined: the weighted average from all meat categories production NUE.
[d] Meat production: the weighted average from Beef, Broiler and Pork production NUE.

does not n account for N_r from biological reserves. The NUE calculated gives a baseline for the anthropogenic N_r utilization efficiency. These NUE are higher than what is generally calculated due to only calculating anthropogenic N_r application to farmed area, see supplementary section 1.1 [48, 49].

3.1.2. VNFs results

The food N-footprint results can be subdivided into two main criteria, the NUE, and recycling factors that influence VNF results. Calculating the VNF of Danish food production and consumption, a range of possible VNF is calculated (see table 5). The range calculated indicates a spectrum of potential NUE based on individual farming practices employed and recycling of waste in the production chain. VNF includes the whole processing chain from farm to plate, so the data encapsulates processing waste, recycling factors and distribution waste. The VNF ranges calculated in table 5 are used to infer the expected range of N_r leakage to the environment from the entire production chain from farm to plate. When calculating the N-footprint from consumption, the weighted averages of main food groups are used.

Table 5 compares each foodstuff's contribution to N_r leaked into the environment. Table 5 indicates a range of N_r released into the environment based on consumption of 1 Kg of dry matter food consumed. These results are given in terms of the average calculated for each foodstuff, minimum (most efficient production) and maximum (least efficient production). Supplementary section 1.4 describes the variance calculated in table 5. The VNF obtained for lettuce production has double the VNF (17.4) compared to beef (8.1); however, beef production contributes 257.5 g N Kg^{-1} dry matter consumed compared to lettuces 143.4 g N Kg^{-1} dry matter consumed. The VNF can be conceptualized for lettuce as every 1 g of N consumed in lettuce, 17.1 g of N is lost to the environment from farm to plate.

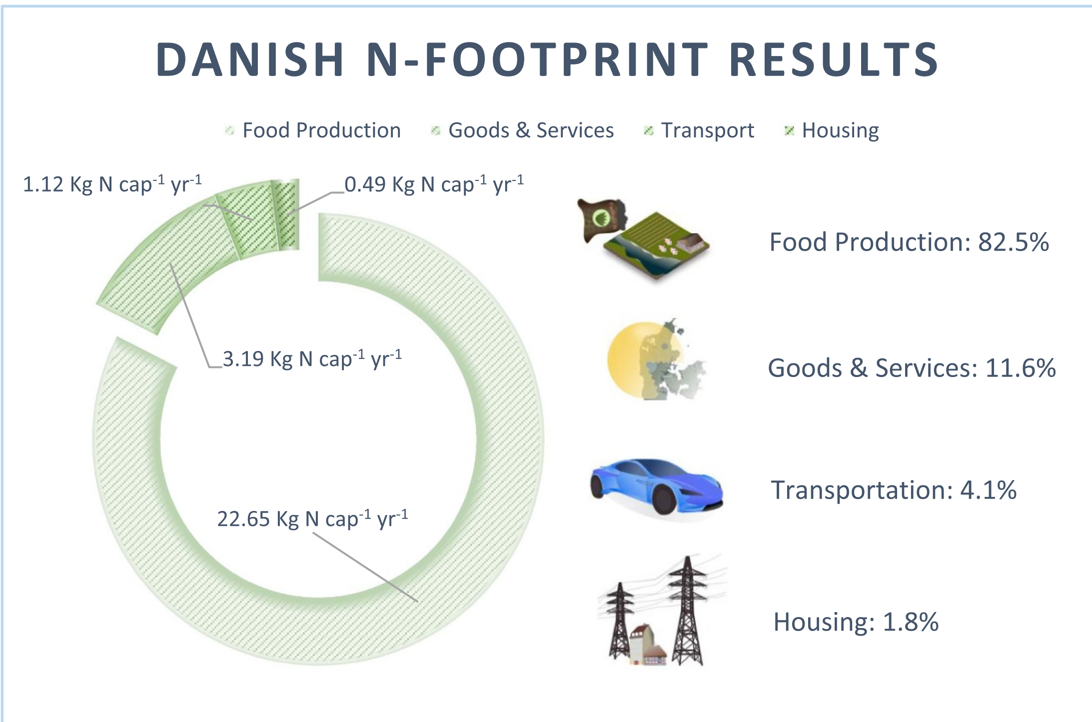

Figure 1. Visualization of the calculated Danish N-footprint results.

Table 5. The total range calculated for all food stuffs potential for N_r released to the environment. Values indicate the virtual nitrogen factors (VNF) which is used to calculate the amount of Nr released to the environment for every 1 kg dry matter consumed.

Virtual nitrogen factors (VNF) + grams N lost per kilogram food consumed						
	Average		Minimum		Maximum	
Meat production	VNF	Grams N lost	VNF	Grams N lost	VNF	Grams N lost
Pork	3.1	93	2.8	82	4.4	131
Poultry	3.3	110	2.9		7.4	245
Beef	8.1	258	−1.0	−33	12.9	413
Meat—average	5.0	158	1.4	45	8.5	271
Fish—farmed	6.3	193	6.3	193	6.3	193
Fish—wild	0.2	8	0.2	8	0.2	8
Fish—average	2.1	65	2.1	65	2.1	65
Animal derived products						
Milk	5.4	228	5.3	222	7.3	305
Eggs	3.0	60	2.7	53	7.4	148
Animal derived—average	5.3	217	5.1	211	7.3	296
Fruits						
Apples	0.1	0.4	−1.5	−6	2.6	10
Pears	2.6	8	1.9	6	2.5	8
Strawberry	5.5	60	7.0	76	10.5	116
Cherries	2.6	39	1.4	22	2.2	34
Black current	3.9	81	1.7	36	6.0	125
Fruits—average	3.1	18	2.5	15	5.8	35
Vegetables						
Leeks	3.3	33	1.4	14	9.1	90
Lettuce	17.4	143	13.2	109	18.6	154
Beets	1.5	23	1.2	19	2.0	29
Sugar beets	0.8	7	0.6	6	1.2	12
Cabbage	1.9	39	1.5	30	7.2	144
Carrots	2.2	21	2.6	24	1.7	16
Onion	2.0	26	0.9	12	2.7	35
Vegetables—average	2.4	29	1.9	23	3.7	45
Root crops						
Potatoes—root crop average	1.9	29	1.3	20	2.2	35
Grains						
Corn	1.1	17	1.1	16	1.2	18
Winter wheat	1.0	19	0.9	17	1.6	30
Winter barley	1.2	21	0.9	16	1.4	26
Oats	1.0	16	0.8	13	1.5	24
Rye	1.1	17	0.9	13	1.6	25
Winter canola	1.5	47	1.3	39	2.0	62
Grains—average	1.0	17	0.9	15	1.6	27
Legumes						
Peas	0.3	12	0.3	12	0.3	12

3.2. Goods and services results

The results for goods and services contribute 3.2 kg N cap^{-1} yr^{-1} to the total N-footprint. As seen with the section on food production table 6, when the EEIO is calculated, the consumption of food contributes the largest to the goods and services N-footprint total. Comparatively, the upstream effect on the environment of food consumption is 4 times bigger than any other sector in Denmark.

3.3. Transport results

The transport N-footprint is the third largest contributing sector with 1.12 kg N cap^{-1} yr^{-1} (figure 1). The calculation methodology is based on compartmentalizing all transport taken by an average Danish

Table 6. Breakdown of results from the EEIO using the classification of individual consumption according to purpose (COICOP) database for goods and services N-footprint. Kg N-footprint is given in Kg N cap^{-1} yr^{-1}.

Results for goods and services: N-footprint		
Classification of individual consumption according to purpose	kg N-footprint	% of total
Food	0.46	0.14
Non-alcoholic beverages	0.051	0.02
Alcoholic beverages	0.082	0.03
Tobacco	0.094	0.03
Clothing	0.087	0.03
Footwear	0.012	0.004
Actual rentals for households	0.065	0.02
Imputed rentals for households	0.17	0.05
Maintenance & repair of the dwelling	0.038	0.01
Water supply & miscellaneous dwelling services	0.0034	0.001
Electricity, gas & other fuels	1.50	0.47
Furniture, furnishings, carpets etc	0.0034	0.001
Household textiles	0.0041	0.001
Household appliances	0.068	0.02
Glassware, tableware & household utensils	0.0043	0.001
Tools and equipment for house & garden	0.0041	0.001
Goods & services for household maintenance	0.0045	0.001
Medical products, appliances and equipment	0.0030	0.001
Out-patient services	0.0060	0.002
Hospital services	0.0053	0.002
Purchase of vehicles	0.016	0.01
Operation of personal transport equipment	0.053	0.02
Transport services	0.021	0.01
Postal services	0.0019	0.001
Telephone & telefax equipment	0.000 77	0.0002
Telephone & telefax services	0.029	0.01
Audio-visual, photo & info processing equipment	0.047	0.01
Other major durables for recreation & culture	0.020	0.01
Other recreational equipment etc	0.061	0.02
Recreational & cultural services	0.027	0.01
Newspapers, books & stationery	0.014	0.004
Education	0.0077	0.002
Catering services	0.040	0.01
Accommodation services	0.0063	0.002
Personal Care	0.017	0.01
Personal effects n.e.c.	0.047	0.01
Social protection	0.016	0.01
Insurance	0.039	0.01
Financial services n.e.c.	0.054	0.02
Other services n.e.c.	0.0081	0.003
N-footprint—total	3.19	

individual in one week and scaling it to a yearly average. The biggest contribution to the transport N-footprint is diesel vehicles. Driving a diesel vehicle has a threefold increase in emissions of N_r compared to other petroleum-based fuels. Figure 2: Results for the individual use of transportation needs in Denmark and the corresponding transport N-footprint indicate the biggest contributing N_r emission calculated for the transport N-footprint.

3.4. Energy results

The results of an individual's household energy consumption N-footprint calculated for the year 2018 is summarized in figure 3. The total household energy consumption is 0.49 kg N cap^{-1} yr^{-1}. Public heating has the largest N-footprint that constitutes 27% of the household N-footprint. Public heating consumes 30% of the total power used by households. When comparing emission factors, public heating has the third lowest emission factor compared to all other energy sectors' consumption. Compared to other countries' energy footprints shown in figure 4 Denmark has the second lowest household energy N-footprint. For a more detailed breakdown of household energy consumption calculations, please refer to the supplementary section S6. Solar panels have no emission factor based on Danish norms (see supplementary section S6).

3.5. Comparing N-footprint results

N-footprint comparisons from different countries is a good method to benchmark the Danish N-footprint.

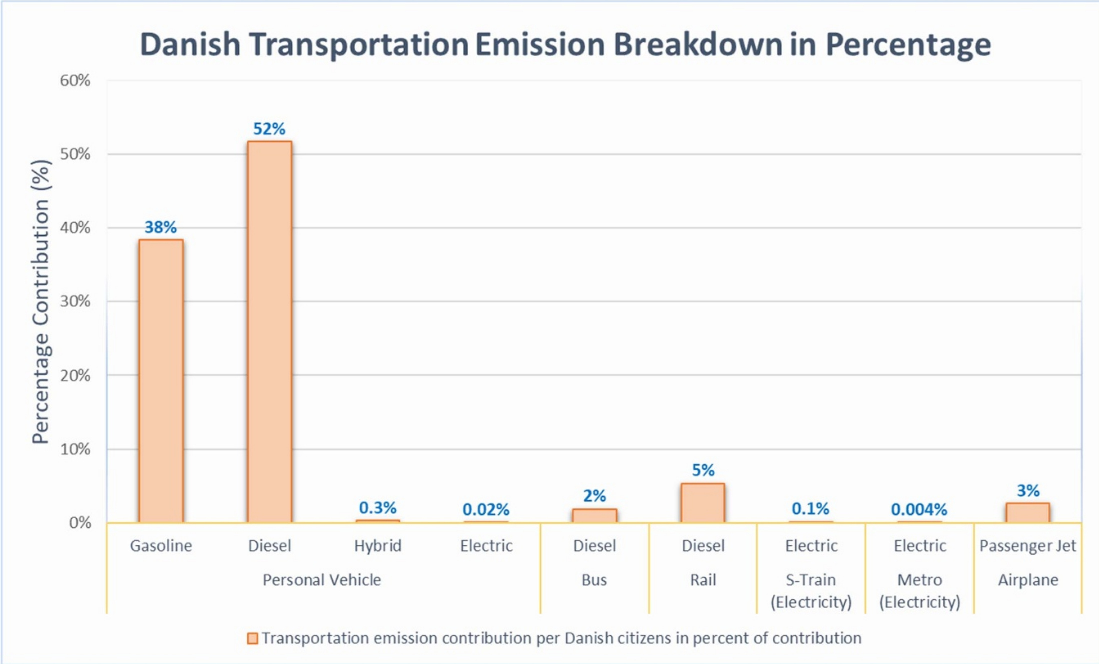

Figure 2. Results for the individual use of transportational needs in Denmark and the corresponding transport N-footprint.

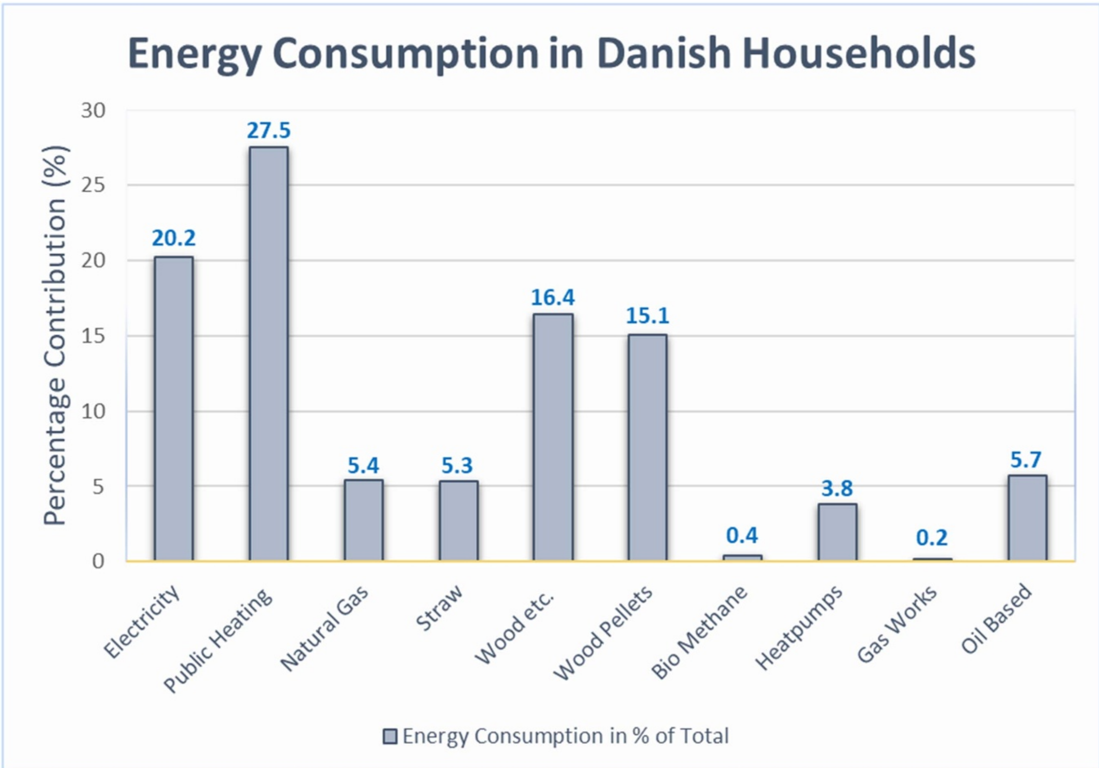

Figure 3. Results for the energy consumption of households in Denmark. Breakdown of the energy calculation for Denmark in 2019.

Table 7 summarizes the VNF that is calculated for the main food groups across the N-footprints calculated. Totals Illustrated in table 7 place the Danish VNF average, at the 3rd lowest of countries calculated. Interpretation of VNF, indicate that the lower the VNF value the higher the NUE from farm-to-plate will be. Comparing the data available, Denmark has the fourth highest N-footprint (figure 4). This indicates that improved agricultural NUE does not lower the N-footprint sufficiently

Table 7. Comparison between countries that calculated their VNF for food production. Countries are listed from highest to lowest averages. Values are listed as virtual nitrogen factors (VNF).

Countries	Cereals	Legumes	Vegetables	Tubers	Fruits	Pig	Beef	Poultry	Eggs	Milk	Seafood	Avg
Japan	3.3	2.8	4.6	6.1	4.6	12.9	27.3	10.7	10.7	3.9	1.7	8.1
China	1.1	2.5	7.7	15.9	19.0	7.9	5.2	5.7	7.2	7.0	4.1	7.6
Australia	1.8	1.2	8.0	4.9	9.4	5.5	16.3	4.8	4.0	4.6	2.4	5.7
Ukraine	0.7	0.5	0.7	2.1	0.5	14.8	23.6	4.4	3.3	4.2	—	5.5
USA	1.4	0.5	9.6	1.5	9.6	4.4	7.9	3.2	3.2	4.3	4.1	4.5
Portugal	1.3	0.5	8.2	1.1	8.2	4.4	7.9	3.2	4.4	3.9	2.9	4.2
UK	1.3	0.5	8.2	1.1	8.2	3.2	7.9	3.2	3.2	3.9	2.9	4.0
Indonesia	0.8	9.2	5.4	1.7	3.9	2.7	2.7	2.7	2.7	4.8	3.6	3.7
Tanzania	6.3	0.3	4.1	1.8	4.1	3.3	7.0	0.8	0.5	8.3	0.2	3.3
Denmark	1.0	0.3	3.0	2.0	3.5	3.1	7.0	3.3	3.0	5.4	3.3	3.2
Austria	1.2	0.4	4.3	2.0	4.3	3.6	5.4	2.5	2.5	3.7	—	3.0
India	1.7	2.1	2.3	0.4	2.7	2.9	5.9	2.9	2.4	5.4	—	2.9

enough to offset high consumption patterns in Denmark.

4. Discussion

4.1. Nitrogen footprint in food production: identifying leakage points from farm to plate

Food production and consumption contribute the biggest percentage to an individual's N-footprint. Reducing the individuals N-footprint lies in identifying the N_r leakage points from farm to plate. Leakage points for N_r calculated for food production indicate a range of variances found with different production methods table 5. When calculating crop variance with regard to N_r; input, crop type chosen, and biomass yield are the biggest contributors to the plant-based food N-footprint. When comparing weighted NUE in crop production, table 4 summarizes all major food groups and their NUE for the entire production chain. All foodstuff groups Leach N_r into the environment due to factors such as the timing of application, unharvested biomass, processing waste, distribution, and food waste. Each of these stages contributes a percentage of N_r that ends up in the environment, as illustrated by the VNF numbers attributed to various foodstuffs. Additional is the fact that this average is calculated via a weighted consumption average, meaning food groups contribution to the N-footprint is based on actual N consumption and not the total dry weight of food produced in Denmark. Consuming more plant-based foods is more environmentally friendlier and amounts to improved full chain NUE. Switching from a meat-heavy diet to a plant-based one will drastically decrease your nitrogen footprint, as calculated based on the amount of nitrogen associated with each food group you consume see supplementary section S1, table 1.

The largest contribution to the meat section variance is based on different feed crops used, recycling of waste and different production systems with varying input to output N_r ratios (NUE). The ranges calculated for all N_r meat and meat derivative production can vary greatly. The variances in N_r (table 5) are based on using different farming inputs to output practices and calculating best case scenarios (minimum VNF) and worst case scenarios (maximum VNF). An example for the minimum scenario in table 5, is using optimal feed crop composition, best case scenario NUE, and most productive farming system to calculate the minimum VNF. The opposite criteria are then used for the maximum scenario, as shown in table 5. Because of the set calculation methodology used, the range and average values of possible N_r leakage into the environment is an indication of the possible size of N_r leakage into the environment. Implying that values calculated indicate more accurately which production sector contributes more to N_r leakage than the other. The best strategy for a consumer to reduce their nitrogen footprint is to substitute food groups with low NUE (high VNF) with those that have high NUE (low VNF). This allows consumers to self-select their preferred food substitutes based on their own preferences to minimize their individual N-footprint.

4.2. Strategies for reducing nitrogen footprint—processing waste

Processing waste's biggest contribution to the N-footprint is the initial input of N_r crop uptake factor, and the amount recycling waste is reincorporated into the farming production this improves the NUE from farm to plate. Production efficiencies on farms and recycling throughout the entire process chain are the two main forms of abatement strategies. Policy incentives to advocate improved NUE strategies and waste reduction would decrease the N-footprint most. From a consumer perspective, switching from meat-heavy diets to plant-based diets decreases the N-footprint considerably. Dependent on the food item substitution between meat and cereals, meat can increase the food N-footprint by between 3 and 9 times compared to cereal consumption. These results emulate studies done in the Nordic and Baltic regions and other N-footprint results as shown in table 7 and figure 4 [50]. The lowest hanging fruit to reduce crop production's N-footprint would

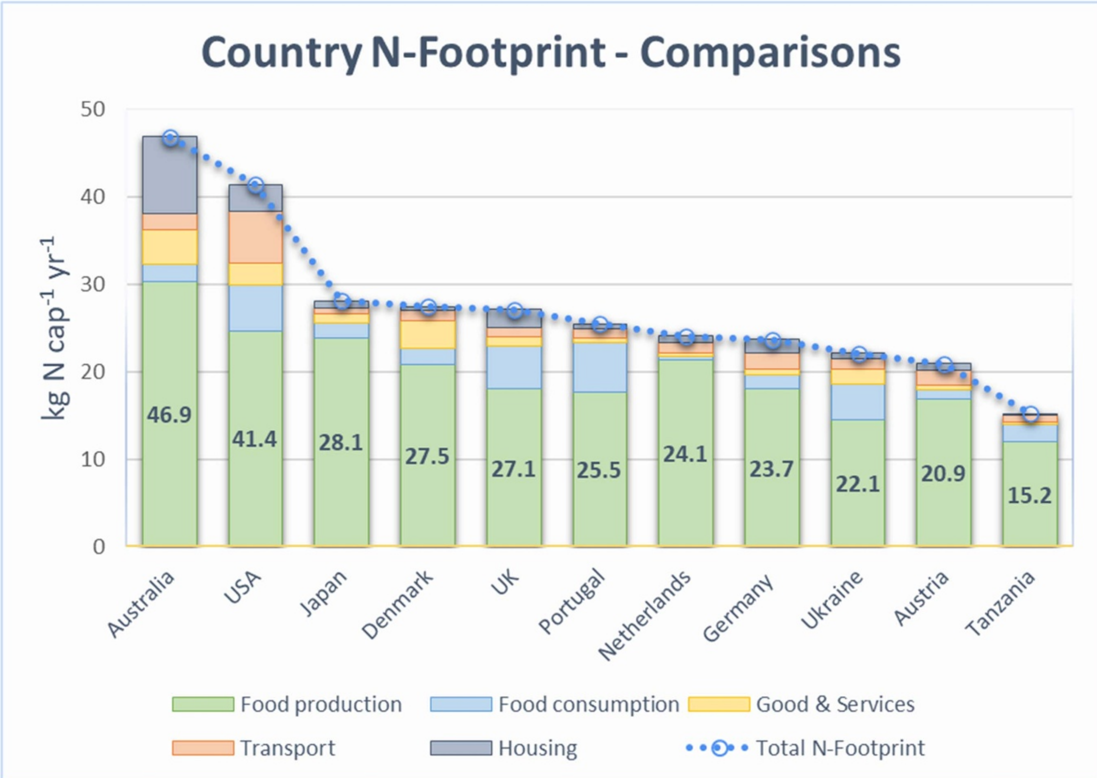

Figure 4. Comparison of country N-footprints calculated. Grouped from highest N-footprint to lowest.

be to reduce waste in the distribution and food waste chain. In this study it was found that waste generated on farm through packaging, distribution and household waste could be as high as 42%–49% of product lost between fruits, vegetables and cereals. Food waste highlights the importance of reducing these losses or incorporating them back into the nutrient cycle. Improving NUE for plant uptake is another abatement strategy, however, more challenging to achieve.

The meat NUE, N_r recycled back into the nutrient loop either via nutrient or energy production, reduced the meat N-footprint considerably. Danish food production waste has three main final processing stages: biogas production, incineration for heat and energy production and biodiesel production [51–53]. These measures to reutilize waste in the form of nutrients, energy or heat had the potential to decrease, for example, the beef N-footprint by 30%. Protein density is also contributing to the effectiveness of recycling. When meat derived waste is recycled you achieve higher NUE based on higher protein density to mass ratio. Top–down regulation to facilitate improved waste utilization of crop and meat production is possible. However, in the short term if consumers are aware of food group substitutes and reduced waste from retail and household consumption large gains could be made in the relatively short term.

Results calculated for Denmark's food N-footprint highlight possible abatement strategies that are aligned with consumer interests. Danish consumption of meat products is high, with 71% of the food N-footprint coming from meat and meat derived products. Combining higher production efficiency and waste reduction with high meat (all meat products) intake places Denmark's N-footprint around the average for country N-footprints calculated (figure 4). The average calculated for the Danish VNF (table 7) is comparatively low, indicating higher NUE and waste reduction. Improving NUE and recycling of waste allows the Danish public to reduce their N-footprint even without changing their diet. However, with a high protein diet, gains made with NUE (low VNF) and waste reduction are negated. The objective with the food N-footprint would be to help Danish consumers substitute some of their meals for improved NUE meals. The N-footprint tool quantifies an individual's footprint based on consumption patterns. Enabling everyone to find diverse options to reduce their N-footprint based on their individual needs and objectives.

Analysing the food production sector, two main drivers of footprint size come to the forefront: NUE and waste recycling. Policy incentives to improve production efficiencies and waste reduction would influence the N-footprint most. The N-footprint tool uses national statistics that indicate leakages from the entire production chain. These hot spots for N_r leakage highlight areas for further investigation and abatement strategies.

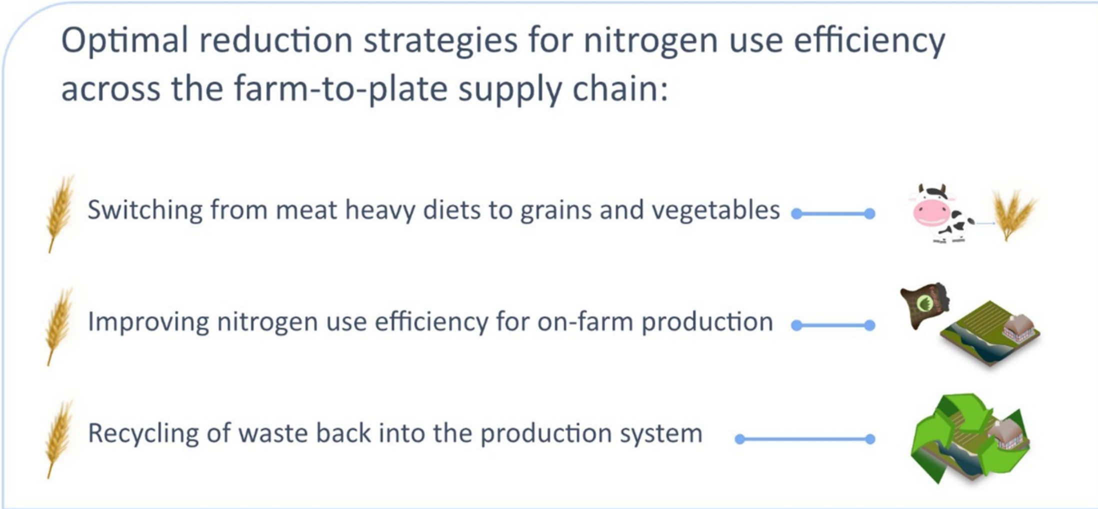

Figure 5. A conceptual diagram of optimal strategies for enhancing NUE to maximize reduction in the Danish N-footprint.

4.3. Transport, energy, goods and services

Comparing N-footprint results from transport and housing (energy) these categories rely less on individual abatement decisions, as they are influenced by the national energy grid's energy mix. While consumers may have limited immediate control over the grid, they can adjust their daily consumption patterns. For instance, transitioning from fossil fuel-based combustion engines to electric vehicles can significantly reduce individual footprints per kilometre driven. Denmark has witnessed a notable shift towards electric car purchases per year, with a remarkable increase from 15 purchased in 2011 to 33 872 in 2023, resulting in a 4.9 times reduction in per kilometre N-footprint. Notably, gasoline and diesel car purchases have declined by 5% and 14%, respectively, while electric car purchases have surged by 204% from a 12 year average [19]. Denmark had a very low energy N-footprint compared to other countries figure 4. This can contribute to the low heating value calculated for households. This indicates that improving household heating efficiencies had a marketable effect on reducing the N-footprint.

Reviewing the goods and services sector, the food industry has a potential magnitude of 4 times the footprint compared to other services. Interestingly, the calculated upstream N_r emissions, food is the largest contributor compared to all other categories calculated. This indicates the importance of reducing food waste from a consumer perspective and a need to improve efficiency from the distribution chain.

Shifting consumption patterns offer individuals the opportunity to lower their N-footprint by opting for more environmentally friendly alternatives. While the N-footprint tool measures total N_r emissions without specifying N species or their sources [54, 55], it serves as an indicator for consumers to gauge the environmental impact of their consumption choice. The objective of this research is to develop a tool enabling consumers to benchmark their consumption patterns and estimate their N-footprint, thereby fostering awareness of environmentally impactful behaviours. In conclusion, figure 5 highlights the top three strategies for improving NUE across the farm-to-plate model. These strategies are expected to have the greatest impact on reducing Denmark's N-footprint. The first strategy emphasizes educating individuals on how their dietary choices affect their personal N-footprint. The remaining recommendations focus on policy-driven initiatives, providing more actionable solutions for broader systemic change.

Looking ahead, several key additions are necessary to enhance this N-footprint analysis. This study does not directly account for the impact of import and export of N_r, which is crucial for understanding Denmark's role in the global nitrogen cycle. Moreover, different species of nitrogen and their respective ratios are not considered at leakage points, making it difficult to fully grasp the nitrogen cascade effect without precise concentration data. To build upon this foundational work, future analyses of the Danish N-footprint should incorporate these aspects for a more comprehensive assessment.

5. Conclusion

The objective with the Danish N-footprint calculation was to estimate a national consumption level N-footprint for Denmark. The calculation of the baseline N-footprint enables the compartmentalization of each sector. These sectors: Food production, Food consumption, Good and services, Transport and Energy can then be used for scenario planning an individual's consumption patterns. This study aligns with the N-PRINT initiative's mission, as stated by

Leach *et al* [4]. Its data will be incorporated into the N-PRINT tools on n-print.org upon update, enabling individuals to calculate their N-footprint based on their own consumption patterns [56]. As stated, the absolute values will always be contested, as each footprint contains specific geographical and spatial real-world data, and uncertainties are inevitable. The goal then should be to view this tool as a comparison tool for individuals to create a baseline consumption pattern based on their own preferences. This enables the individual through voluntary action to make an impact assessment based on their own individual consumption choices. When the N-footprint is scaled to a national level it indicates two main areas for policy implementation: (1) improved production efficiency and (2) food waste reduction. Combining the top–down (policy implementation) and bottom–up (voluntary action) scenarios, alignment of a common goal could be achieved and capture low hanging fruits in the process.

Data availability statement

The data cannot be made publicly available upon publication because no suitable repository exists for hosting data in this field of study. The data that support the findings of this study are available upon reasonable request from the authors.

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Ethical statement

There are no ethical concerns regarding this data analysis or research.

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