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Calculation of a food consumption nitrogen footprint for Germany

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Abstract

Reactive nitrogen (N_r) that is released to the environment has several negative implications for the atmosphere, hydrosphere, biodiversity and human health. A nitrogen (N) footprint is a measure that can help to assess and communicate the impact of personal lifestyle and consumption choices regarding their influences on N_r losses. The N-Calculator tool was developed to estimate this footprint. However, underlying loss factors for the food sector in the N-Calculator rely on data from the US, for which the calculator was originally established. Since the conditions in agriculture and the food industry differ significantly between the US and other countries, and the fact that the food sector is considered the main source of N_r losses in the N-Calculator, a revision of the N-Calculator is required if applied to other countries. Here we present a revised N-Calculator for Germany that is based on German food production data. In this study, virtual nitrogen factors describe the losses of nitrogen in a supply chain. Losses were calculated for 20 plant-based products, 17 feed materials, 18 compound feeds and 14 animal-based products. The N footprint varies considerably between products. While plant-based products amount to a weighted average of 3.4 g N loss per kg product, animal-based products cause significantly higher losses with 40.5 g N loss per kg. Overall, the average N footprint for the German consumer is calculated to be at 9.94 kg per capita and year. To validate the results, the individual categories were scaled up to the national level and then compared with statistical data on N flows in Germany. In general, the results showed good agreement with key production figures and the overall N budget for Germany. Furthermore, some improvements are proposed to increase the informative value and user acceptance of an N-Calculator.

1. Introduction

The release of reactive nitrogen (N_r) compounds into the environment causes considerable pollution of the atmosphere, hydrosphere, biodiversity and human health (Galloway *et al* 2003, Erisman *et al* 2013). By far the largest part of the reactive nitrogen species (NH_3, N_2O, NO_x and NO_3) emissions is attributable to the food sector (Galloway and Cowling 2002, Fowler *et al* 2013, Galloway *et al* 2014), with energy production, transportation, and consumption of goods and services taking lesser parts.

With the invention of the large-scale ammonia synthesis (Haber-Bosch process) in 1913, humankind has strongly influenced the global nitrogen budget (Galloway and Cowling 2002). In Germany, most of the synthesized NH_3 is used for the production of mineral fertilizer, which is used in the agricultural production of food and feed (Bach *et al* 2020). The cultivation of crops and the livestock production are open biochemical systems that are therefore inevitably associated with losses of N_r in different magnitudes.

Following the First Nitrogen Report 2017 of the Federal Government (BMU 2017), the national

'Action Program for Integrated Nitrogen Reduction' was initiated, which provides concrete measures and instruments to achieve a substantial reduction in N_r emissions in Germany. Furthermore, the Nitrogen Report 2017 states that the public must be informed about the consequences of excessive nitrogen emissions and must be motivated to take action individually to reduce nitrogen (BMU 2017).

A noticeable reduction of N_r emissions also requires changes in consumer behavior (Leach *et al* 2012, Galloway *et al* 2014). The N footprint provides a measure of N_r lost to the environment with individual consumption choices (Leach *et al* 2012). As such, the nitrogen footprint gives interested individuals the possibility of estimating the quantity of the N_r emissions that are connected with their respective consumer behavior. Besides the food sector, the nitrogen footprint also needs to consider N losses in the areas of housing, transportation, goods and services. Consequently, Leach *et al* (2012) developed a tool for calculating the personal nitrogen footprint, the so-called N-Calculator (www.n-print.org/). The central parameter of calculating N losses with the N-Calculator is the virtual nitrogen factor (VNF). The VNF concept was first developed by Leach *et al* (2012) and implemented with country-specific information for the US.

Leach *et al* (2011, 2012) define the VNF as 'the units of N_r released to the environment per unit of N_r consumed', i.e. the relation of N release (the N loss) to the amount of N in the final product. When using the N-Calculator, however, the consumer estimates the amounts of their food consumption, which is then transferred to g N losses per g product via the per product N footprint, which is the N loss occurring through consumption of 1 kg of a product. A number of national N footprint studies have been conducted so far, for example for the countries China (Gu *et al* 2013, Guo *et al* 2017), Tanzania (Hutton *et al* 2017), the European Union (Leip *et al* 2014), Japan (Shibata *et al* 2014, Shindo and Yanagawa 2017), the United Kingdom (Stevens *et al* 2014) and Austria (Pierer *et al* 2014). The comprehensive overview by Leip and Uwizeye (2019) reviews N footprint concepts in the context of life cycle analysis and nitrogen budgets and couple it with the quantification of emissions of reactive nitrogen.

From 2012 to 2020, an Adobe Flash-based version of the N-Calculator was also available for Germany. This German version was developed in cooperation with the German Environment Agency and the University of Virginia (USA). A new Flash-free version of the Tool is available as a beta-version at http://calc.nprint.org, but is currently only offered for the US. The German Environment Agency is planning to make a new German N footprint available for the public in the near future. In the previously available version, only the sectors housing, transportation, goods and services were based on statistical data directly available for Germany. The VNF and resulting N losses in food consumption and production were taken from the US study and thus related to the US-american agricultural system and food production. Since the production conditions in agriculture and the food industry differ significantly between countries, using other countries VNF values for this sector can only yield rough estimates.

This was the reason for developing a nitrogen footprint for the food production and consumption sector specifically for Germany. Our approach deals with three questions: (a) how much nitrogen is lost on a national level from the German food sector and how do the results differ from N footprints estimated for the US (Leach *et al* 2012) and for Austria (Pierer *et al* 2014), a country bordering Germany? (b) Can the results of the estimated national N footprint for the food sector in Germany be validated with the help of data on N losses in agriculture and nutrition at the national level? (b) How can the N-Calculator for the German food sector be further developed in the future in regards to well-estimated user input and informative value to the population?

2. Material and methods

The N footprint describes the amount of nitrogen losses occurring in a supply chain. In this paper, both the per product N footprint (g N loss/kg consumed products) and the per capita N footprint (kg N loss/capita/year) are estimated. Where N losses relate to the amount of N in the consumed product, the term VNF is used instead. In this paper, N loss includes all losses related to the environment during production, processing and consumption, but it does not include N in consumed food.

The calculation approaches and results will only be roughly outlined. Data was mainly sourced from KTBL (2018) for the production processes of crop and livestock production. N contents in finished products were taken from Souci *et al* (2016). The calculation methods and data sources are described in greater detail in the supplementary information (available online at stacks.iop.org/ERL/16/075005/mmedia).

In addition to the main product, which is used for human consumption, a number of production processes also generate a by-product that is used again in agriculture. Separate N footprints are calculated for these production processes, and the total N loss is divided between the main product and the by-product in proportion to the N amounts in both products. Coupled commodities in crop production are the following: flour (wheat, rye)—bran, beer—draff, sugar—molasses meal and rapeseed oil—rapeseed meal; in livestock production: milk—meat (slaughtered cow) and meat—offal (processed as meat-and-bone meal for use as fertilizer and

feed). The N footprint of plant-based and livestock-based main products and by-products are calculated according to equation (1)

$$\text{N footprint}_{\text{mainprod}}$$
$$= \text{N\_loss} * \left(\text{N\_prod}_{\text{main}}/\text{N\_prod}_{\text{total}}\right)/\text{Y\_prod}_{\text{main}}$$
$$\times\, [\text{g N/g product}]$$

$$\text{N footprint}_{\text{byprod}}$$
$$= \text{N\_loss} * \left(\text{N\_prod}_{\text{by}}/\text{N\_prod}_{\text{total}}\right)/\text{Y\_prod}_{\text{by}}$$
$$\times\, [\text{g N/g product}] \qquad (1)$$

with

$$\text{N\_loss} = \text{N\_input} - \text{N\_prod}_{\text{total}} - \text{N\_manure}^{4}$$

with

$$\text{N\_prod}_{\text{total}} = \text{N\_prod}_{\text{main}} + \text{N\_prod}_{\text{by}}\,[\text{g N/unit}]$$

$$\text{N\_prod}_{\text{main}} = \text{Y\_prod}_{\text{main}} * \text{C\_prod}_{\text{main}} \text{ and}$$
$$\text{N\_prod}_{\text{by}} = \text{Y\_prod}_{\text{by}} * \text{C\_prod}_{\text{by}}\,[\text{g N/unit}]$$
$$\text{Y\_prod}_{\text{main}} = \text{Y\_yield} * \%\text{share}_{\text{main}}$$
$$* \left(100\% - \sum \%\text{conv\_loss}_{\text{main}}\right)$$
$$\times\, [\text{g product/unit}]$$
$$\text{Y\_prod}_{\text{by}} = \text{Y\_yield} * \%\text{share}_{\text{by}}$$
$$* \left(100\% - \sum \%\text{conv\_loss}_{\text{by}}\right)$$
$$\times\, [\text{g product/unit}]$$

where

N footprint$_{\text{mainprod}}$, N footprint$_{\text{byprod}}$: per product N footprint [g N loss/g product]

N_loss: N losses in food, feed and livestock production (main product and by-product together) [g N/unit]

N_prod$_{\text{main}}$, N_prod$_{\text{by}}$, N_prod$_{\text{total}}$: N quantities in main product and by-product and sum of both [g N/unit]

Y_prod$_{\text{main}}$, Y_prod$_{\text{by}}$: consumable yield of main product and by-product [g product/unit]

C_prod$_{\text{main}}$; C_prod$_{\text{by}}$: N content in main product and by-product [g N/g product]

Y_yield: primary yield (crop harvest, livestock product) of production process [g product/unit]

$\sum\%\text{conv\_loss}_{\text{main}}$, $\sum\%\text{conv\_loss}_{\text{by}}$: Fraction of conversion losses during production chain [%]

%share$_{\text{main}}$, %share$_{\text{by}}$: share of main product and by-product; with %share$_{\text{main}}$ + %share$_{\text{by}}$ = 100% [%]

(a) for plant-based products:
[unit] = [ha]

$$\text{N\_input}$$
$$= \text{N\_mineral\_fertilizer} + \text{N\_organic\_fertilizer}$$
$$+ \text{N\_biolog\_fixation}\,[\text{g N/ha}] \qquad (1a)$$

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[4] N_manure only considered for livestock-based product.

where

N_input = sum of mineral and organic N fertilization and biological N fixation to a field crop [g N/ha]

(b) for livestock-based products:
[unit] = [head] for cattle, pigs, sheep, deer; [kg] for milk, eggs

$$\text{N\_input} = \text{N\_feed} + \text{N\_restocking}\,[\text{g N/unit}] \qquad (1b)$$

where

N_input = N used for the production of N in consumed feedstuff (N_feed) for livestock feeding and in reared animals for restocking (N_restocking) (dairy cows and sows). Both terms include the occurring N losses.

Starting point for calculating the N footprint for plant-based products is the N supplied to the cultivated area with mineral and organic N fertilizers as well as biological N fixation due to legume cultivation. The primary yield corresponds to the crop amount harvested per hectare. The yield consumable as food (main product) or feed (by-product) is reduced by the losses due to storage and, in case of products for human nutrition, inevitable household wastes like peels and bones. Storage losses include spoilage, shrinkage and non-marketable goods at the production, processing and retail level and range from 0% to 10.2% (BMEL 2020). Losses with kitchen waste (peeling, cleaning, etc) mainly concern vegetables and fruits and range from 5% to 39% (Souci *et al* 2016). For vegetable feed material, the N footprints are determined analogously to those of vegetable products for human consumption. Losses associated with storage and provision of feeding stuff were assumed to be 1% for bagged or siloed goods (concentrates, compound feed), 5% for loose goods (cereals, grist, etc.), 10% for field forage, silage, hay and 25% for grassland (LfL 2014).

In the case of processed products such as for example flour and sugar, only the portion of the crop used for human consumption is reported in table 1. The VNF value related to the amount of N in the product (g N loss/g N in the product) is calculated from the per product N footprint and the N content of the product (details including sources ref. Table S2; feed table S7). Thus, adopting this approach, the N loss from edible oils (which are N-free) is allocated 100% to the cake, otherwise the problem would occur, that a value of 'g N/g N' could not be calculated for an N-free product. The N footprint for the category 'vegetables' is calculated by a consumption-weighted average of the six quantitatively most important domestic vegetables (table S3). The footprint for 'fruit' is calculated from four domestic fruits (table S4) as well as bananas and citrus fruits.

For the calculation of animal-based products (equation (1b)), the starting point is the feed amount

required to obtain a production unit of the respective production process. The amount of N used to produce this feed corresponds to the N_input into the production and includes losses that occur along the way (KTBL 2018; details including list of sources ref. Table S9). The 'production unit' in case of meat production is one calve, fattening bull, fattening pig, broiler, mutton or sheep, to each a standard value of living weight is attributed. For dairy production, one unit equals one lactation with 8000 kg milk, and for laying hens a unit is 17.3 kg eggs (290 pieces). In the N footprint Calculator Germany, the consumption of dairy products is subdivided into the three product categories 'milk and dairy products' (yoghurt, cream, etc), 'butter' and 'cheese'; per product footprints are calculated for these product categories (table S10). For dairy production, we consider three lactation periods as average lifespan of dairy cows. Thus, as by-products of the milk production one third is accounted for as slaughtered cow and one calf per lactation period. About one third of the calves are used for restocking the dairy cow livestock while the other calves go into bull or calf fattening. For sows, we assume a productive lifespan of 2.5 years with 6 litters and in total 70 piglets. The feed used to breed young animals for restocking of dairy cows and sow livestock accounts for as N input to the respective main product.

For the calculation of N loss in livestock production, we consider N in manure as a return flow into crop production. However, this N loss is not treated as a by-product according to equation (1), i.e. manure N is not included in the partitioning of N loss in the ratio of N amount into main product and by-product. Instead, the N loss by manure production is calculated directly as the ammonium losses from housing and storage of manure and slurry as well as from grazing by the NH_3 emission factors acc. to Haenel *et al* (2018). From the total animal N excretion the ammonia N loss is subtracted and only the net N in manure (diminished by the housing and storage losses) is transferred as organic N fertilizer to crop production. With this approach, the ammonia N losses are included in the loss of the livestock production.

Conversion losses in livestock production are dead-on-farm animals, estimated to 1% for dairy cows, 2% for cattle and pigs, and 12% for laying hens (KTBL 2018). At slaughter, only part of the animal can be marketed as edible meat. The share of inedible offal varies between 21% (fattening pig) and 54% (lamb) of the living weight. Additional removal of undesirable parts is considered kitchen waste. Based on protein quantities, 26% of this inedible waste as well as the remains of dead-on-farm animal losses were thermally utilized in 2017. Furthermore, 17% were technically utilized (mainly as fertilizer) and 57% were used as feed for pets, animals and aquaculture (STN 2018). Thus, around three quarters of the N

quantity amounted in slaughterhouse waste is therefore not attributed to conversion loss, but is reused in animal feed or as fertilizer.

3. Results and discussion

3.1. VNF values and nitrogen footprint Germany

In total, N footprints were calculated for 20 plant foods, 17 feed materials, 18 compound feeds and 14 animal products (tables S2, S7–S9). Table 1 shows the N losses, partly summarized, for those food categories for which Leach *et al* (2012) presented results (supplemented by cheese and butter). The N footprint values are related to product quantities, while the VNF relate to protein quantities in the consumed product. Furthermore, the average per capita consumption is given for the German population (MRI 2008, 2013). The consumption-weighted average nitrogen footprint in Germany is therefore 14.5 g N per kg product. Clear differences exist between plant-based and animal-based food: The mean N footprint (weighted by the average consumption quantities) of vegetable products is only 3.1, while the mean footprint of animal-based foods is 40.5 g N per kg product. The relationship is somewhat different when we compare the VNF. The average VNF for animal-based foods with 4.94 g N loss per g protein-N is only about one and a half times as high as the average VNF of vegetable products with 3.16 g N/g N.

On average about 686 kg of food (without tea, coffee, soft drinks) is consumed in Germany per capita and year. With the average N footprint of 14.5, the resulting average annual per capita N footprint for the nutrition of the German population is calculated at 9.94 kg N loss per capita and year. Extrapolated to 83 million inhabitants in Germany, this corresponds to a national N footprint of about 825 000 t N per year. Of this amount, about 15% is caused by N losses with plant-based foods, while animal products cause about 85% of the N losses. This considerable discrepancy between the N losses of plant-based and animal-based foods illustrates the great importance of personal nutritional style in the emission of reactive N-compounds. To add to this, Oita *et al* (2018) illustrate how animal protein intake increased from amount to 30% of the total protein intake to 52% in the Japanese diet between 1961 and 2011. While the overall protein intake only increased by 11%, the nitrogen footprint however increased by 55%.

Per capita consumption is associated with an average daily protein intake of around 104 g protein per capita and day (table S11) or 6.1 kg protein-N per capita and year. This value corresponds to the recommended protein intake of 0.8–1 g kg^{-1} body weight and day, totaling to about 60–90 g protein per day (Richter *et al* 2019). This protein oversupply of an estimated 20 g protein per capita and day, in combination with the high N losses of animal-based products

Table 1. Per Capita N footprint for Germany shown with per capita food consumption for different food categories with their respective per product N footprint and VNF.

Product/product category	Per capita consumption (kg product/year)	Per product N footprint (g N loss/kg product)	N footprint (kg N loss per capita and year)	(share %)	Protein-based VNF (g N loss/g N)
Cereals (mean)	87.0	6.0	0.52	5.2%	0.36
Sugar	34.1	0.0	0.00	0.0%	0.00
Potatos	58.6	1.1	0.07	0.7%	0.33
Nuts[b]	4.6	0.7	0.00	0.0%	0.70
Fruits (mean)	69.5	6.4	0.44	4.5%	6.48
Vegetables (mean)	103.2	3.5	0.36	3.6%	2.01
Legumes	1.2	7.7	0.01	0.1%	0.17
Alcoholic beverages	118.7	0.7	0.08	0.8%	6.72
Sum/weighted average for plant-based products[c]	477	3.1	1.49	15.0%	3.16
Milk	89.7	14.4	1.30	13.0%	2.67
Butter	5.9	99.5	0.59	5.9%	97.56
Cheese	23.0	69.2	1.59	16.0%	1.65
Beef	9.8	123.3	1.21	12.2%	3.93
Pork	36.2	55.6	2.01	20.2%	1.98
Poultry	14.2	34.3	0.49	4.9%	1.08
Eggs	14.3	31.4	0.45	4.5%	1.66
Lamb	0.6	265.2	0.17	1.7%	8.90
Venison	0.7	348.0	0.25	2.6%	10.56
Fish	14.2	28.5	0.40	4.1%	0.90
Sum/weighted average for animal-based products[c]	209	40.5	8.46	85.0%	4.94
Sum/weighted average[c] total	686	14.5	9.94	100%	3.70

[a] Food categories according to Leach *et al* (2012), additionally cheese and butter.

[b] N footprint value for nuts taken from US N footprint Calculator.

[c] Averages weighted with per capita consumption.

clearly shows that there is a considerable reduction potential for diet-related N losses.

From the N loss of 9.94 kg N and the N-uptake in food protein of about 6.1 kg N per year, a nitrogen loss factor (g N loss per g protein-N in consumed food) of 164% is calculated. The nitrogen use efficiency (NUE), defined analogous to NUE in crop cultivation (Erisman *et al* 2018) as N available for consumption divided by total N input therefore is 38%.

3.2. Comparison of the N footprint with national N flows in Germany

Some key figures of the N footprint calculation were scaled up to the German agricultural sector as a whole (bottom-up values), i.e. calculated footprint values were multiplied with national statistical data to yield overall loss in tons per year. Resulting values were compared with nitrogen flows determined independently at the national level within agricultural nutrient budget reporting (top down values). With reference to the listing of food N footprint estimates in Leip and Uwizeye (2019), this is for the first time that the outcome of a bottom-up calculation is validated by results derived from top-down national assessment.

With this comparison, the quality and plausibility of the footprint calculation can be assessed. The nitrogen soil surface budget for Germany (Häußermann *et al* 2019, 2020, BMEL 2020) serves as the central source for the top down values. The national nitrogen quantities of the N footprint are calculated as bottom-up values by extrapolating the per product N inputs (N fertilization, fodder), N outputs (crop, animal products) and N losses with the national production quantities of crop and animal products (for details see tables S13 and S14).

For plant production, the values obtained from the bottom-up approach for 'mineral/organic N fertilization', 'N withdrawal with harvest' and 'N loss or N surplus soil surface' are compared with the top down values. Table 2 (see Plant production/soil surface budget) shows that the N fertilization and the N harvest withdrawal as calculated for the N footprint vs the N budget for Germany show only a few percent difference. The difference between the N loss according to the N footprint calculation and the N surplus of the soil surface budget is somewhat larger at 12%. This can be attributed to the fact that the N losses for the N footprint also include storage losses and

Table 2. Yearly nitrogen input, withdrawal and losses (N surplus) in crop and animal production according to N footprint calculations in comparison to Germany's nitrogen budget (mean 2015–2017).

	N footprint calculation[a] (1000 t N/a)	N budget Germany[b] (1000 t N/a)	
	Crop production	Soil surface budget	Difference (%)
Mineral fertilizers	1 718	1 731	−0.7
Organic fertilizers	1 483	1 538	−3.6
N withdrawal with harvest; thereof:	2 407	2 372	1.5
- Crops for human consumption	475		
- Animal feed	1 931		
N losses/N surplus; thereof:	867	985[c]	−12.0
- Crops for human consumption	147		
- Animal feed	575		
- Biogas substrates	145		
	Animal production	Livestock budget	
Animal Feed	1 764	2 074	−14.9
N in organic fertilizers	961	1 196	−19.7
N in main products and byproducts	486	496	−2.0
N losses/N surplus; thereof:	963		
- Animal production processes	388	352	10.2
- Animal feed production	575[d]		

[a] Extrapolated for Germany based on cultivated areas per crop (plant production) and produced amounts of animal production.
[b] According to soil surface budget and livestock budget for Germany (BMEL 2020); aggregation might differ slightly from publication.
[c] Surplus of N soil surface budget, here used without N input from atmospheric depositions and without nitrogen fixation by legumes for better comparison.
[d] Value taken from crop production.

kitchen waste, which are not included in the soil surface as losses but as N withdrawal from the cropland by Häußermann *et al* (2019). The total N loss can be roughly apportioned from the utilization pathways of the products to the three groups of food crops, fodder crops and biogas substrates.

For animal production, the variables 'N-supply with animal feed', 'N in in organic fertilizers', 'N in animal products' and 'N loss or N livestock budget' are compared (table 2, part animal production/livestock budget). The amount of N in animal-based products shows only a slight difference of 2% between the two approaches. For the N supply with animal feed there is a difference of 14.9% between the value from the N footprint calculation and the national N flow analysis (Häußermann *et al* 2021). The lower feed quantity according to the N footprint can be explained, among other things, by the process descriptions of animal production according to KTBL (2018) that assume an optimal feed composition and feed conversion that might be below common agricultural practices.

In the described approach, the amount of N in farmyard manure is calculated from the difference between feed use and the amount of N in the products. Therefore, the aforementioned lower feed quantity according to the footprint approach inevitably leads to a 19.7% lower N accumulation in farmyard manure compared to the national livestock budget. In the N livestock budget for Germany, only

the N surplus is calculated which arises on farm level. The amount of accrued nitrogen in the livestock budget is calculated by multiplying animal head counts with the respective N excretion per livestock place value taken from the German fertilization Ordinance. In order to compare the footprint results of this study to the N surplus, the N losses contained in the preliminary products, i.e. the feed used, is deducted from the total loss. The N loss, which arises in animal production following to the bottom-up approach, is calculated at 39 kt N, which is 10.2% higher than the N surplus given in the national livestock budget.

3.3. Comparison of N footprints for Germany with the USA and Austria

The N footprint calculation for food consumption in Germany was compared to the results for the US (Leach *et al* 2012) and Austria (Pierer *et al* 2014). The latter applies the same VNF methodology first introduced with Leach *et al* (2012) for Austria, which as a neighboring country to Germany offers a comparable structure of the agricultural sector. In this section here we can compare the approaches only in general terms; a detailed discussion of the differences between the calculations for the US and for Germany and the possible reasons for the diverging results is presented for two products (corn/wheat flour and beef) in section 7 of the supplementary information. For most product categories, these per product N footprint
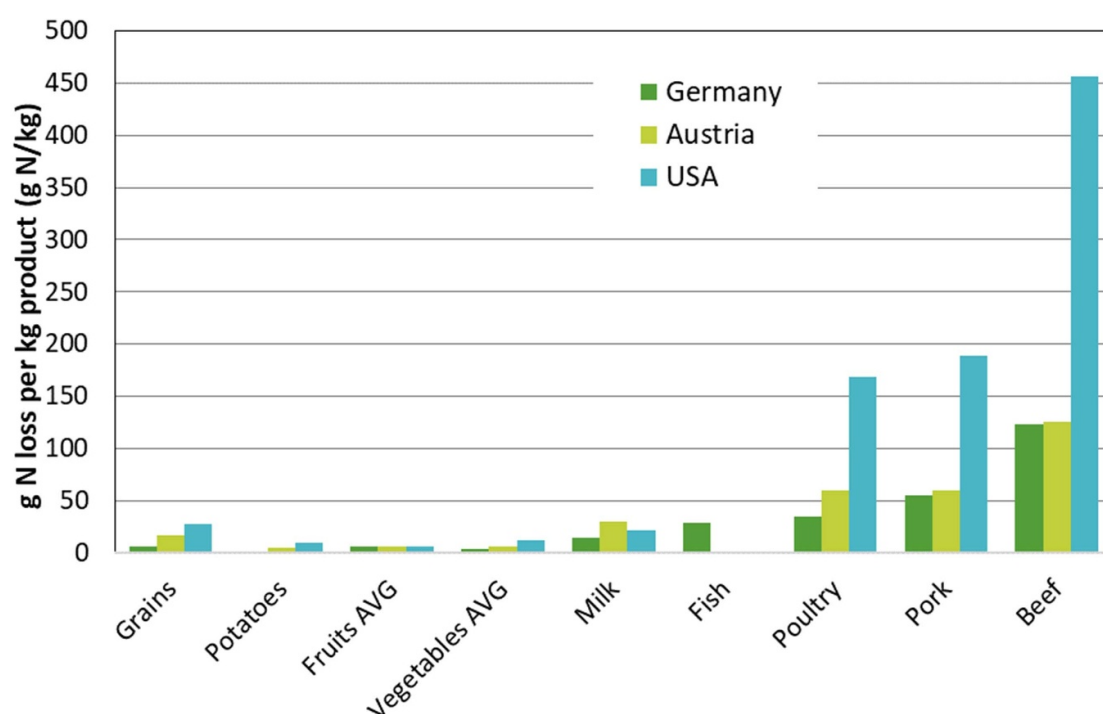
Figure 1. Per product N footprint (g N loss per kg product) for Germany, Austria and the US (Pierer *et al* 2014[a], Leach *et al* 2012[b]).
[a] N footprint for Pierer *et al* (2014) is given as 3.03 for milk; however, it is our impression that an error with the factor 10 has happened here. Protein supply of milk per day, which was used to calculate this, should be ∼29 g instead of 2.9 g as given in the supplementary material of Pierer *et al* (2014). This factor results in a protein content of 0.5% where it should be around 3.3%. Accordingly, value is set to 30.3 in figure 1. [b] Updated values obtained from the authors.

does not show substantial differences between Austria and Germany (figure 1), although both are generally below the per product US Footprints. For grain, milk and poultry the N footprint values for Austria are about two times higher than for Germany. When calculating the total N footprint using the average per capita food consumption of Germany (see table 1) combined with Austrian per product N footprint, it results in a total loss of 15.1 kg N loss per capita and year. This is about 50% more than the N loss of 9.94 kg N calculated with the N footprint values for Germany. All extrapolated bottom-up values then also increase by 50%, the comparison with the top down values in Germany (see table 2) is correspondingly worse.

When comparing the VNF, most product categories (except potatoes and fruit), the US (Leach *et al* 2012) show by far the largest N losses, followed by Austria. When using the US VNF factors for Germany instead of the German factors, the N losses for Germany amount to 17.4 kg N per capita and year, an increase by more than 70%.

This study can only compare the three approaches in general terms; a detailed discussion of the differences in the individual food categories is not possible for two reasons. Even though the publications of Leach *et al* (2012) and Pierer *et al* (2014) specify the rates of total Nr wasted (% of N removed with waste in processing stage) and waste recycling rates (% of N recycled to be used as input in the next

iteration), the N quantities at the beginning of each production process are not known because they were not published in the respective publications. Thus, the amount of N-fertilizer added to the individual crops and the amount of feed used in the animal production processes cannot be compared. In addition, information is lacking on which byproducts or waste products (e.g. manure, slaughterhouse waste, kitchen waste, etc) are considered in the '% recycled'. However, this information is necessary to assess in detail how the assumptions on the recycled N content of Leach *et al* (2012) and Pierer *et al* (2014) differ from our approach for Germany. The comparison of the calculation approaches exemplarily for corn/wheat flour and beef for the US and for Germany in the Supplementary Information gives an indication of the possible causes of the differences. The discrepancy in the N footprint result for corn production between Leach *et al* (2012) and our calculation for wheat flour are mainly due to different assumptions in three points. (a) A better recycling of fertilizer N is assumed for crop production in Germany. (b) The share of recycled N in the processing of wheat into flour is assumed considerably higher for Germany than for the US. It is possible that the by-products of corn processing are not used as feed in the US, or that Leach *et al* (2012) do not consider this pathway. (c) For household food processing, a waste loss of 32% is applied for corn in the U.S., while household losses are much lower for Germany

according to a survey in Germany by Schmidt *et al* (2019).

The difference in the N footprint result for beef production between Leach *et al* (2012) and our calculation is presumably mainly due to the husbandry systems in the USA and Germany. In Germany, cattle are mostly kept in freestall housing with liquid manure. Relatively little gaseous N is lost in housing and storage, and a considerable part of the manure N is recycled as organic fertilizer in the crop production of the farm. In contrast, in the U.S., cattle are often raised in feedlots where manure is only collected to a smaller extent, and instead most of the N is lost to the atmosphere or leached. If we were to calculate the N footprint for beef in Germany with the same breakdown of manure N into loss and recycled N as for the USA, the VNF for Germany would be 6.7 (g N loss/g N in product), which is almost identical to the result of 6.9 for the USA. We assume that the N Footprints for pork and poultry that are more than double the value for the US are mainly due to the different efficiency of recycling and crop use of manure in the agricultural production systems of the two countries.

3.4. Improvements of the food consumption part of the nitrogen footprint calculator

Based on our experience with the N footprint Calculator, we have identified some issues that could be included into the N-Calculator food consumption part in the future. These developments may help to enhance the plausibility of the calculation of the individual N footprint and to increase the user acceptance of the N-Calculator.

3.4.1. Food categories of the N footprint calculator

The N footprint Calculator queries food consumption primarily by categories that enter the diet as basic products (such as grain). However, these categories are partly unspecific and do not correspond to the consumption habits of the population. E.g. cereals are consumed primarily in the form of flour, from which bread and baked goods are made, but also in the form of whole grain products such as muesli. We have certain doubts that such calculations can be or would want to be performed correctly in this way by the average users of the N-Calculator. Querying consumption quantities, e.g. for 'bread and rolls', 'other baked goods (sweet pastry)', 'pasta', 'other cereal products (oat flakes, semolina, bulgur etc)' etc would probably give more accurate results. In view of this problem, the authors believe that the N footprint Calculator should therefore query those food categories that correspond better to the nutritional habits of the population.

Similarly, 'sausages and cold meats' should be introduced as an additional category, as this form of preparation represents a significant form of consumption of meat products (at least in Germany) and

this distinction facilitates the estimation of consumption for the user. Beverages sweetened with isoglucose made from corn or certain vegetable oils would also be an interesting addition.

3.4.2. Checking input data for plausibility

To make sure the user's estimations are realistic, a plausibility check could be implemented by calculation the weekly energy and protein intake of the diet used as input data in the N-Calculator and then give the user a notification if the results deviate significantly from the average value to suggest a reevaluation.

As estimating weekly consumptions portions is a difficult task, it is to be assumed that the user will rely on the given average consumption data for guidance. Given this, a differentiation of the average consumption by gender could be useful, as men have a higher body weight on average and consume an average of 2431 kcal d^{-1}, which is about 32% more energy than women in Germany (MRI 2008). Men, for example, eat 30% more bread and baked goods, almost double the amount of meat and consume 3.7 times more alcoholic beverages than women (table S12).

3.4.3. Differentiation by organic/conventional production

The data on the N losses (N$_r$ emissions) of agricultural products are based on standard values for production methods of conventional agriculture, i.e. the N supply of the plants is at least mainly achieved by fertilization with nitrogen from mineral fertilizers. As a further development, an option 'organic production' should also be offered in the N footprint Calculator. Users could then indicate what percentage of their consumed amounts of each product category stems from conventional and how much from organic farming. This way, a user could be informed how his or her personal N footprint changes when they increase their consumption of organic products. However, Noll *et al* (2020) suggest that at least for the US, increasing the share of organic consumption would only have a 'modest impact' on the N footprint of an individual.

4. Conclusions

The N footprint calculation is carried out for selected products or production processes of plant-based and animal-based production using standard values for N supply with fertilizers or animal feed, for losses in the production process and for the quantities produced per production unit (hectare, animal, etc). The values and assumptions, on which the calculation is based on, represent only a part of the whole range of the configuration of production processes in a country. From our point of view, it is consequently essential that the results of the N losses be checked for plausibility. To this end, the results of the individual categories are scaled up to the national level and then

compared with statistical data on N use in plant and animal production, production volumes and cumulative N losses. In our opinion, the overall good agreement of the key figures of the N footprint calculation with the production figures and the N budget for Germany proves that the assumptions and results for the footprint values are plausible and resilient overall.

Our experience with the calculation of per product N footprint values for Germany, it has been shown that there is considerable scope for detail. In animal production in particular, the footprint depends largely on the assumptions made regarding the utilization (recycling) of the nitrogen in the by-products, i.e. mainly in farm manure (liquid manure, dung). The N footprint calculations by Pierer *et al* (2014) for Austria and especially by Leach *et al* (2012) for the US operate with partly significantly higher N footprint values. For a more in-depth comparison with these approaches, however, it would be necessary to examine the approaches in greater detail beyond the published materials.

We hope that the sensitization of the public for the problem of nitrogen losses, which are strongly connected with the personal consumption pattern (here: in the sector food consumption) will continue to grow in the future. Hopefully, with time, the use of a nitrogen footprint Calculator will become as common as the use of a CO_2 footprint Calculator already is today.

Data availability statement

The data generated and/or analysed during the current study are not publicly available for legal/ethical reasons but are available from the corresponding author on reasonable request.

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References

Bach M, Häußermann U, Klement L, Knoll L, Breuer L, Weber T, Fuchs S, Heldstab J, Reutimann J and Schäppi B 2020 Reactive nitrogen flows in Germany 2010-2014 (DESTINO Report 2) Umweltbundesamt, Dessau-Roßlau, UBA-Texte 65/2020 p 162

BMEL 2020 Statistik des BMEL, Statistische Monatsberichte, Nährstoffbilanzen und Düngemittel: Stallbilanz und Flächenbilanz von 1990 bis 2017 (kt N) Tabellen MBT-0111130-0000, MBT-0111190-0000 Bundesministeriums für Ernährung und Landwirtschaft (BMEL)

BMU 2017 Erster Stickstoff-Bericht der Bundesregierung (Berlin: BMUB) (available at: www.bmu.de/fileadmin/Daten_BMU/Pools/Broschueren/stickstoffbericht_2017_bf.pdf)

Erisman J W, Galloway J N, Seitzinger S, Bleeker A, Dise N B, Petrescu A M R, Leach A M and De Vries W 2013 Consequences of human modification of the global nitrogen cycle *Phil. Trans. R. Soc.* B **368** 20130116

Erisman J, Leach A, Bleeker A, Atwell B, Cattaneo L and Galloway J 2018 An Integrated Approach to a Nitrogen Use Efficiency (NUE) Indicator for the Food Production–Consumption Chain *Sustainability* **10** 925

Fowler D *et al* 2013 The global nitrogen cycle in the twenty-first century *Phil. Trans. R. Soc.* B **368** 20130164

Galloway J N, Aber J D, Erisman J W, Seitzinger S P, Howarth R W, Cowling E B and Cosby B J 2003 The nitrogen cascade *BioScience* **53** 341–56

Galloway J N, Winiwarter W, Leip A, Leach A M, Bleeker A and Erisman J W 2014 Nitrogen footprints: past, present and future *Environ. Res. Lett.* **9** 115003

Galloway J and Cowling E 2002 Reactive nitrogen and the world: 200 years of change *Ambio* **31** 64–71

Gu B, Leach A M, Ma L, Galloway J N, Chang S X, Ge Y and Chang J 2013 Nitrogen footprint in China: food, energy, and nonfood goods *Environ. Sci. Technol.* **47** 9217–24

Guo M, Chen X, Bai Z, Jiang R, Galloway J N, Leach A M, Cattaneo L R, Oenema O, Ma L and Zhang F 2017 How China's nitrogen footprint of food has changed from 1961 to 2010 *Environ. Res. Lett.* **12** 104006

Haenel H D *et al* 2018 Calculations of gaseous and particulate emissions from German agriculture 1990–2016. Report on methods and data (RMD), Submission 2018. Thünen Report 57

Häußermann U *et al* 2021 National nitrogen budget for Germany *Environ. Res. Commun.* 100531 accepted

Häußermann U, Bach M, Klement L and Breuer L, 2019 Stickstoff-Flächenbilanzen für Deutschland mit Regionalgliederung Bundesländer und Kreise—Jahre 1995 bis 2016 Methodik, Ergebnisse und Minderungsmaßnahmen. UBA-Texte 131/2019 (Dessau-Roßlau)

Häußermann U, Klement L, Breuer L, Ullrich A, Wechsung G and Bach M 2020 Nitrogen soil surface budgets for districts in Germany 1995–2017 *Environ. Sci. Eur.* **32** Article no 109

Hutton M O, Leach A M, Leip A, Galloway J N, Bekunda M, Sullivan C and Lesschen J P 2017 Toward a nitrogen footprint calculator for Tanzania *Environ. Res. Lett.* **12** 034016

KTBL 2018 Betriebsplanung Landwirtschaft 2018/19. 26. Auflg Kuratorium für Technik und Bauwesen in der Landwirtschaft (KTBL) (Darmstadt) p 776

Leach A M, Galloway J N, Bleeker A, Erisman J W, Kohn R and Kitzes J 2012 A nitrogen footprint model to help consumers understand their role in nitrogen losses to the environment *Environ. Dev.* **1** 40–66

Leach A M, Kohn R and Galloway J N 2011 *N-PRINT: Calculation of the Virtual N Factor* University of Virginia p 26

Leip A and Uwizeye A 2019 Nitrogen footprints *Encyclopedia of Ecology* 2nd edn, vol 4 (San Diego, CA: Elsevier) pp 370–82

Leip A, Weiss F, Lesschen J P and Westhoek H 2014 The nitrogen footprint of food products in the European Union *J. Agric. Sci.* **152** 20–33

LfL 2014 Gruber Tabelle zur Fütterung der Milchkühe, Zuchtrinder, Schafe, Ziege (Futterwerttabellen) Bayerische Landesanstalt für Landwirtschaft (LfL) p 108

MRI 2008 Nationale Verzehrsstudie II. Ergebnisbericht Teil 2. Die bundesweite Befragung zur Ernährung von Jugendlichen und Erwachsenen Max Rubner-Institut (MRI) (Karlsruhe) p 302

MRI 2013 Nationale Verzehrsstudie II. Lebensmittelverzehr und Nährstoffzufuhr auf Basis von 24h-Recalls Max Rubner-Institut (MRI), Karlsruhe p 12

Noll L C, Leach A M, Seufert V, Galloway J N, Atwell B, Erisman J W and Shade J 2020 The nitrogen footprint of organic food in the United States *Environ. Res. Lett.* **15** 045004

Oita A, Nagano I and Matsuda H 2018 Food nitrogen footprint reductions related to a balanced Japanese diet *Ambio* **47** 318–26

Pierer M, Winiwarter W, Leach A M and Galloway J N 2014 The nitrogen footprint of food products and general consumption patterns in Austria *Food Policy* **49** 128–36

Richter M, Baerlocher K, Bauer J M, Elmadfa I, Heseker H, Leschik-Bonnet E, Stangl G and Volkert D Stehle P on behalf of the German Nutrition Society (DGE) 2019 Revised reference values for the intake of protein *ANM* **74** 242–50

Schmidt T, Schneider F, Leverenz D and Hafner G 2019 Lebensmittelabfälle in Deutschland—Baseline 2015 Thünen-Institut, Braunschweig, Thünen Report 71

Shibata H, Cattaneo L R, Leach A M and Galloway J N 2014 First approach to the Japanese nitrogen footprint model to predict the loss of nitrogen to the environment *Environ. Res. Lett.* **9** 115013

Shindo J and Yanagawa A 2017 Top-down approach to estimating the nitrogen footprint of food in Japan *Ecol. Indic.* **78** 502–11

Souci S W, Fachmann W and Kraut H 2016 Die Zusammensetzung der Lebensmittel 8. Auflg. Wiss Verlagsgesellschaft, Stuttgart p 1263 (www.sfk.online; last checked 1 August 2019)

Stevens C J, Leach A M, Dale S and Galloway J N 2014 Personal nitrogen footprint tool for the United Kingdom *Environ. Sci. Process Impacts* **16** 1563–9

STN 2018 Statistik der Verarbeitung tierischer Nebenprodukte Servicegesellschaft Tierische Nebenprodukte (STN), Bonn, TNN II/2018