

Article

An Integrated Approach to a Nitrogen Use Efficiency (NUE) Indicator for the Food Production–Consumption Chain

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Abstract: Reducing nitrogen pollution across the food chain requires the use of clear and comprehensive indicators to track and manage losses. The challenge is to derive an easy-to-use robust nitrogen use efficiency (NUE) indicator for entire food systems to help support policy development, monitor progress and inform consumers. Based on a comparison of four approaches to NUE (life cycle analysis, nitrogen footprint, nitrogen budget, and environmental impact assessment), we propose an indicator for broader application at the national scale: The whole food chain (NUE_{FC}), which is defined as the ratio of the protein (expressed as nitrogen) available for human consumption to the (newly fixed and imported) nitrogen input to the food system. The NUE_{FC} was calculated for a set of European countries between 1980 and 2011. A large variation in NUE_{FC} was observed within countries in Europe, ranging from 10% in Ireland to 40% in Italy in 2008. The NUE_{FC} can be used to identify factors that influence it (e.g., the share of biological nitrogen fixation (BNF) in new nitrogen, the imported and exported products and the consumption), which can be used to propose potential improvements on the national scale.

Keywords: nitrogen use efficiency; food chain; Europe; budget

1. Introduction

Nitrogen (N) is a key nutrient, vital for the survival of humans and all other living organisms. While di-nitrogen gas (N_2) is abundant in the atmosphere, most organisms are unable to use this chemically unreactive form. First it must be converted or “fixed” into a reactive form such as ammonia (NH_3) or nitrogen oxide (NO_x). This and other forms of reactive nitrogen (all forms of nitrogen other than the inert atmospheric N_2 gas; N_r) are comparatively scarce and represent a limiting resource in most ecosystems and in farmlands (e.g., [1] and references therein).

By the end of the 19th century, the natural sources of fixed nitrogen were not sufficient for the food production needs of a rapidly increasing human population in Western Europe. The development and adoption of the Haber–Bosch process enabled widespread production and use of synthetic N-fertilizers,

leading to a dramatic increase in agricultural productivity. This holds for both crop production and livestock production, the latter as the result of increased feed availability. The growth in livestock production, the specialization and agglomeration of livestock production systems, and the poor management of manure nitrogen contributed to low efficiency of nitrogen use in the food system [2]. Because of the generally low nitrogen fertilizer use efficiency of agriculture, much of industrially fixed nitrogen is eventually released into the biosphere. The burning of fossil fuels also releases large amounts of nitrogen oxide emissions into the atmosphere. Because of these releases, and the fact that the world converts more nitrogen from the atmosphere into reactive forms through anthropogenic processes than all of the Earth's natural processes in terrestrial systems combined, the global nitrogen cycle has been dramatically altered—even more than the global carbon cycle [3,4].

The negative consequences of this human-generated change are becoming ever more apparent. Numerous, often interlinked, thresholds for human and ecosystem health have been exceeded due to excess reactive nitrogen pollution, including thresholds for drinking water quality (due to nitrates) and air quality (smog, particulate matter, ground-level ozone). Eutrophication of freshwater and coastal ecosystems (i.e., dead zones), climate change and stratospheric ozone depletion are also consequences of the human modified N_r cycle. Each of these environmental effects can be magnified by a 'nitrogen cascade' whereby a single atom of reactive nitrogen can trigger a sequence of negative environmental impacts through time and space (e.g., [1,4–6]).

Management of N resources is important, especially in food production, as agriculture is the biggest user of anthropogenic N in the world. The negative impacts of N due to our food production are caused by a general decrease in the nitrogen use efficiency (NUE) in most regions of the world (e.g., [7]). NUE is defined by the Organisation for Economic Co-operation and Development (OECD) as the ratio between the amount of fertilizer N removed from the field by the crop and the amount of fertilizer N applied. Here we expand NUE for the whole food system as the ratio of the amount of nitrogen available for food consumption of the new nitrogen used for the production of that food. N management in agriculture should aim at achieving agronomic, economic, social and environmental objectives. This requires solid data and information about N flows in relation to sustainability and tools and key performance indicators to support management, policies, decisions and actions. Indicators play a key role in management and policy; they should have a solid scientific and analytical basis and should be defined in a uniform and reproducible manner [8]. There are many studies that focus on the farm-level, crop or housing system NUE. However, these are less suitable for policy application on a national level.

The aim of this paper is to develop a NUE indicator for the whole food system in order to understand the NUE for the whole food production–consumption chain to help policy makers develop strategies for a more nitrogen-efficient food production, to minimise losses in the food system and to help elucidate where the efficiency is lowest in the chain and thus where optimization is possible to increase NUE. This action will help policymakers and consumers influence consumption patterns and encourage the consumption of products that contain the most N (i.e., protein) but require the lowest N inputs.

Here we therefore focus on the NUE indicator for the whole food system, which goes beyond the farm level NUE indicator (Figure 1: until 'food industry'), taking into account processing and distribution (Figure 1: Food industry). The NUE indicator for the whole food chain, NUE_{FC} , is defined as the available food for consumption of protein N (protein in food available) for a given human population divided by the newly formed N that was used to produce the food. This full-chain NUE therefore describes the percent of nitrogen invested in food production that is contained in the final consumed food product. It provides a measure about how effectively the new reactive nitrogen created for food production is converted into the food protein N available for consumption.

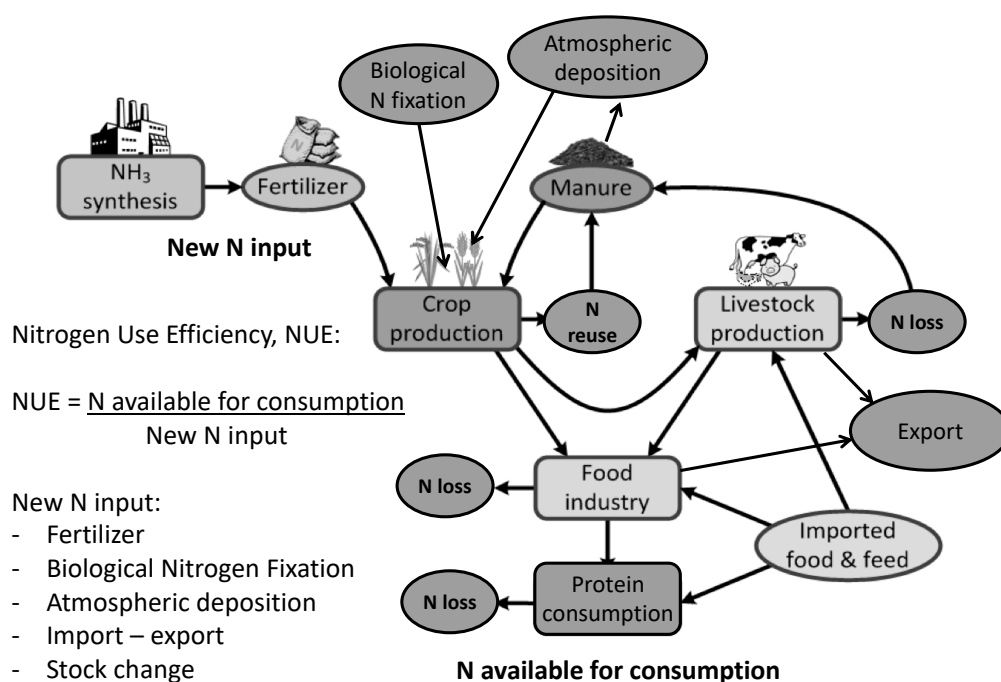


Figure 1. The major components of the full-chain nitrogen use efficiency (NUE_{FC}) in the national food system. This figure also shows where losses (noted as “N-loss”, not being reused) occur that reduce the efficiency. Up to the ‘Food industry’ box, the interactions are as represented by EU Nitrogen Expert Panel [8] in the agricultural system.

There are several methods available to determine the NUE_{FC} . These methods have different aims, system bounds, limitations and advantages when used as a basis for deriving the full-chain NUE. We provide a review of these methods and indicators for NUE with the aim of proposing one (or a more coherent set of) indicator(s) for NUE in the whole food system in Europe (EU28) and its constituent countries, including an assessment of the advantages and disadvantages, the limitations, data availability and potential use.

The aims are to provide:

- A literature review of existing indicators for full-chain NUE in the food production—consumption chain at the national and/or regional scales in European countries;
- A proposal for one indicator or a coherent set of indicators for NUE in the food system in Europe at the national or regional levels, which is ‘linked’ to the general concept agreed upon during the first meeting of the panel (EU Nitrogen Expert Panel, 2014), and which can be used by policymakers and practitioners in Europe (industry, consumers, NGOs, policy, research); and
- A demonstration of the use of the proposed indicator using European national data sets and a discussion of its usability.

2. Literature Review: Approaches to Estimating NUE

Four approaches are commonly used to assess nitrogen use efficiencies of food production—consumption and/or the environmental impact of N use in food production: life cycle analysis, nitrogen footprint analysis, nitrogen budget analysis, and environmental impact assessment. These approaches are briefly described below, with more detailed information given in the Supplementary Material (SM). The four approaches distinguished are not equally specific for estimating NUE, but they do provide information about the N use and possible environmental impacts of the N use. The four approaches are:

- (i) **Life Cycle Analysis (LCA):** A technique to assess the potential environmental and human health impacts associated with a product, process, or service by: (1) compiling an inventory of relevant energy and material inputs and environmental releases and (2) evaluating the potential environmental impacts associated with the identified inputs and releases (e.g., [9–18] (See Appendix ??, Table A1).
- (ii) **Nitrogen Footprint:** Total N losses to the environment resulting from the production of a defined unit of food (e.g., [19–25] (See Appendix ??, Table A2).
- (iii) **Nitrogen Budget:** The inputs and outputs of nitrogen across the boundaries of a system. Can contain information about internal nitrogen fluxes within the system (e.g., [1,26–37]). The **farm-gate nitrogen budget** is a common indicator for assessing the total inputs and outputs across a farm's boundaries. The **nitrogen balance indicator** measures the difference between the nitrogen available to an agricultural system and the nitrogen harvested and exported from the system in agricultural products. The **food system waste/loss indicator:** this category has received special attention by studies that estimate the loss of N through waste [38–40] (See Appendix ??, Table A3).
- (iv) **Environmental Impact Assessment:** A process of evaluating the likely environmental impacts of a proposed project or development, taking into account inter-related socio-economic, cultural, and human health impacts both beneficial and adverse (e.g., [41–43] (See Appendix ??, Table A4).

A literature review was conducted of the aforementioned approaches, and a total of 36 peer-reviewed studies were identified and categorized according to approach, country, and product as displayed in Appendix ???. The different studies cover 17 products and 30 countries. Of the papers collected, 11 used the LCA approach, six used the N footprint approach, 16 used the N budget approach, and three used the EIA approach.

All four approaches are useful for the purpose they serve. The level of detail varies and depends on the goal of the study as well as the availability of data. However, the N budget analysis approach is most suitable for estimating NUE_{FC} ; this approach allows the direct estimation/derivation of NUE , N outputs and N surplus.

3. Literature Values

There were several studies that calculated the NUE_{FC} for a country or a region for all food production using the budget method:

- Norway: 10% ([26])
- Germany: 10% ([44])
- USA: 15% for plant protein and 5% animal protein ([29])
- Global: 4% for meat and 14% for plant production ([28])
- Europe: 18% ([45])
- China: 9% ([33])

World: country ranges from 1% (Mongolia) and 4% (Australia) to 106% (Nepal) and 112% (Rwanda), where nitrogen mining takes place ([7]).

These studies show that the overall full-chain N efficiency (NUE_{FC}) is between 5 and 15%, which is a fairly small range. This means that on average, only 5–15% of the nitrogen invested in global food production is contained in final consumed food products. In some regions, the estimated NUE_{FC} was very high (even more than 100%; Sutton et al. [7]), probably due to soil N mining.

4. Selection of Approach

The four full-chain approaches have strengths and weaknesses (Table 1). These strengths and weaknesses form the basis for our selection of a recommended approach for estimating full chain NUE . Other criteria include the feasibility of linking to the farm-scale NUE indicator, the system boundaries,

and the current and foreseen data availability. The system boundaries defined here are set by the food system. This means that the energy and transport part of the food chain will not be included. However, the atmospheric deposition resulting from these N emission sources is included, similar to the study by the EU Nitrogen Expert Panel [8].

The LCA approach provides an established framework for detailed calculation of the N flows and losses to the environment in the different steps of the food system. Detailed data are needed for this approach. Although LCA has been completed for some food products in Europe, it is clear that the data needed for all European countries and products will not be available in the near future for a complete analysis of the whole food chain for all countries. Recently, Leip et al. [32] used the LCA approach together with the CAPRI (Common Agricultural Policy Regionalised Impact) model to estimate the N losses and impacts of livestock in Europe.

The N footprint and N budget approaches both use N input and output balances. The N footprint approach also considers N losses at each stage of the food production process, whereas the N budget looks at overall inputs and outputs for a given system. Given this, the N footprint approach is generally more data-intensive than the N budget approach. In addition, the N budget approach can be more easily applied at multiple scales (e.g., a step of the food system, an individual product, farm, region, country) given its flexibility in assigning the system bounds.

LCA and EIA both integrate environmental impact assessment; the other approaches simply assess N emissions to the environment. Impacts are region and climate specific; comparison of food systems based on impacts is therefore difficult. Furthermore, directly linking N use to the impact of N use is not part of the objective of 'how to estimate NUE of the food chain'.

In summary, most approaches for estimating N use in the food chain assess the losses of N from the food system and some link these losses to the environmental impacts (life cycle analysis, N-Footprint, environmental impact assessment). The N budget approach, by contrast, compares the overall inputs and outputs of a system. The focus on losses for the step-by-step approaches (LCA, N-Footprint, EIA) is less useful for calculating NUE, because NUE is based on the balance between N supply and the N in a final product. Furthermore, the different approaches should provide comparable results when applied to the same system since N supply should be the same as (the total N input–total N loss), provided all the N losses are known (including denitrification).

The N-budgeting approach is most useful for estimating the whole food system NUE, because it aligns better with the application objectives and the data required for its calculation are readily available. Nitrogen budget approaches compile the inputs and outputs of nitrogen across the boundaries of a system in order to model and quantify internal nitrogen fluxes by using a mass-balance approach. This approach captures all N in all the relevant steps throughout the food system and it can be applied to a range of products and locations with readily available international data sets.

Table 1. Advantages and disadvantages of four different full-chain nitrogen use efficiency approaches: life cycle analysis, nitrogen footprint, nitrogen budget, and environmental impact assessment.

| | Advantages | | | | | Disadvantages | | | | | | | |
|---------------------------------|--------------------------------|-----------------------|-----------------------------------------|--------------------------|-----------------------------------------------------------|------------------------------------|------------------------------|----------------|---------------------------------|-------------------------------------------|--------------------------|---------------|----------------------------------------------------|
| | Links to Environmental Impacts | Can Account for Trade | Flexible System Boundaries ¹ | Models Internal N Fluxes | Socio-Economic, Cultural, and Health Impacts ² | Can Account for Recycled and New N | Mass Flow Model ³ | Data Intensive | Inconsistent Allocation Methods | Difficult to Compare Impacts ⁴ | Regional Level and Above | Site-Specific | Indeterminable Fate of System Outputs ⁵ |
| Life Cycle Analysis | X | | X | | X | | | X | X | X | | X | |
| N Footprint | | X | X | X | | X | X | X | X | | X | | |
| N Budget | | X | X | X | | | X | | X | | X | | X |
| Environmental Impact Assessment | X | | X | | X | | | X | X | X | | X | |

¹ In most cases, the system boundaries are not predetermined and can be established to accommodate data gaps and the study objectives; ² Some N indicator models have the ability to link to environmental, health and socio-economic impacts, which can be advantageous when used to inform policy; ³ The terminology ‘mass flow model’ represents all balance equations that can be used to calculate intermediary stages. This is useful when quantifying flows that cannot be directly measured; ⁴ When linking a study to its environmental effects, it is not yet possible to objectively compare and contrast across impacts. To this point, one cannot definitively rank ‘products’ according to their level of sustainability, and impacts are usually measured on a regional basis, so cannot be scaled up without expanding the system boundaries; ⁵ e.g., leaching vs. denitrification.

5. Definition of a Full-Chain NUE (NUE_{FC})

A food system can be regarded as a chain of sectors and activities: the producers, the collectors, the processors, the distributors, the retailers and the consumers. Within each sector, activities reduce the amount of N that makes it to the next stage of food production, e.g., through food waste or other losses to the environment. The result is that the total amount of N embodied in the product decreases with each step. For a particular food system, a distinction is often made between the production of plant and animal protein (e.g., [20]). Animal protein production adds other steps to the cycle and introduces the recycling of manure. Since nutrition is the essence of food, to achieve a maximum NUE_{FC}, the Consumed N should be as high as possible and the New N as low as possible. The NUE for each step in the food chain (Figure 1) is defined as Consumed N (the outputs) divided by New N (the inputs). For each step in each 'sector', a ratio can be derived, which represents the efficiency of the sector in terms of N use, e.g., Edible crop N/Crop N, which represents the efficiency of the processing of crops.

In order to calculate the NUE for the whole food system using the budgeting approach, the use of N in the system has to be estimated. The amount of N of each sector (Figure 1) is needed to calculate the associated NUE of that sector. One complicating aspect is that NUE is influenced by the import and export of food and feed. These trade flows have to be included in the equation, as NUE_{FC} represents the NUE of the entire food system. NUE_{FC} is defined as follows:

$$\text{NUE}_{\text{FC}} = \frac{\text{N food availability}}{\text{fertilizer} + \text{BNF} + \text{atm. dep} + (\text{import} - \text{export}) + \text{changes in stock}} \quad (1)$$

Here 'N food availability' (consumption) is usually determined by the N supplied to the households.

This equation includes N inputs to agricultural systems via the atmospheric deposition of non-agricultural sources (fossil-fuel-based emissions) and not the total N deposition and not the entire country (total surface area). The major components of NUE_{FC} are shown in Figure 1. The net import (import–export) was used instead of placing 'export' in the denominator and 'import' in the nominator, because for countries where import and export are very high (throughput) this influences the efficiency. In the ideal case, the NUE for the imported products should be taken into account, but because of lack of data this is not included. The same holds for the exported products. In Equation (1) 'change in stock' is the annual net balance of the imports and exports of a country, which includes the storage of products. This term is zero over the long-term, but can be significant for a single year. Since we are focussing here on the national level, we assume that internal cycling of nitrogen within the country does not affect the NUE when using country-scale production and food availability.

The equation above defines the NUE over the whole food system, but it can be split into different parts, such as food processing, the agricultural system, or the consumer whenever data are available. NUE is represented by the agricultural system NUE as defined by the EU Nitrogen Expert Panel [8].

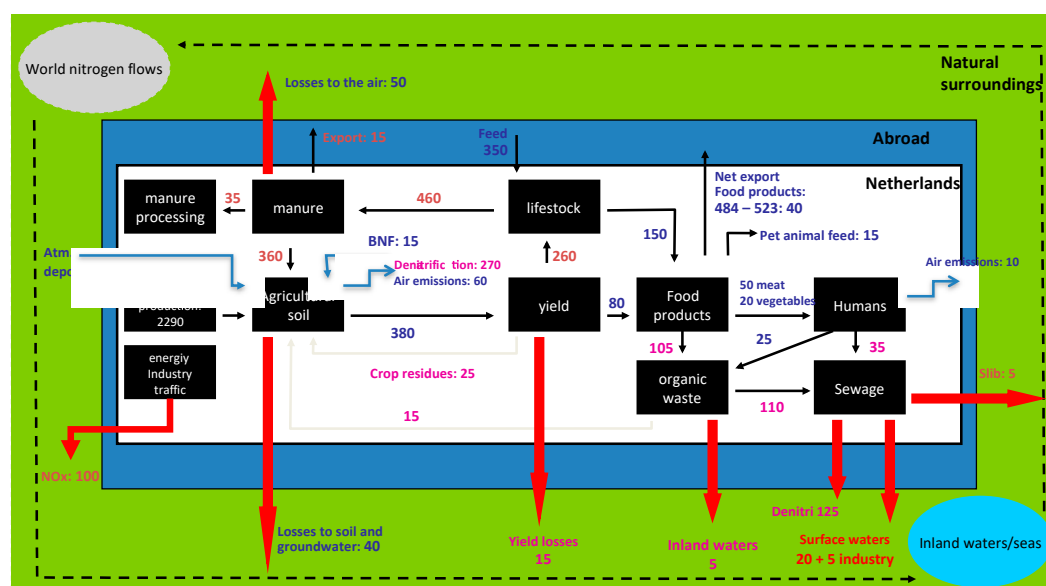
The data needed for the country level are listed in Table 2. With the data available in Europe, the *country level* can be calculated using the FAO Food Balance Sheets for protein consumption (availability of food), while for all commodities the N content was taken from [31] to obtain the total food N supply (N Consumed). Further, fertilizer statistics may be obtained from Fertilizers Europe (through the European Statistical Office—EUROSTAT), biological nitrogen fixation (BNF) from [46], or more recently from [31], and atmospheric deposition to agricultural lands from the European Monitoring and Evaluation Programme (EMEP) [47]. In addition, Edible crop N, Vegetable N and Consumed N for crops are needed, and data for animal protein food availability, which are available from the statistical database of the Food and Agriculture Organization (FAOSTAT). Furthermore, data on the import and export of feed, plant and animal protein are available from the FAO statistics.

Table 2. Overview of data that are needed for the country-level approach for calculating nitrogen use efficiency with a nitrogen budget approach.

| Part of NUE | Specific Flow/Part of NUE | Country Level Data Source |
|----------------------------------------------------------------|----------------------------------------------|-------------------------------------------------------------|
| New N | Fertilizer | Fertilizer application per crop, IFA; FAOSTAT |
| | Biological N fixation | [46] |
| | Atmospheric deposition to agricultural areas | European Monitoring and Evaluation Programme (EMEP) |
| | Import–export | Country matrix, [31] based on FAOSTAT |
| | Stock change | FAOSTAT food balance |
| Agricultural systems NUE (see EU Nitrogen Expert Panel (2016)) | | N-budget on the country scale |
| Food processing | | FAOSTAT Food balance |
| Food N food availability for consumption | | FAOSTAT, note this is the food availability for consumption |
| N content of food products | | [31] |

6. Application of the Country Approach

The previous section provided the general definition and methodology for estimating NUE_{FC} . In this section, the applicability of the methodology is tested using detailed national data for the Netherlands. This detailed result can then be compared to the simpler calculation with internationally available data sets in the following section. The N flows in the food chain of the Netherlands for 2005 are shown in Figure 2. The estimation of the NUE of the food chain (NUE_{FC}) is complicated because of the large trade in food and feed with other countries, which is all included in the FAO database.

**Figure 2.** Nitrogen flows in the Netherlands for 2005 (Kton N) estimated using the budgeting (mass balance) method translated from [48].

Using the budget approach, the NUE_{FC} in the Netherlands for 2005 was estimated at 18% [48]. The total food availability for consumption was 70 Kton N (50 Kton animal protein and 20 Kton vegetal protein). The net import was estimated at 40 Kton (523 Kton of import of mainly feed for animals and 484 Kton of exported food products). The total input of new N to the system includes fertilizer (280 Kton), imported feed (350 Kton), BNF (15 Kton) and atmospheric deposition to

agricultural soils (55 Kton) [48]. Most of the atmospheric deposition results from the national sources (ammonia emissions from agriculture and NO_x emissions from fossil fuels). The NUE_{FC} can be split into a food processing and a food production component. Food processing was calculated using Equation (1) and the data from Figure 2; the efficiency of the food processing sector was 48% (including recycling of 15 Kton), which means that 48% of N is retained during processing. The production of food products (up to the food processing: the farm gate efficiency) has an efficiency of 36%.

The NUE_{FC} for the consumption of plant and animal protein can only be calculated separately if the input as New N for the two sectors (crop production and livestock production) is known. Here, corrected fertilizer and manure inputs were used. This was achieved using the ratio of the output (80 Kton) over the input to livestock (260 Kton) to correct for the animal and plant protein inputs. The resulting NUE_{FC} for plant protein in the Netherlands is 12% and for animal protein 6% (without the net export of protein).

The Netherlands has a high export/import ratio because of the large trade in feed and food. These large flows greatly affect the accuracy of NUE_{FC} . Therefore, the net import (import–export) instead of the ratio of export over import is used in Equation (1).

7. NUE in the Netherlands Based on FAOSTAT Data Compared to National Statistics

For the application of Equation (1), consistent data have to be used, such as the FAOSTAT Food Balances (see Table 2). The level of detail used in the calculations depends on the availability of data. For each food category of the FAOSTAT food balance the nitrogen content was derived from [31] to calculate the nitrogen entering the household (N Consumed). FAOSTAT data were used on country N input (fertilizer, BNF, feed, import-export and stock) and protein food availability for consumption data to calculate the country average NUE_{FC} using Equation (1).

Table 3 shows the comparison between the Netherlands NUE_{FC} as derived from the detailed national statistics using Equation (1) ([48]) and when data from broader and more general databases available for all countries are used. The FAOSTAT data are different from the data for the Netherlands as derived from national statistics. The reason is mainly because different food components are included with different N contents. The NUE_{FC} based on the FAOSTAT data is 18% higher than that based on national statistics. In recent years, manure export has increased from about 10 Kton/yr in the 1990s to currently 40 Kton/yr, which makes it an important component to take into account. However, these data are not available in FAOSTAT.

Table 3. Comparison of different components of the nitrogen balance in the Netherlands (2008) and resulting NUE_{FC} as calculated using Equation (1) in this report.

| | | This Study | Roell and Erisman [48] |
|---------------------------|-------------------------------|------------|------------------------|
| | | Kton N/yr | Kton N/yr |
| year | | 2005 | 2005 |
| Output | Consumption | 112 | 70 |
| | Export food/feed | 292 | 484 |
| | Manure export (national data) | 15 | 77 |
| Input | Fertilizer | 279 | 280 |
| | BNF | 4 | 15 |
| | Deposition | 49 | 56 |
| | Import food/feed | 392 | 523 |
| Net annual change | Annual changes in stock | 18 | |
| | | % | % |
| NUE | | 25 | 18 |
| NUE (incl. manure export) | | 26 | 22 |

Table 3 shows that the NUE_{FC} using the different datasets come to somewhat different outcomes (respectively 25% and 18%). When manure export is taken into account the results are within 20% of

each other. The major differences are caused by the differences in imports and exports and in food availability data. The latter depends strongly on the components that are taken into account.

8. Country Level NUE_{FC} in the EU Based on FAOSTAT

National data were used for a set of European countries to calculate NUE_{FC} using Equation (1) and the data as indicated in Table 2. The resulting NUE_{FC} for the countries are plotted in Figure 3 for the year 2008. It shows that there are large differences between countries: Ireland had the lowest NUE (10%), while Italy had the highest NUE (40%) in 2008. The difference in NUE for the countries can be explained by the difference in N input (such as BNF) and by the import–export ratios. In the next sections, first the NUE values will be compared to the literature values, followed by an estimate of the trends in NUE_{FC} .

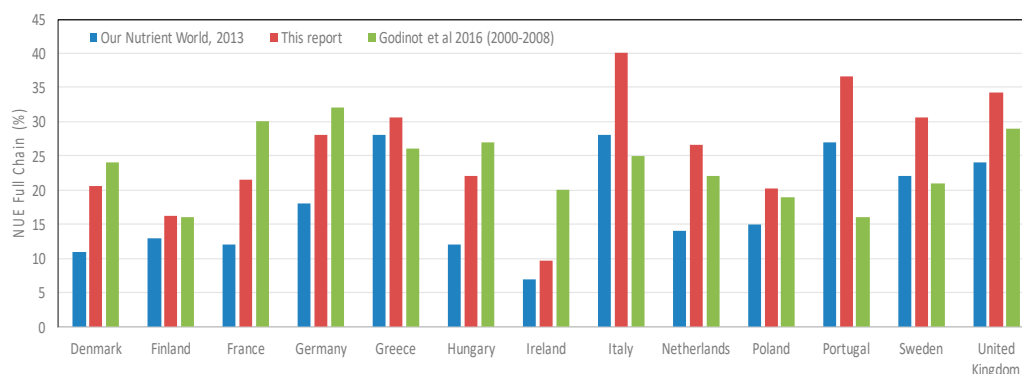


Figure 3. NUE_{FC} calculated by [7] (Our Nutrient World, blue bars); by [34] in green; and data and methods proposed in this report for a country-level NUE indicator for 2008 in red.

Earlier FAOSTAT data were used by Sutton et al [7] on country N input and protein food availability to calculate country average NUE_{FC} , where the total amount of N in plant and animal food is considered as a fraction of the total new N input from mineral fertilizers, BNF and imported feed and food. Figure 3 for the year 2008 shows a comparison of the data in Sutton et al. (2013), and those calculated here for some countries in Europe for the year 2008. Overall, the data by Sutton et al. are at least 25% lower than calculated here, mainly because of the net import considered here in order to correct for the share of inputs that is used for exported food and feed. Recently, Godinot et al. [34] used several methods to calculate NUE for agricultural production (not the food chain NUE). Their estimates, averaged for the years 2000–2008, are also plotted in Figure 3 for comparison. By definition the NUE for agriculture by Godinot et al., should be higher than the NUE_{FC} since more losses further in the food chain after the farm gate reduce the overall NUE . Figure 3 shows that for half of the countries this is indeed the case, but for Italy, the Netherlands, Portugal, Sweden and the UK, the NUE_{FC} values are higher than those for agriculture. The differences clearly represent the uncertainty in the data and approaches. If the differences between the three methods are considered as a measure of the uncertainty, the NUE_{FC} calculated here has an uncertainty of at least 25% (calculated as the average standard deviation between the different national values).

9. Country Level NUE_{FC} in the EU between 1980 and 2011

Figure 4 shows the trend for different countries in Europe between 1980 and 2011. Again, Italy shows the highest and Ireland the lowest NUE_{FC} . Overall, NUE_{FC} increased for all countries with time mainly due to the reduction in fertilizer use and a steady increase in the availability of protein for consumption, either produced nationally or through import. The changes over the years are not smooth because of the different changes in N -stock and import and export of N . In some years the stock increased and only reduced in the following year. Therefore, when trends are presented in

NUE_{FC} it is better to use moving averages of three years. Some countries showed an initial increase until 1990 and a subsequent decrease. This is especially true for the Eastern European countries and has to do with the economic situation that drastically changed since 1989 after the breakdown of the wall and with the reduction in fertilizer subsidies, which influences the input as well as the output.

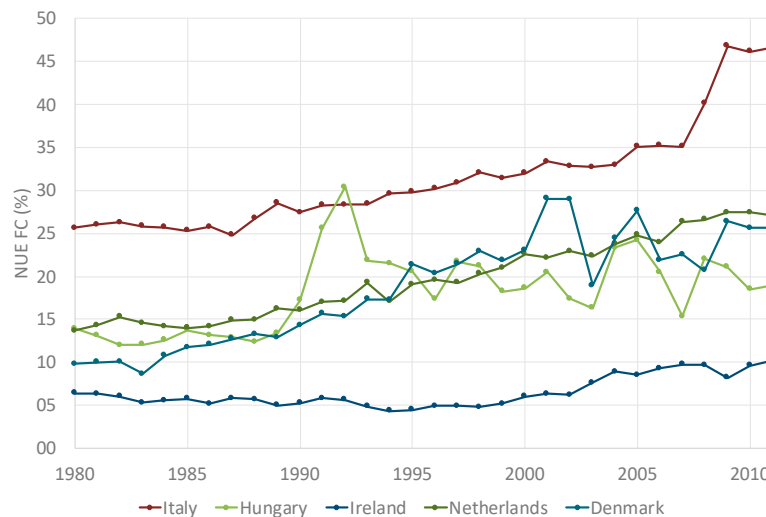


Figure 4. Country-level NUE_{FC} calculated for different countries in Europe between 1980 and 2011.

10. Factors Determining NUE_{FC}

There are several factors that influence the NUE_{FC} . In this section we discuss total N input, import–export and BNF. Five European countries were selected, which show different levels and trends, to determine the influences of the different factors: Hungary, Ireland, Italy, The Netherlands and Denmark. Figure 5 shows the relationship between NUE_{FC} and the total input of new N (nominator of Equation (1)) on a per capita basis. Overall the trend is the same: if the total N input increases, NUE_{FC} decreases. NUE_{FC} strongly depends on the per capita N input, mainly because the total consumption increases with the population number. The curve in this graph is not unexpected, but the position and trends of the individual countries are interesting. These might be caused by the types of food produced in that country, but we do not have the information to test this. The aim should be to move up the curve towards higher NUE_{FC} with lower per capita NUE_{FC} .

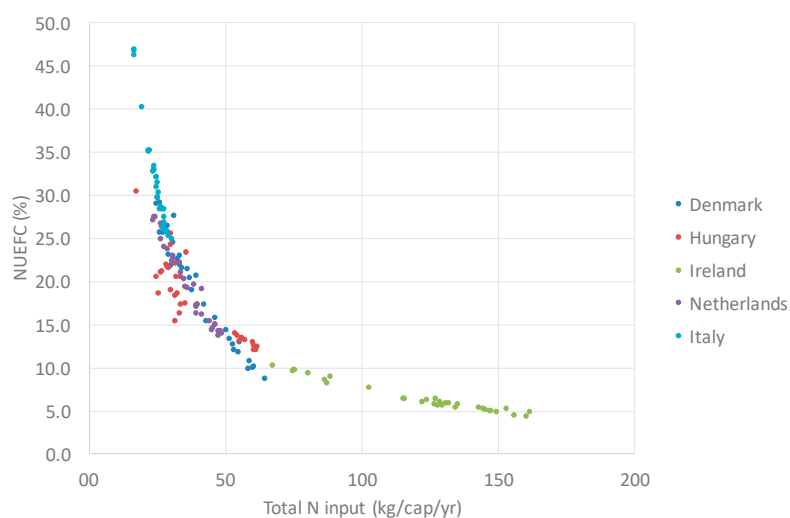


Figure 5. Relationship between NUE_{FC} and the total per capita N input.

Another important factor is BNF. In the calculation, BNF is taken as new N and thus if BNF increases, NUE decreases. However, countries that have a high NUE, such as Italy, have a higher BNF input. This might be explained by the type of agricultural system in the different countries. If BNF is high, the use of soil nitrogen for crop production is higher and less fertilizer is used, therewith the NUE of the agricultural system compared to systems using inorganic nitrogen inputs is lower. Therefore higher NUE_{FC} is observed. This, however, needs to be further quantified.

As shown for the Netherlands, the import–export ratio is very important in the calculation of NUE. The net import was taken into account to calculate NUE_{FC} instead of the ratio of export over import as explained earlier. For the Netherlands, the imported N, mainly as feed, is processed and exported as food leaving behind the wasted N. Italy depends on import for their food supply. For both countries it is shown that if the net import goes up NUE increases. There is no such relation for the net-exporting countries. It must be emphasised here that the NUE for the imported N has not been taken into account and thus is implicitly assumed to be 100%, just like the NUE for exported products, which is untrue. In the next stage of development of the NUE_{FC} , either NUE of imported products should be included with a value that is based on the production and processing in the exporting country. Alternatively, one would have to follow in detail the process level of products being imported and exported, and attribute what happens in each (foreign) country individually—this is obviously a task not easily feasible, and needs to be tackled in a more elaborative approach (i.e., in the future).

11. Use of the Indicator

This section discusses if and how the indicator can be used to support policy and what is needed to further develop the indicator. A target for policy could be the use of the NUE indicator in relationship to per capita consumption. The World Health Organization recommends levels of protein consumption for age classes split between men and women. The average recommended level of consumption (expressed in terms of N) is 3 kg N/capita/year [49]. In general, it would be expected that the NUE will increase if the consumption per capita decreases, because the expectation is that this goes along with lower inputs. This holds especially for a decrease in processed food and a change towards more plant protein. For policy, it could be the aim to increase NUE, together with maintaining nutrition levels, but not exceeding recommended levels of protein consumption. For all countries the food availability for consumption is far above the recommended level. For most countries, the food availability goes up with higher NUE, except for Ireland, which shows no trend, and Hungary, which shows a decrease in food availability relative to NUE. There is therefore no clear relationship between food availability for consumption and NUE. This questions the usability of the indicator based on the current calculations. In the future this needs to be further tested.

Given the limited availability of data and the uncertainty associated with the different steps in the food system, it appears that the NUE_{FC} indicator cannot be used easily for the optimization of the food production—consumption chain, nor can it be used for food labelling. The NUE_{FC} indicator proposed here is suitable for supporting national policies and provides information about nitrogen consumption relative to the new N used to produce the consumed N. For food labelling, Leach et al. [20] propose to use the footprint approach.

The applicability of the NUE_{FC} depends strongly on the availability of data, such as crop-specific fertilizer and manure data, data on the recycling of manure, BNF and deposition, soil N availability and use, N food availability for consumption, and loss fractions for each step in the food system. It was illustrated here for the Netherlands that when these data are available, the NUE_{FC} can be calculated (excluding energy and transportation). It was shown that for the Netherlands the availability of protein N for consumption increased over the past decades both due to increased production nationally and through imports, while the N inputs decreased, implying an improved NUE_{FC} . The current NUE_{FC} is still in the low range, 12% for vegetal products and 6% for animal protein, and there is room

for improvement of the methodology of estimating NUE_{FC} , especially by addressing the balance of feed import.

The NUE_{FC} indicator has the potential to provide information about the developments of the national NUE_{FC} . For policy applications, one can imagine to set a so-called protein target, defined for example as the NUE for the whole food chain, or a food processing target. One could also think of targeting the share of plant protein in the whole food chain to increase NUE . However, the robustness of the indicator has to be improved by better including the NUE of imported protein and by separating national production from the import/export of protein. The ratio and the differences between animal protein and plant protein could also provide important information about the national NUE_{FC} .

12. Next Steps

This initial study points in promising directions but, at the same time, raises numerous issues regarding data availability and the way that various values are used in calculations. The treatment of import and export of food is a particularly tricky aspect that has not yet been satisfactorily resolved. Estimations of biological nitrogen fixation also need better quantification. The way manure is treated in the calculations may also need further consideration. Deriving values for NUE_{FC} at the national level is therefore challenging and differences between countries in the examples given should be interpreted with great care until the methods and data are further improved.

The framework presented in this paper does not take into account the role of the circular economy in N management. With the complexity of the food system, a circular economy is important in moving towards sustainability because it promotes the recycling of food wastes either as compost or feed to animals, recycling of sewage in agricultural soils, and reuse of crop residues either as compost or animal feed, etc. These recycled flows are not taken into account in this framework. If this indicator is to be used for policy and decision-making, the focus should be on how to stimulate the circularity in nitrogen management.

The logical next step is to further develop, improve and test a comprehensive NUE_{FC} indicator as proposed now in Equation (1). This requires further data collection for Europe. This approach requires estimations of country-specific N flows for different steps in the food system, including the NUE for imported protein and the distinction between exported protein and national consumption. These N flows may be used to calculate the NUE_{FC} for the new N inputs and include the recycling of crop residues and manure. This can be carried out for each country in Europe. An uncertainty analysis should be carried out on the national scale per crop and/or meat product. Also, the uncertainty of the data and the robustness of the inventory systems need to be assessed. Finally, the next steps needed to develop the indicators for relevant policy will include a test of the consistency and quality of the data and the set-up of a baseline calculation and a monitoring program.

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Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

This literature review accounts for the major approaches used to assess nitrogen efficiency over the food system: (1) life cycle analysis (LCA); (2) nitrogen footprint; (3) nitrogen budget; and (4) environmental impact assessment. We reviewed the merits and drawbacks to of each approach.

Appendix A.1 Life Cycle Analysis (LCA)

Life cycle analysis quantifies the potential environmental impacts of a product, process, or service by assessing the inputs and outputs within a defined system boundary. The approach is conducted by first compiling an inventory of material inputs and environmental releases. The inputs and losses are then linked to environmental impacts, such as eutrophication potential or acidification potential. All losses and impacts are reported relative to a defined functional unit, such as 1 kg of beef or another product. Software tools are available for LCA.

A benefit of LCA is that it can be widely applied through available LCA software. Though LCAs can be applied to a range of ‘products’ and locations, their design also has limitations. When conducting a LCA, choosing an appropriate system boundary and functional unit is key to expressing results in a succinct yet widely applicable manner. Comparing LCA results is only appropriate when two systems have the same system bounds and functional units. Harris and Narayanaswamy [15] suggest choosing a functional unit that reflects the way a commodity is traded so that results may be translated across trans-national boundaries, and expanded to include economic analyses. Most studies examined here reflected this notion when choosing their functional units. Brentrup et al. [11] performed calculations in terms of tons of wheat, while [14] focused on 1 MJ of biofuel production. When using a software tool, the factors built in to the LCA tools are often not applicable to a system of interest and must be modified.

Though LCAs can link to environmental impacts, they are also data and resource intensive, which can be a significant disadvantage to regional-level analyses. Often data inputs are directly measured, which, though advantageous to site-specific investigations, are difficult to scale to a region.

Life cycle analysis studies:

- Ahlgren et al. [9]: Sweden (straw).
- Brentrup et al. [10]. Germany (sugar beets).
- Brentrup et al. [11]. Europe (no crop specified—general background/challenges associated with farm level LCA).
- Brentrup et al. [11]. United Kingdom (winter wheat).
- Caffrey et al. [12]: United States (LCA challenges/perspectives).
- Cederberg et al. [13]: Sweden (milk).
- Gallejones et al. [14]: Spain (biofuel).
- Grizzetti et al. [38]: LCA of food waste across the food system.
- Harris and Narayanaswamy. [15]: Australia (reviews cases).
- Liao et al. [16]: Model of nitrogen releases in LCA of crop production.
- Pelletier & Leip [17]: Nitrogen characterization factors that can be used to aggregate nitrogen flows in LCA. Tested using average EU-27 consumption.
- Thomassen et al. [18]. The Netherlands (conventional/organic milk).

Appendix A.2 Nitrogen Footprint

The footprint methodology captures total nitrogen losses to the environment resulting from the production of a defined unit of food. Usually completed on a regional scale, N footprints have the capacity to span the entire chain of a product from farm level and food processing to transport and consumption. Though often employing mass balance techniques that are commonly used in nitrogen budget approaches, N footprints aim to quantify commodities in a manner that allows inter-product comparisons to be made and conclusions to be drawn.

Though N footprints do not allow users to link products to environmental or social impacts, they do provide an advantage in that their outcomes are on the same platform, and can thus be compared. These comparisons are, in part, due to the ability of an N footprint to function on a regional level or above. Generalized processing and food waste data can often be used in place of site-specific measurements as are usually required in a LCA.

N footprint approaches are also able to model internal N fluxes and credit the system where recycled N should be accounted for, as in [20]. Chatzimpiros and Barles [19] were able to account for BNF and atmospheric deposition in their N footprint calculations, while also crediting manure excretions back into the system for crop production.

Nitrogen footprint studies:

- Chatzimpiros and Barles. [19]: France (beef, pork, and milk).
- Leach et al. [20]: the Netherlands and the United States (broccoli, lettuce, tomato, spinach, potatoes, beans, corn, broiler chicken, pork, beef, fish, milk).
- Leip et al. [32]: European Union (vegetable and animal products).
- Oita et al. [50]: Global (The nitrogen footprint of nations).
- Pierer et al. [22]: Austria (poultry, pork, beef, milk, vegetables and fruit, potatoes, legumes, cereals).
- Stevens et al. [21]: United Kingdom (poultry meat, pigmeat, beef, milk, fish and seafood, cereals, pulses, starchy roots, vegetables).

Appendix A.3 Nitrogen Budget

Nitrogen budget approaches compile the inputs and outputs of nitrogen across the boundaries of a system in order to model and quantify internal nitrogen fluxes by using a mass balance approach. Within this approach, we classified two subcategories, the nitrogen balance indicator approach and the food system waste/loss approach. A nitrogen indicator uses the mass balance methodology to measure the difference between the N available to an agricultural system and the uptake of nitrogen by agriculture. The food system waste/loss category is similar, but emphasizes the losses of N through waste, especially during transport and processing, where losses can be high.

A major advantage to this approach is its ability to quantify indicators, which are often used to supply information on other variables that cannot be measured directly. In the case of a FAO study in 2011, Gustavsson et al. [40] used mass flows models to account for the loss or waste incurred during each step of the production process. This included agricultural production, postharvest production, handling and storage, processing, distribution, and consumption, indicating its widely applicable nature throughout each stage of the chain. However, though N budgets can effectively quantify intermediary steps, they often have difficulty determining the fates of the system outputs, and examining internal flows in a greater level of a detail.

Nitrogen budget studies:

- Bleken and Bakken [26]: Nitrogen efficiency of food production in Norway.
- Dalgaard et al. [27]: Poland, the Netherlands, France, Italy, Scotland, and Denmark (poultry, sheep, beef and dairy cattle, pigs, maize, forage, oilseed rape, “horticultural crops”, silage maize, winter wheat, “leguminous plants”, water buffalo—dairy, alfalfa, “vegetables”, grass/clover, peas, oats, fava bean, rye, barley, triticale, and wheat) Cover inputs/exports: beet pulp, cereals, eggs, feed milk, fresh milk, alfalfa, grass, grass/clover, hay, various concentrates, meat, rape cake, soybeans, soybean oil cake, straw, sugar beets, whey, and silage—alfalfa, beet pulp, clover grass, grass, maize, whole crop.
- Galloway and Cowling [28]: Global nitrogen efficiency of plant and animal production.
- Grizzetti et al. [38]: quantifies the nitrogen loss to the environment related to food waste at consumption at the global and European scale and analyses its relative impact on the environment. Examined: cereals, roots and tubers, oilseed and pulses, fruit and vegetables, meat, fish and seafood, and milk (Global).
- Gustavsson et al. [39]: Uses mass flows model to account for losses and waste incurred during each step of the commodity’s food supply chain. Examined: cereals, roots and tubers, oilseeds and pulses, fruits, vegetables, meat, fish and seafood and dairy products. A variety of

countries were considered, referred to in paper as industrialized (medium/high income) countries and developing (low income) countries.

- Howarth et al. [29]: USA nitrogen budget, including food and energy production and consumption.
- Isermann and Isermann [44]: Germany nitrogen balance for food and feed production and consumption.
- Lassaletta et al. [31]: Analyzes importance of international trade of food and feed in the alteration of the N cycle at the global scale. Considered 12 regions, with 210 countries (incl. Africa, Europe, India, N. America, etc.) Examined 407 vegetable and 128 animal products.
- Leip et al. [32]: Regionalized focus for Europe (cereals, oilseeds, pulses, fodder maize, fodder beet, grass, beef, pork, poultry meat, cow milk, eggs).
- Ma et al. [33]: NUFER model (Nutrient flows in Food chains, Environment and Resources use) is an integrated assessment model for analysing N and P flows in the food chain from both production and consumption.
- Godinot et al. [34]: Proposes new farm nitrogen budget indicators.
- Oenema et al. [1,35]: The Netherlands (dairy cattle). The UK and the Netherlands—global perspective on manure management (pig, poultry, beef & dairy cattle).
- Oita et al. [50]: Multi-Regional Input-Output analysis that assesses trade-related impacts from a consumption perspective. Applied at a global scale to quantify nations' footprints. Examined 15,000 industry sectors and 189 countries.
- Parfitt et al. [40]: Review of global food waste literature throughout the supply chain.
- Shindo et al. [36]: Reports the nitrogen load for East Asian countries.
- Westhoek et al. [45]: Assesses environmental impacts and health effects of diets with reduced meat and dairy in Europe.

Appendix A.4 Environmental Impact Assessment

Environmental impact assessments provide a means of evaluating the likely environmental impacts of a proposed product, while also taking into account inter-related socio-economic, cultural, and human health impacts both beneficial and adverse.

Though results are can be attributed to specific impacts, the analysis stops short here. Impacts are unable to be objectively compared, as a definitive ranking system has yet to be developed that will allow scientists to compare a product's carcinogenic effects to the degree of eutrophication it causes. Similarly to a LCA, it can be data intensive and site specific, negating the ability to generalize these impacts to another similar product. For this reason, environmental impact assessments cannot be widely applied without significant time and resource inputs.

Environmental impact assessment studies:

- OECD [41]: The guide is not intended to target one specific country, but the following are member countries of the Organization for Economic Co-operation and Development: Australia, Austria, Belgium, Canada, the Czech Republic, Denmark, Finland, France, Germany, Greece, Hungary, Iceland, Ireland, Italy, Japan, Korea, Luxembourg, Mexico, the Netherlands, New Zealand, Norway, Poland, Portugal, Slovak Republic, Spain, Sweden, Switzerland, Turkey, the United Kingdom and the United States. No specific food types are targeted in this analysis.
- Payraudeau and van der Werf [42] has been applied to the following countries and products/foods:
 - Environmental risk mapping: Ecuador (soil nutrient balance), Italy (impacts on water quality).
 - LCA: Europe (energy crops), Germany (complete conversion from conventional to organic farming).

- Environmental impact assessment: Brazil (ag. technology).
- Multi-agent system: France (groundwater evaluation). Thailand (catchment irrigation).
- Linear programming: Germany (farm level—crops not specified), Mali (crops unspecified).
- Agro-environmental indicators: Europe, Bangladesh.
- Van der Werf and Petit [51]: The guide reviews 12 indicator-based methods spanning a variety of countries and agricultural topics. The relevant studies are as follows: Malaysia (cabbage), four undisclosed locations in Europe (energy crops), Philippines (rice), France (integrative farming animal/crop diversity), and Switzerland (farm pollution sources).

Relevant Gaps

Inconsistent allocation methods are the most notable gaps in each of the reviewed approaches. It is during this phase of the calculations that the most bias is introduced. ISO 14040 standards recommend system expansion and substitution whenever possible, but often these are not viable options due to resource and data limitations. Harris and Narayanaswamy (2009) review alternative methods of allocation and the merits associated with each, including mass weight and economic value. The overwhelming conclusion states that choice of allocation method is subjective, and there has yet to be data supporting one alternative method over the other.

The following gaps were identified in the reviewed methods:

- There is inconsistency in accounting for exports as a portion of national production.
- When performing an N-footprint, some studies chose to include atmospheric emissions and others did not. This can drastically change a food product's environmental footprint.
 - If including atmospheric emissions, estimating emissions can often be difficult since emission factors (EF) can vary drastically depending on a variety of variables (i.e., soil type, amount of precipitation, amount of N fertilizer applied, etc.)
 - Additionally, emission factors must be included from the extraction of raw materials to make fertilizer, from all farm equipment on a farm site, as well as emissions from manure.
- Variability in accounting for biological N fixation.
- Not many studies differentiate between new (e.g., synthetic fertilizer) vs. recycled (e.g., manure) N inputs.
- Difficulty with and a relatively high amount of inconsistency in approaching crop rotations, which, most articles agree, is a limitation in calculating an accurate N footprint.
- Animal product allocation at farm gate. There are a variety of methods for determining how much of the N-footprint should be allocated toward multiple products resulting from one animal (for example: butter, milk, meat, etc.), and it is difficult to choose the appropriate methodology.
 - Weight, economic value, system expansion, by-product displacement, etc.
- Accurately assessing nitrogen leaching. This usually needs to use a model, and in order to estimate leaching, most studies suggested examining farm dynamics on a relatively small scale.
- Main limitation: Connecting the results of the N-footprint, LCA, etc. to actual environmental impacts. This is the number one limitation in all of the studies.

Appendix B

Detailed literature review of four full-chain nitrogen efficiency indicators: Life cycle analysis (Table A1), nitrogen footprint (Table A2), nitrogen budget (Table A3), and environmental impact assessment (Table A4).

Table A1. Literature review: Life cycle analysis as a nitrogen efficiency indicator.

| Reference | Study Domain | Methodological Scope | Key Features | NUE Value | N Input Values | N Output Values |
|------------------------|---------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----------|----------------------------------------------------------------------------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Ahlgren et al., 2012 | National (Sweden) | Land use, energy use and greenhouse gas emissions from the production of ammonium nitrate based on biomass. Cradle-to-gate. | 1. Describes how N flows change in response to a possible decision and includes effects both inside and outside the life cycle of the system. 2. Identify short and long-term marginal target changes to determine fluctuations in system. 3. Accounts for recycling of nitrogen fertilizers. | n/a | n/a | n/a |
| Brentrup et al., 2001 | National (Germany) | Determine Eco-indicator values & evaluate the impact of three different nitrogen fertilizers on the entire environmental burden associated with a sugar beet production system. | 1. Life Cycle Impact Assessment—aggregate inventory data to produce one index representing environmental burden. Particularly weighting factors using the “distance-to-target principle”: ratio b/w current level and a target level of an effect. 2. Key issues missing in the Eco-indicator 95 method: the use of resources and land. 3. Comparative analysis related to global warming, acidification, eutrophication and summer smog. 4. Impact assessment cannot be performed site-specific. | n/a | N minimum in soil in spring, fertilizer N, atmospheric N deposition (15 kg/ha), net N mineralization during vegetation (15 kg/ha/day). | Ammonia volatilization (1–20% applied), nitrous oxide emissions, N removal with beets (1.8 kg/t sugar beet), N content of leaves (4 kg/t leaves), N uptake of winter wheat in autumn (5–10% of total N uptake, 210 kg/ha). |
| Brentrup et al., 2004 | Regional (Europe) | Evaluates impact of emissions and resource consumption associated with crop production on the following environmental effects: depletion of abiotic resources, land use, climate change, toxicity, acidification, and eutrophication. | New characterization method for abiotic resources and land use; particularly new aggregation, normalization and weighting. Foundation of weighting factors used the ‘distance-to-target principle’. | n/a | n/a | n/a |
| Brentrup et al., 2004 | National (United Kingdom) | Environmental impact of different N fertilizer rates in winter wheat production. | Assess resource depletion and environmental impacts. Impact categories: land use, climate change, toxicity, acidification, eutrophication. | n/a | Extraction of raw materials, production and transportation of inputs, all ag operations in field, application of fertilizer (0–288 kg N/ha). | Nutrient removal in grain and straw (30–212 kg N/ha), emissions due to energy consumption, volatilization, leaching. |
| Caffrey and Veal 2013 | Literature Review | Review inconsistent methodologies associated with co-products, regional and crop specific management techniques, temporal variations, spatial variations, and nonpoint emission sources. | 1. Land use change—examines direct and indirect implications regionally and globally. Discusses leachate and volatilization models, the consequences and processes of livestock production that should be considered. 2. Enteric fermentation and manure handling. 3. Considerations when including aquaculture. 4. Recommends the consideration of economics when comparing systems to determine the best mitigation strategies. | n/a | n/a | n/a |
| Cederberg et al., 2000 | National (Sweden) | LCA comparing organic and conventional milk production in Sweden in terms of environmental impacts and land requirements. | Conventional milk production was found to have a larger nitrogen surplus than organic per unit area, but organic has a greater N surplus per unit milk. | n/a | n/a | n/a |

Table A1. Cont.

| | | | | | | |
|-------------------------------|------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Gallejones et al., 2014 | National (Spain) | 1. Evaluates the variability due to site-specific conditions of climate and fertilizer management of the LCA of two different products: biodiesel from rapeseed and bioethanol from wheat. 2. Improves the estimates of the LCA impacts due to N losses normally estimated with unspecific emission factors, that contribute to the impact categories analysed in the LCA of biofuels at local scale. | 1. Integrated model simulations into a LCA assessment of biofuels; model accounted for local factors in the estimation of yield and N losses. 2. Crop production was the most influencing stage to every impact category. 3. Nitrous oxide subject to large variability in the LCA. 4. Coproducts addressed with system expansion. | n/a | Soil inorganic N flux (mineralized N from SOM, plant debris and organic amendments to soil), fertilizer N, mineralization. | Roots N, shoot N, grain N, volatilization, denitrification/nitrification/leaching losses, handling and storage, production of biofuel. |
| Harris and Narayanaswamy 2009 | Literature Review | Focuses on LCA agricultural literature relevant to the pork, poultry, cotton, sugar, red meat and livestock sectors. | 1. Goals: generally compared the environmental impact of farming practices or types of fed. 2. Allocation of co-products: economic allocation used in the past, but studies of beef and dairy have shown this to increase uncertainty. Preference—system expansion, physical relationships/causality, composition and economic value. 3. Merits of foreground (input processes, farm processes and production processes) and background (mining and extraction, grain production, transport) data sources. 4. Argues for uncertainty calculations to be incorporated into LCA results. | n/a | Varies by study: fertilizer N, soil organic and inorganic N, mineralization, manure, green manure. | Varies by study: root N, grain N, residue N, manure, coproducts, leaching, denitrification, nitrification, storage, food system processing. |
| Liao et al., 2014 | Varies | Study provides an overview of aspects that need to be taken into account for improved modelling of Nr releases in the LCA of crop production. | 1. On-site crop production must include the harvested portion of the crop and the soil with a changing depth down to the water table. 2. Nitrate, nitrous oxide and ammonia should be distinguished within the crop product system and b/w the crop product system and the ecosphere. 3. Stand-alone LCA studies of crop production and those coupled with process-based models should be based on a consistent spatial scale. 4. Fate of Nr losses in the ecosphere should be explicitly modelled in the life cycle impact assessment phase of the LCA of crop production. | n/a | 1. PRODUCTS & PROCESSES TO CONSIDER (multiple inputs & outputs). 2. Extraction of natural resources, fertilisers, pesticides, machinery, infrastructure, energy, allocation of crops and crop functions, crop residues, soil N processes (volatilization, nitrification, denitrification, runoff, leaching, fixation, etc.). | |
| Pelletier & Leip 2014 | Regional (Europe) | Provide set of over 2000 N characterization factors for use in aggregating N flows in LCA. Used life cycle data and N characterization factors to estimate aggregated fixed N losses for an average EU-27 consumer. | 1. Provided a set of over 2000 nitrogen characterization factors, which can be used to convert N species into weight of total N for aggregation. 2. The N characterization factors can be used in LCA and other approaches to estimate total N. 3. Applying the N characterization factors for an average EU-27 consumer using an LCA approach generated findings comparable to other studies, which confirms the use of the N characterization factors. | n/a | Inputs for LCA not explicitly described. Sectors considered in LCA were nutrition/food, shelter, consumer goods, and mobility. | Outputs/emissions for LCA not explicitly described. Sectors considered in LCA were nutrition/food, shelter, consumer goods, and mobility. |
| Thomassen et al., 2008 | National (Netherlands) | 1. Two Dutch milk production systems (organic—11 farms, and conventional—10 farms) were examined from cradle-to-farm-gate. 2. Animal manure, animals, milk, roughage/bedding material were outside of system boundary. 3. Excluded medicines, seeds, machinery, buildings, transport or processing of raw milk. | 1. Integral environmental impact (land use, energy use, climate change, acidification, and eutrophication) and hotspots were identified. 2. Conventional: purchased concentrates were found to be the hotspot in off farm and total impact for all categories. 3. Organic: purchased concentrates and roughage were found to be the hotspots in off farm impact. 4. Allocation of multifunctional processes was done on the basis of economic allocation. | n/a | Concentrate N content, electricity, diesel, methane emission (enteric fermentation & manure management). | Leaching of nitrate and phosphate (farm-gate balance approach), ammonia volatilization (manure in stable, manure storage, grazing, application of manure & fertilizers), nitrous oxide emission. |

Table A2. Literature review: Nitrogen footprint as a nitrogen efficiency indicator.

| Reference | Study Domain | Methodological Scope | Key Features | NUE Value | N input Values | N output Values |
|----------------------------|---------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Chatzimpiros & Barles 2013 | Local (France) | Livestock system for consumption of dietary N in the form of beef, pork and fresh milk in France. | 1. N Food-print: N loss associated with its agricultural production. 2. Uses the N Food-print to connect N flows and losses in livestock systems to the consumption of dietary N in the form of beef, pork and fresh milk. 3. Weight the amount of consumption proportionally to French administrative regions' share in the national gross meat and milk production; foreign countries: proportionally to their share in national trade balances. | 1. Feed crop cultivation on the livestock farms: Beef (76%) Milk (76%) Pork (62%). 2. Rapeseed Farms: Milk (40%) Cereal Farms: Pork (63%), Soybean Farms: Beef (50%). 3. Overall NUE in ration production: Beef (72%) Milk (56%) Pork (53%) 4. Overall NUE per livestock system: Beef (7.2%) Milk (13.4%) Pork (12.7%). | 1. Feed N—roughages (grasses and legumes), annual fodder (maize, beetroots, cereals and protein meals from soybeans/rapeseed crops). 2. N return in manure to fodder crops. 3. N losses from livestock farms (fodder land on the livestock farms). | 1. N in animal product and by-products (slaughter waste, as well). 2. N manure to crop agriculture. |
| Leach et al., 2012 | National (United States, Netherlands) | Per capita nitrogen footprint including housing energy, transport, food consumption & production, and goods and services. | 1. The food sector is the largest contributor to personal nitrogen footprints, especially food production. 2. Dietary choices influence the food nitrogen footprint; meat and dairy products have a larger nitrogen footprint than vegetable protein sources. | Farm-level data reported as virtual N factors, which describe the N losses during food production by food category. | Fertilizer, manure and BNF inputs, feed for livestock. | Food produced, losses to the environment at each stage of food production. |
| Leip et al., 2014 | Regional (European Union) | 1. Two different models (CAPRI & MITERRA) were used to quantify the N flows in agriculture in the European Union, at country-level and for EU agriculture as a whole, differentiated into 12 main food categories. 2. Did not include wastage that occurs during further processing, retail or preparation of food products. | 1. N footprint, defined as total N losses to the environment per unit of product, varies widely b/w different food categories with substantially higher values for livestock products (c. 500 g N/kg beef) as compared to vegetable products (c. 2 g N/kg product for sugar beet, fruits and vegetables, and potatoes). 2. Did not consider fish and seafood products. 3. Agricultural sub-pools considered: livestock production systems, manure management systems, soil cultivations systems, and links to human society (consumption, trade) and environment. | N footprint: Vegetables: 4.5–6.3; Livestock Products: 63.5–64.7; Food products: 31.5–33.1. | Crop residues; fertilizer; atmospheric deposition, biological N-fixation. | Losses dominated by N leaching and run-off, and ammonia volatilization. N outputs: product for which N footprint was calculated; 'waste' streams that are recycled; slaughter house waste; manure. |
| Oita et al., 2016 | Global | N emission flows embodied in international trade using a high-resolution global Multi-Region Input-Output (MRIO) database for 189 countries | 1. Connect the IPCC's model for the global N cycle with data on emissions of all forms of Nr to generate a complete account of emissions for 189 countries & 15,000 industry sectors. 2. Of the 117,000 Gg of N emitted worldwide, 25% of the total became embodied in international trade. 3. Traded N amounts vary significantly across countries. 4. Main net exporters are often developing countries and net importers are almost exclusively developed countries. | 117,000 Gg of N emitted worldwide per year. | Crop production, livestock manure, fertilizers, harvest area (161 crops, 215 countries); deposition; crop residues. | Emission to water and air: manure management, emissions to soil, surface water and underground water; Mineralization, leaching, denitrification. |

Table A2. Cont.

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|-------------------------|------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Pierer et al., 2014 | National (Austria) | 1. Footprints describe Nr losses, but do not link to effects. 2. Food production virtual N: real losses of Nr along the entire production and consumption chain (fertilizer application to final consumption). 3. Food production energy N: N loss associated with processes such as packaging and transportation; combustion-related emissions of NOx. 4. Food consumption N: all N consumed as food is excreted. | 1. Total N footprint dominated by food production & consumption (85%). 2. Avg. N Footprint: 19.8 kg N/yr per Austrian inhabitant. 3. Do not account for co-production; no allocation. 4. Compared N footprints to simple mass of food and protein content. Ex: vegetables & fruits as well as potatoes have very low N footprints per mass, but relatively high footprints per amount of protein. 5. Do not include fish or seafood. | Poultry: 24% Pork: 18% Beef: 11% Milk: 16% Cereals: 45% Vegetables & fruits: 19% Potatoes: 33% Legumes: 72%. | Applied N, N in harvested crop, N in the product after first raw processing, N in the product after second processing and packaging, N in meat product, N in milk product, N available as feed for animals, N in live animal, N in slaughtered animal. | N not taken up by crop, crop processing waste, handling & storage, processing waste, retail food waste, consumer food waste, food preparation waste, N excreted, slaughter waste. |
| Stevens et al., 2014 | National (United Kingdom) | 1. Food N Footprint: sum of the food consumption and food production N footprint. N parameters: available N, % of previous N available, N waste produced, % N recycled, N recycled, and N loss. 2. Energy N Footprint: housing and transport energy consumption, NOx emission factors, Environmental Extended Input Output analysis for food, housing, transport, goods and services. | UK N-Calculator used to test scenarios that would be affected by changes in consumption patterns: (1) Recommended protein; (2) Vegetarian diet; (3) 50% food waste; (4) Sustainable food; (5) Advanced wastewater treatment plant; (6) renewable energy; (7) Public transit, (8) Combination (#1-7). | N Footprint: 27.1 kg N per capita per year. | Applied N, N in harvested crop, N in product after processing, packaging, N in meat production, N in animal by-products, N in live animal, N in slaughtered animals. | N not taken up by crop, crop processing waste, handling & storage, processing waste, retail food waste, consumer food waste, food preparation waste, N excreted, slaughter waste. |

Table A3. Literature review: Nitrogen budget as a nitrogen efficiency indicator.

| Reference | Study Domain | Methodological Scope | Key Features | NUE Value | N input Values | N output Values |
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| Bleken and Bakken 1997 | National (Norway) | Estimation of the N efficiency of the food producing sector in Norway, including the overall production system as well as specific products. | 1. The food producing sector is the largest N-flow sector in Norway. 2. N-cost is defined as the ratio between fertilizer N-input and the N in products. 3. Recycling of wastes and dietary changes are key mitigation efforts. | Norway NUE = 10% | Synthetic fertilizer, biological fixation, atmospheric deposition, feed. | Wholesale food supply, food waste, sewage, trade export. |
| Dalgaard et al., 2012 | National/Regional (Poland, the Netherlands, France, Italy, Scotland, Denmark) | 1. Analyses farm N-losses and the complex interactions within farming systems by developing efficient methods for identifying emissions hotspots and evaluating mitigation measures at the farm and landscape scale. 2. Farm N balance defined as from the farm gate, including N inputs to the farm, and N outputs from the farm. | 1. Developed a common method to undertake farm inventories and the derivation of farm N balances, N surpluses and for evaluating uncertainty for the 222 farms and 11,440 ha of farmland. 2. Results showed farm N surpluses may be used as an independent dataset for validation of measured and modelled N emissions in agricultural landscapes. | n/a | Fodder: N in imported fodder and seed, minus N in cash crops sold, fertilizer: N imported in synthetic fertilizer and animal manure, deposition: atmospheric deposition and biological N fixation. | Milk and other animal produce (incl. meat, live animals, eggs and wool). |
| Galloway and Cowling 2002 | Global | Overall N efficiency of plant and animal production, starting with the input of N to a crop field and ending with the final food product. | 1. Global average NUE is 14% for plant products and 4% for animal products. 2. Most of N used in food production is lost to the environment. | Global NUE = 14% for plant products and 4% for animal products. | N fertilizer or other input applied to a crop field, feed. | Food product, N loss at each stage of production. |
| Grizzetti et al., 2013 | Global and regional (Europe) | 1. Quantifies N losses to the environment related to food waste at consumption at the global and European scale. 2. Analyses its relative impact on the environment. | 1. 7 regions: (1) Europe (2) USA, Canada & Oceania (3) Industrialized Asia (4) Sub-Saharan Africa (5) North Africa, West and Central Asia (6) South & South-East Asia (7) Latin America. 2. Food Groups: (1) Cereals (2) roots and tubers (3) oilseed & Pulses (4) fruit and vegetables (5) meat (6) fish and seafood (7) milk. 3. Applied virtual N and N footprint concept to quantify the amount of N delivered to the environment that is related to the production of food then wasted. | n/a 9% of the total nitrogen food supply is lost to environment; 2% of the global annual input of synthetic N fertilizer. | Total N in food at consumption. | Amount of N lost or wasted at consumption. |
| Gustavsson et al., 2011 | Global | 1. Losses occurring along the entire food system (food intended for human consumption). 2. Assesses magnitude of food loss, mass flows. 3. Identifies causes & prevention methods. | 1. Roughly 1/3 of food produced for human consumption is lost or wasted globally (1.3 billion tons). 2. On a per-capita basis, more food is wasted in the industrialized world than in developing countries: Developing countries have greater food losses in the first steps of the FSC. Developed countries have greater food losses at the retail and consumption levels. 3. Study revealed major data gaps in the knowledge of global food loss and waste. | n/a | 1. N LOSSES: Vegetable Commodities & Products. 2. Agricultural production: losses due to mechanical damage and/or spillage during harvest operation, crops sorted postharvest, etc. 3. Postharvest handling & storage: losses due to spillage, degradation during handling, storage and transportation b/w farm and distribution. 4. Processing: losses due to spillage during industrial or domestic processing. 5. Distribution: losses and waste in the market system. 6. Consumption: losses and waste during consumption at the household level. | 1. N LOSSES: Animal Commodities & Products. 2. Agricultural Production: animal death during breeding, discards during fishing, decreased production due to animal sickness. 3. Postharvest handling & storage: death during transport to slaughter and condemnation at slaughterhouse. Spillage and degradation during packaging, storage and transportation. 4. Processing: trimming spillage during slaughtering and losses during industrial processing. 5. Distribution: losses and waste in the market system. 6. Consumption: losses and waste during consumption at the household level. |

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| Howarth et al., 2002 | National (USA) | Anthropogenic nitrogen budget for the United States, including food and energy production and consumption. | 1. About 50% of new reactive N inputs to agricultural fields are removed as harvested crops. Most of these crops go towards livestock feed. 2. 15% of crop harvest N is consumed directly by humans, and about 70% goes towards livestock feed. 3. About 5% of the new reactive N inputs to agricultural feeds for animal protein production is consumed by humans. | USA NUE = 15% for plant protein and 5% for animal protein. | Inorganic N fertilizer, N fixation in agricultural systems, NO _x emissions from fossil fuel combustion. | Export in rivers, food and feed export, atmospheric advection to oceans, denitrification and storage. |
| Isermann and Isermann 1998 | National (Germany) | Country-level N balance for food and feed production and consumption. | 1. The production and consumption of food and feed in Germany is 50% higher than what is needed for basic nutrition needs. 2. Inefficiency leads to N losses to the hydrosphere and atmosphere that were 2–8 times too high. 3. Propose a need-oriented production food production/consumption system. | Germany NUE = 10% | Atmospheric deposition, biological fixation, sewage sludge, biocomposts, imported feeds, net mineralization, mineral fertilizer, manure. | Removal by biomass; surplus to the pedosphere, atmosphere, and hydrosphere; leaching; volatilization. |
| Lassaletta et al., 2014 | Global | 1. Analyses the importance of international trade of food and feed in the alteration of the N cycle at the global scale. 2. Assigned N content to every product (407 vegetables, 128 animal products) with data from different literature sources. 3. Calculated total net importer and exporter values for all 210 countries. | 1. Used information on food and feed trade, and assumed that N constitutes 16% of proteins to quantify the N traded annually during 1961–2010. 2. Amount of N traded between countries increased eightfold, now concerns 1/3 of the total N in world crop production. 3. Divided world in 12 regions and studied N transfer in 2 reference years: 1986 & 2009. 4. A small number of countries, with regard to proteins, are feeding the rest of the world. 5. Globally, system is becoming less efficient—disconnect b/w crop and livestock production across regions | n/a Net importer and exporter status varies by country. | N contained in imported products. | N contained in exported products. |
| Leip et al., 2011 | Regional (Europe, EU27 countries) | Farm, land and soil N-budgets for countries in Europe and the EU27 using agro-economic model CAPRI. | 1. CAPRI: global economic model for agriculture with a regionalized focus for Europe. 2. Farm N budget is constructed by a combination of the market and animal balances. 3. Market Balances: captures market appearances from domestic production and imports, and their distribution to various domestic uses and exports. 4. Animal Balance: calculates inputs of N by feed and the output in animal products. | Farm N budget NUE: 31% (varies from 15% Ireland—50% Romania) Land N budget NUE: 60% Soil N budget NUE: 63%. | Manure (application): accounts for losses from housing & management; N content of crops; N intake of crude protein; Feed (concentrates); Crop residues returned; Biological N fixation; Atmospheric deposition; Mineral fertilizer. | Manure (excretion): includes leaching, runoff & gaseous emissions; Product output (milk or meat); Sold crop products; Fodder; Crop residues; Soil N-stock changes; Leaching, runoff, and gaseous emissions before manure. |

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| Ma et al., 2010 | National (China) | Nutrient flows (nitrogen and phosphorus) along the entire food system. | 1. The NUFER model (NUTrient flows in Food systems, Environment and Resources use) tracks N and P efficiencies and losses at a national scale. 2. Links to species of N lost to the environment (ammonia, nitrous oxide, dinitrogen, and nitrogen oxides). 3. N and P efficiency can be improved with increased production, balanced fertilization, and improved manure management. | China N use efficiency for crop production (26%), animal production (11%), and the whole food chain (9%). | Fertilizer inputs, crop yields and areas, number of animals, consumer diets, harvested crop and animal product nutrient content, rate and content of animal excretion. | Regional N and P flows, use efficiencies, and emissions by type. |
| Godinot et al., 2016 | Regional (Europe) | Applies three new proposed farm nitrogen indicators at the European scale: system N efficiency (SyNE), relative N efficiency (RNE), and system N balance (SyNB). | 1. The farm NUE and FGB do not adequately account for all nitrogen flows in systems. 2. Proposed indicators (SyNE and SyNB) better account for indirect N losses. 3. RNE compares the actual N efficiency to an attainable N efficiency, which can identify how much N efficiency can be improved on a given farm. | European NUE is 0.35 and Farm-Gate Balance (FGB) is 86 kg N/ha, whereas the SyNE is 0.23 and SyNB is 113 kg N/ha. Mean RNE is 0.43. | 1. NUE and FGB: Inorganic fertilizers, manure, fixation, atmospheric deposition, crops, animals, energy. 2. SyNE and SyNB: Inorganic fertilizers, manure, fixation, atmospheric deposition, crops, animals, energy, indirect losses. 3. RNE: SyNE divided by an attainable efficiency. | 1. NUE and FGB: Crops, animal products, manure. 2. SyNE and SyNB: Crops, animal products, manure. 3. RNE: SyNE divided by an attainable efficiency. |
| Oenema 2003 | Varies | 1. Explores nutrient budgeting approaches and summarizes sources of uncertainty associated with these approaches. 2. Implications of uncertainties are discussed. | 1. Three types of nutrient budgets: (1) farm-gate: most integrative measure of environmental pressure; (2) Soil surface: estimating net loading of the soil with nutrients and (3) soil systems budgets: nutrient inputs and outputs, recycling of nutrients within the system, nutrient loss pathways and changes in soil nutrient pools. 2. Considerable uncertainty in budget: personal bias, sampling bias, measurement bias, data manipulation bias, sampling and measurement errors, partitioning of nutrient losses. 3. Note: N losses from silage conservation, livestock buildings and manure storage systems, and changes in the N stocks of livestock, animal manure and animal feed are not addressed in any of the budgets. | n/a | 1. Farm-gate budget: fertilizer, feed, manure, cattle, bedding material, Biological N fixation, atmospheric deposition. 2. Soil surface budget: fertilizer, urine and dung deposition, manure, forage losses, BNF, atmospheric deposition. 3. Soil system budget: fertilizer, urine and dung depositions, manure, forage losses, BNF, atmospheric deposition. | 1. Farm-gate budget: milk, cattle, animal manure, animal feed. 2. Soil surface budget: harvested grass by grazing animals, harvest silage maize & grass. 3. Soil system budget: harvested grass, harvest silage maize & grass, ammonia volatilization from dung & urine, manure, and forages, denitrification, leaching and runoff, net immobilization. |

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| Oenema 2006 | Varies | Reviews N input-output budgets and N losses in livestock farming systems. | 1. Generally, N inputs and losses increase in the order grazing systems < mixed systems < land-less systems. 2. Difficulties of establishing N budgets arise from the tendency of N to dissipate into the wider environment in a variety of species, including gaseous N species. 3. Standardization of methodologies is required to allow comparison of budgets. 4. Improve utilization of animal manure as fertilizer and manure management in general. | n/a | Feed, fertilizer, deposition, biological fixation. | Milk, meat, manure export, ammonia loss, denitrification, leaching. |
| Parfitt et al., 2010 | Global | Review of literature on food waste throughout the supply chain in developing, transitional, and developed countries. | Food waste is highest at the immediate post-harvest level in developing countries and the post-consumer level in developed countries. | n/a | n/a | n/a |
| Shindo et al., 2003; 2006 | Regional (East Asia) | Report the N load for East Asian countries using a budget approach, including N from biological fixation, energy production, human waste, and farmland. | 1. Food production contributed more than 90% of the nitrogen load in East Asia. Fossil fuel N was only significant in Japan and South Korea. 2. N load was reported by sector as the difference between N input and N uptake. | East Asia NUE has a large range. | Fertilizer consumption, food balance sheets. | Food production and consumption, NO _x emissions by region, N losses to waterways, denitrification, organic matter accumulation. |
| Westhoek et al., 2014 | Regional (Europe) | The environmental impacts (nitrogen emissions, greenhouse gas emissions, and cropland) and health effects of 6 alternative diets with reduced meat & dairy were reviewed. | 1. Nitrogen emissions could be reduced by 40% from reductions in meat and dairy intake. 2. A variety of data sets and models were used to assess nitrogen inputs and emissions across the US. Resources include FAO for dietary data and the GAINS model for livestock excretion rates and N emissions. | Current Europe NUE = 18%. NUE would increase to 41–47% with meat and dairy reduction scenarios. | Feed imports, fertilizer, N fixation, N deposition. | Food produced, food exported, emissions to air, emissions to groundwater and surface waters. |

Table A4. Literature review: Environmental impact assessment as a nitrogen efficiency indicator.

| Reference | Study Domain | Methodological Scope | Key Features | NUE Value | N input values | N output Values |
|----------------------------------|--------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----------|----------------------------------------------------------------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| OECD 2001 | Global | Reviews existing agricultural environmental indicators and their results over the last several decades. | 1. A nitrogen-specific indicator for the environmental impacts of nitrogen does not yet exist. 2. Existing environmental impact indicators for agriculture assess soil quality, water quality, land conservation, greenhouse gases, biodiversity, wildlife habitats, and landscape. | n/a | n/a | n/a |
| Payraudeau and van der Werf 2005 | Global | Review of six methods for environmental impact assessment: Environmental Risk Mapping (ERM), life cycle assessment (LCA), environmental impact assessment (EIA), multi-agent system (MIA), linear programming (LP), agro-environmental indicators (AEI). | 1. The methods presented all link to environmental impacts; the authors state that indicators that link to environmental effects are preferable over those based on specific farming practices. 2. Two important metrics are impact per kg of product and impact per unit of land area. | n/a | n/a | n/a |
| Van der Werf & Petit 2001 | Varies | Reviewed 12 methods that use a set of indicators to evaluate the environmental impact of agriculture at the farm level. | 1. Taylor et al., (1993) use a Farmer Sustainability Index (FSI)—farmer production practices yield a positive or negative score, which are summed. 2. Ecopoints: assign scores to farmer production practices and landscape maintenance (used to establish payment incentives). 3. Agro-ecological Indicators (AEI): reflect the impact of one production practice on ALL environmental components. 4. Multi-objective parameters: accounts for a set of ecological, economic and social objectives chosen to solve problems in the current system. 5. Environmental management for agriculture (EMA): computer based systems produces eco-ratings reflecting environmental performance by comparing actual farmer production practices and site-specific details. 6. Solagro diagnosis: performance levels for criteria, the number of production systems w/in the farm, diversity of crops grown, management of inputs and management of space. 7. LCA for farm management: identifies the main pollution sources and evaluates possible modifications of the farms or farming methods. 8. Indicators of farm sustainability: assigns scores to production practices and behaviours. | n/a | Use of non-renewable energy & other non-renewable resources, land use, water use, nitrogen fertilizer use, pesticide use, waste utilization. | Emission of: greenhouse gases, ozone depleting gases, acidifying gases, nutritious substances, pesticides, terrestrial ecotoxicity, aquatic ecotoxicity, human toxicity, waste production. |

There are some general gaps and trends across the different approaches. The general gaps in the four approaches are the following (depending on the application whether relevant or not):

- Inconsistency in accounting for exports as a portion of national production.
- Variability in accounting for biological nitrogen fixation (BNF), total soil nitrogen, nitrogen sources, and nitrogen sinks.
- Limited differentiation between new (e.g., synthetic fertilizer) versus recycled (e.g., manure) N inputs.
- Inconsistency in approaches that address crop rotations, which in most cases is a limitation in calculating crop specific N use.
- Animal and plant product allocation to different final products at the farm gate. There are a variety of methods for determining how much of the N use should be allocated toward multiple products.
- For the approaches based on losses, some studies chose to include gaseous emissions to the atmosphere and others did not. Atmospheric nitrogen deposition is often lacking as well as denitrification. In these studies, N leaching estimation is uncertain and therewith the N outputs.
- There are limited connections between the N use results and actual environmental impacts.

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