Nitrogen Footprint of a Food Chain

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Abstract

Nutrients such as nitrogen are required to secure food production. However, nitrogen cycles have been disturbed by excess nitrogen intake and low nitrogen use efficiency (NUE), which have several environmental impacts.

In order to address nitrogen-related issues, the magnitude of the problem and hotspots in the value chain must first be identified. Various methods to quantify nitrogen use, NUE, and nitrogen-related environmental impact potential have been proposed to tackle this challenge. The approaches, methods, and indicators that can be used in assessing particular food systems are presented in this chapter.

The methods serve different purposes and present certain differences in terms of scoping and system boundaries. The aim of this chapter is to present currently relevant methods to analyze the nitrogen footprint of a food chain in order to help those tasked with carrying out assessments to choose the method which best meets their needs.

Keywords

Nutrient, Nitrogen, Nitrogen footprint, Food chain, Environmental impacts

1. Introduction

Nitrogen and other nutrients such as phosphorus and potassium are essential in all forms of food production. Due to human interaction, however, nutrient cycles have been disturbed. Population growth, efficiency efforts in agriculture, and increased energy use have led to a multiplying of nutrient intake. The intake of N_2 from the atmosphere and its conversion to reactive nitrogen has already exceeded the safe operating space of planetary boundaries (Rockström et al. 2009; Steffen et al. 2013). Production chains might not be utilizing nutrients efficiently but, rather, have nutrient leakages. It has been estimated that over 80% of the nitrogen taken into use is lost into the environment (Sutton 2013). These emissions have various environmental impacts affecting water bodies, soil, and air. In addition, the production of nitrogen fertilizers with the traditional Haber-Bosch process, in which nitrogen in the atmosphere and methane from natural gas are converted into ammonia, is very energy-intensive and highly polluting. The Haber-Bosch process produces 450 million tons of carbon dioxide annually, which corresponds to approximately 1% of all human CO_2 emissions (Service 2019).

The aforementioned challenges related to nutrients have led to the development of various methods to quantify their usage and impacts on the environment. As the major nutrient flows are interconnected with food chains, mainly in fertilizer and food production as well as food consumption (Antikainen 2007), it is natural for this chapter to concentrate on those methods developed for food chains. In this chapter, the focus is on nitrogen alone. Phosphorus and potassium are also essential in the food chain; however, their cycles and related challenges are different. For example, in fertilizer manufacturing, 92.5% of energy used is for nitrogen, whereas potassium consumes 4.5% and phosphorus 3.0% (Galloway 2008). Nitrogen reserves are abundant in the atmosphere, while phosphorus, in particular, is a limited resource mined from the Earth’s crust. Due to the different nature of the nutrients, some indicators have been developed solely for nitrogen. Such nitrogen-related methods are presented in this chapter, along with other methods, indicators, or footprints that are suitable for examining nitrogen-related challenges in food chains.

2. Indicators for nitrogen

This chapter presents several methods that have been proposed to consider the use of nitrogen and/or its environmental impacts on the food chain. The studied indicators are: N-print tools including the N-calculator and other relevant approaches (Leach et al. 2012); the full chain nutrient use efficiency (NUE) by Sutton et al. (2013); the whole food chain nitrogen use efficiency

(NUE_{FC}) by Erisman et al. (2013); the nutrient footprint by Grönman et al. (2016); the life cycle nitrogen use efficiency by Uwizeye et al. (2016); the N food-print by Chatzimpiros & Barles (2013); and, finally, the life cycle assessment (LCA), as methods which assess the environmental impacts related to nitrogen. All these methods provide information for N users or policy makers about the use of N resources and their impacts on the environment.

All approaches are complemented with a figure, presenting the characteristics of each approach. Firstly, the figures indicate the aim or purpose of the approach, whether it is meant for understanding nitrogen flows at a local scale and related to food consumption or is it more on studying and improving the N balance of a specific food production system. In addition, the suggested system boundaries, differentiating the presented methods are shown in figures 1-7. The included life cycle phases, as well as included nitrogen categorizations are colored with a gray pattern for each of the presented N indicators.

2.1. N-print by Leach et al.

Leach et al. (2012) were among the first to tackle the challenge of disrupted N cycles by a collection of tools into a system they named N-print. Their aim was to create a set of tools for consumers, producers, and policy makers to make informed decisions to reduce N-related challenges without endangering food production. Leach et al. (2012) presented the N-calculator to quantify consumer footprint, plans for the N-producer to quantify producer footprint, and the N-policy to calculate the effect of policies on the N cycle. In addition, N-print forms the base for the N footprint label (Leach et al. 2016), institutional N-print (Leach et al. 2013) N neutrality approach (Leip et al. 2014), and N-loss indicator (Bleeker et al. 2013; Galloway et al. 2014; Biodiversity Indicators Partnership 2016).

2.1.1 N-calculator

The N-calculator is designed to estimate the nitrogen footprint of a consumer in a certain country. It utilizes food consumption data from the UN Food and Agriculture Organization (FAO), virtual N factors (VNFs) of units of food consumed, and fossil fuel consumption needed in housing, transportation, goods, and services. VNFs are created for different foods and describe the share of reactive nitrogen released to the environment in relation to unit of Nr consumed (Leach et al. 2012). The N-calculator was first developed for consumers in the United States and the Netherlands but has since been applied in several European and Asian countries as well as Australia and Tanzania (Galloway et al. 2014; Leach et al. 2016).

The N-calculator characteristics are presented in Figure 1.

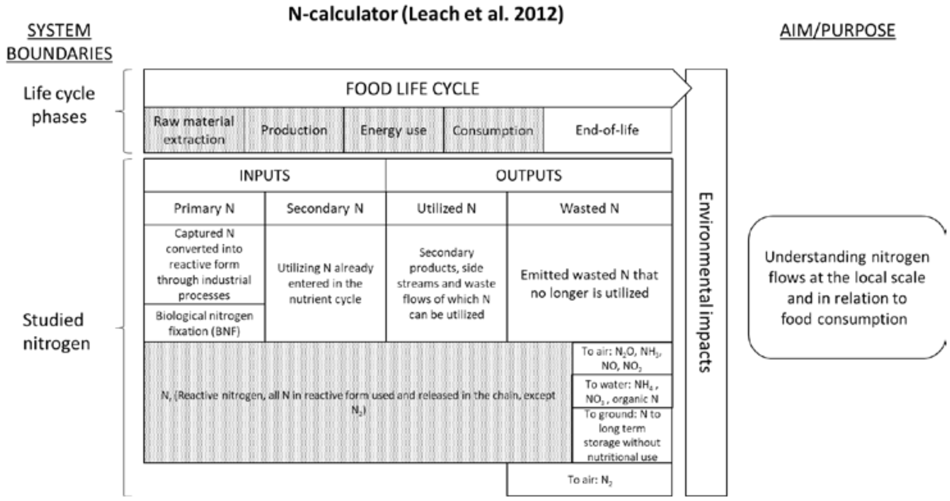

Figure 1. N-calculator by Leach et al. 2012

To further elaborate on the N-calculator tool by Leach et al. (2012), it quantifies the annual amount of Nr released into the environment as part of food consumption and production in a country [kgN capita^{-1} year^{-1}]. For example, the WHO has estimated the required protein intake in a healthy diet, based on which healthy N consumption can be determined. Comparing the footprint value to the healthy value shows whether a country is experiencing overconsumption of N, as is the case in most developed countries. Options to decrease this N footprint include reducing protein intake to a healthy level, using less animal protein, and reducing Nr losses to the environment by developing wastewater treatment through increasing denitrification and improving sludge recycling for agricultural production. (Galloway et al. 2014.) The N-calculator has been expanded to meet different purposes. It bases the N footprint of a consumed food on its protein content; hence, the N footprint of protein-free foods is treated as zero. Hayashi et al. (2020) developed an N-calculator application to assess the N footprint of protein-free food, such as oils and sugar. In the model of Hayashi et al., the VNF is replaced by the virtual nitrogen factor for protein-free foods (VNFree), which can be defined as the potential N load per unit weight of consumed food. Consequently, more realistic nitrogen footprints for protein-free foods can be derived.

2.1.2 N footprint label

The purpose of a product’s N footprint label is to inform consumers about its N footprint, which is expressed in the unit [% of daily N footprint of a healthy diet]. A definition of a healthy diet can be obtained from the guidelines given by health authorities (Galloway et al. 2014.) The N footprint label can say, for example, that one serving of a certain product represents 2% of your daily N footprint. The N footprint is based on Nr released to the environment by food production. Energy production from fossil fuels can be included or excluded (Leach et al. 2016.)

2.1.3 Institutional N footprint

The institutional N footprint is developed from the N-print indicator by extending the N-print to institutions. It depicts all Nr that enters an institution and which is generated by, or due to, the institution's activities [kg N/year] (e.g., food, energy, transportation) (Leach et al. 2013; Galloway et al. 2014). Leach et al. (2013) applied the institutional N footprint to a university, and it may be further applied to a range of organizations and even cities. Based on the information provided by the indicator, organizations can formulate strategies to reduce their institutional N footprint (Galloway et al. 2014.)

2.1.4 N Neutrality

The N-calculator has been used as a basis for calculating the amount of Nr in order to reduce that to zero. N neutrality requires actions to 1) reduce the N footprint by directly reducing Nr released to the environment (e.g., changing diet); and 2) compensate the N footprint that which cannot be reduced through mitigation actions under 1) (e.g., reducing the N footprint elsewhere or increasing sustainable land management in food production) (Galloway et al. 2014; Leip et al. 2014). The compensation measures suggested by the N neutrality approach can be applied to products, individuals, organizations, or regions (Galloway et al. 2014).

2.1.4 N-loss indicator

The N-loss indicator is another application of the N-print indicator. In contrast to the N-print, which shows the loss of N due to consumption by individuals, the N-loss indicator depicts reactive nitrogen losses to the environment at a country or regional level due to production and consumption of food, and energy use [Nr loss capita^{-1} year^{-1}] (Bleeker et al. 2013; Galloway et al. 2014.) The indicator does not distinguish between losses to air, soil, or water (Bleeker et al. 2013). It allows easy comparison of countries or regions, such as continents, in terms of Nr losses. The food production and consumption components are especially highlighted in regions with extensive livestock production and meat consumption, while the energy consumption component in similarly highlighted in industrialized countries. The indicator is used in the context of the Convention on Biological Diversity. (Bleeker et al. 2013; Galloway et al. 2014; Biodiversity Indicators Partnership 2016.)

2.2. Full chain nutrient use efficiency by Sutton et al.

One of the first studies to expand the concept of nutrient use efficiency to cover the whole food system was presented in the Our Nutrient World report published in 2013. Sutton et al. (2013) proposed full chain NUE, which, in the case of nitrogen, can be defined as the ratio of nitrogen in final products to new nitrogen inputs.

$$Full\ chain\ NUE, \mathrm{N} = \frac{N\ in\ food\ and\ durable\ products}{Industrial\ N\ production + BNF + combustion\ source\ NOx}$$

N inputs include, for example, virgin N inputs through Haber-Bosch, biological N fixation, and NOx formation. Sutton et al. explicitly excluded secondary nutrients, such as manure and animal feed, from the inputs as they regarded these as not directly representing the goal of feeding people. However, they state that use of these secondary nutrients is advisable, and it shows in the reduced need for primary nutrients. The characteristics of the full chain NUE by Sutton et al. are presented in the Figure 2.

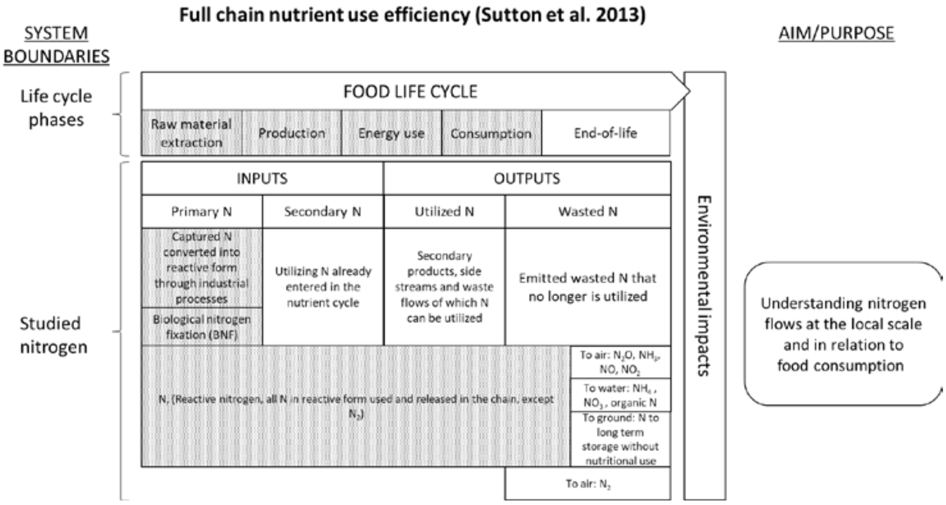

Figure 2. Full chain NUE by Sutton et al. (2013)

2.3. Whole food chain nitrogen use efficiency by Erisman et al.

Different approaches to the whole food system NUE have been introduced in addition to that by Sutton et al. (2013). Erisman et al. (2018) proposed whole food chain nitrogen use efficiency (NUEFC), which is an indicator suitable for broader application at national scale. In this study, NUEFC is defined as the ratio of the N protein available for human consumption to the newly fixed and imported nitrogen input to the food system. In other words, NUEFC describes what percentage of input N to the food system is converted to food protein N available for consumption. NUEFC helps to identify strategies for more efficient nitrogen use in food production, minimize N losses in the food system, and, additionally, recognize which phases in the food chain have the lowest N efficiency. Therefore, NUEFC could be used in policy making to promote efficiency and steer consumers to use products with efficient N use. The characteristics of the whole food chain nitrogen use efficiency are presented in the Figure 3.

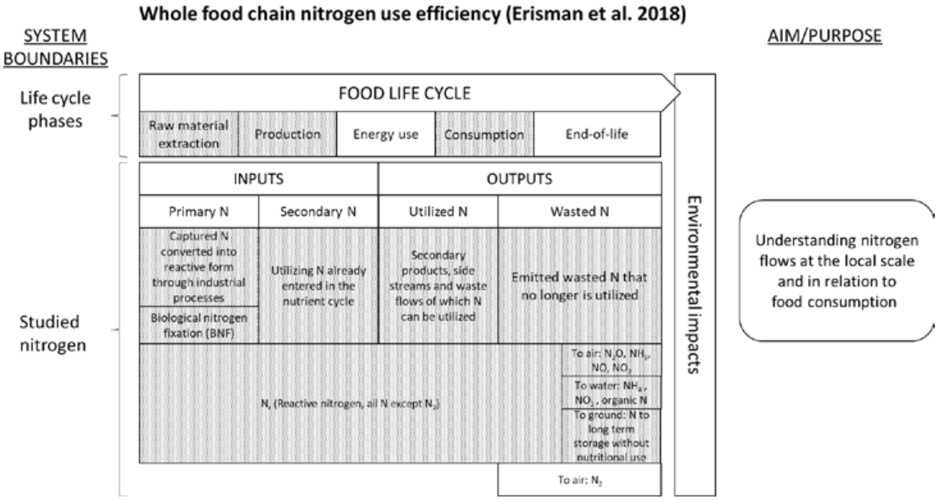

Figure 3. NUEFC by Erisman et al. (2018)

The NUEFC can be calculated by using the budgeting approach. As the food chain consist of a chain of different sectors and activities, the NUE for each step within it must be determined. This requires the amount of used N in each sector to be calculated, after which the NUE for each step in the food chain can be calculated as consumed N (the outputs) divided by the new N (the inputs). Hereafter, NUEFC can be defined as follows:

$$\mathrm{NUE_{FC}} = \frac{N\ food\ availability}{fertilizer + BNF + atm.dep. + (import - export) + changes\ in\ stock}$$

In the equation, N food availability refers to consumption or, in other words, N supplied to households. N food availability is then divided by the inputs, like fertilizer N, biological nitrogen fixation (BNF), atmospheric deposition of N, difference of imports and exports, and changes in N stock. The N stock refers to the annual net balance of a country’s N imports and exports, including storage of products. Although $\mathrm{NUE_{FC}}$ is best suited to examining the whole food chain, it can also be applied across different sectors, such as the agricultural system or consumer sector. (Erisman et al. 2018.)

2.4. Nutrient footprint by Grönman et al.

The nutrient footprint proposed by Grönman et al. (2016) is a combined indicator for nutrient intake and NUE. It is suitable for the assessment of the nitrogen balances of food chains and other bio-based production chains. In addition to nitrogen, the nutrient footprint is recommended for use in assessing phosphorous. The method is designed to assess and improve specific food chains. The characteristics of the nutrient footprint are presented in Figure 4.

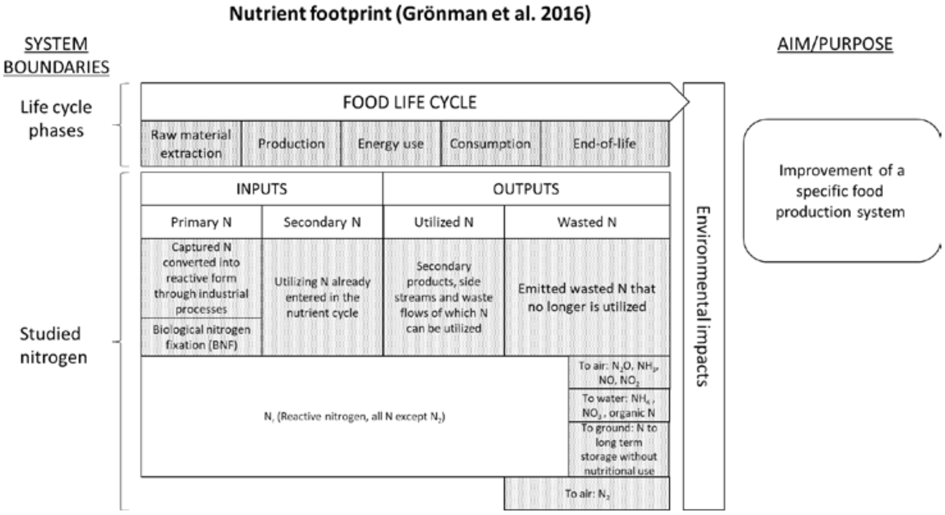

Figure 4. Nutrient footprint for nitrogen by Grönman et al. (2016)

The nutrient footprint takes into account the whole life cycle of the food chain, starting from raw material extraction and ending in the end-of-life phase with waste disposal or recycling. Throughout the life cycle of the studied food chain, the entering nitrogen inputs and exiting nitrogen outputs are identified. Nitrogen inputs are separated into virgin and recycled nitrogen. Virgin nitrogen refers to nutrients captured from the atmosphere and converted into reactive form to be utilized in this particular chain. In addition to industrial fertilizers, other primary material and fuels consisting of nitrogen, such as nitrogen entering the system through BNF, are considered virgin nitrogen. Recycled nitrogen, on the other hand, relates to nitrogen that has already been taken into use and is thus present in the nutrient cycle. For this particular process, recycled nitrogen can, for example, comprise process side-flows, manure, and sewage sludge which is continuing its life cycle in the studied food chain. The total amount of nutrient intake in the studied food system [kg N / functional unit] forms the first basis of the Grönman et al. (2016) nutrient footprint indicator. The authors emphasize the importance of identifying virgin and recycled nutrients separately, so that although NUE is improved, the share of virgin nutrients is the primary target for reduction.

Secondly, the nitrogen outputs leaving the system are quantified. A distinction is made between nitrogen that is released to the environment as emissions or waste and whose nutrient content is thus no longer utilized, and the nitrogen which continues to serve as a recycled nutrient. N_2 released to the environment is also considered to be wasted, as it requires a great deal of nutrient inputs in terms of energy to return it to the nutrient cycle. (Grönman 2016.)

When the amounts of nitrogen entering and exiting the food chain have been quantified, one can calculate the NUE of the food item:

$$\mathrm{NUE, N}_{food} = \frac{Nitrogen\ content\ of\ the\ food}{Total\ amount\ of\ nitrogen\ captured\ by\ the\ food\ chain} \times 100$$

The higher the percentage of this first equation, the smaller the quantity of nitrogen taken into use throughout the food chain, and the more the captured nutrients remain in the food item.

In the second equation, other utilization possibilities along the food chain are also noted:

$$\mathrm{NUE, N}_{total} = \frac{Nitrogen\ content\ of\ the\ food + Utilized\ secondary\ nitrogen}{Total\ amount\ of\ nitrogen\ captured\ by\ the\ food\ chain} \times 100$$

The total nitrogen use efficiency also taking into account the exiting nutrient flows which are captured and whose life cycle is continued, is more useful if one desires to develop the whole food chain and, for instance, find use purposes for side-flows.

The nutrient footprint method proposed by Grönman et al. (2016) is different to methods such as life cycle inventory in life cycle assessment, material or substance flow analysis, the N-print (Leach et al. 2012), or the NUE of Sutton et al. (2013), as it categorizes the input nutrients into virgin recycled nitrogen and output nutrients into utilized secondary nutrients and losses throughout the life cycle of the food product. In addition, including the utilization of secondary nutrient flows allows more detailed improvement potential for nitrogen efficiency to be found.

The proposed nutrient footprint approach has been utilized to assess vegetable food products (oat flakes and porridge) (Grönman et al. 2016) and animal food products (beef) (Joensuu et al. 2019). For nitrogen use efficiency, the results are reported as follows: 1000 kg of Finnish oat flakes and porridge consumed requires 42 kg of nitrogen, of which 88% is considered virgin nitrogen. Nitrogen use efficiency in the oats chain is 55%, and the nitrogen use efficiency including secondary products is 71%. (Grönman et al. 2019.) 1000 kg of Finnish beef consumed requires 1700 kg of N of which 50% is virgin nitrogen. Nitrogen use efficiency in the beef chain is only 1%, but if secondary products are taken into account, NUE,N_{total} increases to 47%. (Joensuu et al. 2019.)

2.5. Life cycle nitrogen use efficiency by Uwizeye et al.

Improving the N use efficiency along the supply chain is essential when aiming to increase the sustainability of nutrient use. The study by Uwizeye et al. (2016) introduced an LCA-based framework to assess life-cycle nitrogen use efficiency from a regional or global perspective in the livestock supply chain. The framework can be utilized in the assessments of Nr flows in crop production, animal production, and processing, and it includes internal processes, loops, and recycling of Nr. The characteristics of the life cycle nitrogen use efficiency are presented in Figure 5.

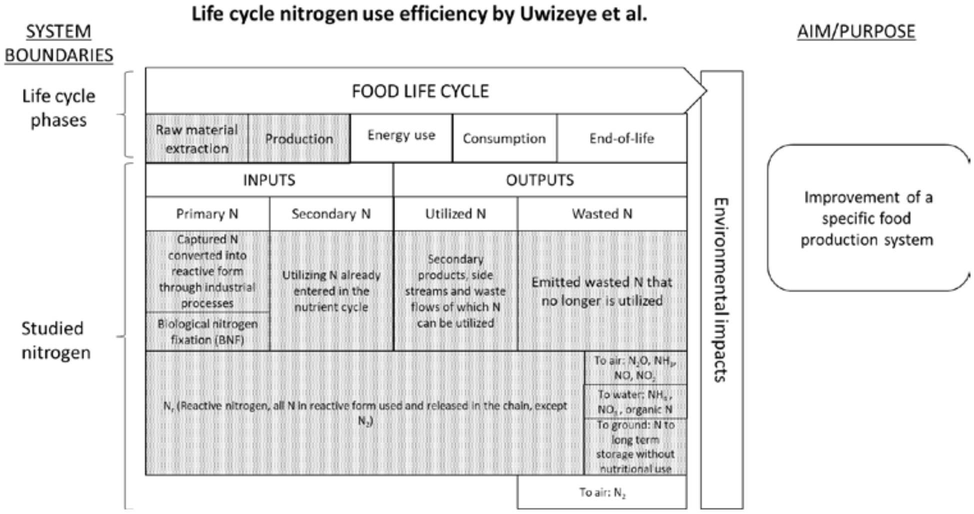

Figure 5. Life cycle nitrogen use efficiency by Uwizeye et al. (2016)

Uwizeye et al. proposed that three indicators are needed to entirely describe the nitrogen dynamics in the livestock supply chain: life-cycle NUE, life-cycle net nutrient balance (NNB), and nutrient hotspot index (NHI). They concluded that the combination of these three indicators gives relevant and complementary information to monitor nutrient management performance. Moreover, it helps to understand efficiency of nutrient use, as well as nutrient balance per hectare, and distribution of nutrient pressures along the chain. These indicators are introduced in the following subchapters.

2.5.1 Life-cycle nitrogen use efficiency

Life-cycle NUE defines how efficiently nutrient inputs are recovered in final products. Additionally, it considers nutrient mobilization, use, change in nutrient stocks, and recycling. It can be calculated as one unit of nutrient in final products divided by the amount of “new” nutrient mobilized in the supply chain to produce it. (Uwizeye et al. 2016.)

2.5.2 Life-cycle net nutrient balance

Life-cycle NNB is expressed as Nr losses (kg) per area of land used (ha). In other words, it indicates the amount of nutrients that are used for neither end-products nor the build-up of soil fertility, wherever they occur in the chain. (Uwizeye et al. 2016.)

2.5.3 Nutrient hotspot index

The NHI is calculated as the standard deviation of NNB divided by the average of NNB of all stages of the supply chain. High NHI indicates that there is one or a few significant nutrient hotspots in the supply chain. Conversely, a low NHI indicates an evenly distributed nutrient balance along the supply chain. (Uwizeye et al. 2016.)

2.6. N food-print by Chatzimpiros & Bales

The N food-print is a consumption-based indicator of Nr inputs and losses from spatially scattered livestock systems (Chatzimpiros & Barles 2013). As N use efficiency is examined from a system perspective, the N food-print can be used, for example, to track where the most significant N emissions occur along the production chain and, subsequently, inform measures to reduce N losses (Chatzimpiros & Barles 2013). The characteristics of the N food-print are presented in Figure 6.

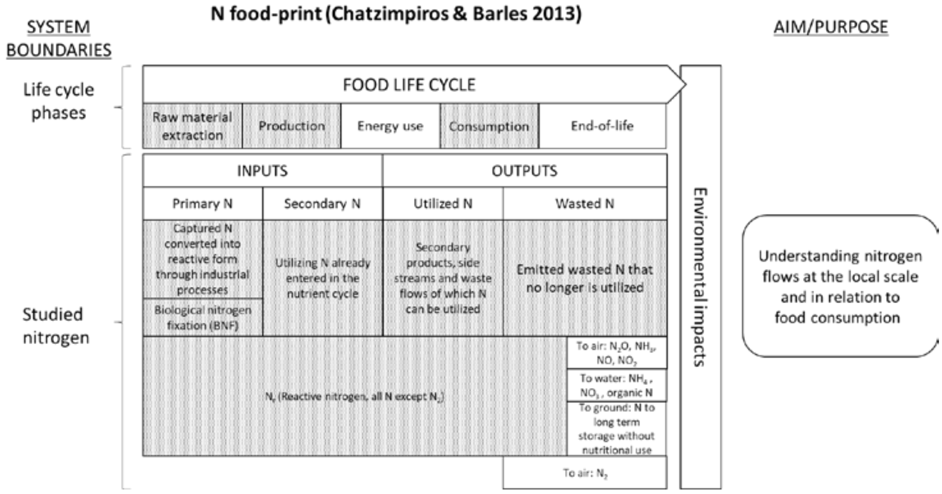

Figure 6. N food-print by Chatzimpiros & Barles (2013)

2.7. LCA and environmental impact assessment

LCA addresses potential environmental impacts throughout a product’s life cycle, from raw material extraction to end-of-life treatment. Once the goal and scope of an LCA study are defined, LCA includes inventory analysis and impact assessment phases (ISO 14040).

The relation between footprints and LCA is ambiguous. Some footprints can be addressed according to LCA principles; however, many footprint indicators exist independently of LCA (Fang & Heijungs 2015.) Ridoutt et al. (2016) suggested a new paradigm, areas of concern, that ties footprints and LCA together without requiring a comprehensive environmental evaluation from footprints and supports developing footprints with a narrower scope within the LCA community.

Many of the reviewed nitrogen footprint methods are at the inventory analysis level. That is, nitrogen flows (inputs and outputs) at different stages of a life cycle are identified and quantified without any evaluation of their further impacts on the environment. For example, the nutrient footprint method by Grönman et al. (2016) considers virgin and recycled nutrient inputs, outputs lost from or continuing in the nutrient cycle, and nutrient use efficiency of a (food) system. Methods based on the N-calculator by Leach et al. (2012) focus on emissions of Nr into the environment. The LCA community has criticized the N footprints for not including impact assessment according to the LCA principles (Einarsson & Cederberg 2019).

LCA includes further assessment of potential environmental impacts of input and output flows. In life cycle impact assessment (LCIA), input and output flows are classified into impact categories. As concerns the environmental impacts of nitrogen, the focus is on nitrogen emissions (outputs from a system). As nitrogen resources are abundant in the atmosphere, input impact categories, such as resource scarcity, are irrelevant, even though atmospheric N_2 conversion into reactive form causes environmental impacts, particularly due to high energy consumption. Impacts of nitrogen emissions include damage to the natural and human-made environment and to human health through various impact pathways. Typical impact categories of nitrogen emissions that contribute to such damage include aquatic and terrestrial eutrophication potential, acidification potential, global warming potential, depletion of stratospheric ozone, formulation of tropospheric ozone, ecotoxicity, and particulate matter (PM)/respiratory inorganics (Antikainen 2007; Sutton et al. 2013.) The characteristics of LCA are presented in Figure 7.

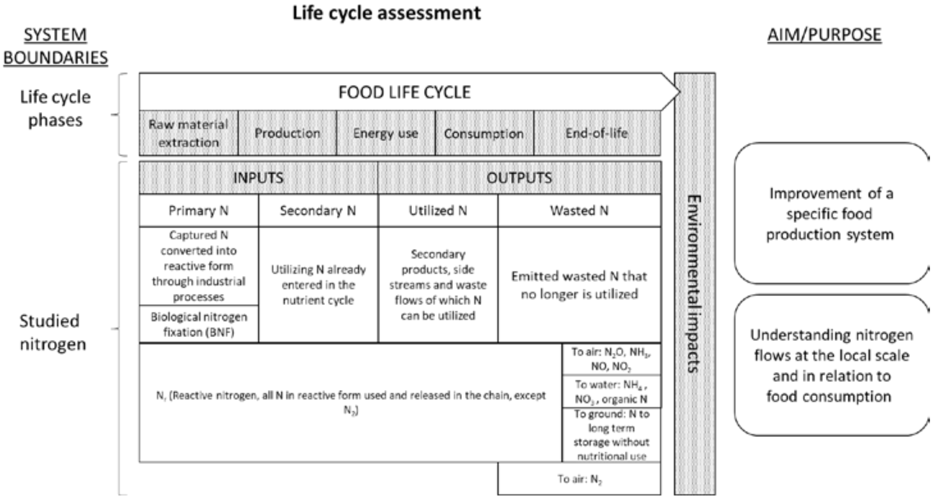

Figure 7. Life cycle assessment

The form of nitrogen release determines the possible impact categories. For example, mineral (ammonium and nitrate) nitrogen releases, which are available for further use as a nutrient, may cause terrestrial eutrophication; N_2O contributes to global warming and the formulation of tropospheric ozone; and NO_x from combustion processes causes acidification and eutrophication, and contributes to PM and respiratory inorganics (Antikainen 2007; Sutton et al. 2013.)

3. Summary and conclusions

As presented above, several indicators can be used to assess the use, use efficiency, and nature of used nitrogen, and the environmental impacts of nitrogen. They usually aim either at improving a specific food production system or at understanding and minimizing nitrogen flows at national or regional scale and in relation to food consumption. Some methods, such as LCA, go as far as quantifying the environmental impact potential of nitrogen, but most indicators, as presented in this chapter, communicate and categorize nitrogen resource use and release in a food chain. Different approaches address different life-cycle phases in the study, based on their aim and scope. NUE approaches always compare the amount of nutrient in the food product against the nutrients needed to produce it. However, there are differences in where the system boundaries in terms of life-cycle phases are laid, and which nutrients are included in the study.

Table 1 and Table 2, below, summarize the presented methods.

Table 1. Summary of the presented indicators assessing NUE in the food chain.

Indicator	Author & year	Short description	Scope	Indicator result example or unit
N-calculator	Leach et al. 2012	An N footprint tool which calculates annual per capita N losses to the environment caused by food consumption. For each food category a VNF is defined which equals total N loss in the production chain divided by the N that remains in the consumed product	Local scale (national)	"The nitrogen footprint of the Netherlands is 24 kg N/capita/yr"
Full chain nutrient use efficiency	Sutton et al. 2013	Full chain NUE, defined as the ratio of nutrients in final products to new nutrient inputs	Local scale (national)	"Nutrients in food available for human consumption in a country as a % of the total nutrient inputs to that country"
Nitrogen use efficiency of a food chain	Erisman et al. 2018	Ratio of the protein (expressed as nitrogen) available for human consumption to the (newly fixed and imported) nitrogen input to the food system	Local scale (national)	"The NUE-FC in the Netherlands for 2005 was estimated at 18%"
Nutrient footprint for nitrogen	Grönman et al. 2016	The amount of captured virgin and recycled nutrients (kg) for use in the production chain and the share of nutrients utilized [%] either in the food itself or in the entire production chain, accounting also for side-products	Specific food production system	"1000 kg of Finnish oat flakes and porridge consumed requires 42 kg of nitrogen, of which 88% is considered virgin nitrogen. NUE in the oats chain is 55% and the NUE including secondary products is 71%"
Life-cycle nitrogen use efficiency	Uwizeye et al. 2016	Includes three indicators: life-cycle NUE, life-cycle NNB, and NHI	Local scale (national)	“For France, the life-cycle-NUE-N was estimated at 44%, life-cycle-NNB-N at 105 kg N/ha, and NHI-N at 123%”
N food-print	Chatzimpiros & Bales 2013	Consumption-based indicator of Nr inputs and losses from spatially scattered livestock systems. N food-print of a product is the N loss associated with its agricultural production	Local scale (national)	“Beef farming to feed an individual in France uses 11.1 kg N/capita/yr, of which 3.8 kg N/capita /yr (or 35 %) is the N food-print, 7% is recovered in retail products, and 3% is slaughter waste”

Table 2. Summary of indicators assessing nitrogen-related environmental impacts through LCA

Indicator	Short description	Scope	Indicator result example or unit
Eutrophication potential	Impacts on terrestrial or aquatic ecosystems due to emissions of nutrients, which causes, e.g., acceleration of algae growth and oxygen depletion	Depends on the aim and scope of the study, but most often used to study a specific food production system	mol N eq./functional unit (terrestrial), kg P equivalent/functional unit (freshwater), kg N equivalent/functional unit (marine)
Acidification potential	Impacts due to emissions of acidifying substances		mol H+ eq./functional unit
Global warming potential	The capacity of a greenhouse gas to affect radiative forcing in a specified time horizon		kg CO2-eq. / functional unit
Depletion of stratospheric ozone	Degradation of stratospheric ozone due to emissions of ozone-depleting substances		kg CFC-11 eq./functional unit
Formulation of tropospheric ozone	Formation of ozone at the ground level of the troposphere caused by photochemical oxidation of VOCs and CO in the presence of NOx and sunlight. Damages vegetation, the human respiratory system, and human-made materials		kg NMVOC eq./functional unit
Ecotoxicity	Toxic impacts on an ecosystem (damage to species and changes in the structure and functioning of the ecosystem) due to emissions of ecotoxic substances		CTUe (Comparative Toxic Unit for ecosystems)/functional unit
PM/Respiratory inorganics	Adverse impacts on human health caused by PM and its precursors, such as NOx and NH3		kg PM2.5 eq./functional unit

Different approaches to studying nitrogen in the food life cycle are presented for various needs to improve nitrogen cycles. Moreover, planetary boundaries could be included in the assessment. Li et al. (2019) and Uusitalo et al. (2019) have suggested that footprint indicators become more meaningful when compared to biophysical limits (planetary boundaries). Consequently, Li et al. (2019) introduced a phosphorus exceedance footprint that shows excessive phosphorus use in relation to the sustainable use defined by planetary boundaries caused by a country, mainly due to food consumption and production. The approach could be further applicable, for example, to excessive Nr releases, although this has not yet been demonstrated.

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