# A framework to assess life cycle nitrogen use efficiency along livestock supply chains

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**ABSTRACT**

Due to the significant contribution of the livestock sector to nitrogen (N) losses, improving N use efficiency ($NUE_{-N}$) along the life cycle of livestock products is one of the important step towards increasing production performance and reduction of its environmental impacts. We developed a comprehensive framework and novel metrics to assess $NUE_{-N}$ along the livestock supply chain (i.e. "cradle-to-primary-processing"). Our framework was illustrated for the case study of mixed dairy production in Western Europe. Metrics developed included the life cycle $NUE_{-N}$; total N losses to the environment per unit of N in the final co-products; and the N hotspot index ($NHI_{-N}$), defined as the relative evenness of the N losses along the supply chain. Averaged across countries, the life cycle $NUE_{-N}$ was 36±3.1%, N losses were 6.6±1.8 g N per g N in the final animal co-products, and $NHI_{-N}$ of 1.0±0.1. The N losses and $NHI_{-N}$ also revealed large differences in hotspots across supply chains, and allowed to identify priority areas where improvement actions are necessary to enhance the efficiency. We show that the combination of life cycle $NUE_{-N}$, N losses and $NHI_{-N}$ gives valuable information to guide N management in livestock supply chains.

Keywords: life cycle, nitrogen use efficiency, hotspot, livestock, supply chain

## 1. Introduction

The livestock sector is identified as a significant contributor of nitrogen (N) losses into the air, water and soil, which can create environmental burdens including climate change, eutrophication, degradation of water and air quality (Erisman et al. 2007; Galloway et al. 2010; Xue and Landis 2010; Leip et al. 2013; Sutton et al. 2013). Due to an increasing world population and changing dietary patterns, driven by rising incomes and urbanization, especially in developing countries, the global demand for livestock products is expected to increase in the coming decades (Alexandratos and Bruinsma 2012). Acknowledging the need to improve its environmental sustainability, the livestock sector is increasing its efforts to improve nutrient management and nutrient use efficiency in livestock supply chains[1].

Several researchers proposed N use efficiency ($NUE_{-N}$) as a valuable metric to manage and benchmark N use and improve performance (Powell et al. 2010; Leip et al. 2011; Gourley et al. 2012a; Sutton et al. 2013). $NUE_{-N}$ is generally computed at animal level (Powell et al. 2010) or farm level (Aarts et al. 2001; Gourley et al. 2012b; Godinot et al. 2014). Livestock supply chains, however, are increasingly long and complex, implying that $NUE_{-N}$ at animal or farm level captures only a fraction of actual emissions. Potential inefficiencies taking place upstream or downstream from the farm are thus ignored. It is necessary to bring the life cycle approach to $NUE_{-N}$, in order to identify "hotspots" along the entire supply chain, and to avoid interventions that would result in shifting nutrient inefficiency problems from one production step to another.

Few studies have addressed nutrient use efficiency (NUE) at chain level (Suh and Yee 2011; Wu et al. 2014) and several challenges remain concerning the computation of a representative life cycle $NUE_{-N}$. The aim of this paper, therefore, is to present a comprehensive framework and related metrics to assess $NUE_{-N}$ along the livestock supply chain, from "cradle-to-primary-processing." The framework will be illustrated with a case study.

[1] This research takes place in the context of a multi-stakeholder partnership gathering private, governmental and non-governmental organizations and aiming at developing methods and metrics relevant to guide the sustainable development of the livestock sector. See Livestock Environmental Assessment and Performance (LEAP) website: http://www.fao.org/partnerships/leap

## 2. Materials and methods

### 2.1. Description of the system

We propose a comprehensive method to assess the life cycle $NUE_{-N}$ of livestock supply chains, from cradle-to-primary-processing-gate. This framework can be also used for other nutrients, such as phosphorus. To illustrate the computation and results from this framework, we apply it to mixed dairy systems in 28 countries of Western Europe. Mixed dairy systems were selected because of data availability, and the fact that they offer a relevant mix of inputs and outputs to test the framework. Mixed dairy systems are defined as systems combining dairy farming with other associated agricultural activities, such as feed cropping, other animal species production, and are characterized by an intensive exchange of products and services between these different activities (Oomen et al. 1998).

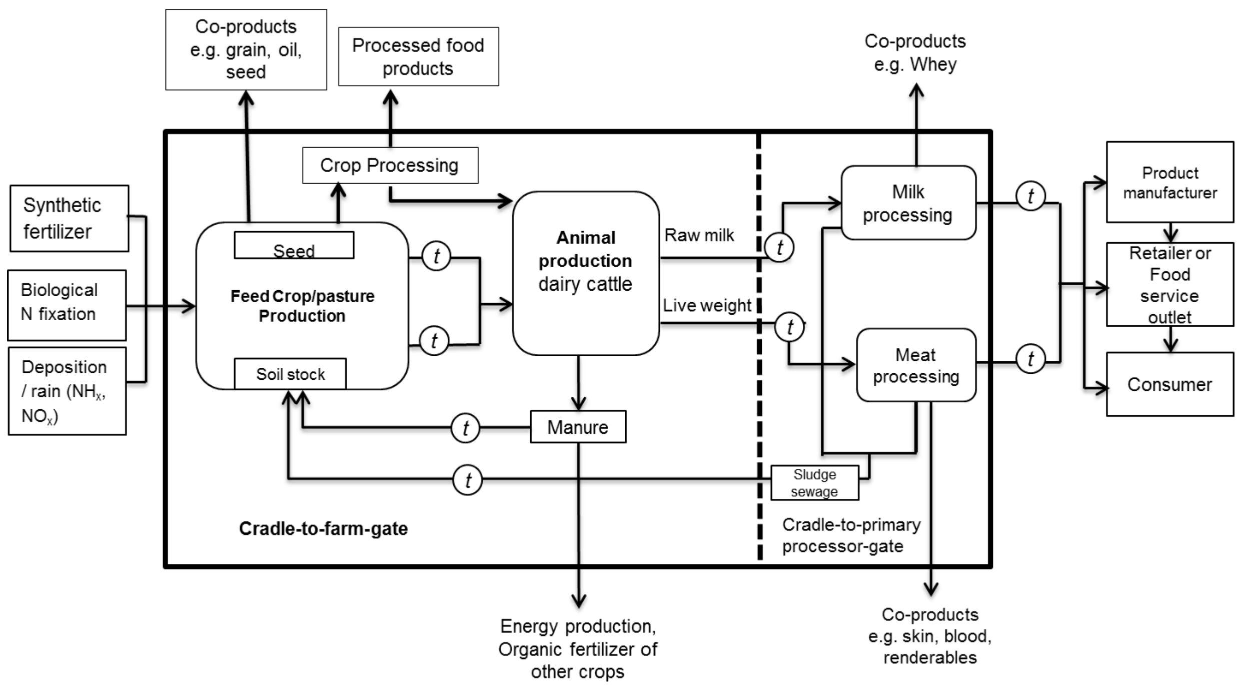



Figure 1. System boundary proposed for the life cycle of dairy cattle covering cradle-to-primary-processor-gate for two main products (milk, meat), the large box covering the cradle-to-primary-processing gate represents the stages covered by life cycle $NUE_{-N}$ methodological framework. (*t*): refers to transportation.

### 2.2. System boundary

The framework assumes that all N flows occur during the same year, and the system operates in a fixed state. The system boundary illustrated in Figure 1 represents the cradle-to-primary-processing-stage of the life cycle. This choice of the system boundary is motivated by data availability. It includes three main stages, which are interconnected: feed crop/pasture production, animal production, and animal products processing. All N flows entering, leaving or within the system boundary are included in the assessment. Nitrogen flows enter the system mainly through synthetic fertilizer, biological N fixation (BNF), and atmospheric deposition (ATD) to produce feed crop and forage. Other inputs of N to feed crop/pasture are internal to the system and come from recycled manure (urine, dung and litter), crop residues or seeds. N inflows related to fossil fuel are excluded in this study because of lack of sufficient data on national and international transportation of feed stuffs and on-farm fossil fuel use. The N outflows are estimated based on products' yields. We assume that all outflows are separated after their excretion, which imply that, when a food crop, crop residue or by-product is used as feed, an economic allocation factor is only applied to split N losses between crop co-products. At the animal production stage, N flows are associated with feed, milk, live animals and manure recycled. Only milk and live animals are processed into final animal co-products, while manure is used as organic fertilizer in crop production. These final co-products mainly include milk, meat, leather, fat and other non-edible products. At each stage of the supply chain, the fundamental principle of mass balance conservation is applied: "N inflow = N product + N loss + δN stock." N product includes all co-products delivered at each stage, whereas N loss refers to N lost via volatilization, run-off and leaching.

## 2.3. Metrics

We propose to calculate three metrics based on the analysis of the N flows along the chain, i.e. $NUE_{-N}$, the N losses and the N hotspot index ($NHI_{-N}$). $NUE_{-N}$ is a relatively common metric, but it is calculated here for the entire supply chain, following a life cycle perspective. The "N losses" indicate the amount of N lost to produce 1g of N in the final co-product. $NHI_{-N}$, on the other hand, is proposed as a new metric that qualifies the evenness of inefficiencies along the supply chain.

### 2.3.1. Computation of the life cycle $NUE_{-N}$

$NUE_{-N}$ refers to the total N outflow excluding losses to the total N inflow within each stage or subsystem of the supply chain. The calculation model includes three interconnected stages: feed crop/pasture production, animal production and processing, to ensure that an intervention arising from a particular stage of the chain is transferred throughout the supply chain. This concept was previously defined in Suh and Yee (2011) and Wu et al. (2014).

***Feed crop and pasture production***

At the level of the cropping system, $NUE_{-N}$ is estimated for all crops and pastures produced. $NUE_{-Nc}$ is defined as the ratio of N outputs (harvested in plant biomass) plus the variation of the mineral N in soil stock pool to N inputs (inorganic fertilizers, livestock manure, crop residues, ATD, and BNF). Furthermore, it is assumed that extra N which is not up-taken or lost; is stocked as mineral N in the soil pool. $NUE_{-Nc}$ is estimated as follows:

$$NUE_{-Nc} = \frac{\sum(O_c + \delta S_c)}{\sum I_c} x100 \qquad \text{Eq. 1}$$

where $O_c$ is the total N in harvested crop or pasture; $\delta S_c$ is the change of the stock of N in soil (either as accumulation or removal of mineral N in soil); $I_c$ is the total N input materials to feed crop/pasture production.

***Feed ration***

Feed assessment requires the identification of all feed component used in animal ration. We estimate the average $NUE_{-N}$ of ration ($NUE_{-Nf}$) based on proportion of each feed component in the ration. Feed ration may vary during the year or over a period of a year. It is assumed that animals of the same cohort are fed a similar ration the whole year. In this study, the country specific feed rations are extracted from the Global Livestock Environmental Assessment Model (GLEAM) (Gerber et al. 2013). $NUE_{-Nf}$ is estimated as follows:

$$NUE_{Nf} = \sum_{i=1}^{k}(NUE_{Nci} x\, \beta_i)\ (k = 1,2,\dots,k) \qquad \text{Eq. 2}$$

where $NUE_{-Nci}$ is the N use efficiency of feed component i, $\beta_i$ is the proportion of feed component i in the ration, k is number of feed component used. $NUE_{-Nf}$ is calculated at herd level.

***Animal production***

At the level of the animal production system, $NUE_{-N}$ refers to the capacity of animals to incorporate N in feed into animal products. After the ingestion, N intake is partitioned into edible protein (e.g. meat, milk) and inedible protein (e.g. leather, blood, offal) as well as in animal excreta according to Powell et al. (2013). We considered manure as a valuable product of the animal production system, contrary to most studies that examine N balances of livestock systems (Segato et al. 2010; Leip et al. 2011; Oenema et al. 2012). N losses associated with manure management are estimated using GLEAM (Gerber et al. 2013). We assume that manure managed in mixed dairy systems is used either as organic fertilizer or for energy production. Similarly to crop production, $NUE_{-N}$ in animal production ($NUE_{-Na}$) is defined as the ratio of N in co-products to N in inputs (feed intake), and is estimated as follows:

$$NUE_{-Na} = \left[\frac{O_a+\delta S_a}{I_a}\right] x100\% \qquad \text{Eq. 3}$$

where $O_a$ is the N in product including edible and non-edible products such as manure; $\delta S_a$ is the change of N stock in animal herd related to calving or input of new animals; $I_a$ is the total N intake.

***Processing***

After the farm gate, live animals and primary animal products are processed. The inedible products from processing may be used as compound feed (e.g. blood, bones) for other animal species, as input to industrial processes (e.g. leather, cosmetics, food or pharmaceutical industries) or other use such as fertilizer. N concentration in manure produced during transportation or during stalling of animals at the slaughterhouses and in waste water, which is not treated at factory level, is considered a pollutant to the environment, therefore, is included in the estimation of N losses. $NUE_{-Np}$ is defined as the ratio of N content in final animal co-products to N entering the processing unit and is estimated as follows:

$$NUE_{-Np} = \left[\frac{O_p}{I_p}\right] x100\% \qquad \text{Eq. 4}$$

where $O_p$ is the total N in final animal co-products at primary processing and $I_p$ is the total amount of N in animal production output which equals to $O_a$ (Eq. 3). It is assumed that no stock exists in processing plants.

***Supply chain***

The entire life cycle $NUE_{-N}$ is estimated as the product of $NUE_{-N}$ of each stage of the supply chain, and is estimated as follows:

$$\text{Life cycle } NUE_N = \prod_{i=1}^{n} NUE_{-N_i} (i = f, a, p) \qquad \text{Eq. 5}$$

Where $NUE_{-Ni}$ represents $NUE_{-N}$ of stage i of the supply chain.

2.3.2. Nitrogen losses

"N losses" is defined as the total N losses to the environment that occur for the production of one unit of the final co-product. N losses are estimated as N in output products plus stock change minus N inputs. The reference unit used to report the N losses is 1 g of N in final animal co-products at the primary processing gate. N losses may occur through volatilization of $NH_3$, emissions of $N_2O$, NO, and nitrates leaching and run-off at every stage of the supply chain. They are estimated based on tier-1 equations from IPCC guidelines (IPCC 2006).

2.3.3. Nitrogen hotspot index ($NHI_{-N}$)

$NHI_{-N}$ is defined as the relative evenness of the N losses in the supply chain. $NHI_{-N}$ is calculated as the standard deviation of N losses divided by the average N losses of all stages of the supply chain, and, therefore, quantifies the relative evenness or concentration of losses along the chain. A high $NHI_{-N}$ implies that the occurrence of major hotspots of N losses in the chain, whereas a low $NHI_{-N}$ implies that N losses are evenly distributed. $NHI_{-N}$ is estimated as follows:

$$\mathrm{NHI_N} = \frac{\sigma}{\mu} \quad \text{Eq.6}$$

where σ is the standard deviation of the N losses at the different stages of the supply chain; μ is the corresponding average of N losses.

2.4. Data and parameters

Country average data regarding crop and livestock activities were extracted from the GLEAM database. GLEAM was developed to assesses the environmental performance of livestock supply chains at global level (Gerber et al. 2013). GLEAM is a Geographical Information system (GIS) based model which represents processes and activities, from the production of inputs into the production process to the farm-gate. It is composed of five main modules: herd module, manure module, feed module, system module and allocation module. GLEAM relies on IPCC Tier 1 and Tier 2 approaches and emission factors to estimate the greenhouses gas emissions and thus the N flows. The Tier 1 approaches are used in this study for the estimation of $N_2O$ emissions. Additional data on N ATD were obtained from global maps of atmospheric N deposition (Dentener 2006), while BNF data are estimated from Herridge et al. (2008). The fourteen feed components considered were different types of fresh grass, legumes, cereals, and by-products (soybean cake, maize gluten meal, etc.) according to Opio et al. (2013). The data represented the year 2005.

2.5. Sensitivity and statistical analysis

The descriptive statistics and sensitivity analysis were performed with R software (R Core Team 2013). The sensitivity analysis of key data was carried out to identify the most sensitive parameters to the life cycle $NUE_{-N}$ result. Each key data of the input has been changed by 10% and the corresponding change in life cycle $NUE_{-N}$ was evaluated.

## 3. Results

3.1. Overall $NUE_{-N}$ and N losses at different stages of the supply chain

The country-level $NUE_{-N}$ and N losses of mixed dairy supply chains for Western European countries are summarized in Figure 2. Of the 11 Tg N applied annually to feed crop and pasture, only 0.79 Tg N were found in final animal co-products and 2.5 Tg N were recovered as manure available for recycling. The $NUE_{-N}$ is higher at processing stage: 79% compared to 61% and 76% at the biophysical stages of feed crop/pasture production and animal production, respectively. The lower $NUE_{-N}$ in feed crop/pasture production is related to the relatively large amounts of N lost via volatilization, leaching and run-off during the process of application of synthetic fertilizer and manure and manure deposition during grazing. On the other hand, the relatively higher $NUE_{-N}$ in animal production is explained by the large proportion of manure that is estimated to be recycled. About 3.9 Tg N were lost during feed crop/pasture production representing 74% of total N losses in supply chain. The amounts of N losses in animal production and processing stage were lower: 1.1 Tg N and 0.18 Tg N, respectively.

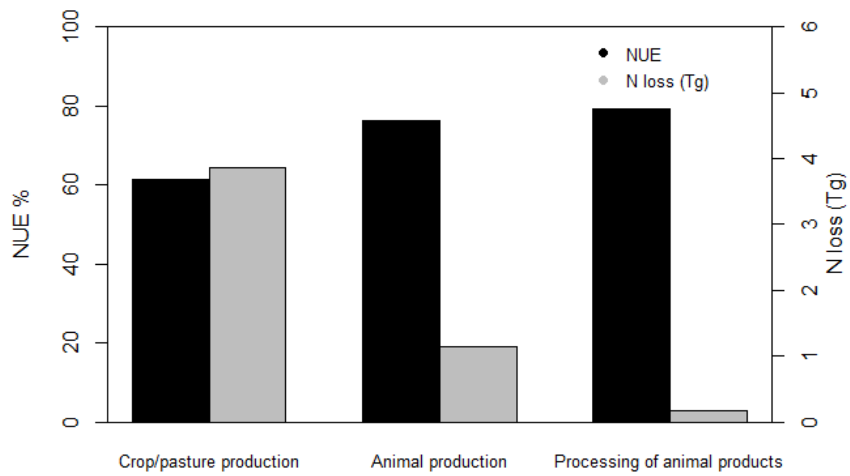
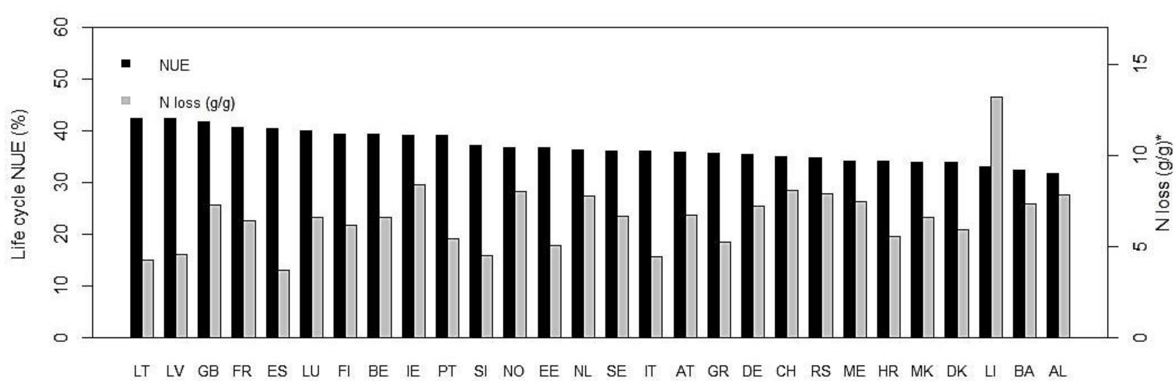



Figure 2. The NUE$_{-N}$ and N losses for every stage of the mixed dairy cattle supply chains for Western European countries.

3.2. Life cycle NUE$_{-N}$, NHI$_{-N}$, and N losses

The average life cycle NUE$_{-N}$ and N losses of mixed dairy supply chains for Western European countries are summarized in Figure 3, whereas results of NHI$_{-N}$ are presented in figure 4. There were large differences between countries in average life cycle NUE$_{-N}$ which ranged from 32% to 43%, with an overall average of 37±3%. Depending on the country, N losses per g of N in final co-product varied from 3.7 g N per g N to 13 g N per g N with an average of 6.6±1.8 g N per g N. NHI$_{-N}$ varied from 0.61 to 1.4, with an average of 1.0±0.1. These results show that the countries with higher life cycle NUE$_{-N}$ do not necessarily have lower N losses per unit of product or NHI$_{-N}$ or vice-versa. For instance, the United Kingdom (GB), and the Spain (ES) have a similar life cycle NUE$_{-N}$ but the dairy cattle system in GB has a higher N losses than in ES. This is because in GB the feed system is dominated by forage (around 62% of total feed), whereas this material plays a less important role in the feed rations of ES (around 42% of total feed) and that fodder production is characterized by a lower feed use efficiency.




AL: Albania, AT: Austria, BE: Belgium, BA: Bosnia and Herzegovina, CH: Switzerland, DE: Germany, DK: Denmark, EE: Estonia, ES: Spain, FI: Finland, FR: France, GB: United Kingdom (of Great Britain and Northern Ireland), GR: Greece, HR: Croatia, IE: Ireland, LI: Liechtenstein, IT: Italy, LT: Lithuania, LU: Luxembourg, LV: Latvia, MK: Macedonia, NO: Norway, NL: Netherlands, PT: Portugal, ME: Montenegro, MK: The former Yugoslav Republic of Macedonia, RS: Republic of Serbia, SE: Sweden, SI: Slovenia.
* N loss is expressed as g N losses per 1 g of N in final animal co-products (edible and non-edible).

Figure 3. The life cycle NUE$_{-N}$ and N losses of mixed dairy cattle supply chains for Western European countries.

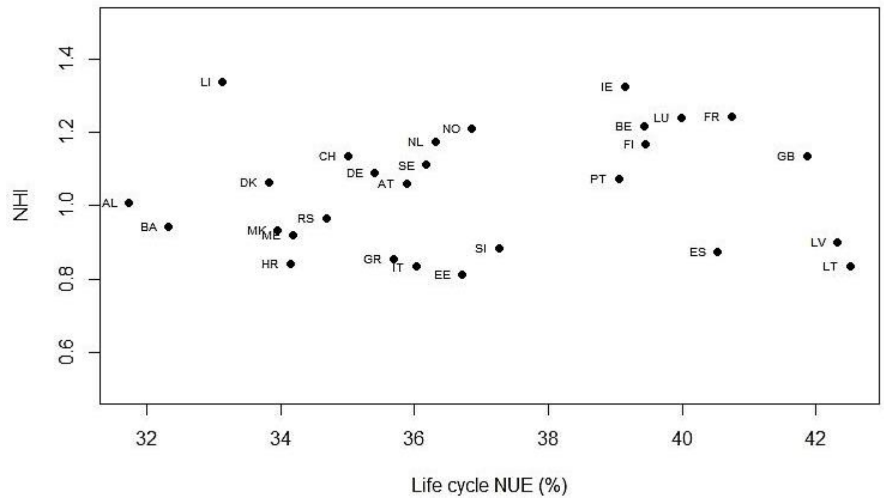



Figure 4. $NHI_{-N}$ and life cycle $NUE_{-N}$ of mixed dairy cattle supply chains for Western European countries.

Around 15 countries have a $NHI_{-N}$ greater than the average (1±0.1), indicating the presence of hotspots in the supply chains. All countries irrespective of their life cycle $NUE_{-N}$, the feed crop/pasture is the stage with higher N losses due to the over-fertilization. $NHI_{-N}$ also allows comparison of supply chains with equal life cycle $NUE_{-N}$. In this case, for example, Norway (NO) and Estonia (EE) have similar life cycle $NUE_{-N}$ but the lower $NHI_{-N}$ in EE implies that N losses are similarly spread along the supply chains than in NO where there is a presence of a hotspot in the feed crop/pasture production.

## 4. Discussion

4.1. Sensitivity analysis and methodological limitations

Data used in this study were mainly extracted from GLEAM and literature. Obviously, these data are subject to various degrees of uncertainty. A partial sensitivity analysis was thus carried out to identify the most sensitive key data to the life cycle $NUE_{-N}$ result. A 10% increase/decrease in the synthetic fertilizer use resulted in a 0.3% increase/decrease in the life cycle $NUE_{-N}$, whereas it resulted in 1% increase/decrease when applied to feed N intake. On the other hand, the 10% change on manure use resulted in 7% decrease/increase of life cycle $NUE_{-N}$, which shows the largest range among the key data tested. Any change of this parameter impacts also the $NHI_{-N}$ and N losses. Other sources of uncertainty are related to the modeling of soil mineral N stock change which is simplified in this assessment, and based on a mass balance approach. In addition, the use of Tier 1 and Tier 2 approaches presents a limitation to the accuracy of quantification; more research is needed to develop Tier 3 approaches that improve the accuracy and precision of computation.

The main challenge of computing $NUE_{-N}$ at each life stage of the supply chain compared to computing a unique overall efficiency, is obviously the high data requirements and the dependence on data quality and uncertainty. Therefore, the exploration of minimum data requirement to perform a representative regional or global life cycle $NUE_{-N}$ is crucial. The other limitation is related to the difficulty to estimate mineral N stock in the soil pool. Leip et al. (2011) assumed a soil stock change of zero to simplify the calculation. In contrast, the framework we propose, considers that the extra N which is not uptaken or lost through leaching, run-off and volatilization is stocked as mineral N in the soil pool. The long-term accumulation of N may however result in high leaching with impacts on water quality and aquatic ecosystems. Further improvement of the framework should thus aim at estimating the maximum storage capacity of the soil to avoid the under-estimation of N losses to the environment.

### 4.2. Comparison with other studies

This study computes $NUE_{-N}$ in a life cycle dimensions of mixed dairy production systems in Western Europe. It shows that, for production of final animal co-products, the life cycle $NUE_{-N}$ was on average 36±3.1%. The country-level life cycle $NUE_{-N}$ computed in this study is not directly comparable with previous results computed at animal or farm level. Nevertheless, partial validation is possible by comparing the $NUE_{-N}$ in different stages of the supply chain with actual quantifications. The average $NUE_{-N}$ at feed crop/pasture production (61%) is comparable to the average of soil $NUE_{-N}$ of 59% estimated for all crops in fifteen countries of European Union (OECD 2001). In animal production, the $NUE_{-N}$ is 76%, which is higher than previous estimates of about 22% in dairy production system (Powell et al. 2013). The difference is related to the N outflows included in the quantification. Powell et al. (2013) only considered the raw milk as output whereas in this study, raw milk, live animals, and recycled manure were included as products, which increased considerably the $NUE_{-N}$ in this stage. The high performance at the processing stage in terms of $NUE_{-N}$ is related to the technological control of flows, treatment of waste water and re-use of organic wastes usually applied at industrial level.

The average N losses calculated in this study are not comparable to the N footprint defined by Leip et al. (2013), which focuses on the total direct N losses to the environment per unit of food product. The N footprint, therefore, is higher than the estimated N losses which are related to the unit of N in the final animal co-product. Furthermore, livestock supply chains deliver non-edible final co-products which constitute raw material for other industries e.g. leather, cosmetics, pharmaceutical industries, etc. Therefore, the harmonization of the quantification methods and interpretation of the results are essential to allow the comparability.

### 4.3. Relevance and comparative advantages of the proposed framework

The proposed framework relies on the computation of three indicators. Complementarily to life cycle $NUE_{-N}$, $NHI_{-N}$ facilitates the design of interventions, by giving information on the presence of hotspots. Furthermore, N losses gives information on the likely environmental impacts, although pathways aren't described in this assessment. At crop/pasture level, this framework may support the improvement of land management, and precision of N application. At the animal production level, increasing feed digestibility and manure management are suggested options. Although further research is needed to explore their applications in contrasting farming systems (Oenema and Tamminga 2005; Erisman et al. 2007; Oenema et al. 2012; Sutton et al. 2013). Relatively high values of $NHI_{-N}$ indicate that interventions can be targeted to few hotspots, which may well improve their cost-effectiveness; whereas designing and implementing interventions for supply chains with lower $NHI_{-N}$ would require greater monitoring and evaluation efforts.

The life cycle approach applied to N use allows to account for the use, recycling and disposal of different agricultural resources such as crop residues and manure. The proposed framework provides indications on potential N pressure on the environment but does not give direct information on the impacts e.g. on water quality. Assessing impacts and evaluating the possibility to use life cycle $NUE_{-N}$ as a potential proxy of impact, requires an approach that takes into account the N migration and transformation pathways in the environment. This requires detailed data on soil types, climate, water catchment, hydrology, drainage capacity of the soil, altitude, intensity of mechanization, as well as the interaction of livestock activities with other agricultural supply chains (Schulte et al. 2006).

Compared to life cycle assessment (LCA), the proposed framework requires less data and assessment steps, while supplying relevant information to support decision making. It is therefore proposed as a tool that can support the design and monitoring of N management in livestock systems that is less data demanding than LCA.

## 5. Conclusion

The life cycle $NUE_{-N}$ provides information on N performance in livestock supply chains. It explores the capacity of livestock supply chains to convey N contained in inputs into products for human use. The life cycle $NUE_{-N}$ considers the ability of livestock stakeholders to recycle, reuse and dispose of nutrients to limit the continuous importation of "new nutrient" in the supply chain. The combination of life cycle $NUE_{-N}$, N losses and $NHI_{-N}$ provides relevant information to improve production technology and practices for a better management of nutrients. The framework requires less data than LCA but global and regional assessment would still require much information. Further work is thus needed to evaluate the minimum data requirement of the framework, ensuring wider applicability.

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