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Implementation of the Product Environmental Footprint Category Rules for dairy products: An approach to assess nitrogen emissions in a mass balanced dairy farm system

D. Egas [a], V. Vasilaki [b], E. Katsou [b], P. Stanchev [b], S. Ponsá [a], J. Colon [a, *]

[a] BETA Tech Center. TECNIO Network, U Science Tech, University of Vic-Central University of Catalonia, de la Laura 13, 08500, Vic, Spain
[b] Department of Civil & Environmental Engineering, Institute of Environment, Health and Societies, Brunel University London, Uxbridge Campus, Middlesex, UB8 3PH, Uxbridge, UK

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A B S T R A C T

Following the Single Market for Green Products, the European Commission released the Product Environmental Footprint Category Rules for Dairy Products (PEFCR-D). According to the PEFCR-D, nitrogen (N) emissions must be calculated as stated by The Intergovernmental Panel on Climate Change (IPCC) and the European Environmental Agency (EMEP/EEA) methods. However, since the IPCC method and the EMEP/EEA method follow different N flows, the estimated N emissions differ at common farm stages resulting in incompatibilities in the reported PEFCR-D emissions from a mass balance perspective. This work proposes a comprehensive approach to calculate N emissions to satisfy the PEFCR-D guideline in a N balanced farm system. The proposed approach coordinates and balances the N flows at each stage in order to estimate the N emissions from the dairy system. In this regard, emissions such as N_2O, NH_3, NO_x, N_2 and NO_3^- are estimated following the IPCC and EMEP/EEA methods from a single N flow in the system. The N losses in the whole dairy farm are estimated to increase 4.41% as a result of the implementing the PEFCR-D in a N balanced system instead of a non-balanced one. Consequently, an increase in environmental impacts of the farm such as Global Warming Potential (6.68%), Marine Eutrophication (4.91%) and Terrestrial Eutrophication (4.26%) were also measured. Moreover, the proposed approach to implement the PEFCR-D enabled the redistribution of emissions between farm stages; particularly relocating N emissions and environmental impacts between manure management and application. This resulted in a decrement on the manure management stage environmental impacts such as Global Warming (−41.88%) and Photochemical Ozone formation (−25.49%). On the other hand, at application stage, increments in Global Warming (26.94%), Marine Eutrophication (8.48%) and Terrestrial Eutrophication (7.52%) were evidenced when contrasting the outcomes between the non-balanced and balanced PEFCR-D calculation approach.

1. Introduction

Since the release of the Roadmap to a Resource Efficient Europe communication (COM(2011) 571) by the European Commission (EC), as a component of the Europe 2020 Strategy, the main focus has been on the establishment of sustainable consumption and production of goods and services. The emphasis on reporting the levels of sustainability (either voluntary or mandatory) by the industry has created the impetus to develop tools and techniques for measuring environmental and sustainable credibility (EC, 2011). Currently, the European Union (EU) regulations provide product policies to different stakeholders (e.g. business, producers and consumers) to support the expansion of green markets (e.g. Ecodesign Directive 2009/125/EC (2009), Labelling Directive 2010/30/EU (2010), Green Public Procurement COM (2008) 400 (2008) and the EU Ecolabel Regulation No 66/2010 (2009)). Moreover, there are international, national, and corporate product environmental regulations that belong to the same framework of the ISO 14020 "Environmental labels and declarations" (2000).

* Corresponding author. BETA Technology Centre: "U Science Tech", University of Vic-Central University of Catalonia, Carrer de la Laura nº13, 08500, Vic, Barcelona, Spain.
E-mail address: joan.colon@uvic.cat (J. Colon).

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Abbreviations

$App_{Grazing}$	Application stage of manure directly excreted by livestock during grazing
App_{Mm}	Application stage of managed manure
CH_4	Methane
D-N_2O	Direct nitrous oxide
EC	European Commission
EDA	European Dairy Association
EF	Emission factor
EI	Environmental impact
EMEP/EEA	The European Monitoring and Evaluation Programme and the European Environmental Agency
EMEP/$EEA_{N\ flow}$	N flow generated and followed by the EMEP/EEA guideline
EU	European Union
FU	Functional unit
GHG	Greenhouse gas emissions
GWP	global warming potential
H&H	Livestock housing and holding areas stage at farm
I_L-N_2O	Indirect nitrous oxide emissions due to leaching
I-N_2O	Indirect nitrous oxide (leaching + volatilisation)
IPCC	The Intergovernmental Panel on Climate Change
$IPCC_{N\ flow}$	N flow generated and followed by the IPCC guideline
I_V-N_2O	Indirect nitrous oxide emissions due to volatilisation
LCA	Life Cycle Assessment
M-EP	Marine eutrophication potential
MM	Manure management/storage stage at farm
Mm	Managed manure
MMS	Manure management systems
N	Nitrogen
N_2	Di-nitrogen
N_2O	Nitrous oxide
$N_{ex(T)}$	Total excreted nitrogen by a livestock subcategory (T)
NH_3	Ammonia
N_{MMS_Avb}	Nitrogen available for the application to soils
NO_3^-	Nitrate
NO_x	Nitrogen oxide
OEF	Organization Environmental Footprint
PEF	Product Environmental Footprint
PEFCR-D	Product Environmental Footprint Category Rules for Dairy Products
PEFCR-$D_{(B)}$	Implementation of the PEFCR-D in a balanced system (calculation approach)
PEFCR-$D_{(NB)}$	Implementation of the PEFCR-D in a non-balanced system (calculation approach)
PEFCRs	Product Environmental Footprint Category Rules
PMFP	Particulate matter formation potential
POFP	Photochemical ozone formation potential
T	Livestock subcategory
TAN	Total ammoniacal nitrogen
T-EP	Terrestrial eutrophication potential

Consequently, many choices of methods and initiatives can be found to generate credentials for green products, which confuse stakeholders (Brécard, 2014; EC, 2013).

To face the uncontrolled proliferation of green credentials for products, in 2013 the EC released the Communication “Building the Single Market for Green Products” (EC, 2013), which encourages the application of the Product Environmental Footprint (PEF) and Organization Environmental Footprint (OEF) methods (EU, 2013). The PEF Guide (Manfredi et al., 2012) provides a general framework for measuring the environmental performance of a product or service through its lifetime based on the Life Cycle Assessment (LCA). The PEF primary goal is to harmonise the existing LCA methods and to provide objective criteria for comparing the environmental performance of products. It defines requirements for some of the methodological aspects and provides guidelines for conducting the environmental assessment. However, each of the existing groups of products in the market requires a specific assessment method to reach the PEF goals. Hence, the Product Environmental Footprint Category Rules (PEFCRs) were issued with the aim to provide a product category specific guidance when developing a PEF study to increase reproducibility, consistency and comparability (EU, 2017). In this context, a three-year environmental footprint pilot phase took place between 2013 and 2018 resulting in the development of validated PEFCR methodologies (EC, 2018).

Milk has a significant role in the dairy and food industry. Milk production has increased during the last decade, and it is expected to reach 1077 million tonnes by 2050 to satisfy the growing demand for dairy products (Alexandratos and Bruinsma, 2012). Livestock supply chains are responsible for 14.5% of the total anthropogenic greenhouse gas (GHG) emissions of which 19.7% are specifically generated by dairy cattle (Gerber et al., 2013). Consequently, due to the environmental relevance of the dairy sector and its products (e.g. milk, cheese and yogurt), the Product Environmental Footprint Category Rules for Dairy Products (PEFCR-D) was developed during the pilot phase and officially released by the European Dairy Association (EDA, 2018).

The study of the environmental impacts (EI) generated by the dairy industry has gained momentum in recent years and LCA has been one of the most widely used assessment methods. For example, dairy products, such as processed milk (Noya et al., 2018), cheese (González-García et al., 2013), and yoghurt (Vasilaki et al., 2016) have applied LCA to measure the environmental performance of the industry. Their studies concluded that raw milk production at the dairy farm is the major source of the emissions affecting the environmental performance of the dairy products. Moreover, some authors have determined key activities in the dairy farm during raw milk production (i.e. livestock feed production, enteric fermentation, and the manure management/storage) from which the majority of the GHG and other pollutants arise (Meul et al., 2014). Enteric fermentation of livestock mostly generates methane (CH_4), while production of animal feed, excretion of manure on pastures, manure management/storage at the farm and manure application to soil is related with different types of nitrogen (N) emissions.

The estimation of N emissions, such as nitrous oxide (N_2O), ammonia (NH_3) and nitrogen oxide (NO_x) influences the environmental assessment of dairy farms and their products due to their relevance in the calculation of EI such as climate change (global warming potential), photochemical ozone formation and terrestrial and marine eutrophication. Most LCA studies use commercial databases with emissions derived from a wide range of production systems. Three of the most used LCA databases are Ecoinvent v3.4 (Weidema et al., 2013), Agri-foodprint v3.0 (Durlinger et al., 2017), and Agribalyse v1.3 (Koch and Salou, 2016). The datasets included in these databases comprise raw milk production emissions; including N emissions generated in the dairy farm by the livestock. Table 1 presents the methodologies used by the commercial databases to estimate N emissions from the dairy

Table 1
Methodologies used by commercial databases to determine N emissions at the dairy farm and the PEFCR-D requirements.

Emission	Farm Activities	PEFCR-D (EDA, 2018)	Ecoinvent v3.4 (Weidema et al., 2013)	Agri-foodprint v3.0 (Durlinger et al., 2017)	Agribalyse v1.3 (Koch and Salou, 2016)
Nitrogen excreted (N)	Excretion by dairy livestock	IPCC, Tier1	IPCC 2006 Tier2	IPCC 2006 Tier2	CORPEN, 1999 [a]
Direct nitrous oxide (N_2O)	Manure storage/ management	IPCC, Tier1	IPCC 2006 Tier2	IPCC 2006 Tier2	IPCC 2006 Tier2
	Excretion on pastures	IPCC, Tier1	IPCC 2006 Tier1	IPCC 2006 Tier1	IPCC 2006 Tier1
	Manure application	IPCC, Tier1	IPCC 2006 Tier1	IPCC 2006 Tier1	IPCC 2006 Tier1
	N fertilizers application	IPCC, Tier1	IPCC 2006 Tier1	IPCC 2006 Tier1	IPCC 2006 Tier1
	Crop residues	IPCC, Tier1	IPCC 2006 Tier1	IPCC 2006 Tier1	IPCC 2006 Tier1
	Organic soils	IPCC, Tier1	IPCC 2006 Tier1	IPCC 2006 Tier1	IPCC 2006 Tier1
	Mineral solis	IPCC, Tier1	IPCC 2006 Tier1	IPCC 2006 Tier1	IPCC 2006 Tier1
Ammonia (NH_3)	Manure storage/ management	EMEP/EEA, Tier2	Agrammon Tier3 [b]	IPCC 2006 Tier2	EMEP/EEA 2009, Tier2
	Excretion on pastures	EMEP/EEA, Tier2	Agrammon Tier3 [b]	IPCC 2006 Tier1	EMEP/EEA 2009, Tier2
	Manure application	EMEP/EEA, Tier2	Agrammon Tier3 [b]	IPCC 2006 Tier1	EMEP/EEA 2009, Tier 2
	N fertilizers application	EMEP/EEA, Tier2	Asman 1992 [c]	IPCC 2006 Tier1	EMEP/CORDINAIR 2006, Tier 2 [d]
Nitrogen Oxide (NO_x)	Manure storage/ management	EMEP/EEA, Tier2	Nemecek 2011 [e]	–	EMEP/EEA 2009, Tier 1
	Excretion on pastures	EMEP/EEA, Tier2	Nemecek 2011 [e]	–	EMEP/EEA 2009, Tier 1
	Manure application	EMEP/EEA, Tier2	Nemecek 2011 [e]	–	EMEP/EEA 2009, Tier 1
	N fertilizers application	EMEP/EEA, Tier2	Nemecek 2011 [e]	–	EMEP/EEA 2009, Tier 1
Indirect nitrous oxide (N_2O) due to volatilisation of NH_3 and NO_x	Manure storage/ management	IPCC, Tier1	IPCC 2006 Tier2	IPCC 2006 Tier2*	IPCC 2006 Tier2
	Excretion on pastures	IPCC, Tier1	IPCC 2006 Tier1	IPCC 2006 Tier1 *	IPCC 2006 Tier1
	Manure application	IPCC, Tier1	IPCC 2006 Tier1	IPCC 2006 Tier1 *	IPCC 2006 Tier1
	N fertilizers application	IPCC, Tier1	IPCC 2006 Tier1	IPCC 2006 Tier1 *	IPCC 2006 Tier1
Nitrate (NO_3^-)	Excretion on pastures	IPCC, Tier1	SALCA-NO3**[f]	IPCC 2006 Tier1	Basset-Mens 2007 [g]
	Manure application	IPCC, Tier1	SALCA-NO3**[f]	IPCC 2006 Tier1	IPCC 2006 Tier1**
	N fertilizers application	IPCC, Tier1	SALCA-NO3**[f]	IPCC 2006 Tier1	IPCC 2006 Tier1**
	Crop residues	IPCC, Tier1	SALCA-NO3**[f]	IPCC 2006 Tier1	IPCC 2006 Tier1**
Indirect nitrous oxide (N_2O) due to N leaching	Excretion on pastures	IPCC, Tier1	IPCC 2006 Tier1	IPCC 2006 Tier1	IPCC 2006 Tier1
	Manure application	IPCC, Tier1	IPCC 2006 Tier1	IPCC 2006 Tier1	IPCC 2006 Tier1
	N fertilizers application	IPCC, Tier1	IPCC 2006 Tier1	IPCC 2006 Tier1	IPCC 2006 Tier1
	Crop residues	IPCC, Tier1	IPCC 2006 Tier1	IPCC 2006 Tier1	IPCC 2006 Tier1

*Does not considers NO_x, **For European countries, *** Only for tropical crops.
[a] (CORPEN, 1999).
[b] (Kupper and Menzi, 2013).
[c] (Asman, 2012).
[d] (EMEP/CORINAIR, 2006).
[e] (Nemecek and Schnetzer, 2011).
[f] (Richner et al., 2014).
[g] (Basset-Mens et al., 2007).

farm and their compliance with the requirements of the PEFCR-D. According to the literature (summarised in Table 1), there is consensus about the methodologies used to determine direct nitrous oxide (D-N_2O) and indirect nitrous oxide emissions due to leaching (I_L-N_2O) during the dairy farm activities. Agri-foodprint and Agribalyse use the Intergovernmental Panel on Climate Change (IPCC) Tier 2 methodology with country-specific data (Nederland and France respectively) to calculate the D-N_2O during manure storage/management. All three databases, as stated in the PEFCR-D, use the IPCC to calculate indirect nitrous oxide (I-N_2O) emissions due to volatilisation of NH_3 and NO_x. However, Agri-foodprint only considers NH_3 emissions.

For the determination of the NH_3 or NO_x emissions, neither Ecoinvent nor Agri-foodprint conform to the PEFCR-D; while, Agribalyse partially complies to it. Ecoinvent uses Agrammon (Kupper and Menzi, 2013) and Asman (2012) to estimate NH_3 and the methodology suggested by Nemecek and Schnetzer (2011) to quantify NO_x, while Agri-foodprint uses IPCC to determine NH_3 emissions but does not consider NO_x emissions. On the other hand, Agribalyse uses the Tier 1 EMEP/EEA (European Monitoring and Evaluation Programmed and the European Environmental Agency) methodology to determine NO_x and the EMEP/CORINAIR (2006), former EMEP/EEA, to calculate NH_3 from the application of N fertilisers.

Regarding nitrate (NO_3^-) emissions, only Agribalyse and Agri-foodprint partially meet the PEFCR-D requirements. Agribalyse calculates NO_3^- from the direct excretion of manure on pastures as suggested by Basset-Mens et al. (2007), and only uses IPCC when assessing tropical crops in the remaining farm activities. Agri-foodprint uses IPCC-Tier1 but considers all the leached N as NO_3^-, while Ecoinvent uses the SALCA-NO_3 model (Richner et al., 2014). In summary, none of the assessed databases (Ecoinvent v3.4, Agri-foodprint v3.0 and Agribalyse v1.3) fully achieve the PEFCR-D requirements to calculate the N emissions in the dairy farm.

There is a clear need of an approach to link both IPCC and EMEP/EEA methodologies in order to obtain credible N balanced results and comply with the PEFCR-D requirements. In this regard, the IPCC (2006a, 2006b) proposes the development of NH_3 country-specific emission factors (EF) and suggests the use of the EMEP/EEA mass balance/mass flow methodology to estimate NH_3 and NO_x; including di-nitrogen (N_2) emissions at manure management before the application to soil. On the other hand, the EMEP/EEA (2016b) states that its mass-flow approach ensures consistency with the N species estimated with the IPCC. However, apart from these acknowledgements between the methodologies, neither the PEFCR-D, IPCC nor EMEP/EEA state how the outcomes from the EMEP/EEA should be integrated into the IPCC and vice versa from a mass balance perspective. Furthermore, the documentation of the analysed commercial databases does not clearly explain how the interaction between the outcomes of these and other methodologies, to calculate N emissions, is being managed to obtain a balanced farm system. Section 2.1 of this paper discusses and provides greater detail regarding the source of the mass balance gaps between the IPCC and EMEP/EEA when applied in the PEFCR-D framework.

The assurance of a balanced N flow system when simultaneously applying the IPCC and the EMEP/EEA is necessary for validating the process definition and associated data, to check the quality of data (Guinee, 2002; ISO 14041 Standards, 1998) and to ensure the comparability between different dairy products and systems in accordance to PEF aims. The environmental performance of the systems under comparison are evaluated and interpreted following the ISO 14044 standard (2006) for LCA. Therefore, solving the N mass balance in the system is an imperative requirement to ensure the system's data quality, obtain reliable input for the calculation of the system's emissions and compare the environmental performance of different dairy farms in the PEFCR-D framework.

The goal of this work is to propose a comprehensive approach to calculate N emissions from a dairy farm balanced system based on the IPCC and EMEP/EEA methodologies to comply with the PEFCR-D requirements. This proposed approach is especially relevant to achieve a N-balanced system throughout the different farm stages ensuring (i) proper allocation of N-emission between farming stages and (ii) reliable input for the calculation of EI categories such as Climate Change, Terrestrial & Marine Eutrophication or Acidification. To our knowledge, this is the first attempt to provide a coherent and balanced N emission calculation approach to be used when performing PEF studies.

2. Materials and methods

The following section (2.1) provides greater detail regarding the origin of the gaps between the IPCC and EMEP/EEA, from a mass balance perspective, when applied in the PEFCR-D framework, and then (Section 2.2), a clear calculation approach to overcome these gaps and obtain a common N balanced farm system in agreement with the PEFCR-D is presented. A tool to calculate the individual IPCC and EMEP/EEA methodologies as well as the PEFCR-$D_{(NB)}$ and the PEFCR-$D_{(B)}$ approaches can be downloaded from http://www.betatechcenter.com.

2.1. IPCC and EMEP/EEA methodologies

To calculate N emissions during the livestock housing, holding areas and manure storage the PEFCR-D requires the use of IPCC Chapter 10 (2006a) and EMEP/EEA Section 3.B (2016a), while to quantify emissions from the application of manure or fertilizers to soil the IPCC Chapter 11 (2006b) and EMEP/EEA Section 3.D (2016b) must be used. The methodologies provide equations, EF and default values to determine N emissions generated in the dairy farm from different N sources (e.g. managed manure, inorganic and organic fertilisers). The main differences and limitations of both methodologies per dairy farm stage are summarised in Table 2. Furthermore, a summary of the different N emissions calculated at each stage following the two methodologies is presented in Table 3.

As shown, both methodologies imply different methodological approaches to calculate N emissions at similar farm stages (i.e. livestock housing and holding, manure management/storage and application of manure that has been managed or directly excreted by the livestock during grazing). The unrelated N emissions obtained from the IPCC and EMEP/EEA at one of the dairy farm stages result in different and incoherent N flow inputs for the subsequent stages (Fig. 1). Despite the incoherent N flows between the IPCC and EMEP/EEA, the PEFCR-D directly reports their calculated emissions without any further considerations. Hence, the outcomes reported by the PEFCR-D cannot be considered reliable due to the discrepancies of the N-mass balance in the system (PEFCR-$D_{(NB)}$). Fig. 1 represents the N flow diagram of a dairy system, and the related emissions reported by the PEFCR-$D_{(NB)}$ per dairy farm stage.

2.2. Harmonisation of the IPCC and EMEP/EEA within PEFCR-D

The harmonisation of EMEP/EEA and IPCC is presented through four iterations exclusively to facilitate the understanding of the proposed approach. The first iteration obtains the N emission from the independent application of the methodologies; then, based on those results, each of the following iterations balance the N flows of an specific farm stage. By the fourth iteration, all N flows in the system are adjusted to obtain a common and balanced N system for the quantification of the N emissions.

This new calculation approach includes additional N sources (e.g. cheese whey or wastewater) and outputs (e.g. compost sold at third parties) that are not stated in the PEFCR-D but exist in a conventional dairy farm system; these and all the additional inputs and outputs are allocated to each livestock subcategory (T) in the farm (e.g. high or low producing mature cows, non-productive cows or calves). The complete equations used to harmonise the IPCC and EMEP/EEA methodologies are presented and discussed in detail in the supplementary material (Eqs. S1 to S50). This section only describes the most relevant aspects of each iteration for determining the N flows throughout the different system stages: livestock housing and holding at farm (H&H), manure management/storage at farm (MM) and application of manure that has been managed (App_{Mm}) or directly excreted by the livestock during grazing ($App_{Grazing}$). Fig. 2 illustrates the common and balanced N flow diagram that the proposed approach (PEFCR-$D_{(B)}$) follows to determine N emissions. As presented in Section 2.1, the dairy farm system emissions reported by the PEFCR-$D_{(NB)}$ come from two unrelated and non-balanced N flows (Fig. 1). Therefore, the proposed method aims to harmonise the two methodologies (IPCC and EMEP/EEA) allowing them to work together in a N balanced system where the same N inputs and outputs are obtained at each farming stage (Fig. 2), overcoming the inconsistencies between their N flows.

The harmonised approach starts with the calculation of the excreted nitrogen of the livestock subcategory ($N_{ex(T)}$) applying the

Table 2
Differences between the IPCC and EMEP/EEA methodologies through the different farm stages.

Farm Stage	IPCC	EMEP/EEA
N source	- Based on the Nitrogen excreted (N_{ex})	- Based on Total Ammoniacal Nitrogen (TAN) excreted
Livestock housing and holding areas, **H&H** (Fig. 1A)	- Does not report direct or indirect N emissions, as they are included in the manure management stage	- Reports NH_3 emissions from the TAN deposited in buildings and yards. - Considers that a fraction of the solid manure TAN has been immobilised in organic matter while it was transferred from buildings to the storage facilities. - The nitrogen from the animal bedding is added to the solid manure nitrogen that leaves the buildings.
Manure management/ storage, **MM** (Fig. 1B)	- Provides emission factors (EF) for D-N2O and I-N2O emissions for different manure management systems (MMS). - The produced fraction of gaseous and leached N emissions at each MMS is required for the calculation of the I-N_2O - Provides produced fractions of gaseous N emission for several MMS; nevertheless, due to the lack of data on leaching and runoff N losses from MMS are not given and are not considered in the IPCC Tier 1 approach. - From the given fractions of gaseous N emissions, it is possible to infer the total NH_3 and NO_x emissions from each MMS. However, it is not possible to determine the corresponding amount of each gas or the amount that corresponds to H&H	- Provides EF to calculate D-N_2O, NH_3, NO_x and N_2 from only two types of manure management: solid and liquid (slurry) - Emissions from slurry storage are calculated from a modified quantity of stored slurry TAN. Which considers the fraction of TAN that has been mineralised from the quantity of N stored as slurry. - Acknowledges the existence of soluble N emissions from the storage of solid manure and encourages their inclusion. However, EF are not given
Coordination step	- Calculates the remaining nitrogen available for the application to soils (N_{MMS_Avb}) by Applying a fraction of total N losses from the MMS which includes N losses from H&H and MM. The proposed fraction incorporates losses in form of NH_3, NO_x, N_2 and contains leaching and runoff losses from solid storage and dry lots. Hence the amount of each source of N loss cannot be known. - The remaining N that exits the MM stage will not be equal to N_{MMS_Avb} due to incongruence between fractions of gaseous N emission and total N losses at MMS. - Before application, the N_{MMS_Avb} can be used for feed, fuel and construction. Thus only the remaining fraction could be finally applied (Fig. 1C). The N in animal manure fraction is part of the organic nitrogen applied fraction to soil which might include other organic N sources.	- No coordination steps. - This methodology is based on a N and TAN flows through the dairy farm system. Therefore, a balanced system can be obtained.
Application of managed manure, $\textbf{App}_{\textbf{Mm}}$ (Fig. 1C)	- Calculates D-N_2O and I-N_2O emissions from the application of organic and other N sources such as synthetic fertilisers, crop residues, mineral soils and organic soils. - I-N_2O emissions from organic sources due to leaching (I_L-N_2O) are calculated from a fraction of N leached as NO_3^-. - I-N_2O emissions due to volatilisation (I_V-N_2O) from organic sources and synthetic N fertilisers are calculated from their respective fractions of volatilized N. - it is feasible to estimate NO_3 emissions to water and a total N volatilized (NH_3+NO_x) emission to air	- NH_3 emissions are calculated from the quantity of TAN left in the solid manure and slurry that leaves MM. - NOx emissions are calculated from the applied N from manure. - NO3- emissions from manure to water are not quantified, the methodology focuses on gaseous emissions. - NH3 and NOx emissions from the application of synthetic N fertilisers are calculated from their N quantity.
Manure directly applied while the livestock is grazing, $\textbf{App}_{\textbf{Grazing}}$ (Fig. 1C)	- Calculates the grazing I_L-N_2O, I_V-N_2O and D-N_2O emissions.	- Determines NH_3 emissions from the applied TAN during grazing whereas the NO_x emissions are calculated from the applied N.

Table 3
Nitrogen emissions estimated by the IPCC and EMEP/EEA from manure in the dairy farm ("✓" = emission considered in the methodology; "–" = N emission not considered in the methodology).

Stage	Flow	IPCC [a]	EMEP/EEA [b]
Housing and Holding (H&H) Areas	NH_3	–	✓
Manure management (MM)	N_2O	✓	✓
	NH_3	✓*	✓
	NO_x	✓*	✓
	N_2	–	✓
Coordination of emissions between stages		✓	No needed [c]
Application to soil of managed manure (AppMm) and excreted manure during livestock grazing (AppGrazing).	N_2O	✓	–
	NH_3	✓*	✓
	NO_x	✓*	✓**
	NO_3^-	✓	–

*NH3 and NOx emissions are calculated as a single total value, ** NOx emissions are calculated from N applied.
[a] Estimates the emissions from the total N excreted.
[b] Estimates the emissions from the Total ammoniacal Nitrogen excreted (TAN).
[c] Is a N-flow approach.

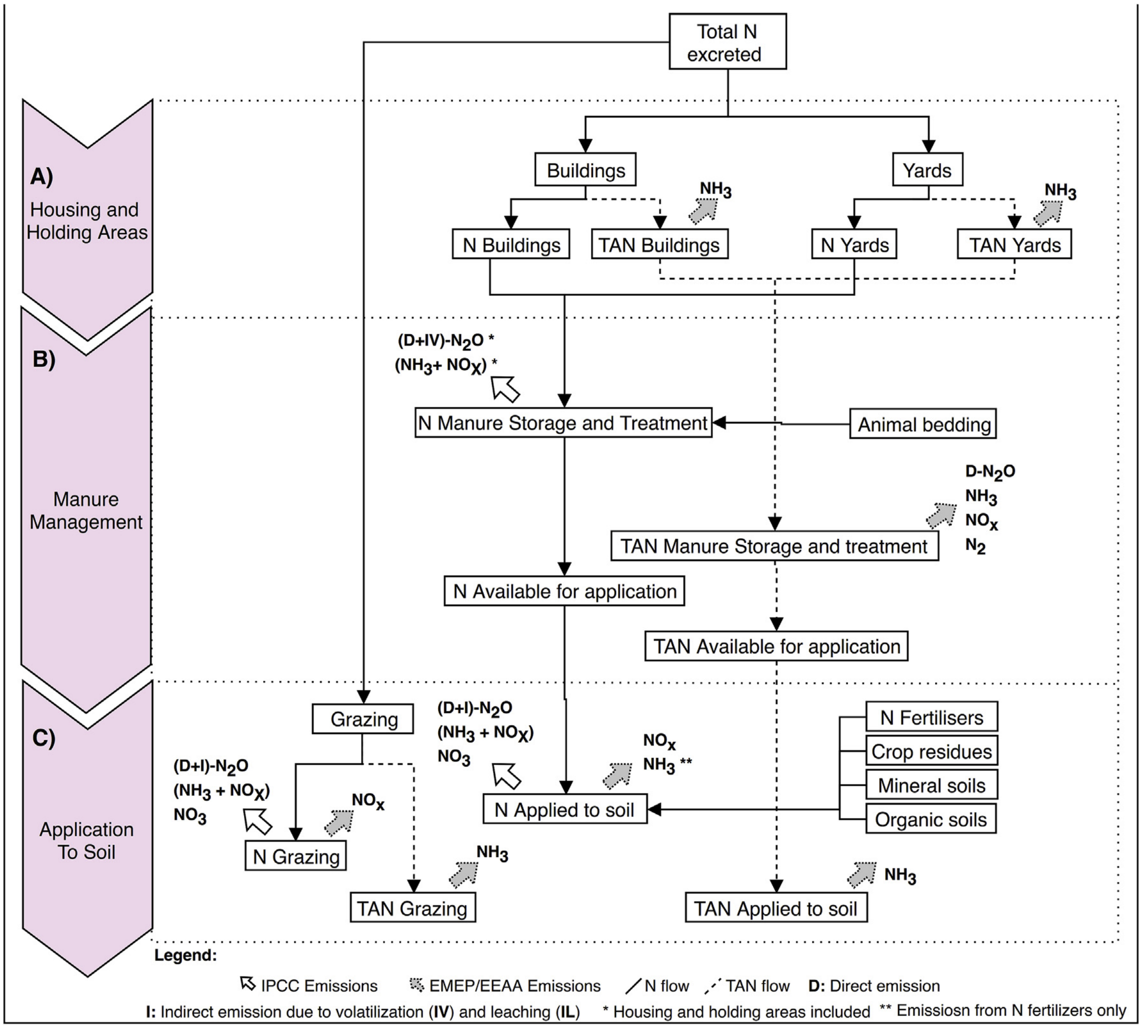

Fig. 1. Flow diagram followed by the non-balanced PEFCR-D (PEFCR-$D_{(NB)}$) calculation approach: IPCC and EMEP/EEA nitrogen emissions determined from their particular N flows in a dairy farm during A) housing and holding areas B) manure management C) application to soil. Continuous arrows refer to the organic N flow (IPCC) and broken arrows to the TAN flow (EMEP/EEA).

IPCC (2006a) Tier 2 methodology; which is also the starting point of both IPCC and EMEP/EEA. Additionally, EMEP/EEA requires the calculation of the excreted Total Ammoniacal Nitrogen (TAN), which is calculated as a proportion (0.6) of $N_{ex(T)}$. Hence, the reported emissions correspond to the assesses livestock subcategory in the dairy farm. The total farm emission is the sum of all the livestock subcategory emissions.

The first iteration applies both IPCC and EMEP/EEA methodologies independently (Section 2.1). The emissions obtained from their particular N flows in a non-N balanced system (Fig. 1) can be directly reported as outcomes of applying the PEFCR-$D_{(NB)}$ approach. In this first iteration, extra N sources (if applicable), different from the $N_{ex(T)}$ such as wastewater and waste whey are also taken into account as new N inputs to the farm system. It is considered that these allocated extra N sources are mixed with the animal manure in a slurry tank, which is a liquid manure management system, hence they contribute to its specific emissions (Fig. 2B). The remaining manure management systems (MMS, e.g. solid manure) do not consider any additional N sources (Eqs. S(1) to S(17)).

The harmonisation between IPCC and EMEP/EEA start at the **second iteration** (Eqs. S(18) to S(19)) after obtaining the PEFCR-$D_{(NB)}$ results from Iteration 1. This second iteration focusses on balancing N outputs from the H&H stage (Fig. 2A) and on the calculation of the H&H indirect nitrous oxide emissions due to N volatilisation (I_V-N_2O). The volatilized N emissions determined by the EMEP/EEA (NH_3, NO_x and N_2) are used by the IPCC to achieve a consistent calculation of I_V-N_2O emissions through the dairy farm system. At H&H (yards and buildings), the independent application of the EMEP/EEA determines NH_3 emissions while the IPPC neither determines NH_3 emissions nor its concomitant I_V-N_2O emissions (Fig. 1A). Hence, this iteration allows the PEFCR-$D_{(B)}$ approach to determine I_V-N_2O emissions from the NH_3 volatilisation at H&H and balances the N outputs from H&H entering the different types of MMS at the MM stage (Fig. 2A).

Once the N flows leaving H&H stage have been balanced (Iteration 2), the **third iteration** aims to balance the nitrogen output from the MM stage. In this stage, NH_3, NO_x and N_2 emissions are calculated using the EMEP/EEA methodology; then, they are coordinated with the IPCC to calculate I_V-N_2O emissions (Fig. 2B). The MM D-N_2O emissions reported by the IPPC differ from the ones reported by EMEP/EEA, therefore the variation of the direct emissions (N-N_2O_{EMEP} - N-N_2O_{IPCC}) has been reallocated into the N remaining in the manure by distributing it among the different existing N fractions in the MM stage (e.g. solid manure, liquid manure, waste water, waste whey, etc.) (Eqs. S(20) to S(34)). The

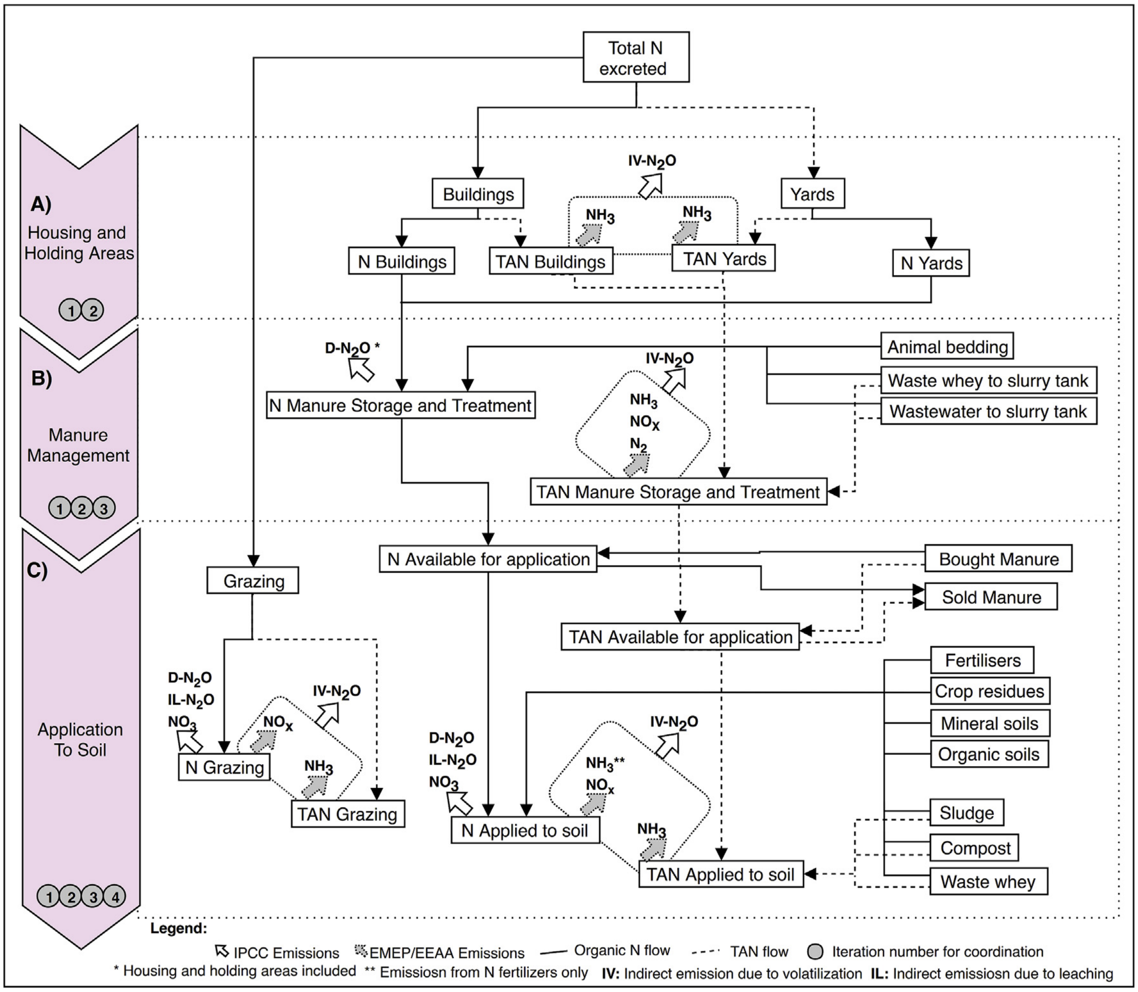

Fig. 2. Flow diagram followed by the balanced PEFCR-D (PEFCR-$D_{(B)}$) calculation approach: IPCC and EMEP/EEA final harmonised N flow from which emissions in a dairy farm arise during A) housing and holding areas B) manure management C) application to soil. Continuous arrows refer to the organic N flow (IPCC) and broken arrows to the TAN flow (EMEP/EEA).

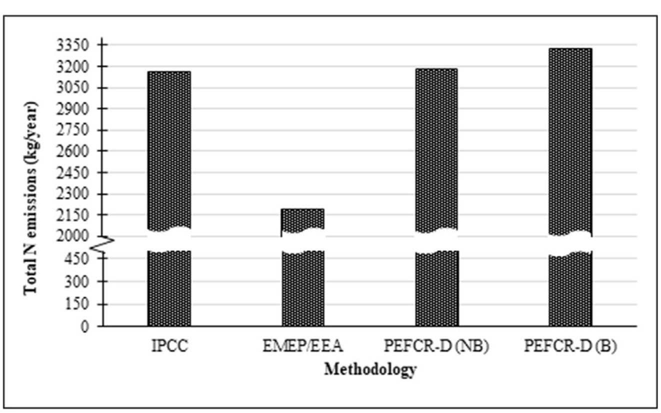

Fig. 3. IPCC, EMEP/EEA, PEFCR-$D_{(NB)}$ and PEFCR-$D_{(B)}$ Total N emissions.

latter results in a balanced N output from MM.

The PEFCR-$D_{(B)}$ approach does not use the IPCC coordination step (described in Table 2) between MM and application because all the upstream dairy farm N flows (NH_3, NO_X, D-N_2O and N_2) are now correctly balanced between stages which means that all gross N leaving MM can be applied to the soil without any other considerations. However, in some cases, a fraction of it can be valorised as organic fertiliser and sold before application (e.g. compost sold), or manure sourced from other farms can be applied on the fam's land. Since these additional N inputs and outputs modify the final available N for application (Fig. 2C), they are considered in the presented approach as well.

The **fourth iteration** focuses on calculating N emissions at the application stage (i) from N flows coming from MM (App_{Mm}), (ii) from N directly excreted by grazing animals ($App_{Grazing}$) (iii) from external organic sources (e.g. compost produced outside the farm), and (iv) from synthetic N fertilisers (Fig. 2C). NH_3 and NO_X emissions are determined with the EMEP/EEA, and on this basis, I_V-N_2O application emissions are calculated while D-N_2O and NO_3^- application emissions have been calculated with the IPCC. Finally, the I_L-N_2O emissions due to application are determined from the IPCC NO_3^- emissions, (Eqs. S(35) and S(48)). At the fourth iteration, all the N flows within the dairy farm stages are balanced, and the outcomes are reported as part of the PEFCR-$D_{(B)}$.

2.3. Case study

To demonstrate the proposed approach a case study was conducted in a conventional dairy farm in the Northwest of Spain, where the N emissions related to high-production mature cows (45 heads) were assessed. The farm's livestock was also integrated by non-productive cows (31 heads) and calves (14 heads). The average weight of the high-production mature cows is 600 kg/head, and the daily milk production is 22.19 kg/head·day^{-1} with an average fat and protein content of 3%. The livestock feeds in a stable (housing) facility 87% of the year and 13% on natural pastures while grazing. Therefore, 13% of the manure is excreted while the livestock is grazing. The remaining manure is excreted in a stable which is collected and treated as solid manure (29%) and liquid manure (58%). All the stored manure is applied to soil after manure management. Following the IPCC Tier 2 requirements, the total N excreted by this livestock subcategory (high-production mature cows) is 4730.40 kg/y. The other farm N sources (i.e. wastewater, waste whey and animal bedding) that correspond to the assessed livestock subcategory are given in Table 4.

3. Results and discussion

The following subsections present and discuss the results of implementing the PEFCR-$D_{(B)}$ and the PEFCR-$D_{(NB)}$ calculation approaches (i) from a N flow perspective and (ii) from an emission and EI perspective.

3.1. N flows in the dairy farm system

The N inputs and outputs of the dairy farm stages were quantified and assessed by the mutual application of the IPCC and EMEP/EEA methodologies on one hand; and PEFCR-$D_{(B)}$ and PEFCR-$D_{(NB)}$ calculation approaches on the other.

Table 5 shows the results from quantification of the N emissions related to the IPCC and EMEP/EEA N flows ($IPCC_{N\ flow}$ and $EMEP/EEA_{N\ flow}$ respectively). There is a significant difference (44.1%) in the total N emissions mostly, but not only, due to the lack of NO_3^- emissions when applying the EMEP/EEA methodology (see Fig. 3). Another reason of discrepancies between the IPCC and the EMEP/EEA N flows is the IPCC coordination step; it reduces 130 kg N from the $IPCC_{N\ flow}$ between MM and App_{Mm} without imputing this N difference to any IPCC-MM emission. Due to the inconsistent N flows and emissions, the total N retained in the soil obtained by the EMEP/EEA is 1055.8 kg higher than the by the IPCC.

Since the PEFCR-$D_{(NB)}$ directly reports the IPCC and EMEP/EEA emissions without any further considerations, Table 5 also shows the incoherence between the emissions reported by the PEFCR-$D_{(NB)}$ and the N flows ($IPCC_{N\ flow}$ or $EMEP/EEA_{N\ flow}$) from which they arise; spotting the necessity of applying the proposed PEFCR-$D_{(B)}$ approach. A clear example is during App_{Mm} where the reported PEFCR-$D_{(NB)}$ N-N_2O and N-NO_3^- emissions (25.8 and 773.9 kg respectively) are calculated from the total $IPCC_{N\ flow}$ entering this stage (2579.7 kg N), while the N-NH_3 and N-NO_x emissions (956.9 kg) are calculated from the total $EMEP/EEA_{N\ flow}$ entering the same stage (3018.4 kg N). Since the reported PEFCR-$D_{(NB)}$ emissions are not coherent, it is not possible to determine the available N in the stages of the dairy farm. The PEFCR-$D_{(B)}$ approach solves the problem and uses a common balanced N flow from MM (3025.6 kg) to determine the App_{Mm} N emissions. Through all the dairy farm system, the PEFCR-$D_{(B)}$ approach applies both IPCC and EMEP/EEA methodologies to calculate N emissions based on an equal quantity of N coming from the respective upstream farm stage. As result, 4.41% more total N emissions are determined by the PEFCR-$D_{(B)}$ than by the PEFCR-$D_{(NB)}$.

Table 4
Quantity and sources of the dairy farm system N inputs for the IPCC and EMEP/EEA methodologies.

N source (kg N/year)	N quantity corresponding to high-production cows	
	IPCC	EMEP/EEA
Total N excreted	4730.40	
N excreted during grazing	614.95	
N excreted at buildings and yards	4115.45	
N from wastewater added to the slurry tank	15.74	
N from Bedding materials*	91.35	50.90
N from waste whey directly applied to the soil	9.61	

*IPCC for manure that is managed as solid: 7 kg N/head/year. EMEP/EEA: 4 g N/kg straw.

3.2. Emissions and environmental impacts

N emissions together with the characterisation factors stated in the PEFCR-D are used to estimate farm's EI (i.e. global warming, particulate matter formation, photochemical ozone formation and terrestrial, and marine eutrophication). Since the N emissions are a basis for the EI assessment of the whole dairy farm system and its individual stages, the EI results differ when using the PEFCR-$D_{(NB)}$ or PEFCR-$D_{(B)}$ calculation approaches (Table 6).

At H&H, the PEFCR-$D_{(NB)}$ and PEFCR-$D_{(B)}$ report same amount of NH_3 emissions (589.68 kg). However, the PEFCR-$D_{(NB)}$ does not consider I-N_2O emissions at H&H and therefore it is unable to report EI categories as global warming (GWP) and photochemical ozone formation (POFP). Due to the separation of the volatilized N emissions between H&H and MM (Table 6), the PEFCR-$D_{(B)}$ enables the calculation of I-N_2O emissions at H&H (7.6 kg I-N_2O). In the other EI categories, the PEFCR-$D_{(NB)}$ reports 0.10% less particulate matter (PMFP) and 0.41% less terrestrial eutrophication (T-EP) than the PEFCR-$D_{(B)}$; while for the marine eutrophication (M-EP) both PEFCR-D approaches report the same value (485.9 mol N_{eq}).

The PEFCR-$D_{(B)}$ reports fewer emissions at MM in comparison with the PEFCR-$D_{(NB)}$. Despite that both consider the same volatilized N emissions (e.g. NH_3, NO_x and N_2), the PEFCR-$D_{(NB)}$ I-N_2O emissions are 55.49% higher than the PEFCR-$D_{(B)}$ (Table 6). This is because the I-N_2O calculations in PEFCR-$D_{(NB)}$ are based on the MM volatilized N emissions from the $IPCC_{N\ flow}$ (1515.3 kg N) which are higher than the common N flow used by the PEFCR-$D_{(B)}$ (674.4 kg N) as shown in Table 5. Furthermore, the PEFCR-$D_{(B)}$ reports 11.80% lower D-N_2O emissions at MM because they arise from the balanced N flow entering MM (3645.7 kg N), which is lower than the $IPCC_{N\ flow}$ entering MM (4131.2 kg N) used by the PEFCR-$D_{(NB)}$ to calculate D-N_2O emissions. The PEFCR-$D_{(B)}$ reports significantly lower overall EI (e.g. 41.88% and 25.49% for GWP and POFP) at MM compared to the PEFCR-$D_{(NB)}$.

During the App_{Mm} stage, the D-N_2O, I-N_2O, NO_3^-, NH_3 and NO_x emissions calculated with PEFCR-$D_{(B)}$ show higher emissions 17.29%, 49.64%, 17.29%, 0.33% and 0.24% respectively in contrast to the PEFCR-$D_{(NB)}$ (Table 6). The incoherent N flows between the PEFCR-D approaches at App_{Mm} (discussed in Section 3.1) and the redistribution of N emissions between MM and this stage are the main sources for the differences. The increment on the PEFCR-$D_{(B)}$ N_2O and $NO^-{}_3$ emissions particularly affected GWP, T-EP and M-EP; these EI categories increased by 26.94, 7.52 and 8.48% respectively.

Finally, I-D_2O emissions show a reduction of 23.53% when assessing the emissions from the $App_{Grazing}$ stage with the PEFCR-$D_{(B)}$ approach instead of PEFCR-$D_{(NB)}$. Since the PEFCR-$D_{(B)}$ and PEFCR-$D_{(NB)}$ do not differ in the calculation of the volatilized N emissions and NO_3^- emissions, the expected I-N_2O emissions of this stage should be consistent (Table 6). However, this is not observed because the PEFCR-$D_{(NB)}$ uses a total of 307.5 kg of volatilized and leached N (123 kg N + 184.5 kg N) from the $IPCC_{N\ flow}$ to determine I-N_2O, while the PEFCR-$D_{(B)}$ uses a balanced N flow giving 246.0 kg of total volatilized and leached N (61.5 kg N + 184.5 kg N) resulting

Table 5
N flows and emissions at each dairy farm stage determined by the IPCC and EMEP/EEA methodologies and by implementing the PEFCR-D calculation approach in a balanced system (PEFCR-$D_{(B)}$) and in a non-balanced system (PEFCR-$D_{(NB)}$).

Stage		N flows [a] and emissions [b] (Kg N/year)	IPCC	EMEP/EEA	Δ (IPCC/EMEP)	PEFCR-$D_{(NB)}$	PEFCR-$D_{(B)}$	Δ PEFCR-D $_{(B/NB)}$
H&H	I	N excreted	4115.5	4115.5	0.0%	4115.5	4115.5	0.0%
	E	N-NH_3	–	485.6	–	485.6	485.6	0.0%
	E	Indirect N-N_2O *	–	–	–	–	4.86	–
	O	N excreted	4115.5	3629.8	13.4%	-**	3629.8	–
MM	I	N excreted	4115.5	3629.8	13.4%	-**	3629.8	–
	I	Wastewater and whey N	15.7	15.7	0.0%	15.7	15.7	0.0%
	I	Total N	4131.2	3645.6	13.3%	3645.6	3645.6	0.0%
	E	N-NH_3, N-NO_x and N-N_2	1515.3	674.4	124.7%	674.4	674.4	0.0%
	E	Indirect N-N_2O *	15.2	–	–	15.2	6.7	−55.5%
	E	Direct N-N_2O	6.9	13.2	−48.2%	6.9	6.1	−11.8%
	I	Animal bedding N	91.4	50.9	79.5%	-**	50.9	–
	O	N exiting MM	2700.4	3008.8	−10.3%	-**	3016.0	–
App_{Mm}	I	N from MM	2570.1	3008.8	−14.6%	-**	3016.0	–
	I	Whey N	9.6	9.6	0.0%	9.6	9.6	0.0%
	I	Total N	2579.7	3018.4	−14.5%	-**	3025.6	–
	E	N-NH_3 and N-NO_x	515.9	956.9	−46.1%	956.9	959.9	0.3%
	E	Indirect N-N_2O *	11.0	–	–	11.0	16.4	49.7%
	E	N-NO_3^-	773.9	–	–	773.9	907.7	17.3%
	E	Direct N-N_2O	25.8	–	–	25.8	30.3	17.3%
	O	N retained in the soil	1264.0	2061.6	−38.7%	-**	1127.8	–
$App_{Grazing}$	I	N excreted during grazing	615.0	615.0	0.0%	615.0	615.0	0.0%
	E	N-NH_3 and N-NO_x	123.0	61.5	100.0%	61.5	61.5	0.0%
	E	Indirect N-N_2O *	2.6	–	–	2.6	2.0	−23.8%
	E	N-NO_3^-	184.5	–	–	184.5	184.5	0.0%
	E	Direct N-N_2O	12.3	–	–	12.3	12.3	0.0%
	O	N retained in the soil	295.2	553.5	−46.7%	-**	356.7	–
Total Dairy farm system	I	Total excreted N	4730.4	4730.4	0.0%	4730.4	4730.4	0.0%
	I	Total N	4847.1	4806.7	0.8%	-**	4806.7	–
	E	Total N	3157.6	2191.6	44.1%	3181.7	3322.2	4.4%
	O	Total N	4847.1	4806.7	0.8%	-**	4806.7	–
	O	Total N retained in the soil	1559.2	2615.0	−40.4%	-**	1484.5	–

* Emissions derived from NH_3, NO_x and N_2 emissions.
**Values not reported because the PEFCR-D(NB) approach directly reports the IPCC and EMEP/EEA emissions that arise from their respective N flows. The IPCC and EMEP/EEA N flows are different among common farm stages making not feasible the estimation of the PEFCR-D(NB) N flow values.
H&H = livestock housing and holding, MM = manure management/storage, App_{Mm} = application of manure that has been managed, $App_{Grazing}$ = Manure directly applied while the livestock is grazing.
[a] N flows that get in (I) and out (O) each dairy farm system or stage.
[b] N emissions (E) from the dairy farm system or stage.

Table 6
N emissions and environmental impacts resulting from implementing the PEFCR-D in a balanced system (PEFCR-$D_{(B)}$) and in a non-balanced system (PEFCR-$D_{(NB)}$) at the dairy farm and its stages.

Emissions/Impacts (/year)		Dairy farm stages												Total Dairy Farm		
		H&H			MM			App_{Mm}			$App_{Grazing}$					
		NB	B	Δ% (B/NB)	NB	B	Δ% (B/NB)	NB	B	Δ% (B/NB)	NB	B	Δ% (B/NB)	NB	B	Δ% (B/NB)
D-N_2O	(kg)	–	–	–	10.8	9.51	−11.8	40.5	47.6	17.3	19.3	19.3	0.0	70.6	76.4	8.1
I-N_2O	(kg)	–	7.6	100	23.8	10.6	−55.5	17.2	25.8	49.6	4.1	3.1	−23.5	45.2	47.2	4.4
NO_3^-	(kg)	–	–	–	0	0	–	3427.3	4019.8	17.3	817.0	817.0	0.0	4244.3	4836.8	14.0
NH_3	(kg)	589.7	589.7	0.0	564.2	564.2	0.0	1015.3	1018.6	0.3	44.8	44.8	0.0	2214.0	2217.3	0.1
NO_x	(kg)	–	–	–	22.2	22.2	0.0	396.7	397.7	0.2	80.8	80.8	0.0	499.8	500.7	0.2
N_2	(kg)	–	–	–	405.9	405.9	0.0	0	0	–	0	0	–	405.9	405.9	0.0
GWP	(kg CO_{2eq})	–	2022.3	100	9166.4	5327.6	−41.9	15308.1	19431.7	26.9	6210.0	5953.9	−4.1	30684.5	32735.6	6.7
PMFP	(DI, x10^{-2})	1.24	1.24	0.1	1.19	1.19	−0.2	2.20	2.21	0.43	0.11	0.11	−0.1	4.75	4.76	0.2
POFP	(kg NMVOC $_{eq}$)	–	7.63	100	56.82	42.33	−25.5	454.48	470.98	3.6	104.3	103.3	−0.9	615.6	624.2	1.4
T-EP	(mol N_{eq})	7943.1	7975.6	0.4	7842.4	7780.7	−0.8	26444.1	28431.5	7.5	3629.8	3625.7	−0.1	45859.3	47813.4	4.3
M-EP	(mol N_{eq})	485.9	485.9	0.0	464.93	464.93	0.0	1611.2	1747.8	8.5	221.56	221.56	0.0	2783.6	2920.2	4.9

NB= PEFCR-D calculation approach in a non-balanced system (PEFCR-$D_{(NB)}$), B= PEFCR-D calculation approach in a balanced system (PEFCR-$D_{(B)}$).
H&H = livestock housing and holding, MM = manure management/storage, App_{Mm} = application of manure that has been managed, $App_{Grazing}$ = Manure directly applied while the livestock is grazing.
DI = Disease Incidences, GWP = Global Warming Potential, PMFP=Particulate Matter Formation Potential, POFP= Photochemical Ozone Formation Potential, T-EP = Terrestrial Eutrophication Potential.
M-EP = Marine Eutrophication Potential.

in lower I-N_2O emissions.

As shown, the use of the PEFCR-$D_{(B)}$ or PEFCR-$D_{(NB)}$ directly influences the EI assessment of the dairy farm. Depending on the selected PEFCR-D approach, the environmental profile and the conclusions might change when assessing the whole system or single stages. The application of the PEFCR-$D_{(B)}$ approach, results in an overall increase, in a range of 0.18–6.68%, of the analysed impacts; where GWP (6.68%), M-EP (4.91%) and T-EP (4.26%) reported the higher increments. More significant differences among the EI were evidenced when individually assessing the dairy farm stages. Moreover, because of the harmonised N balanced flows used by PEFCR-$D_{(B)}$, the EI were redistributed in the entire system; especially relocating EI from MM to App_{Mm}. This resulted into lower EI at MM and higher EI at App_{Mm}

Depending on where the boundaries of the dairy farm system are defined, the relocation of emissions and EI achieved by the PEFCR-$D_{(B)}$ can even increase the influence on the environmental performance and competitivity of the dairy farm. In this case study, the system boundaries are located at the end of the application stage meaning that all the N leaving the MM stage is applied in the farm's land together with the total N that was directly excreted on the land while grazing. Therefore, all the emissions and EI of application (App_{Mm} + $App_{Grazing}$) are reported as part of the assessed dairy farm system. However, in cases where the total manure from MM is sold and applied somewhere, the different emissions derived App_{Mm} should be allocated accordingly. In this scenario, when comparing the results obtained from the PEFCR-$D_{(B)}$ and the PEFCR-$D_{(NB)}$, the PEFCR-$D_{(B)}$ approach results in 13.48% less GWP and 4.86% less POFP than the respective outcomes from the PEFCR-$D_{(NB)}$ approach evidencing the importance of the redistributed emissions between manure management and application stages when evaluating these impact categories.

The N emissions and EI results variations (Δ%) obtained in this case study should not be significantly different when assessing other farming scenarios. No significant differences regarding N emissions are expected because of the nature of the IPCC and EMEP/EEA methodologies (linear equations); and also, because both calculation approaches (the PEFCR-$D_{(B)}$ and PEFCR-$D_{(NB)}$) maintain and use the same IPCC and EMEP/EEA EF. On the other hand, no significant differences regarding the EI results are expected since the PEFCR-D specifically defines the characterisation factors to be used when determining the farm's environmental profile (EDA, 2018). The N emissions and EI variations could only differ among farming scenarios if the quantities of N inputs and outputs, apart from $N_{ex(T)}$, change (i.e. waste whey, wastewater, bedding or chemical fertilisers).

4. Conclusions

This paper analyses the IPCC and the EMEP/EEA methodologies and their reported emissions from a mass balance perspective, focusing on the N flows of a dairy farm system. The PEFCR-D approach without any mass balance considerations (PEFCR-$D_{(NB)}$) reports merely the outcomes from the IPCC and EMEP/EEA emission results. The straightforward application of the IPCC and EMEP/EEA methodologies resulted in inconsistent N flows which resulted in significantly different emissions. The latter affects the assessment of the environmental performance of the dairy products, and the reliability of the emissions and EI reported by the PEFCR-$D_{(NB)}$. In this regard, an approach to harmonise the IPCC and the EMEP/EEA N flows within the PEFCR-D framework has been proposed (PEFCR-$D_{(B)}$) and demonstrated in a typical dairy farm case study. The main outcome of the proposed approach is the generation of a consistent N flow mass balance in the dairy farm from which N emissions can be calculated, as well as enhancing the data quality and the reliability of environmental performance assessment. This approach enables PEFCR-D users to trace the N flows that enter and leave each stage of the dairy farm chain, which is not possible without mass balance considerations. Furthermore, it determines the exact share of the different N emissions (NH_3, NO_x and N_2) that cause the IPCC indirect N_2O emissions at each dairy farm stage.

The analysis of the case study evidenced the incoherence between N flows and emissions within the different farm stages when applying the IPCC and EMEP/EEA methodologies. Moreover, the harmonisation of the IPCC and EMEP/EEA N flows, as fundamental part of the proposed PEFCR-$D_{(B)}$ approach, has enabled the redistribution of N emissions and their respective EI in the dairy farm system.

The assessed EI increased between a range of 0.2–6.7% when analysing the whole system, showing major increments in GWP and M-EP. Moreover, the individual EI assessment of the dairy farm stages evidenced that the PEFCR-$D_{(B)}$ approach has redistributed the emissions between MM stage and the App_{Mm} stage accordingly; which resulted in a trade-off of emissions between them. The latter enables the proper identification of the environmental hotspots in the system and provides useful information to the dairy producers to improve the environmental performance of the system. The future versions of the PEFCR-D should provide more guidance regarding how to assess the challenges spotted in this research. If a suitable solution to achieve the basic concept of a balanced mass system is not explicitly stated in the PEFCR-D, its interpretation will be open and then its main objective, the comparability of the results between dairy products, would not be achieved.

5. Future challenges

The quantification of N emissions at the different stages of dairy farming using the PEFCR-D should be improved. There are still gaps in the guidelines regarding the quantification of N emissions. These gaps could jeopardise the final goal of having a verifiable universal "Ecolabel" to report the environmental performance of the dairy products to the different stakeholders and enhance the development of an EU green market.

The mantra "Comparability over flexibility" prevails in the PEF methodology thus, this it can be easily adopted by many companies. However, in the long run, it can discourage the continuous improvement of the farming systems because the current models will not be able to reflect technological or management improvements of the farming systems. For example, emission models at MM do not include relevant MM technologies, such as nitrification/denitrification or membrane technologies among others widely applied as manure/slurry treatments. Moreover, different management strategies of conventional technologies, such as composting or anaerobic digestion should be included. At application stage, the models do not consider neither different managed manure application methods such as broadcast spreading, band spreading or soil injection nor soil properties or climate conditions which are known as relevant parameters that affect the global emissions. Although the PEFCR-D states that alternative estimation methods based on country-specific methodologies can be applied, these alternative methods must be clearly defined to ensure and maintain product comparability. If these issues cannot be reflected in the "Ecolabel" of dairy products, dairy companies will not be able to inform the consumers about the real environmental performance of the product, thus losing environmental credibility.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2019.01.110.

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