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Insights into nitrogen footprint accounting for products and application to an organic pig farm

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ABSTRACT

The Nitrogen Footprint (N-Footprint) is the total amount of reactive nitrogen (Nr) released to the environment as a result of an entity's consumption patterns. N-Footprint assessments have mainly been consumer-oriented and country-sized, although concern has recently focused on single products, especially particular foods.

While traditionally obtained from several software and/or calculators, the N-Footprint is here proposed to be evaluated by combining the Life Cycle (LCA) approach with a specific N based impact assessment modelling, as derived from Intergovernmental Panel on Climate Change guidelines.

The theoretical procedure is then applied to a real livestock case study (the Mora Romagnola pig that provides high quality pork), mainly based on primary data. The total amount of Nr released was about 40 kg per pig (live weight), mainly due to direct components (i.e. manure management ~ 85%). The results highlight the importance of more comprehensive and systematic quantification of emissions, especially direct ones that are neglected in the classical database and software. The Virtual N-Factor (VNF) was 2.3, which indicates that about 30% of N input by weight is incorporated in the meat, while most of it (~70%) is dispersed to different environmental compartments (38% atmosphere, 35% soil, 27% water). A comparative analysis to check the reliability of outcomes and the robustness of the accounting procedure is also offered and show that these results are consistent with those reported in the literature for other pork products.

The main benefit of this procedure is that it produces a unique aggregate result of the entity of human pressure on nitrogen cycle. This ensures a high comparability for results, transparency, and reproducibility of the method.

1. Introduction

Reactive nitrogen (Nr), defined as all nitrogen (N) species except the nitrogen gas molecule (N_2), arises naturally from unreactive atmospheric N_2 by natural phenomena such as lighting and biological nitrogen fixation (Galloway et al., 2003). Nitrogen, an essential element for all organisms, is a limiting factor for terrestrial and aquatic ecosystems. Consequently, Nr concentrations remains low in most environmental compartments (Galloway et al., 2004; 2014). Human population growth and associated food production, based on intensive management, monocultures, mechanization, water consumption, pesticides and chemical fertilizers (Haber–Bosch process), have expanded the quantity and mobilization of Nr (Razon, 2018; Boh and Clark, 2020). Increased cultivation of legumes and other nitrogen fixing cultures (~20%), together with the growing energy demand met by combustion of fossil fuels, also add to anthropogenic Nr mobilization and acceleration of the nitrogen cycle (Galloway et al., 2013; Galloway et al., 2014).

Release of excess Nr into the environment threatens the quality of air, soil and water (Sutton et al., 2011), triggering a cascade involving the sequential transfer of Nr through ecosystems. Whether Nr moves through or is temporarily stored in a system, the result is environmental damage (Galloway et al., 2003, 2004; Fowler et al., 2013). Nitrous oxide (N_2O), ammonia (NH_3), ammonium ion (NH_4^+), nitrogen dioxide (NO_2), nitrogen oxides (NO_x) and nitrate ion (NO_3^-) are the most common reactive forms.

Since the 1970 s, world population has increased by 78% and Nr release has increased by 120% (Galloway et al., 2008; Vitousek et al., 2013). Humans are therefore significantly altering the nitrogen cycle through agriculture, energy production and industrial activities.

Human interference with the nitrogen cycle has been identified as

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one of four planetary boundaries (i.e. the nitrogen and phosphorus cycles, climate change, land system change and biosphere integrity), perturbations of which significantly impact the integrity and stability of the Planet and human development on a global scale (Rockström et al.; 2009, Steffen et al., 2015; Wu et al., 2021). Perturbations in the nitrogen cycle have negative impacts on practically all other Earth systems, especially the water cycle, land systems, biosphere integrity and climate. It is therefore important to know the status and dynamics of this cycle.

Leach et al. (2012) developed the Nitrogen Footprint (N-Footprint), an indicator to quantify total Nr released into the different environmental compartments (i.e. air, water and soil), in order to identify Nr environmental effects and suggest impact mitigation strategies. The N-Footprint, like all environmental footprint indicators (e.g. Carbon, Ecological, Water, Phosphorus, and so forth), has greatly aided measurement of the degree to which different processes stay within or exceed planetary boundaries (Vanham et al., 2019, Wu et al., 2021), even if the assessment models are still debated (e.g. Einarsson and Cederberg, 2019).

Though recent, the N-Footprint has aroused interest and has improved the accounting approach in major case studies. Some applications of this indicator include experiences at individual, organization and institution level (De la Reguera, 2014; Leach et al., 2015; Shibata et al., 2017; Einarsson and Cederberg, 2019); others concern agriculture and animal production (Chatzimpiros and Barles, 2013; Leach et al., 2013; Liang et al., 2016; Xue et al., 2016; Zhang et al., 2018; Liang et al., 2021; Oita et al., 2016; Halberg et al., 2010) and others are at consumer level to raise health and environmental awareness (Grizzetti et al., 2007, 2013; Gu et al., 2013; Cui et al., 2016; Shindo and Yanagawa, 2017).

In the European Union, a large share of Nr release is related to food production (Wang et al., 2020), and in particular to livestock farms and meat supply chains (Leip et al. 2011a; Leip et al., 2011b; Anestis et al., 2020; Oita et al., 2020). Human population growth leads to increasing livestock numbers, intensifying agricultural practices and habitat degradation at local and global level (Zeller et al., 2017). Indeed, about 85% of the nitrogen contained in agricultural products/feedstocks is used by livestock and only 15% is used directly to feed humans, making Nr release to the environment greater for a carnivorous than for a vegetarian diet (Galloway and Cowling, 2002).

The N-Footprint of livestock is usually calculated as total Nr emission per unit product (meat, milk, eggs …), on the basis of national average production parameters (Leach et al., 2012; Leip et al., 2013). However, the N-Footprint of livestock is not only used to compare the impacts of different food products but may also be used to assess per capita Nr release on the basis of an average citizen's yearly food consumption (Chatzimpiros and Barles, 2013; Pierer et al., 2014).

Published guidelines or standards that ensure a consistent, accurate, transparent and replicable assessment are not yet available. Examination of literature highlights the diversity of calculation approaches (N-Print, 2018). Some studies are based on national averages, others on 2006 IPCC Guidelines, CAPRI or MITERRA models (Velthof et al., 2009; Lesschen et al. 2011; 2013). CAPRI is an agricultural sector model, based on EUROSTAT statistics, with a global market calculator for agricultural products (Lesschen et al., 2011), while MITERRA is an environmental assessment model that calculates nitrogen emissions (in the form of N_2O, NH_3, NO_x, NO_3^-) and greenhouse gases on an annual basis, using European average emissions and leaching fractions (Lesschen et al., 2011).

The main aim of this paper is to develop a reliable accounting procedure for N-Footprint, devoted to products (or services). This procedure benefits from: i) the Life Cycle Assessment (LCA) framework to draw up a systematic and detailed inventory of all items supporting the system production ii) the Intergovernmental Panel on Climate Change (IPCC) framework (2006) to model the impact assessment, focused just on nitrogen. In this way we capture in a single indicator the overall amount of reactive nitrogen associated to resources consumption, escaping the scattering of the information in multiple impact category indicators (as for example, the output of classical LCA).

This accounting procedure is then tested in a real livestock case study, i.e. pork produced by extensive organic methods of the Italian Mora Romagnola breed. This case study is particularly functional to our scope due to a wide availability of primary data and details on the breeding system that help us depict a representative environmental profile of the system.

The reliability of the proposed procedure and its relevance within the sustainability context is argued also by a comparison with similar cases from the literature.

2. Method: N-Footprint accounting

The N-Footprint accounting procedure for products used in this study was inspired by the Life Cycle approach and includes four phases (Fig. 1) that can be repeated:

The different phases are described and detailed for our case study, to illustrate their purposes and application.

1) *System description*: definition of the scope of the analysis through description of the spatial and temporal boundaries of the system, functional unit, data quality, assumptions, allocation procedure, if applied, and so on.
2) *Data collection and processing*: collection and processing of all product data (i.e. inventory), expressed per functional unit.
3) *N-Footprint*: quantification of all Nr emissions (kg) associated with inputs based on the set of equations and conversion factors provided by IPCC Guidelines (2006) and the Air Pollutant Emission Inventory Guidebook (EMEP/EEA, 2016), including differentiation by compartment (atmosphere, water and soil);
4) *Evaluation and interpretation*: total Nr released to the environment and other N-based indexes (e.g. VNF) are quantified, evaluated, explained and compared with the literature.

2.1. Phase 1: System description

The product is Italian pork produced by "Società Agricola Zavoli", an organic farm at Saludecio (43.913748 N, 12.6460672E; Province of Rimini, Italy), selected as representative of Mora Romagnola breeding (Slow Food, 2019a; Slow Food, 2019b; Neri and Pulselli, 2017). The Mora Romagnola pig is a threatened local breed, which was reared until the mid-1900 s and subsequently neglected because it is unsuitable for intensive and industrial breeding. This free-grazing breed grows slowly and is less efficient in terms of resource consumption per unit weight of meat produced. In 2011, the Mora Romagnola became a Slow Food Presidium (a protection and quality control mechanism developed and managed by the Slow Food Foundation for Biodiversity). The Presidium was instituted to help breeders preserve, protect and safeguard the breed, ensuring animal well-being, integrity of the production chain and of the excellent quality of the products, while protecting the environment (Slow Food, 2019a).

The Zavoli farm is on about 30 ha, 5 ha of which are dedicated to rearing the Mora Romagnola (pigpen and pasture in grassland and forest). The remaining area is cropland, managed organically for feed production (3.5 ha wheat, 6 ha barley, 1.5 ha fava bean and peas and 1.5 ha sorghum) and pasture/scrub/forest. The land carries 77 head of livestock: 70 piglets, 5 sows and 2 boars. Each sow farrows about 8 piglets per pregnancy, twice a year. Gestation, suckling and weaning last 114 days, 1 month and 2 months, respectively. The piglets are then reared for about 12 months in three stages: in a large fenced area (2 months), free grazing (8 months) and fattening in the pigpen (2 months). They are slaughtered at about 150 kg live weight. The average carcass yield is about 80%.

Organic feed is self-produced on the farm and supplemented from neighbouring organic farms (with maize, leftover bread from school canteens and cereal pellets). The sows are fed with pigswill (a mix of

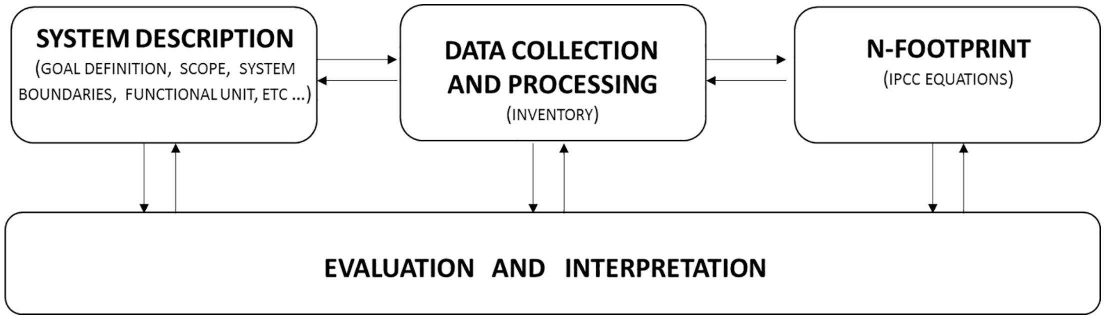

Fig. 1. N-Footprint accounting procedure.

cereal flour, water, bread and vitamins) during gestation and with cereal pellets during suckling and weaning. Piglets are fed with sow milk during suckling, cereal pellets during weaning and pigswill from weaning until slaughter. During the 8-month free-grazing period that follows weaning, piglets supplement their diet with field and forest products (e.g. roots, tubers, acorns). Manure from the pigpen (piglets and sows) is collected and stored in an open outdoor tank and after 3 months of maturation is spread as organic fertilizer on the crop fields.

In compliance with Slow Food philosophy on animal well-being, the pigs graze free-range for most of the rearing period, and piglets listen to classical music to reduce weaning-stress (Edwards, 2005; de Jonge et al., 2008).

In the assessment, pigpen consumption (i.e. electricity and water) was shared between piglets and sows. Machinery, buildings and all inputs with a lifetime greater than five years, as well as the boars, have a negligible contribution to overall impacts and were not included (ISO, 2016; ISO, 2018). Slaughter and transport of pigs are considered outside the scope of the analysis, because the assessment focused on valorising breeding practices, and in any case they do not significantly affect the final result.

The sows' contribution to piglet impacts was accounted (all feed, water and electricity consumed and manure produced during gestation, lactation and weaning) and attributed to each piglet (i.e. divided by 8), as each farrow produced about 8 piglets (ISO, 2016; ISO, 2018). Pig lifetime is the time necessary to reach 150 kg (about 15 months).

The system boundaries were those of a cradle-to-gate approach and included the overall production chain, from field operations for feed production to pigs ready for slaughter at the farm gate. Fig. 2 shows the flow chart of the Mora Romagnola breeding system. The temporal boundaries are the year 2014. The functional unit (FU), to which all the data refers, was one pig live weight (LW), although the results were also expressed per kilogram of carcass weight (CW) to enable comparison with the literature.

Most of the data (primary) was collected by direct interview with the farmer. The only exception concerned the production of purchased feed. In this case the field operations were assumed to be the same as those of Zavoli farm because they had the same production standards (Neri and Pulselli, 2017).

2.2. Phase 2: Data collection and processing

A quantitative inventory of Mora Romagnola pig raising was compiled, listing all inputs supporting the entire life cycle, i.e. from cradle (i.e. production of materials) to gate (i.e. before slaughter). All the data was expressed per pig (LW) (about 150 kg) and summarized in Table 1. The account includes estimates of upstream emissions (indirect) - traditional software outputs - and direct emissions (core), that are usually neglected in the LCA software and/or database, although in some case they may be considerable.

The inventory was organized in four main categories for pigs and sows: i) fuel (diesel) consumption by machinery (for self-production of feed and livestock management); ii) transport of feed (from market to farm); iii) feed consumed by pigs (cereal-based flour, bread, vitamins and pellets) and iv) manure, self-produced by the farm and used as fertilizer.

The contribution of the sow in the gestation/suckling period was allocated to her piglets and included in the accounting of fuel, transport, feed and manure. Consumables for pigpen management (i.e. electricity for lightening, water for drinking and washing, and straw) were also included and allocated per pig.

The data was essentially primary (i.e. provided directly by the breeder) and refers to one reference year; some (secondary) data was obtained from the literature or databases.

2.3. Phase 3: N-Footprint

Inventory data was processed to estimate direct and indirect contributions to the nitrogen cycle of the system. The total amount of Nr released to the environment was quantified by the assessment model proposed by IPCC guidelines (2006). "Agricultural, Forestry and Other Land Use (AFOLU)" was the reference document for organic fertilizer use, manure management and feed crop residues of the pig farm. "Energy" was the reference document for fossil fuel combustion and electricity consumption.

Emission factors were IPCC default values (IPCC, 2006) for N_2O and "Air Pollutant Emission Inventory Guidebook" values (EMEP/EEA, 2016) for NO_2, NO_x and NH_3. The relative masses of N_2O, NH_3, NO_2 and NO_x were converted to Nr on the basis of molecular weights. It was assumed that all NO_x was released as NO_2, as proposed by Leach et al. (2012). For equations, parameter descriptions, values and units, see supplementary material (Table S.1).

Particular attention was paid to manure, which releases Nr directly due to nitrification and denitrification and indirectly due to volatilization and leaching. These emissions vary in relation to how manure is managed and the climatic zone. In our case, solid manure was stored with straw, whether the pigs were penned or at pasture. Matured pig manure was used as organic fertilizer for feed production. The annual nitrogen excretion of livestock, used to quantify Nr from manure, includes N intake from crude protein in the diet. Gross energy intake (expressed in MJ per kg dry matter) was calculated for the different components (proteins, lipids, cellulose) and the percentage of dry matter in each type of feed.

Where organic bedding material (e.g. straw) was a manure component, the additional nitrogen was also considered part of the N applied to cultivated fields as organic fertilizer. These organic fertilizer inputs were estimated for self-produced and purchased feed: the former has a circular path on the farm and was not counted twice.

The inclusion of direct site-specific contributions of manure is very significant in such case studies and for livestock in general, because they are a significant portion of the outcomes with respect to those calculated by software (i.e. as usually done in LCA).

The areas of cropland needed to produce purchased feed were

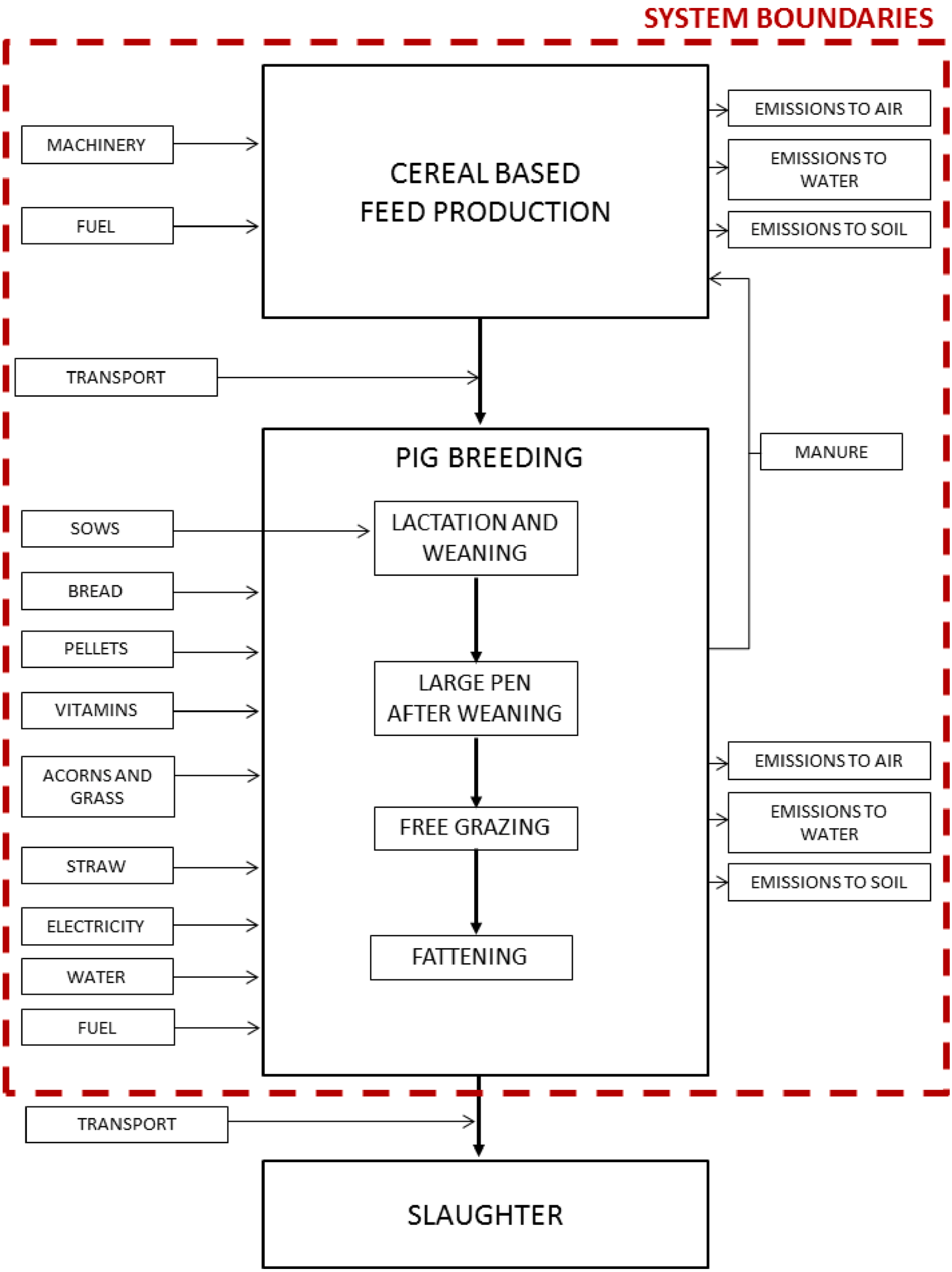

Fig. 2. Flow chart of the Mora Romagnola breeding system.

Table 1
Data inventory of the pig breeding farm. Data refers to the year 2014. Functional unit: 1 pig Live Weight.

	ITEM	DETAILS	QUANTITY PER FU	UNIT	DATA*	NOTES
PER PIG	FUEL CONSUMPTION	gasoline for feed production on the farm	63.83	kg	P	includes tillage, sowing, harvesting and milling of self-produced feed (wheat bran, barley, fava beans and peas)
	TRANSPORTATION	market-farm maize	2330.16	kg km	P	0.067 kg diesel (ECOINVENT, 2016)
		market-farm vitamins	4106.25	kg km	P	0.117 kg diesel (ECOINVENT, 2016)
		mill-farm self-produced bran	6570.00	kg km	P	0.188 kg diesel (ECOINVENT, 2016)
		school-farm bread	7117.50	kg km	P	0.203 kg diesel (ECOINVENT, 2016)
		market-farm pellets	11,700.00	kg km	P	0.334 kg diesel (ECOINVENT, 2016)
	FEED	cereal based flour	876.00	kg	P	15% bran, 12% fava bean/pea/sorghum, 35% barley, 38% maize
		water	164.25	kg	P	added to flour, bread and vitamins to obtain a semi-liquid mash
		bread	54.75	kg	P	leftover from school canteen
		vitamins	18.25	kg	P	
		pellets	90.00	kg	P	18% protein content
		grass	435.00	kg	S	Quantity of grass eaten during free grazing; estimated according to Comellini et al., 2012
		acorns	130.50	kg	S	Quantity of acorns eaten during free grazing; estimated according to Comellini et al., 2012
	MANURE	manure	21.00	kg	P	assuming an average production of 1.4 kg/day used as fertilizer
PER SOW-TO-PIG	FUEL CONSUMPTION	gasoline for feed production on the farm	0.44	kg	P	this consumption includes tillage, sowing, harvesting and milling
	TRANSPORTATION	market-farm maize	87.78	kg km	P	14.37 kg diesel (ECOINVENT, 2016)
		market-farm vitamins	210.94	kg km	P	25.34 kg diesel (ECOINVENT, 2016)
		mill-farm self-produced bran	247.50	kg km	P	40.51 kg diesel (ECOINVENT, 2016)
		school-farm bread	268.13	kg km	P	43.89 kg diesel (ECOINVENT, 2016)
		market-farm pellets	975.00	kg km	P	0.03 kg diesel (ECOINVENT, 2016)
	FEED	cereal based flour	33.00	kg	P	15% bran, 12% fava bean/pea/sorghum, 35% barley, 38% maize
		water	6.19	kg	P	added to flour, bread and vitamins to obtain a semi-liquid mash
		bread	2.06	kg	P	leftover from school canteen
		vitamins	0.94	kg	P	
		pellets	7.50	kg	P	18% protein content
		grass	90.00	kg	S	Quantity of grass eaten during free grazing; estimated according to Comellini et al., 2012
		acorns	47.81	kg	S	Quantity of acorns eaten during free grazing; estimated according to Comellini et al., 2012
	MANURE	manure	21.00	kg	P	assuming an average production of 1.4 kg/day used as fertilizer
AGGREGATED INPUTS	CONSUMPTION AT FARM LEVEL	water	1470.23	kg	P	for watering pigs and washing pigpen
		electricity	19.48	kWh	P	consumed for lighting pigpen and watering pigs
		straw	57.14	kg	P	consumed for pigpen

*data obtained directly from the breeder (P - Primary data) and from the literature (S - Secondary data).

estimated on the basis of specific yields per hectare (e.g. 2 t ha^{-1} for corn, 4 t ha^{-1} barley and 3 t ha^{-1} soy) indicated in the literature (Wernet et al., 2016). Separate calculations were performed for each crop type. N values from crop residues of self-produced and purchased feed were added for grain (corn, wheat, barley, sorghum), roots/tubers, N-fixing forage crops (soy, broad bean, pea) and other forage including grass.

The Nr released to the air and water compartments by volatilization and leaching/runoff was quantified on the basis of regional default values (IPCC, 2006; ANPA, 2002). The total amount of Nr in soil was calculated as the difference, i.e. subtracting the part lost to the air and water from the total nitrogen content of manure, bedding and crop residues, using a mass balance approach (IPCC, 2006). Changes in soil N stock were assumed to be zero due to large uncertainties in soil N accumulation/depletion data (Leip et al., 2011b).

Quantities of electricity and natural gas used for the production of bread, added to the pigswill (i.e. 0.02 kWh electricity/kg bread and 1 MJ natural gas/kg bread), were obtained from the literature (Wernet et al., 2016).

2.4. Phase 4: Evaluation and interpretation

Fig. 3 illustrates the aggregate N flows associated with the Mora Romagnola breeding system, including input, output and lost flows (N loss), and the corresponding repartition in the three environmental compartments. The analysis shows that total Nr release was 40.69 kg Nr per pig LW, or 271.30 g Nr per kg LW.

Contributions to total N-Footprint are dominated by inputs directly linked to pig growth (about 90%), with a limited contribution by sows (<10%). Major inputs are manure management (~85%) and feed production (~11%). It is useful to remember that N loss during manure management, due to direct and indirect emissions (volatilization, nitrification and denitrification), was not accounted for excreted manure. N-losses were estimated to be 50% of the nitrogen contained in effluents, due to solid storage with straw. This assumption avoided double accounting of Nr emissions first from manure management in pigpen/pasture and again from organic fertilizer (i.e. manure was usually removed from the pigsty, allowed to mature and then spread as natural

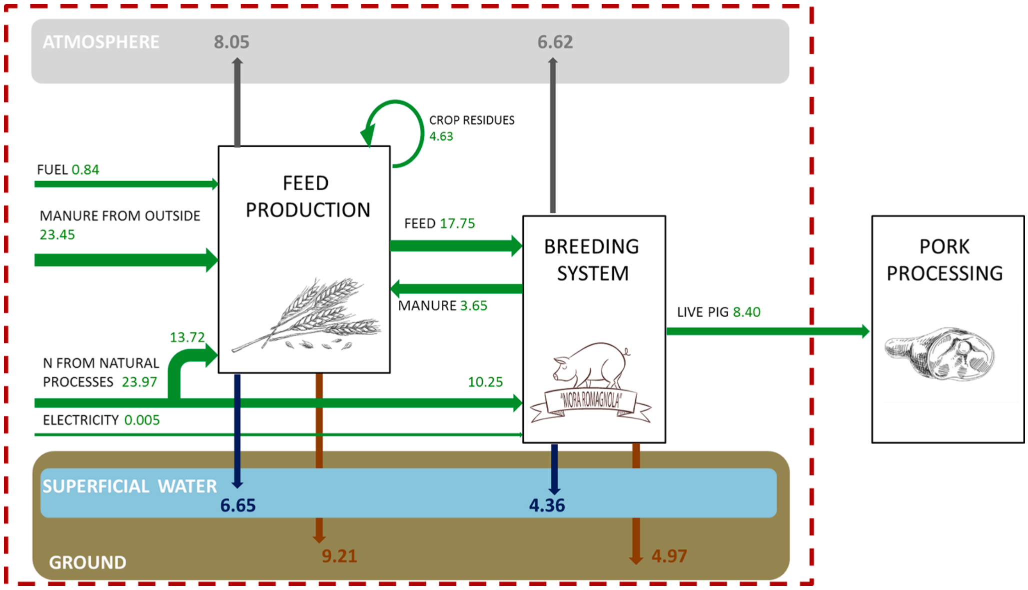

Fig. 3. The main N flows associated with the "Mora Romagnola" breeding system (units: kg Nr per pig LW). The red dotted line indicates system boundaries. Grey, blue and brown lines show N losses, while green lines show N input/output and feedbacks. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

fertilizer for crop production). The sources of Nr from manure come from inside (about 60%) and outside (40%) the system boundaries (the latter concerns external manure used to produce purchased feed). If the manure were not returned to the process, feed cultivation would necessarily require an extra contribution of synthetic fertilizer, implying an additional 21% in total Nr emissions, mostly due to direct emission of ammonia from soil. In this case the contribution of manure to total Nr would decrease from 85% to 68%. The order of magnitude of manure contribution to N-Footprint strongly supports our choice of including its direct emissions.

For validation, the N balance, quantified by adding inputs (+) and subtracting outputs (-), is zero g Nr. Nitrogen from natural processes (see Fig. 3) includes N deposition, N-fixation by plants and the nitrogen previously stocked in soil, available for feed crops.

The outcomes highlight that only ~ 30% of the N-mass input is finally incorporated in the meat, while most of it (~70%) is dispersed in the environment. This result is also confirmed by IPCC data

(2006), although other studies reported higher N use efficiency for intensive livestock production (Uwizeye et al., 2019).

Since only a fraction of the nitrogen mobilized throughout the production chain is embodied in the final food product (meat), the Virtual N Factor (VNF) is defined as any nitrogen that was used in the production process but is not contained in the final product (Leach et al., 2012). VNF is a pure number obtained by dividing total N losses to the environment by total N intake by the product. VNF is considered a proxy of environmental cost for products (Zhang et al., 2018).

The VNF of the Mora Romagnola pig was 2.3: the N lost to the environment was more than twice the total N uptake by meat.

Once released to the environment, Nr has different destinations (i.e. air, groundwater, surface water) with different environmental consequences (Fig. 4):

- 38% was found to be emitted to the atmosphere as N-gas·NH_3 was the dominant N-gas (~90%); the contributions of N_2O and NO_2 were very low (~5% for both). These percentages confirm the results of Leip et al. (2013) ascribed to the high volatility of ammonia;
- 62% was lost to soil, where part remains (~35%) and part is leached into watercourses (~27%) as nitrates and organic N.

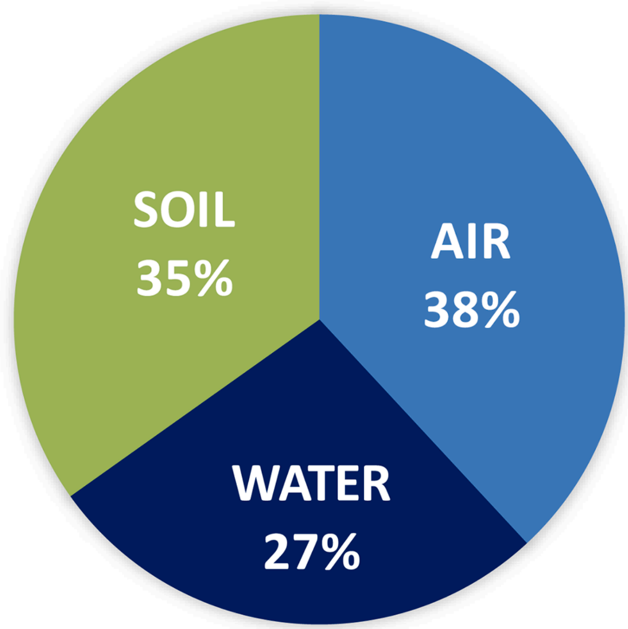

Fig. 4. Distribution of Nr in the environmental compartments: air, soil and water.

3. Discussion

The N-Footprint method was developed to measure human pressure on the nitrogen cycle. It quantifies the amount of all Nr emissions, both direct and indirect, released to the environment as result of production. The N-Footprint, like all other footprint-based indicators, concerns a single environmental issue, in contrast to the impact assessment profiles of LCA that includes the several impact categories (i.e. climate change, eutrophication, acidification, …) originating from that single pressure factor (Galli et al., 2012; Ridoutt et al., 2015).

With the growing numbers of N-Footprint applications, there is also a greater need for an international standard protocol and/or shared

Table 2
N-Footprint for various case studies of pigs.

Source	Nr released(gNr FU^{-1})	Functional Unit (FU)	Virtual N factor (VNF)	Note
This study	217.04	1 kg $_{CW}$	2.3	*Case study: "Mora Romagnola" traditional organic breeding livestock (Italy)* *Scale: small* *System boundaries: from cradle* (i.e. *field operations for feed production) to farm gate (to slaughter)* *Accounting framework model: IPCC (*IPCC 2006 *Guidelines) and LCA, EMEP/EEA emissions inventory guidebook (2009)* *Approach: Bottom-up* *Note: most data is primary*
Leach et al., 2016	126	1 kg $_{CW}$	4.7	*Case Study: Average conventional production (USA)* *Scale: large* *System boundaries: none defined (environmental impact food label for consumers)* *Accounting framework model: CAPRI and MITERRA models (based on* Leach et al., 2012*)* *Approach: Top-down* *Note: Nr emissions from fossil fuel combustion are not considered due to their relatively small contribution*
Westhoek et al., 2015	~ 60–70	1 kg $_{CW}$	2.9	*Case Study: Average value of pork (Europe)* *Scale: large* *System boundaries: = none indicated* *Accounting framework model: CAPRI and MITERRA models* *Approach: Top-down* *Note: a meat/dairy greening scenario and a high price scenario are elaborated*
Pierer et al., 2014	64	1 kg $_{CW}$	3.6	*Case Study: Average situation (USA)* *Scale: large* *System boundaries: from cradle (feed production) to cradle (consumers)* *Accounting framework model: CAPRI and MITERRA models (based on* Leach et al., 2012*)* *Approach: Top-down* *Note: Some specific values were adapted to Austrian food production systems when calculating the virtual N factor.*
Lesschen et al., 2013	100	1 kg $_{CW}$	Not provided	*Case Study: Average values based on range of global studies and data sources.* *Scale: large* *System boundaries: housing, manure management, grazing, mineral fertilizer use, fertilizer production, fossil fuel use* *Accounting framework model: 2006 IPCC Guidelines (Greenhouse gases and Soil Organic Carbon), EMEP/EEA emissions inventory guidebook 2009 (NH_3 emissions) and MITERRA model (N leaching and runoff)* *Approach: Top-down* *Note: N-Footprint of pork was slightly higher in Africa than in Europe due to different breeding practices.*
Leip et al., 2013	70–200	1 kg $_{CW}$	4.7	*Case Study: Average conventional livestock production (Europe)* *Scale: large* *System boundaries: from cradle (feed production) to cradle (consumers)* *Accounting framework model: CAPRI and MITERRA model* *Approach: Top-down* *Note: the N-Footprint was based on a partial life-cycle assessment, without considering NOx emissions from energy use or N_2O emissions from land use changes, normally considered in a full cradle-to-gate approach.*

guidelines for N-assessment to ensure a transparent, reproducible, and consistent approach and fully comparable results.

The framework for N-Footprint accounting of products presented here is inspired by the Life Cycle approach. The framework is bottom-up and mostly product-oriented. Four main steps are identified: i) system description, ii) data collection and processing, iii) N-Footprint assessment, iv) evaluation and interpretation. These steps promote clear and replicable use of the method, making it more widely accessible and easily applied, even without the aid of software or calculator.

The method is particularly accurate, but depends on data availability, since it does not rely upon structured databases, as is the case for calculators and software, that use general and unspecific data. The product chosen has a high primary information content, provided directly by the breeder, so the results can be considered reliable.

For comparison a detailed review of the N-Footprint literature for pig raising systems is shown in Table 2, where the major features of the most relevant case studies are summarized. For each of them, when defined, the following parameters are considered: scale (small or large), system boundaries (from cradle to gate or cradle), accounting framework model (specific software, calculator, or methodology), approach (top-down or bottom-up) and any additional information about the breeding management, data allocation procedure, etc. All these elements are compared for an in-depth discussion of the outputs and the methodological consistency and reliability of the method.

The N-Footprint of the Mora Romagnola, expressed here in terms of carcass weight for appropriate comparison (217.04 g Nr $(kg_{CW})^{-1}$), was consistent, even if slightly larger, with other cases reported in the literature, since reactive nitrogen ranges from 60 to about 200 g Nr $(kg_{CW})^{-1}$.

This is due to differences in:

- *breeding management* (organic *vs* conventional and/or local *vs* national average): sometimes organic agricultural and livestock productions (e.g. Mora Romagnola) have a slightly larger impact than conventional ones, due to the higher resource requirements per unit product, e.g. longer pig growth period to obtain the same output as conventional/intensive systems (Cederberg and Mattsson, 2000; Sundrum et al., 2000). Local, highly specific, small scale breeding farms also report impacts higher than the national average (Seufert et al., 2012);
- *feed quality (fibre vs protein based) and quantity*: the Mora Romagnola diet is principally based on fibre-rich cereals, whereas intensive breeding (i.e. Large White) diets are often silage-based and protein/fat-rich with a higher energy content. The quantity of feed necessary for extensive farming (e.g. Mora Romagnola) is higher than for intensive raising (e.g. Large White) because free-range pigs consume more energy and their feed has a lower energy content.
- *system boundaries*: the breeding phase is always the major one, although other inputs (e.g. feed production) may increase the total N-Footprint. The lifecycle approach here used included the production processes (and related impacts) of materials and energy used in the system while, for example Leach et al.(2012) and Leip et al. (2013) did not include energy use;
- *accounting framework model*: LCA/IPCC-based *vs* CAPRI, MITERRA or other methodologies or calculator; the latter models have a top-down approach as they treat a country as a representative (aggregate) farm and the combination of national market balance, regional fodder availability and animal requirements goes to build a farm N-budget with information from official sources such as EUROSTAT, FAOSTAT and OECD (Leip et al. 2011a; Leip et al., 2011b; Leip et al., 2013). On the other hand, since the present work concerns a site-specific case study with a wide primary data availability, a bottom-up approach was selected (LCA and IPCC), considered more robust, and specific for product assessment.
- *data source* (specific primary *vs* secondary data, i.e. average European values): this is a critical point of every inventory phase. The more primary data used, the more reliable and robust the results. In the present case study, most of data was primary.
- *type of allocation*: here mass allocation was used, as suggested by ISO (ISO, 2016; ISO, 2018). The contribution of the sow has been also included to correctly represent the real situation. Unfortunately, no specific information was provided for the other case studies.

Other aspects that influence the results are for example, the type of raising system (free range *vs* stabled), weight per head and animal lifespan. In conventional/intensive farms, pigs are usually slaughtered at 10–12 months, whereas free range pigs live to an age of about 15 months.

Comparison of the Virtual N Factor (VNF) parameter offered further insights for a more robust assessment. As opposite to N-Footprint trend, the calculated VNF (2.3) is lower than that of the other case studies that ranged from 2.9 to 4.7. The value is closer to that typical of cereals and plant foods instead of other meat products (e.g. poultry and beef) as the other literature case studies (Xia et al., 2020; Shibata et al., 2014; Liang et al., 2016 Pierer et al., 2014). Since VNF is the ratio of Nr released to the environment during pork production per unit Nr consumed, our result means that Mora Romagnola pork is the most efficient (~70%) in nitrogen capturing within the pork meat with respect to all the case studies explored: this may be due to the low protein diet of the pigs, which reduces nitrogen excretion, as documented by Wang et al. (2018). The low protein diet also contributes to better animal health, that together with greater N retention, leads to higher quality meat, in terms of organoleptic properties such as polyunsaturated fatty acid content (Wang et al., 2018), than intensively and industrially produced pork.

This information is particularly relevant from an environmental impact point of view. Whilst quantitative results highlighted the hotspot (i.e. critical element) in manure management, VNF (i.e. as a “quality indicator”) valorised the best practices implemented, the farm commitment for animal well-being and the organoleptic properties of the final product (Slow Food, 2019a).

Furthermore, the identification of potential Nr-mitigation measures together with Nr-compensation strategies is a tool to manage the system towards nitrogen neutrality of the product, strengthening the sustainability of the pig breeding sector (and supply chain) (Abad-Segura et al., 2020). For example, the contribution of N-losses in solid storage with straw could be mitigated by implementing systems that reduce the loss of substances in the environment e.g. anaerobic management of manure in pigpen that could be efficiently used as resource to produce biogas/electricity/fertilizer.

4. Conclusions

The N-Footprint is an accounting tool that can provide valuable insights into the links between humans and nitrogen cycle dynamics in relation to planetary boundaries. Though recently introduced, the interest around the N-Footprint has increased rapidly but a well-structured and reliable approach is still lacking. The methodological framework proposed here is based on a combination of the standardized LCA approach (to make an analytical inventory of all inputs from cradle to gate) with the IPCC impact assessment model (to convert inputs into the corresponding direct and indirect N emissions), avoiding the support of calculators or specific software. The accounting method has the major advantage of providing an unique and overall measure to quantify the environmental pressure produced by the Nr released, rather than observing the Nr contribution to several impact categories (such as climate change, eutrophication, acidification, …) as in a classical LCA.

When we tested the proposed N-footprint accounting method on a case study (high quality extensively raised organic pork from the Mora Romagnola pig), our results were fully consistent with those of the recent scientific literature on similar case studies analysed with different methodological approaches for Nr assessment. This confirms that the procedural set up is accurate, and reproducible whenever suitable data are available. Therefore, commitment of the farmers/breeders is a key aspect for the success of the method. Indeed, the importance of primary data availability is a key aspect for informing all the policies for sustainable development as underlined by Bastianoni et al (2019) and within UN Sustainable Development Goals framework (United Nations General Assembly, 2015). Therefore, we are confident that data collection at all levels, including that of the farm, will be increased in the next future also thanks to the boost coming from the policies and measurements for reducing impacts on climate change.

Future extensions of this research could consider two different perspectives:

i) the development of specific guidelines for the standardization of the N Footprint assessment of products to identify potential environmental impacts related to Nr circulation, consistently with other footprint indicators (e.g. carbon and water footprint);
ii) the identification of possible scenarios for mitigation measures for Nr reduction as well offset strategies for Nr compensation towards nitrogen neutrality of the product analyzed.

CRediT authorship contribution statement

V. Niccolucci: Conceptualization, Methodology, Writing – original draft, Writing – review & editing. **M. Marchi:** Conceptualization, Methodology, Writing – original draft, Writing – review & editing. **E. Neri:** Data curation, Software, Writing – original draft, Writing – review & editing. **R.M. Pulselli:** Data curation, Software. **S. Bastianoni:** Supervision, Validation, Writing – review & editing. **N. Marchettini:** Supervision, Project administration.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ecolind.2021.108411.

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