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Nutrient use efficiency: a valuable approach to benchmark the sustainability of nutrient use in global livestock production?

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Livestock have a large impact on nutrient cycles, with repercussions on environmental and public health issues. Designing interventions for better environmental sustainability will require indicators adapted to the increasingly long and complex supply chains. Nutrient use efficiency is a well know approach to benchmark nutrient management at the animal level, and to some extent at the farm level. Integrating the life cycle approach into NUE allows for the computation of supply chain level NUE, which is proposed as a valuable indicator of nutrient management sustainability. It characterizes the use of finite nutrient and energy resources and the losses of nutrients per unit of product, likely to have impacts on the environment and public health. Further research is required to harmonize life-cycle-NUE and test its validity as an indicator of nutrient management sustainability.

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Introduction

The internationalization of livestock supply chains

The management of nutrient flows is central to agriculture and food supply chains. It has driven the development of agricultural practices since their origins: flood control, crop rotation, manure recycling and crop residues management are examples of techniques aimed at, inter alia, harnessing nutrients and maintaining them in agricultural systems. Animals have always played an important role in agricultural nutrient cycles, whether we think about their capacity to 'harvest' nutrients in natural rangelands, or about intensive systems were they are fed nutrient dense rations specifically cropped for this purpose.

The manipulation of nutrient cycles and amplification of nutrient flows have dramatically increased since the industrialization of agriculture, with a positive effect on the volume and stability of food production, but also with associated risks of detrimental effects on ecosystems and public health [1]. Several studies have highlighted these environmental impacts and developed analytical frameworks for their assessment (see e.g. [2•,3,4,5]).

At the same time, livestock supply chains are increasingly internationalized, spanning across borders and continents. Fertilizers and feed have been internationally traded in large quantities over the past decades, but livestock products, too, are increasingly exchanged on global markets: today, it is estimated that 16% of poultry meat, 12% of pig meat and 15% of beef are traded on international markets, compared to a 35% of soybean cakes, 28% of nitrogen (N) fertilizers and 31% of phosphorus (P) fertilizers (FAO STAT: http://faostat.fao.org/). These figures indicate that livestock supply chains are increasingly global, diverting from a pre-industrial situation where domestic animals essentially converted locally available feed resources (nutrient) into products for local consumption.

The management of nutrient use in livestock supply chains, therefore, needs to take these recent trends into consideration. New indicators and approaches are required that are applicable to longer and more complex supply chains and can assist in improving the performance of the entire livestock systems, going beyond the mere assessment of performance at animal or production unit level.

Management of natural resources along the supply chain

In this context, the management of natural resources, and nutrient flows in particular is increasingly focusing on the concept of efficiencies along the supply chain. Used in different fields, efficiency is a measurement of performance, relating the result of a process to the mix of inputs mobilized for its delivery. The concept has gained growing importance in the sustainability debate, playing a pivotal role in addressing the basic conflict between continuous growth in the consumption of material goods and the finite natural resources of the planet. It is of particularly high relevance to the agricultural sector, which needs to deliver on the dual objective of food security (output growth) and environmental sustainability (reduced natural resource mobilization) [6,7,8•].

Natural resource use efficiency, defined as the amount of natural resources engaged per unit of product is of particular relevance to livestock supply chains, which are typically longer than crop supply chains; involve more biophysical processes and often include the recycling and reuse of by-products from other sectors. The livestock sector is a major user of natural resources, such as land and water, using about 35% of total land and representing about 8% of total water withdrawals, mostly for feed production [1].

Improving natural resource use efficiency is an objective of global relevance. It applies to the most affluent areas of the globe, where the sector is requested to minimize its environmental impact [9], and to emerging economies, where livestock production expands rapidly in a context of relatively weak environmental policies and often wastes natural resources [10]. It is equally relevant to the poorest regions of the world, but from an opposite perspective: here, there is a need for maximizing production out of limited resources [11].

The need for harmonized metrics of resource use efficiency

As a consequence, improved efficiency is increasingly proposed as the panacea to environmental sustainability, possibly overlooking some of its limitations. At times the term is misused and confused with a range of other metrics, in the plethora of indicators that have been developed to assess nutrient use in agriculture. Furthermore, the quantification of efficiency can pose challenges in the context of data availability and comparability, given the sparse information available in some regions and production systems and discrepancies in the data collection procedures. In addition, the increasing role played by private sector organizations in improving the sustainability of livestock supply chains calls for the development of metrics that can easily be communicated to producers and thus possibly based on concept and data used for the computation of other production management indicators.

The main objectives of this paper are thus (i) to clarify concepts and definitions regarding nutrient use in livestock systems, (ii) to review recent work on Nutrient Use Efficiency (NUE) and (iii) to discuss the relevance, comparative advantages and development opportunities of NUE indicators in the context of sustainable livestock development. Although relevant to all nutrients, the paper focuses on nitrogen and phosphorus because of the higher environmental impacts associated to these nutrients in animal production systems [1,2•,3–7,8•,9].

'New' versus recycled N and P resources, implications of these differences

Galloway *et al.* [12••] introduced the N cascade as a global pattern of reactive N[a] (Nr) circulation in Earth's atmosphere, hydrosphere and biosphere. The authors describe how each new atom of Nr flows through the cascade, impacting ecosystems and human health along the way, involving processes such as tropospheric ozone and aerosol formation, deposition on natural habitats, acidification, eutrophication and climate change.

According to Sutton *et al.* [8•], three major human activities involve the transformation of N_2 into new Nr entering the cascade: synthetic N fertilizer production based on the Haber-Bosh reaction (120 Tg N $year^{-1}$), cultivation of legumes and other crops capable of converting N_2 into Nr through biological N fixation (60 Tg N $year^{-1}$) and fossil fuel combustion which converts atmospheric N_2 and fossil N into Nr (40 Tg N $year^{-1}$). Livestock supply chains play an important role in each of these processes: they are estimated to consume about 47.9 Tg of N-fertilizer and 14.3 Tg of N from legumes [7], and while no figure is available for fuel consumption by livestock, the food sector in general is estimated to account for about 30% of the energy consumption worldwide [13].

The cascade of impact is limited by the capacity of certain systems to accumulate Nr, for example, forests and unmanaged grasslands storing Nr in soil and biomass, or to host denitrification processes that convert Nr back into N_2, for example, wetlands, streams and marine coastal regions [12••]. Despite remaining uncertainties regarding N flows in agro ecosystems [14,15], the low to moderate potential of agricultural systems to act as Nr sink and to produce N2 indicates that any Nr that does not exit the agricultural system in the form of agricultural products is highly likely to enter the Nr cascade [12••].

Furthermore, the high energy requirement of the Haber-Bosh reaction makes Nr generated through this process economically costly and associated with the environmental impacts of energy production and consumption. It is estimated that industrial N fixation uses about 2% of world energy supply [8•], mostly in the form of natural gas [1].

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[a] Refers to all forms of N, except for di-nitrogen gas. The metabolism of most organisms cannot use N_2 and thus entirely depend on Nr.

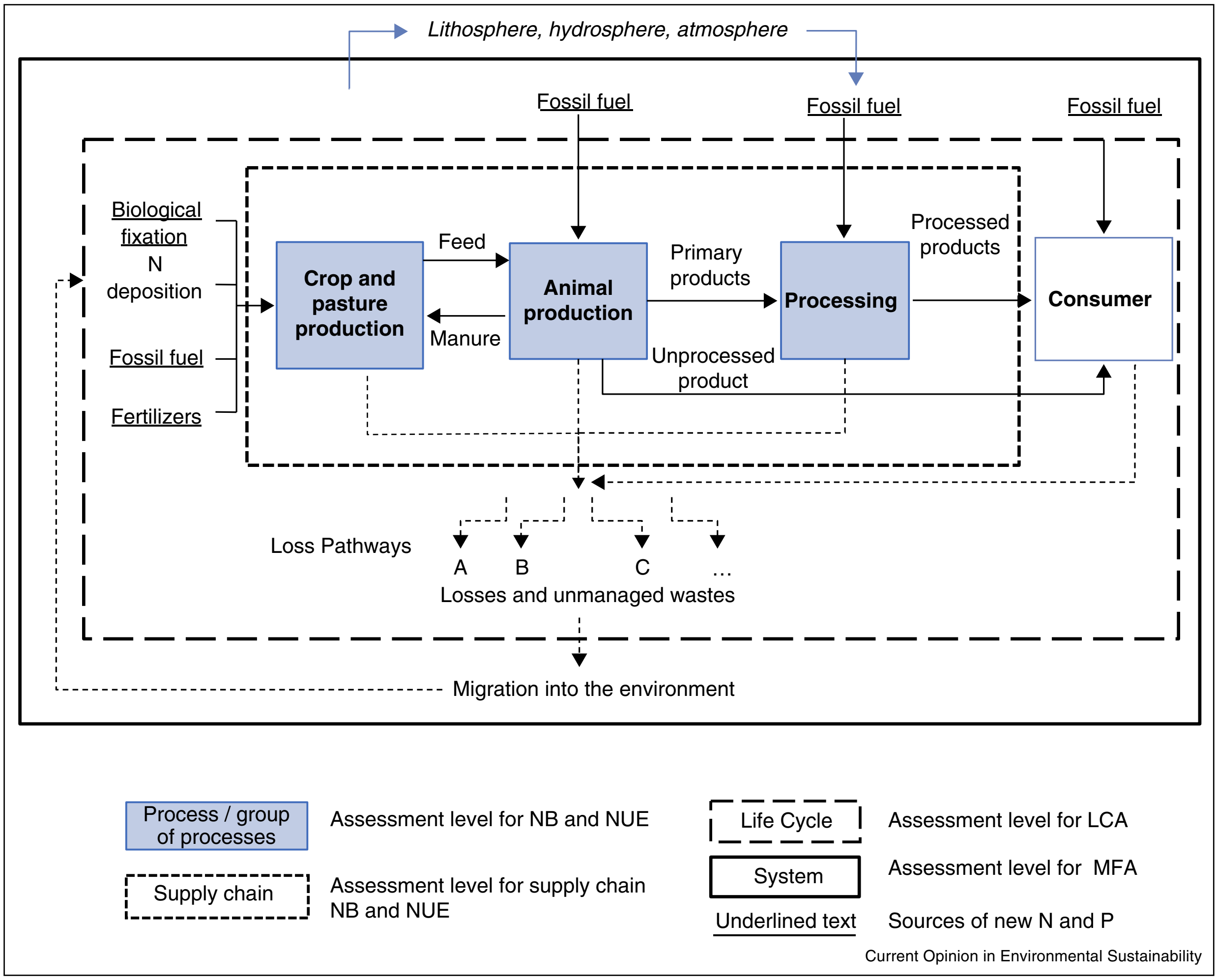
At aggregate level, the efficiency with which new Nr is used in agricultural systems, and livestock supply chains in particular, is thus a pertinent indicator of the potential environmental impact. First, because at such level, only new Nr can be considered to be brought into the system (Figure 1). Second, because any inefficiency will generally result in additional N entering the Nr cascade and in fossil fuel use inefficiency, both associated with negative environmental effects.

A similar observation can be drawn for P, although with partially different considerations. In this case, it is mostly the finite nature of P resources that drives the need for efficient use. Rock P reserves are indeed estimated at 71,000 Tg P_2O_5, and given current levels of extraction and technology, it is projected that these resources will be exhausted at some point in the medium-term future, albeit that projections vary widely from 50–100 years [16] to 370 years [8•]. NUE thus appears as the key strategy to extend this period until either new resources or extraction techniques are discovered or systems that tend to fully recycle P are developed. The fact that rock P reserves are also concentrated in few countries accentuates this issue by posing the problem of global access to P resources: almost 90% of P_2O_5 reserves are concentrated in only five countries [8•]. The migration of P losses from agricultural sources into the ecosystem also causes environmental and public health concerns, although P is less mobile than N and, contrary to N, accumulates in agricultural soils [17,18].

Frameworks for the assessment of nutrient use in livestock production systems

Several frameworks have been developed for the assessment of nutrient use in livestock system, tailored to the objectives and scope of the analyses. We can broadly classify them into four categories: nutrient balance (NB), NUE, material flow analysis (MFA), and life cycle assessment (LCA).

Figure 1



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Main flows of nutrients and levels for the analysis of nutrient use in livestock systems.

Nutrient balance

NB (or nutrient budget) is computed as the difference between aggregated inputs and outputs of a production process, usually expressed in kg nutrients (Nut) year^{-1}. This simple approach is being widely used as an indicator to raise awareness and advise farmers and policy makers on issues related to fertiliser use, manure management and water quality protection [4,19,20,21••,22,23].

NB can be computed at a range of levels in the food supply chain, from unit processes [24–26], to farms [2•], or entire food supply chains [3,8•] cf. Figure 1. NB can also be computed for spatial units integrating several agricultural activities [27].

The relative data parsimony of NB is an advantage of the approach, although aggregated data on regional or system level can be sparse and lead to important uncertainties and biases. Limitations of NB are related to the simplicity of the approach: only inputs and outputs of the analysed production process are quantified, the difference being an estimate of surplus or deficit that aggregates losses, mining and stock changes in a unique figure. This may result in a black-box effect, especially when the analysis is carried out at aggregated level and sub-systems are not analyzed separately. The spatial resolution at which the analysis is carried out also matters: the redistribution of P and N is likely to be heterogeneous, so while N and P balances may be fine at the farm level, within farm (i.e., field or sub-field scale) surpluses and deficits may occur.

Furthermore, although a surplus can generally be interpreted as an indicator of environmental pressure, no information is provided on the nature or the likelihood of the related environmental impact.

Different metrics have been used to express the NB in an intensity form, either relating surplus or deficit to a surface area, for example, kg Nut ha^{-1} year^{-1} [4] or to units of output, for example, kg Nut year^{-1} kg^{-1} output [28•].

Nutrient use efficiency

Drawing on the same data as NB, NUE is a dimensionless indicator computed as the ratio between the aggregated amount of nutrients in the outputs and in the inputs. As NB, NUE can be computed for different systems, for example, a field with crop cultivation, a herd, or an entire chain, supporting decision making at various levels (Figure 1). Similar to the NB approach, NUE does not provide direct information on environmental impacts. However, performed at an aggregated level encompassing all processes in the supply chain, NUE interestingly informs on the efficiency with which new nutrients are used. Knowledge of the overall efficiency of a chain is however insufficient to identify and guide decision making at the process level.

Several shortcomings of NUE are described by Godinot *et al.* [2•] who provide technical adjustments, including the extension of system boundaries to account for the life cycle of products, the clarified definition of end products, and the computation of net flows and changes in stock. These developments allow for a greater comparability of results and prevent bias related to ‘purchase-release’ effect (NUE is altered if the same value is added to input and output) and to unaccounted stock changes, for example, in soil organic matter. Despite these refinements, some of the more intrinsic limitations of NUE remain, including the fact that it does not provide information on overall pressure nor on the environmental impacts and that, when calculated at supply chain level, it does not inform on the distribution of inefficiencies in the chain, nor on their location.

In animal production, NUE has been evaluated at animal level [29], farm level [26,29,30] or food system level, for example [31•], cf. following section.

Derivatives of NUE include the crop recovery efficiency, which calculates the nutrients in harvested products as a proportion of nutrient fertilization [32]; or the partial factor productivity of applied nutrients, which accounts for quantity of harvested crop product per quantity of nutrient applied (kg output kg^{-1} Nut).

Material flow analysis

MFA, or substance flow analysis, is used to map and quantify flows of selected elements through production systems [33–36]. This approach has been used in agriculture to assess nutrient fluxes, accumulation of hazardous substances (heavy metals) and sources of environmental pressure. MFA is built on input–output models applied to each unit-process along the supply chain, and connected to each other [37]. Several studies applied MFA to map P flows throughout regional [31•,36–38] or global food production systems [16,35].

Starting with one input or chemical element in inputs, for example, Nr from biological N fixation, MFA maps and quantifies the flow of this element through-out the entire system or through a defined sub-system. MFA informs on the forms of losses (pressure) but not on their impacts on the environment, for example, it informs on Nr migration to surface water (eutrophication) but not on the impact this may have on biodiversity.

Results from MFA can be used to compute several indicators. For example, Suh and Yee [31•] compute NUE at different stages and levels of food supply, based on an MFA of the US food system.

Whereas MFA is an effective approach to better understand ‘hotspots’ of nutrient losses and to develop mitigation strategies [16], it requires large amounts of high-resolution data, which is often not available on a regional to global scale.

Life cycle assessment

LCA takes a reverse perspective to MFA, taking a unit of product as reference and looking at all upstream (and downstream) activities and related environmental impacts. It is a holistic accounting approach that captures environmental pressure related to the production, usage and disposal (life cycle) of a product or a service [39]. Characterization factors are used to estimate the related environmental impacts, reported to a unit of product (Impact kg^{-1} output). Originally developed for industrial processes, LCA has been extended to agricultural studies. A growing number of studies have used LCA to assess the environmental impacts associated with livestock commodities. Although the reference unit is always a unit of product, LCA assessment can be computed at different levels of aggregation, from a single supplier to a production system or entire region [40–44]. Most of the recent studies focus on climate change, land use, fossil energy use, eutrophication and acidification [45,46].

Relying on consolidated procedures and international standards [47], LCA is commonly accepted as a valuable environmental management tool for decision-makers [48]. As MFA, LCA is however a data intensive approach, which can represent a considerable constraint to its use, especially at high levels of aggregation.

Nutrient use efficiency: relative advantage and applications

NUE demonstrates a number of relative advantages compared to the other approaches reviewed.

NUE and NB are basically two different expressions of the same information. Compared to NB, NUE however has the advantage of expressing the potential impact in an intensity form (per unit of product), and therefore cancelling the effect of the size of the activity (cf. Table 1). Although NUE does not provide direct information about the environmental impacts of agriculture, at aggregated level, it informs on the performance with which new N and P are used. This provides a crucial insight into potential environmental and resource issues related to nutrient use in livestock production (cf. above).

NUE can be calculated at different scales, embracing one, several or all of the supply chain involved in the supply chain and thus supporting performance improvement at various levels. Computing supply chain NUE as the combination of NUE in each process or group of processes avoids the 'black box' effect but is obviously much more data-intensive.

NUE can be coupled with other indicators. NB is a natural complement, using the same information but providing an overall estimate of losses and stock change. Losses and stock changes however do not have the same environmental implications and should thus be possibly differentiated in the computation [2•]. This is especially the case for P, which has a greater potential of retention within soils than N. Long time positive/negative balances or inefficiencies may potentially lead to accumulation/depletion of nutrients (P in particular) in soils [49•]. Attention should therefore be paid either to the timeframe of the analysis (a long timeframe would capture accumulation/depletion), or to the existing soil P status in the case of short term analysis. Gourley *et al.* [49•] thus argue that while farm-level N NB and NUE can greatly assist management decision, P NB and NUE cannot, unless they are combined with soil fertility levels and accumulation/depletion trends. They also note the spatial and temporal heterogeneity of P NB and NUE, further complicating their use for decision support.

The other two reviewed approaches provide more information on environmental pressure (MFA) and impacts

Table 1

Overview of main approaches used to assess nutrient use in livestock supply chains.

Approach	Definition	Scale	Environmental impacts	Data requirements
Nutrient balance	Difference between nutrients in inputs and nutrients in outputs.	From process to entire supply chain. Can be applied to geographical area including several processes.	Partial information: computes an aggregated amount of losses or mining.	+
Nutrient use efficiency	Ratio between nutrients in outputs and nutrients in inputs.	From process to entire supply chain.	Partial information as NB. At Chain level, informs on the efficiency of 'new' nutrient use.	+
Material flow analysis	Map of quantified material flows in the system.	System	Characterizes fluxes of environmental pressure.	+++
Life cycle assessment	Environmental impact per unit of product.	Supply chain	Quantified per unit of output.	+++

(LCA), with however the major drawback of being much more data-hungry. It is also not certain whether the full mapping of flows or the quantification of environmental impacts is actually necessary to inform decision making at the supply chain level. Since any loss of nutrient is likely to cause negative environmental impacts and poses issues with regard to the management of finite resources, one may argue that benchmarking supply chain level NUE provides relevant information to guide nutrient management: any improvement of NUE is likely to generate environmental benefits. The quantification of these benefits would however require implementing analyses such as MFA, LCA or impact assessment.

Nutrient use efficiency in the literature

NUE has been used by a large number of authors to assess nutrient use in livestock systems, at animal, farm and supply chain level. Table 2 provides a non-exhaustive summary of this literature, reporting results by species and level of analysis. Only N and P were considered in this review, given the scarcity of references addressing other nutrients.

Many studies have assessed animal level NUE, generally computing NUE as the percentage of nutrient in feed that is recovered in edible products. Results are therefore comparable and differences between studies mostly related to species and management practices, for example, feed rations, climate, animal health, among others. Computations at this level are quite common and the results presented in Table 2 are only a fraction of existing literature. They nevertheless tend to confirm a pattern of decreasing efficiencies for N and P, as we move from poultry to pig, dairy cattle, and beef cattle. Results found for all species are lower than could be expected when considering those for single species. This may be related to bias in the geographic coverage of assessments at specie level — predominantly addressing industrialized countries — whereas studies addressing all species are global.

NUE assessments carried out at farm and system level encompass livestock rearing as well as other activities on the farm, such as crop and pasture management. The comparability of these studies is more challenging than for animal level NUE.

First, because of the many potential methodological discrepancies. An important source of inconsistencies is the selection of the flows that are considered in the calculation, for example, the inclusion/exclusion of manure and other non edible products in the outputs, and the inclusion/exclusion of non-purchased nutrients in the inputs. In Table 2, results are given separately for studies including or excluding non edible products from the outputs. Regarding dairy and beef cattle, for which several published research could be gathered, NUE computed including non edible product is generally higher than NUE excluding non edible products. This is a logical result given the NUE computation formula. Ranges of results however greatly overlap and this relation is not observed in other species, for which limited literature is available. The lack of harmonized data regarding the nutrient content of the various inputs and outputs, as well as differences in the temporal scale of the analysis are further sources of discrepancy. Differences in approach

Table 2

Non exhaustive summary of NUE results found in the literature.

	Animal level NUE (%)				Farm and system level NUE (%)			
	N		P		N		P	
	Range	References	Range	References	Range	References	Range	References
Dairy cattle	15 to 35[b]	[25,26,29, 51–57]	19 to 60[b]	[25,51,58,59]	15 to 41[d] 15 to 55[e]	[2•,19,21••,29,30, 51,55,60,61•,62] [19,30,61•,62,65]	31–48[d] 56 to 74[e]	[26,51,63,64] [62,65,66]
Beef cattle	4 to 8[b]	[51,66]	14 to 28[b]	[51]	7 to 38[d] 26–34[e]	[21••,67] [19]	21–44[e]	[51,67]
Pig	10 to 44[b]	[51,62,65]	34[b]	[51]	50[d] 41–45[e]	[51] [18,20]	37[e]	[51]
Poultry	25 to 62[b]	[51,62,65, 67–69]	34 to 58[b]	[51,68]	39[d] 35 to 48[e]	[69] [20]	61[e]	[69]
All species combined	7.1 to 10.5[b] 74.1[c]	[8•,70]	4 to 19[b] 362	[8•,31•]	5 to 45[e]	[20,71]		

Note: when several studies are referenced, the range make reference to mean values provided in the studies; when one study only is referenced, the range or the single value provided in the study are reported in the table.

[b] Calculated as the percentage of nutrient in feed that is recovered in edible products.

[c] Calculated as the percentage of nutrient in feed that is recovered in edible and non-edible products, including recycled manure.

[d] Calculated as percentage of total nutrient input (including deposition and biological fixation) recovered in edible outputs.

[e] Calculated as percentage of total nutrient input (including deposition and biological fixation) recovered in edible and non-edible outputs.

are well explained by diverse purposes and users of single analyses but represent a major issue when producing aggregated assessments of the sector and providing guidance to producers and policy makers [49•,50]. In addition to these methodological issues, Oenema *et al.* [50] describe several sources of biases and errors that can occur during the analysis and can affect results.

The second major challenge regarding comparability of results at farm level is the great diversity of activities and processes that can be combined in a farm and that have an effect on the overall NUE. This issue calls for a disaggregated NUE analysis or for completing the farm level NUE analysis with other assessments of single processes.

As for animal level, farm level P NUE tends to be higher than N NUE. This trend was observed by previous authors [51] and is to be related to the many pathways of N losses, in gaseous or liquid form.

No studies were found to assess NUE at supply chain level (life-cycle-NUE, cf. Figure 1), including fertilizers production and post-farm gate processing.

Conclusion

Drawing on relatively simple and generally accessible information, NUE can inform the efficiency of animal production systems and is confirmed as a valuable indicator to guide decision making and improve sustainability of nutrient management [8•,9]. Computed at supply chain level, it notably characterizes (i) the use of finite resources (rock P and fossil fuel for Nr production), and (ii) the losses of nutrients per unit of product, likely to have impacts on the environment and public health.

Relating nutrient use to a unit of product, NUE can be considered a production oriented indicator that producers and the private sector can use to benchmark activities and monitor progress. This is likely to ease its adoption into existing monitoring and reporting systems. Relying on the same data, NB is a complementary indicator that may be used in parallel to NUE.

Recent assessments have improved NUE calculation but further methodological developments are required to deliver effective support to decision making. These include (i) the full incorporation of the life cycle thinking in NUE assessment and the identification of the major causes of inefficiency along the supply chains, to better address longer and increasingly complex food systems, (ii) the harmonization of definitions regarding system boundaries, inputs/outputs and timeframes that can be consistently applied, to ensure comparability of results and (iii) the development of common datasets on nutrient content in feed and other nutrient sources, to overcome current data shortage and shortcomings. Several initiatives address these needs, among which the Livestock Environmental Assessment and Performance (LEAP) multi-stakeholder partnership (http://www.fao.org/ag/againfo/livestock-benchmarking). Initiated in 2012, LEAP focuses on the development of approaches, metrics and databases to guide environmental sustainability decisions in the livestock sector.

These developments could be the initial steps towards a better understanding of the variability in NUE within systems and the related gap between production and processing units operating at relatively high levels of efficiency and those which on the contrary are less efficient. Quantifying the efficiency gap and understanding underlying drivers is key in helping the sector to make relatively quick and cost effective sustainability gains, by generalizing the adoption of best practices [7].

Further investigations are also required to test the hypothesis that, at aggregated level, the efficiency with which new nutrients are used is indeed a good proxy for environmental and public health impacts related to nutrient management.

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