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Defining common criteria for harmonizing life cycle assessments of livestock systems

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ABSTRACT

Animal production intensification puts pressure on resources, leads to environmental impacts, animal welfare and biodiversity issues. Livestock products provide key components of the human diet and contribute to rural territories through ecosystem services such as nutrient and biomass recycling. Life cycle assessment (LCA) is key to assess environmental impacts in livestock systems and products. A harmonization of LCA methods is necessary to improve evaluations in these areas as LCA still lacks accuracy and robustness in addressing sustainability across livestock systems and products. Here, a participatory harmonization approach was applied to provide a framework to evaluate LCAs of current and future livestock systems. A total of 29 workshops with targeted discussions among 21 LCA experts were organised, together with two anonymous surveys to harmonise evaluation criteria. First, key research topics for improving LCAs of livestock systems were identified as follows: i) Food, feed, fuel and biomaterial competition, crop-livestock interaction and the circular economy; ii) Biodiversity; iii) Animal welfare; iv) Nutrition; v) GHG emissions. Next, general evaluation criteria were identified for livestock focussed LCA methods, considering livestock systems characteristics: Transparency and Reproducibility, Completeness, Fairness and Acceptance, Robustness and Accuracy. Evaluation criteria specific to each key topic were also identified. This participatory method was successful in narrowing down general and specific evaluation criteria through targeted discussion. Moreover, this study provided a holistic participatory framework for the evaluation of LCA methods addressing the impacts of livestock systems across a range of key topics which can be further used for other sectors.

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1. Introduction

Worldwide demand for animal products is predicted to double in the coming decades (Godfray et al., 2018), while food production is responsible for 26% of all greenhouse gases, and for 70% of land-use globally (Poore and Nemecek, 2018; Van Zanten et al., 2018b). At the same time there are increasing societal concerns about the impacts of intensive livestock production and animal welfare (Godfray et al., 2018); while overconsumption of food, in particular some processed meat, can increase the risk of illnesses and death globally (Gaupp et al., 2021; Godfray et al., 2018). However, livestock farming plays a vital role in food and nutrition security by providing several key nutrients for human diet, including vitamin B12, Decosahexaenoic acid (DHA), iron and zinc, and livestock products have greater bioavailability than equivalent plant compounds; whilst also contributing to efficient agriculture and to the vitality of rural territories (Godfray et al., 2018; Mehrabi et al., 2020).

In this context, the lack of a holistic sustainability assessment approach makes it difficult to measure livestock's contribution to society, hampering evidence-based debates about trade-offs and leading policymakers to focus on highly tangible, but essentially weak, leverage points (Abson et al., 2017; Scown et al., 2019). The contribution of livestock to a sustainable circular bioeconomy and agroecology should therefore be further investigated, to develop suitable policies for healthy and efficient agroecosystems (Scown et al., 2019; Van Zanten et al., 2018a). These approaches could contribute in valorising livestock by-product and waste for feed, fuel and biomaterial purposes (Van Zanten et al., 2018a).

Participatory approaches have been successful in assessing design and innovation in agriculture, using new methods and tools. These could either involve experts or potential stakeholders (Macombe et al., 2018; Mullender et al., 2020). Open design and innovation approaches applied to agriculture, food and livestock systems better account for the diversity of production situations and for strong interconnections between the various components of agri-food systems in a more systemic and holistic way (Berthet et al., 2018). Recently, a Delphi-style participatory approach was successfully adopted to develop a food sustainability tool (Mullender et al., 2020), while participatory approaches were also employed to assess the sustainability of small ruminants (Belanche et al., 2021) and in the Life Cycle Assessment (LCA) of farming systems (Kulak et al., 2016). A participatory approach was also suggested to improve LCA adoption among agri-food companies (Testa et al., 2022).

Holistic assessments including LCA were successfully used to assess livestock systems and products to identify environmental hotspot, and trade-offs across different types of pollution (Cederberg et al., 2013). LCA has been also widely used to assess climate change impacts of food and livestock products (Grossi et al., 2019; Poore and Nemecek, 2018) and to evaluate livestock systems including pig production (McAuliffe et al., 2016), beef meat (Flysjö et al., 2012; McAuliffe et al., 2016; Van Zanten et al., 2018b), milk and dairy systems including cheese production (Flysjö et al., 2012; Kristensen et al., 2015), sheep and lamb production systems (Bhatt and Abbassi, 2021; Geβ et al., 2020; Vagnoni et al., 2015), and poultry production systems (Kalhor et al., 2016; López-Andrés et al., 2018; Skunca et al., 2018; Williams et al., 2016). However, LCA still lacks accuracy and robustness to address different aspects of sustainability across a range of livestock systems and products. In particular, the LCA methodology needs to be improved with regard to C sequestration and greenhouse gas emissions (FIL-IDF, 2022; Goglio et al., 2015), farm system assessments, crop-livestock interactions, feed-food-fuel competition (Muscat et al., 2020; Van Zanten et al., 2018a), biodiversity, nutrition, animal welfare and circular economy assessments (Goglio et al., 2017; Scherer et al., 2018; Sonesson et al., 2019, van der Werf et al., 2020). Both product and system LCA approaches are relevant to better capture the characteristics of livestock and agricultural systems (Goglio et al., 2017; Grossi et al., 2019; Nemecek et al., 2014; Van Zanten et al., 2018a).

Within several LCA methods, harmonization attempts were carried out in sectors other than agriculture (Segura-Salazar et al., 2019; Siegert et al., 2019), while others focused on wines (Jourdaine et al., 2020), generally on food (Ponsioen and van der Werf, 2017) or food waste, in the latter case advocating for a better integration between LCA and soil science (Morris et al., 2017). Other LCA harmonization attempts broadly focused on agricultural systems (Audsley et al., 1997) or just on soil carbon in livestock systems (FIL-IDF, 2022), providing guidelines on how to account for soil C in LCA of livestock systems. On the other hand, several guidelines have been proposed as part of the Livestock Environmental Assessment Performance partnership (LEAP) of the Food and Agriculture Organisation (FAO), including on soil carbon, feed, biodiversity, pig, poultry, small and large ruminants (FAO, 2020). These provide insights and recommendations on how to account for greenhouse gases and biodiversity in livestock systems. Several meta-comparisons of LCA methods were also reviewed by Heijungs and Dekker (2022), but none of these were specifically focused on livestock systems and products.

Despite these previous harmonization attempts (FAO, 2020; FIL-IDF, 2022; Heijungs and Dekker, 2022), there has been no robust attempt to develop an evaluation framework for the assessment of methods addressing greenhouse gases, biodiversity, animal welfare, nutrition, circular economy, feed-food-fuel competition, and crop-livestock interaction within LCAs of livestock systems and products. Here this gap was addressed through a participatory expert consultation approach focussing on the life cycle inventory accounting for livestock systems across livestock sectors (e.g., beef, dairy, pig, poultry, sheep and goats).

2. Methods

2.1. Overall participatory approach

A harmonization approach based on the Delphi method was adopted to identify key topics and evaluation criteria for LCAs of livestock systems (Mullender et al., 2020). The general, specific, search and screening criteria for LCA methods of livestock systems were identified through a literature review and 29 workshops with experts (n = 21) on LCA, GHGs, biodiversity, nutrition and animal welfare. These were drawn across academia and farmer advisory boards and had 14 different nationalities. Further details on the experts are provided on Table 1. Participatory approaches as adopted in this research proved to have the advantage of building consensus across the participants (Mullender et al., 2020), which helps the harmonization, as was previously carried out in other LCA research (Testa et al., 2022). However, participatory

Table 1
Fields of expertise and research experience, including PhD research years, in the expert panel (the number in the table indicates the number of experts)[a].

Field of expertise		Years of experience		
		1–3	<3	<10
LCA		1	7	4
Key topic	**Greenhouse gases**		8	4
	Biodiversity	2	2	1
	Animal welfare	1	1	2
	Nutrition aspects	1	2	2
	Feed-food-fuel- biomaterial competition, crop livestock interaction, circular economy		10	3
Livestock systems	**Dairy**	1	7	2
	Beef	1	7	2
	Pigs	1	2	2
	Sheep and Goats	1	4	3
	Poultry	1	2	1

[a] The total number of experts can be higher than 21 as some have multiple fields of expertise.

approaches can present the disadvantage of being time consuming and characterized by a lack of engagement of peers (Macombe et al., 2018).

The workshops were organised as structured discussions aimed at eliciting expert knowledge (Mullender et al., 2020). Key conclusions, arguments and observations were also recorded (Bard et al., 2017). As outlined in Fig. 1, the harmonization approach adopted here includes three phases: key topic selection, general criteria selection, specific and search criteria selection. Each specific and search criterion was formulated specifically for each key topic (Fig. 1).

2.2. Key topic selection

First, priority topics for improving the LCA method for livestock systems were identified through a discussion with LCA experts in three structured workshops. The primary pool of topics was selected based on both literature and expert judgement. The search engines used were Web of Science, Scopus and Google Scholar, while the following search words were used: “livestock systems”, “LCA”, “sustainable”, “livestock product”.

The identification of the key topics was based on peer-reviewed literature. Next, the list was narrowed down and key topics selected through an anonymous survey to provide a priority list (survey 1, Fig. 1, Supplementary material 1). Each expert was asked to rank the priority of each key topic based on: (1) the evidence provided by the public and political debate at global level; (2) stakeholders’ interest, with specific regard to LCA methodological discussions; (3) the research needs identified through the LCA literature. The survey was carried out by each expert anonymously and independently, as in previous participatory approaches (Mullender et al., 2020; Testa et al., 2022). Descriptive statistical indexes were calculated and discussed as part of the workshop discussion. Key topic survey results were processed using both MS Excel and R (Microsoft, 2019; R Development Core Team, 2005). The identification of the key topics was carried out on the follow up workshop where the survey results were discussed and scrutinised among experts.

2.3. General criteria selection

A structured review of current LCA frameworks was used to select evaluation criteria for LCA methods targeting livestock systems, using Web of Science, Scopus, and Google Scholar. Search words were defined for each of the identified topics, with each search string including the following terms: “LCA methods”, “LCA framework”, “livestock”, “agriculture”. Only publicly available documents were screened.

The literature review considered a range of assessment frameworks, including those developed by independent researchers to address specific impact criteria, e.g. the RACER framework, used to assess resource dissipation (Wiedmann et al., 2009) and those developed by government or the European Joint Research Centre (JRC) for the International Life Cycle Database (ILCD) or for the Product Environmental Footprint Category Rules (PEFCR), which are based on the LCA methodology (JRC, 2010; Zampori and Pant, 2019). Other identified frameworks were specifically developed for livestock systems, for example the Food and Agriculture Organisation (FAO) Livestock Environmental Assessment Performance (LEAP) guidelines (FAO, 2018). As outlined in Supplementary material 2, for each general criteria, key characteristics were provided to the experts, including a general definition/description of the criteria, type(s) of review conducted to develop the framework, and the scale type and allocation used in the criteria evaluation (Supplementary Tables 1 and 2; Supplementary material 2).

General criteria were presented to experts together with their characteristics in two workshops to identify missing criteria and/or to suggest additional criteria. Next, an anonymous survey was carried out to rank the criteria identified through the structured review and expert consultation (survey 2, Fig. 1; Supplementary material 3). Each participant was asked to provide a value for the level of importance from one (low importance) to ten (high importance) for each criterion. The level of importance was attributed by each expert based on the suitability and appropriateness of the criteria for the harmonization of LCA methodology for livestock systems and products. The data were processed in a similar manner as described in the key topic selection section.

The general criteria selected through the survey were then further screened by LCA experts to ensure that both the definition and the scale would be appropriate for a harmonization effort focused on livestock systems and products, avoiding subjectivity and biases in the LCA method assessment. This was carried out through a series of targeted and structured discussions during the workshops. Anonymised quotes from the workshops were used to illustrate emerging issues in LCA methodology (Macdiarmid et al., 2016).

2.4. Specific criteria selection

The specific criteria selection was carried out with a combined approach involving both literature and expert knowledge. Among the 21 experts, five groups of experts composed of at least three or four individuals were formed, as in previous studies assessing LCA implementation (Testa et al., 2022). Each group worked on a specific allocated topic for at least three workshops. A full rationale for the inclusion of each topic is presented in the Supplementary material 2 and summarized

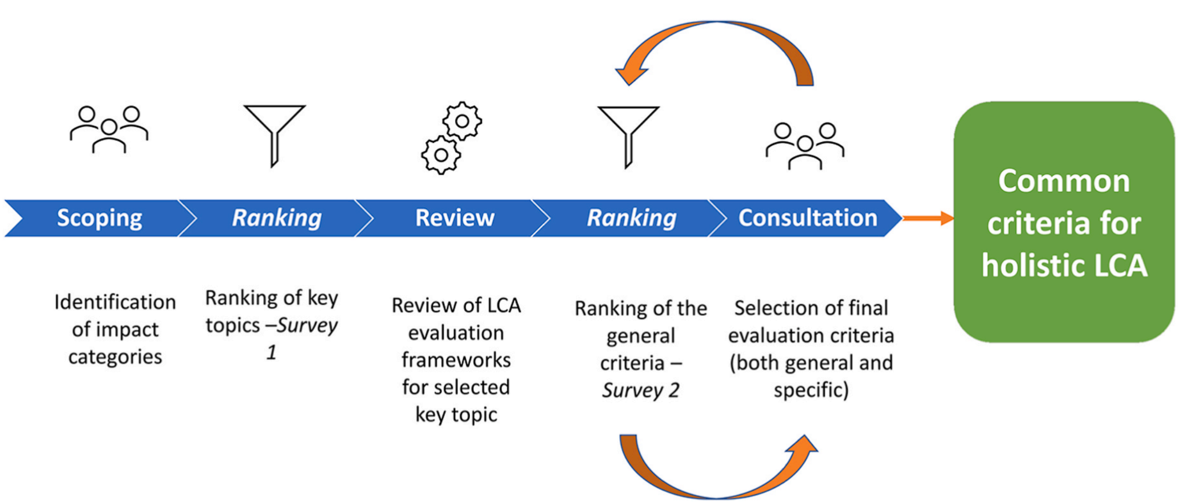

Fig. 1. Flow chart for the participatory approach adopted in this research for the development of common criteria for the assessment of LCA methods used for livestock systems and product.

in the following section.

2.4.1. Food, feed, fuel and biomaterial competition, crop-livestock interaction, circular economy

Production of food is driven by two main challenges: producing enough food and sustainability. At the same time, the use of inedible products, marginal lands or other co-products in livestock production requires consideration of strategies that limit/reduce environmental impact (Van Zanten et al., 2018b). Interactions between systems should be identifiable to fully assess crop-livestock integration (Marton et al., 2016).

To integrate circularity in LCA, accounting for all output streams, including by-products and manure, was considered particularly important. At the same time, livestock consume by- and co-products as well as residues from crop production and processing, which globally constitute 30% of feed, and thereby utilise resources which might otherwise create environmental strains (Mottet et al., 2017). Overall, the agricultural sector generates many residual streams (e.g. manure), which could be used by other activities, displacing the use of industrial products (e.g. mineral fertilisers). With regards to circularity, it should be taken into account that streams considered "waste" could become co-products in the future, e.g. through technological innovation, as highlighted for plastic waste previously (Klemeš et al., 2021). Thus, specific criteria were defined considering all these issues with regards to food-feed-fuel-biomaterial competition, crop-livestock interaction, and the circular economy.

2.4.2. Biodiversity

Despite the need for biodiversity assessment and several attempts to capture it in LCA, several limitations were found by Souza et al. (2015) including: a poor definition of indicators, such as unclear position on the cause-effect chain, missing levels of biodiversity (e.g., genes, communities, landscapes), missing attributes of biodiversity (e.g., structure, diversity, function), differentiation of vulnerable species, and missing consideration of habitat fragmentation. Furthermore the need to assess functional biodiversity in agroecosystems was highlighted (Souza et al., 2013).

Nevertheless, species richness and diversity were found to be common indicators of biodiversity within the LCA literature (FAO, 2016a, 2020) although other major aspects included the presence and abundance of invasive and endangered species (CBD, 2010), the ability to capture livestock, crop and farm management and landscape continuity. Hence, these elements were assessed as to their possible compatibility with the LCA approach. Specific criteria were defined recognising that animal farming can be linked to habitat degradation through feed production, grazing practices, land transformation and ecological integrity (FAO, 2016a).

2.4.3. Animal welfare

Incorporating animal welfare impacts into sustainability assessments is important and would be beneficial to understand the impacts of our choices and identify actions required to improve sustainability (Fan et al., 2015; Hellweg and Milà i Canals, 2014). However, so far, animal welfare has only been included in a limited number of LCA studies (Geβ et al., 2020; Paris et al., 2022; Scherer et al., 2018; Tallentire et al., 2019); but it is of rapidly increasing interest. The type and complexity (i.e. differences across animals species, indoor/outdoor systems) of welfare criteria used have varied greatly and there is currently no consensus on how animal welfare can be incorporated in a sustainability analysis in a valid and practical way. On this basis, during workshops, specific criteria for animal welfare were defined.

2.4.4. Nutritional aspects

Protein sources play key roles in the environmental impacts of food (Aiking, 2014). When evaluating the environmental impact of different protein sources, like meat, fish and legumes, dairy products, eggs, it is important to take into consideration that the function of these products is to provide humans with several nutrients that come only from animal products (Ridoutt, 2021).

The combined assessment of environmental and nutritional aspects could be approached in different ways, depending on the goal of the study (Ridoutt, 2021). These approaches include both analyses on production level and on dietary level (Perignon and Darmon, 2021; Ridoutt, 2021). Thus, the specific criteria were defined by the LCA experts distinguishing both levels in the assessment.

2.4.5. GHG emissions issues

Within the livestock sector, feed production, manure management and enteric fermentation are the main contributors to climate change impacts (FAO, 2013). In addition to the aforementioned GHG emissions, soil contains the largest share of terrestrial carbon under a dynamic equilibrium which depends *inter alia* on soil types, climate and management practices (Brady and Weil, 2002; Lal and Stewart, 2018; Paustian et al., 2016).

Accounting for fluxes of CO_2 and N_2O in agro-ecosystems is important for evaluating the enhancing or mitigating climate change effects of different livestock systems (Grossi et al., 2019; Sykes et al., 2019). In general, CO_2 is released from soils mainly as a product of microbial or root respiration (Lal and Stewart, 2018), but soils can be net emitters as well as net sinks of GHGs (Paustian et al., 2016). These processes are affected by the soil and climate conditions, type of residues, tillage, use of fertilizers, use of perennial crops, C/N ratios of the soil and of the applied residues to the soil (Brady and Weil, 2002; Paustian et al., 2016; Sykes et al., 2019). Whilst for N_2O, climate, soil types, use of fertilizer, tillage and residue management largely affect soil emissions (Ogle et al., 2019; Saggar, 2010).

Manure handling and storage are both associated with GHG emissions, and are largely affected by the type of storage (Owen and Silver, 2015). Drivers of CH_4 and N_2O emissions for manure and slurry handling are temperature, moisture content, C/N ratio, degradability of carbon compounds, pH level, N content, solid content and the physical structure of the organic biomass (Brady and Weil, 2002; Gavrilova et al., 2019; Philippe and Nicks, 2015). Housing is another source of GHG emissions, which is affected by temperature, ventilation, floor type, feed composition, manure removal strategy and type of bedding (Bohran et al., 2012; Philippe and Nicks, 2015). In anaerobic digesters, the level of methane leakage is also an important factor affecting emissions (FAO, 2016b).

Enteric fermentation emissions are a source of CH_4, generated in the digestive system of ruminant livestock during the microbial fermentation of feed. The amount of CH_4 released depends on many aspects, such as the animal species, the age and weight of the animal, and the type and quantity of the feed consumed (Gavrilova et al., 2019). Thus, considering altogether the characteristics of soil C, soil N_2O emissions, manure handling and storage and enteric fermentation related to livestock systems, specific criteria were formulated by the LCA experts during the workshops.

3. Results and discussion

3.1. Key topics

Five key topics were identified based on the structured workshops (n = 3) and survey (Supplementary material 1, Fig. 1): i) Food, feed, fuel and biomaterial competition, crop-livestock interaction, circular economy; ii) Biodiversity; iii) Animal welfare; iv) Nutrition; v) GHG emissions (Fig. 2). Biodiversity had the highest priority among respondents with a median value of 3.9. This was followed by social aspects (4.0), soil C sequestration and food-feed interaction (4.6); except for methane emissions and animal welfare which were indicated as top priority by only one LCA expert. Most of the experts showed relative agreement in the responses (Standard error (SE)≤ 1.1), however there was a larger

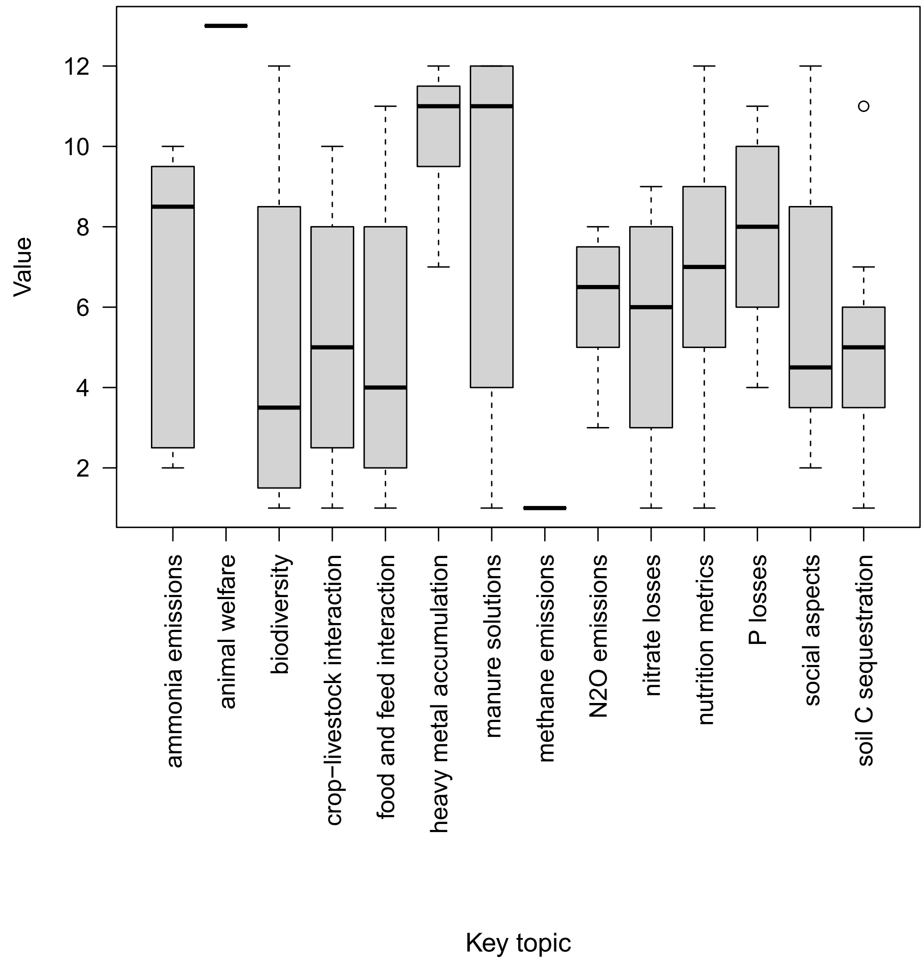

Fig. 2. Box plot of the LCA expert responses to identify key priority for LCA of livestock systems. The boxes indicate the 1st and 3rd quartiles, dark lines indicate the median. Error bars indicate the maximum and minimum values. Outliers responses more than 1.5 times the inter-quartile range away from the box are shown with hollow circles. High value indicate low priority, low value indicates high priority.

variation for feed and food interaction, biodiversity, manure solutions and ammonia emissions (SE > 1.1) (Fig. 2).

While social aspects were retained as a relevant issue with regards to the LCA methodology of livestock systems, it was decided to exclude this aspect from the present investigation as this would be investigated within a separate task within the same work programme, i.e., the Pathways for transitions to sustainability in livestock husbandry and food systems (PATHWAYS) project.

The key topics selected partially aligned with the FAO LEAP agenda but also addressed several sustainable development goals, including life on earth, climate action, zero hunger, gender quality, quality in education (FAO, 2020; UN, 2015). During the workshops, it was reported "the choice of the key topic is often affected by the LCAs own research agenda". To overcome this issue, a general structured discussion was carried out to refine the topic selection (Mullender et al., 2020).

3.2. General and specific evaluation criteria

The general criteria drawn from the identified frameworks are fully described in the Supplementary material 2. In addition to the literature derived criteria, "comprehensiveness", "interpretability" and "accuracy/robustness/data quality" criterion were defined by the French farmers' development board association in the online discussions (Association de Coordination Technique Agricole, ACTA). Criteria for "applicability" and "interpretability" were also proposed by the broader community of experts (Supplementary Table 1, Supplementary Material 2).

The general evaluation criteria presented in Supplementary Table 2 (Supplementary material 2), were included in a second anonymous survey (Supplementary material 3) where experts were asked to rank the criteria identified according to level of importance. Results of the survey were shown in Fig. 3. The "Credible" (RACER method, (Wiedmann et al., 2009), and the "Transparency and Reproducibility" (JRC, ILCD (JRC, 2010) general criteria received the highest median score (10) (Fig. 3). Both these general criteria were followed by "Completeness" (JRC PEFCR (Zampori and Pant, 2019) (9), then by "Fairness and Acceptance" (JRC ILCD (JRC, 2010)), the ACTA proposed criteria "Accuracy/Robustness/Data Quality", FAO LEAP criterion (FAO, 2018) and Robust (RACER method (Wiedmann et al., 2009),) with a median value of 8. Among the top general criteria, completeness had the largest standard error (1.1). The other top general criteria identified had lower scores (<1.1) (Fig. 3).

The following criteria were prioritised through follow-up workshops (n = 7) based on the survey results: "Transparency and Reproducibility", "Completeness", "Fairness and Acceptance", "Robustness" and "Accuracy". During the follow-up workshops, LCA experts highlighted that "it was very difficult to associate a clear scale for accuracy in each of the topics, as the level of accuracy was largely dependent on the LCA methodological development within each topic". Therefore, an accuracy criterion was also formulated for each key topic, together with the applicability criterion, during the workshops (Table 2). Furthermore, several specific criteria were discussed in workshops (n = 19) among the LCA experts (Supplementary material 2).

Several challenges emerged from the harmonization approach. For

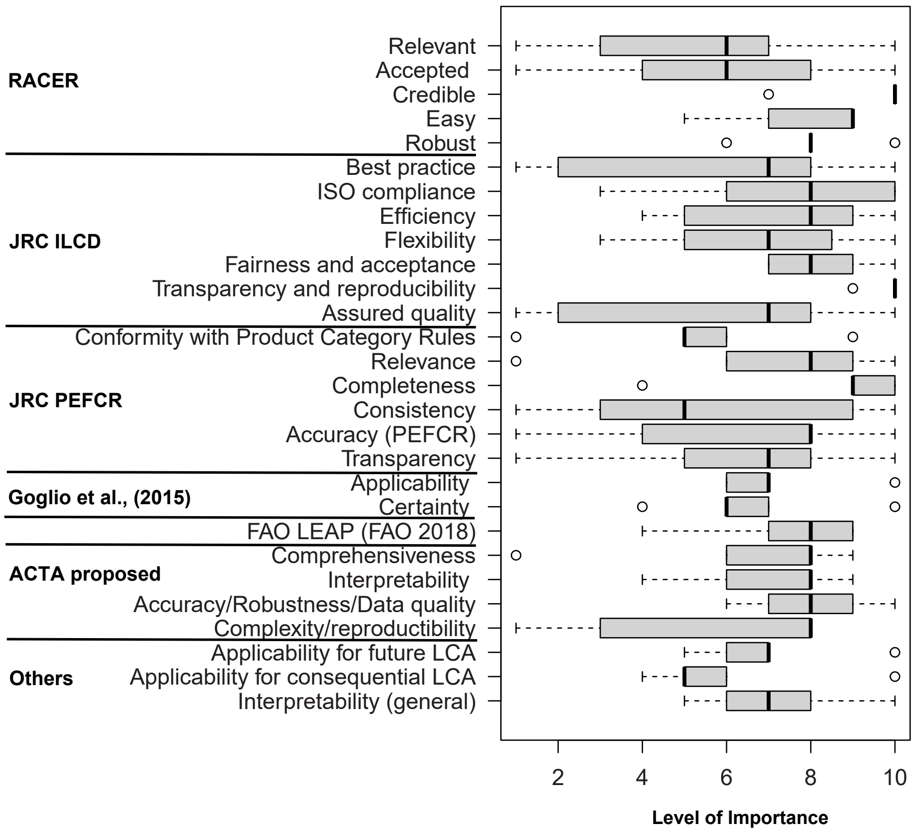

Fig. 3. Box plot of the LCA expert responses to identify general criteria for the assessment of LCA methods for livestock systems and product. The boxes indicate the 1st and 3rd quartiles, dark lines indicate the median. Error bars indicate the maximum and minimum values. Outliers responses more than 1.5 times the inter-quartile range away from the box are shown with hollow circles. High value indicates a high level of importance and a low value indicates a low level of importance.

instance, guaranteeing consistency across topics only partially related was hard to achieve. While defining general criteria, it was also observed that many similar concepts amongst frameworks were present and that many criteria were intuitively defined without a clear definition or scale. It was also noted that "several criteria were voted for by experts because of the framework they belong to (ie. PEFCR) rather than the clarity of the definition". Thus, during workshops, most of the general criteria needed further screening, and/or rephrasing to provide clear, unique, and objective general criteria and evaluation scales (Supplementary material 2). For each general and specific criterion, a scale from 1 to 4 was established (Table 2).

During the workshops, several experts reported "soil C methods or soil C observations did not achieve sufficient quality if the timescale was too short or if the soil carbon monitoring was not done appropriately". This led to an adaptation of specific criteria in agreement with the FAO LEAP report and recent IDF guidelines (Supplementary material 2) (FAO, 2018; FIL-IDF, 2022). During the discussion regarding nutritional aspects, several experts reported that "the issue of protein sources in the diet was very controversial", as discussed also in previous papers (Ridoutt, 2021).

3.3. Participatory approach

The participatory method adopted was successful in narrowing down the general and specific criteria. This exercise was difficult to conduct as previously reported (Heijungs and Dekker, 2022). However, differently from the paper reviewed by Heijungs and Dekker (2022), this research adopted a discrete scoring framework across a wide range of topics, anonymously judged as a priority by LCA experts. The different backgrounds and specific expertise profile of the experts allowed for a comprehensive and inclusive approach. However, the community of peers consulted in this research could be viewed as too limited, as previously discussed in social LCA eco-efficiency improvements (Macombe et al., 2018). Here, this was overcome by involving a relatively large pool of LCA experts (n = 21), as suggested in the Delphi method (Mullender et al., 2020), with different expertise.

Other researchers also reported that peers (i.e. the LCA experts in this case) might be elusive (Macombe et al., 2018), showing lack of engagement and participation. In this study, engagement was ensured through scientific publication co-authorship and involvement in a variety of discussion and exchange activities (one to one structured discussions, workshops and surveys), as carried out for LCAs of products and in PEFCR (Testa et al., 2022).

In this LCA method harmonization, it was important that exchanges between participants should be focused and structured on the main objective of the harmonization process (Macombe et al., 2018). Transparency and clarity in communications were also key throughout the process. As in all participatory approaches, engagement and involvement of peers or stakeholders from the beginning was critical (Macombe et al., 2018; Mullender et al., 2020). As discussed, regarding the Delphi method, further discussions among experts and critical evaluation of the survey results contributed to refining the key topics, general and specific criteria for the harmonization of LCA methods for livestock systems. Whilst having the limit of being time consuming, these approaches allowed for a broader consensus among peers (Mullender et al., 2020).

The general criteria identified in this participatory approach could be used for the improvement of the LCA methodology when applied to other types of production systems such as cropping systems, fish farming, or bioenergy. For all these related frameworks, several research papers reported the need to improve the assessment to inform policy makers, technological development and innovations (Awasthi et al., 2022; Bohnes and Laurent, 2018; Djomo et al., 2011; Goglio et al., 2017;

Table 2
Identified general criteria to assess LCA methods in the LCA of livestock systems.

General criteria definition	Level 1	Level 2	Level 3	Level 4
Transparency and Reproducibility: Comprehensive documentation and mechanisms that allow reviewers to verify/ review all data, calculations, and assumptions	LCA methodologies which do not allow reviewers to verify/review the results, calculations and assumptions.	LCA methodologies which could be reviewed together with the results but some calculations and assumptions cannot be reviewed.	LCA methodologies which fully allows reviewers to verify/review the results, calculations and assumptions	
Completeness: quantification of the environmental impact including all material/energy flows and other environmental interventions as required for adherence to the defined system boundary, the data requirements, and the impact assessment methods employed	the quantification of the environmental impacts including all material/energy flows and other environmental interventions do not have adherence to the system boundary, the data requirements and the impact assessment methods employed	the quantification of the environmental impacts is conform either to the defined system boundary or the data requirements or the system method employed	the quantification of the environmental impacts conforms to two aspects between the defined system boundary, data requirements and impact assessment method employed	the quantification of the environmental impacts fully corresponds to the system boundary, data requirements and the impact assessment methods employed
Fairness and acceptance: associated with providing a level playing field across competing products, processes and industries. Exceptions must not relatively disfavour competitors. The role of interested parties and of review is strengthened for achieving broad stakeholder acceptance. Protecting confidential and proprietary information in confidential reports that are available exclusively to the critical reviewers.	the LCA methodology does not provide level playing field across products, processes and industries	the LCA methodology provides a level playing field for at least two products, processes and industries (e.g. beef and dairy; beef and pig)	LCA provides a level playing field for several products, processes and industries	
Robustness: associated in the RACER framework, the following subcriterion is associated with providing a defensible theory, Sensitivity, Data quality, Reliability, Consistency, Comparability, Boundaries	the LCA methodology is not based on defensible theory, lacks sensitivity on certain environmental impacts either because of its reliability, comparability, the chosen system boundary or its comparability	the LCA methodology is based on a defensible theory but it lacks sensitivity, reliability, comparability and it is not in agreement with the system boundaries	the LCA methodology is based on a defensible theory with a satisfactory sensitivity, reliability, data quality, consistency, comparability and in agreement with the system boundaries	
Applicability: the ability of the method to be used by a wide range of LCA practitioners	the LCA method can be easily used with very limited LCA expertise and data availability	the LCA method can be used with either limited LCA expertise or data availability	the LCA method can only be used with LCA expertise and extensive data availability	

Newton and Little, 2018). This framework could be also used to better characterize future land based GHG removal technologies using either attributional, consequential or anticipatory LCA (Goglio et al., 2019), where agricultural systems are involved.

3.4. Comparison with previous harmonization framework

This research allowed the construction of a unique set of criteria which 21 experts were able to find consensus upon, as discussed previously (Macombe et al., 2018). Previous frameworks and criteria were not discussed among peers or were just subject to public review (FAO, 2018; Wiedmann et al., 2009; Zampori and Pant, 2019). Furthermore, this approach was targeted to LCA methodology for livestock systems and products, which was broader than the product environmental footprint approach (Ponsioen and van der Werf, 2017; Zampori and Pant, 2019). This methodological exercise was also necessary to capture cropping system characteristics to account for crop-livestock interactions (Goglio et al., 2017; Van Zanten et al., 2018b).

This harmonization framework was also broader than the guidelines to account for soil C in livestock systems (FIL-IDF, 2022), which addressed only soil C in the LCA of livestock systems and sought through the definition of general criteria to ensure a coherence in the assessment of LCA methodology for the topics selected. In contrast with the LEAP reports, this research presented a harmonization approach which aimed at capturing the characteristics of the specific LCA methods with regards to the livestock systems (FAO, 2020). It included, together with GHG, biodiversity, circular economy and material flow issues, discussed in the FAO LEAP reports (FAO, 2020), also animal welfare and nutrition with a coherent and comprehensive framework across the various topics.

This harmonization approach might be subject to biases, as highlighted by previous participatory approaches (Mullender et al., 2020). These were overcome through a series of review processes by different review expert of the LCA harmonization framework, and using anonymous independent surveys where the experts were able to see the overall results of the survey. Furthermore, the LCA experts had a wide range of expertise and nationalities, which also contributed in reducing the subjective bias.

4. Conclusions

This harmonization approach addressed the need for improved methods and indicators in the assessment of livestock systems across a range of key topics: greenhouse gases; food, feed, fuel and biomaterial competition, crop-livestock interaction, circular economy; biodiversity; animal welfare and nutrition aspects. These topics are prominent in the public and political domain, and are subject to high levels of stakeholder interest regarding methodological development and future research needs. Through a participatory research process, several general criteria were identified and further defined to assist with the development of such topics: Transparency and Reproducibility, Completeness, Fairness and Acceptance, Robustness, Applicability and Accuracy. These set of criteria provided a robust framework for the assessment of LCA methodologies for livestock systems and their products.

This harmonization approach followed a structured development and consultation process which could be further used for other agricultural systems and products. Furthermore, the topics and assessment criteria identified in this study could be further utilised in other sectors to better address global sustainability assessment.

Author's statement

Pietro Goglio, Laurence G. Smith: Conceptualization, Methodology, Investigation, Writing-original draft; Writing-review and editing, project administration, Funding Acquisition; **Marie Trydeman Knudsen, Simon Moakes**: Conceptualization, Methodology, Writing-original draft; Writing-review and editing, Funding Acquisition; **Gilles Nassy, Catherine Pfeifer, Robert Borek, David Yanez-Ruiz**: Conceptualization, Funding Acquisition; **Klara Van Mierlo, Nina Röhrig, Fossey Maxime, Alberto Maresca, Fatemeh Hashemi, Muhammad Ahmed Waqas, Roline Broekema, Monica Quevedo Cascante, Alina Syp, Tomasz Zylowsky, Manuel Romero-Huelva, Jenny Yingvesson**: Conceptualization, Methodology, Investigation, Writing-original draft.

Declaration of competing interest

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Data availability

Data will be made available on request.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.clpl.2023.100035.

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