D4.1 Developed methods for True Cost Accounting, Social LCA, and Consequential LCA of livestock systems

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Abstract:	European livestock production is associated with impacts not accounted for in the production costs in the total value chain. These are environmental, social and economic externalities. To value these externalities True Cost Accounting (TCA) methods were considered, alongside social-LCA (S-LCA) and consequential LCA (C-LCA). This study comprises literature reviews on the application of these methods to European livestock production systems, the assessment of the state of the art of these applications, and a Delphi-approach for prioritising externalities and the development of a methodology for using TCA to estimate the direct impact of livestock systems in biodiversity. Main results show that valuation methods in livestock production are still in development and that issues around data availability and data quality are the main issues to be addressed in future.

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6.	EUROPEAN FORUM OF FARM ANIMAL BREEDERS	EFFAB	Netherlands
7.	AGENCIA ESTATAL CONSEJO SUPERIOR DE INVESTIGACIONES CIENTIFICAS	CSIC	Spain
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Table 1: List of abbreviations and acronyms

List of Abbreviations and Acronyms	
A-LCA	Attributional Life Cycle Assessment
CF	Characterisation Factor
C-LCA	Consequential Life Cycle Assessment
EPS	Environmental Priority Strategies
EU	European Union
FADN	Farm Accountancy Data Network
FAO	Food and Agriculture Organization
GHG	Greenhouse Gas
HE	Horizon Europe
iLUC	indirect Land Use Change
IP	Impact Pathways
ISO	International Organization for Standardization
LCIA	Life Cycle Impact Assessment
LU	Livestock Units
LUC	land use change
NGO	Non-governmental Organisation
PDF	Potentially Disappeared Fraction of species
PRISMA	Preferred Reporting Items for Systematic reviews and Meta-Analyses
RS	Reference Scale
SHI	Social Hotspot Index
S-LCA	Social Life Cycle Assessment
SPIQ-FS	Shadow Prices of Impact Quantities - Food System
SRT	Social Risk Time
TCA	True Cost Accounting
UK	United Kingdom
UNEP	United Nations Environment Programme

Executive summary

Background

European livestock production is associated with many externalities, i.e. societal impacts not accounted for in production costs. In the literature these externalities are grouped in environmental, social and economic categories. To value these externalities different types of Life Cycle Assessment (LCA) are used within the TCA methodology. For the STEP-UP project, a list of potential methods per indicator for the environmental, social and economic impact categories was developed, together with an overview of monetisation methods. True Cost Accounting (TCA) methods were considered, alongside social-LCA (S-LCA) and consequential LCA (C-LCA) methods. For a TCA analysis S-LCA and attributional LCAs are the basic approaches followed. Therefore, the advantages / disadvantages of social LCAs and attributional LCA will become part of the TCA analysis.

Research objectives

The research objective for the section of the Deliverable focusing on TCA is to give an overview of the existing uses of TCA for European livestock production, and the drive for the development of new modules within the TCA methodology. The research objective for the part on S-LCA was to assess the weighting methods applied in literature on the social impact of livestock production in Europe. The research objective for the part on C-LCA was to provide an overall picture of C-LCAs of European livestock systems, and recent advances of the C-LCA methodology.

Methodology

For TCA, S-LCA and C-LCA, a literature review has been executed using the PRISMA methodology. For TCA a Delphi-approach was also executed for prioritising externalities and checking the importance and applicability of a TCA module for assessing the direct impact of livestock production systems on biodiversity for different livestock production systems in Europe. Within Task 4.2 this module has been developed for STEP-UP and showcased for three dairy systems in the Netherlands.

Main results

True Cost Accounting (TCA)

A total of 50 Scientific papers were selected, dealing with TCA and livestock production in Europe. Most papers deal with dairy systems and the most important externalities were climate change, acidification and eutrophication. Social and economic externalities were hardly dealt with, except animal welfare. Most papers were recently published showing that TCA is still in development. For monetising the impact, two methods can be distinguished; the abatement cost approach and the damage cost approach. In many studies, an abatement cost curve was established showing the relation between the increased sustainability on the one hand and the increasing cost in the value chain to increase the sustainability on the other. The damage cost approach estimates the societal damage related to certain externalities. The so-called TCA handbooks are mostly used for monetising the used indicators.

In the Delphi-study respondents were asked to prioritise 22 externalities distinguished within the Horizon Europe project FOODCoST on their importance in European livestock production. The Delphi-approach shows that next to the externalities dealt with in the scientific literature, the direct impact of livestock production on biodiversity is regarded as a priority by the 14 respondents (most of them researchers). Social and economic externalities were low on the priority list of the respondents except for animal welfare. To fill the gap of assessing the direct impact of livestock production on biodiversity a module was developed and described and applied to the case of three dairy system in the Netherlands. Most respondents thought that such a module should be applied for other livestock systems in Europe, but relevant measurement packages need to be developed, and there is doubt if the required knowledge and data are available. Data availability

should not be a reason to exclude an externality from the TCA analyses, it should be a reason to collect the relevant data. Respondents foresee a combination of market- and government-driven implementation with a mix of incentives, in which long-term contracts should ideally play an important role. According to survey respondents, the government should take the leading role. The main hurdles for biodiversity TCA implementation, mentioned by the respondents, are the lack of awareness and responsibility in society and the food sector, the economy's current short-term view, the lack of required data, and the complexity of generalisation across landscapes when it comes to biodiversity measurements.

Social Life Cycle Assessment (S-LCA)

Twelve studies were found on the social impact of European livestock production. These studies apply different weighting methods using both equal and unequal weights. They present the data prior to weighting, but fail to report a justification of their weighting method choice and a sensitivity analysis on the applied weights. Future studies should address these shortcomings. This could also aid the development of guidelines for selecting weighting methods in studies to assess the social impact of European livestock production.

Consequential Life Cycle Assessment (C-LCA)

Twenty-three studies were included. Among these C-LCA studies, different approaches were used to develop scenarios, among which adjustments to the technical processes and management strategies were the most prevalent. Depending on the specific goal, either one or more approaches could be used. In terms of building inventories, a mix of different sources of data were used, among which Ecoinvent is the most common database. Experiment-based data, expert-based estimation, or data from surveys could also support inventory building, especially when data is not available. Moreover, different types of models can provide data for inventories. Most studies carried out the impact assessment at mid-point level. Furthermore, most of the included studies applied uncertainty analyses, using either Tier 2 (e.g., Monte Carlo method) or Tier 3 approaches (e.g., sensitivity analysis, scenario analysis).

Main conclusions

TCA is a methodology in development. This also holds for its application in European Livestock production. The number of scientific publications is limited but has increased in recent years. TCA is mostly applied for dairy systems with climate change, acidification and eutrophication as the main externalities. Social and economic externalities are hardly researched. Many studies focus on estimating abatement cost curves, evaluating the relationship between an increase of sustainability, and costs of production.

In the Delphi approach, the same externalities as in the literature were mentioned by experts to focus on in TCA analysis. The experts mention one additional issue, i.e. the direct impact of a livestock production system on biodiversity. According to our knowledge, no module has been developed within the TCA community, until now, for this issue. This is one of the reasons to develop a module for the direct impact of a livestock production system on biodiversity, based on an abatement cost curve approach. Experts think that this methodology could be widely applied to livestock systems in Europe. However, the approach needs to be adapted to specific circumstances, and there is some doubt if the knowledge and/or data are available to apply this methodology across production systems. Experts are of the opinion that data availability should not hinder the development of such methodology given the importance of biodiversity related to livestock production.

Studies on the social impact of European livestock production apply different weighting methods, using both equal and unequal weights. They present the data prior to weighting but fail to report a justification of their weighting method choice, and do not perform a sensitivity analysis on the applied weights. Future studies should address these shortcomings. This could also aid in developing guidelines for selecting weighting methods in studies to assess the social impact of European livestock production.

C-LCA studies assessing livestock systems are under-represented. Scenario assessments in C-LCA studies of livestock systems have focussed on technical process and management decisions. A robust life cycle inventory requires a careful selection of the most updated data from different data sources, and the choice of data from databases, and the literature should be suitable for the studied geographical scope.

The selection of impact categories indicators should consider a wide range of factors, especially corresponding to the goal for data interpretation and the topic of the study. This holds for S-LCA, C-LCA and TCA. Uncertainty analysis is necessary in C-LCA, S-LCA and TCA modelling, to quantify the variability related to the results and to allow for more informed decision-making.

Based on the conclusions, we recommend future studies assess the sustainability of livestock production systems directly, for example, by changing different processes of the production cycle and by taking all possible relevant impact categories into account. To obtain a robust result, it is important to build a detailed scenario; using updated data for building inventories, selecting appropriate impact categories that match the goal of the study; and including uncertainty analysis where possible. This holds for S-LCA, C-LCA and TCA.

For the HE STEP-UP the conclusion do imply that a full assessment of all possible externalities is very impossible given the lack of methodologies, lack of data and lack of weighting the externaliities. On the other hand there is agreement about the most important externalities that should be included and for these externalities methodologies and data are available or can be developed as shown by the case of direct impact of livestock production systems on biodiversity. . The research further shows that attention is needed for explaining weighting externatlities and for uncertainty analysis.

1. Introduction

1.1. Background

1.1.1. True Cost Accounting: overview of important externalities for European livestock production

True Cost Accounting (TCA) is a method for measuring and valuing environmental, social and economic externalities. In the Horizon Europe project FOODCoST, 22 externalities are distinguished. Currently no overview of the use of TCA in European livestock is available, nor on how TCA is applied. Therefore, in this study we focus on how TCA is used in studies on European livestock production, the opinion of experts on the use of TCA in European livestock production, and a TCA methodology for direct impact of livestock production on biodiversity.

1.1.2. Social Life Cycle Assessment: Overview of weighting methods applied in studies on European livestock production is lacking

Social Life Cycle Assessment (S-LCA) methods to quantify the social impact of products suggest the use of a long list of social impact categories, each capturing a different aspect of social impact, such as fair wage, child labour, labour conditions, or impact on local communities. For example, the framework proposed by United Nations Environment Programme (UNEP, 2020) suggests a list of 40 impact subcategories with, often multiple, indicators underlying each of these impact subcategories. To quantify the social impact and aid interpretation and communication of findings, S-LCA methods require the aggregation of indicators into impact subcategories, and impact subcategories into social impact, a process referred to as weighting. Weighting is a crucial step in S-LCA, enabling practitioners to assign relative importance to various indicators and impact subcategories. Both the UNEP (UNEP, 2020) and ISO 14075 (ISO, 2024) underscore that weighting, whether applied explicitly or assumed implicitly through equal importance, must always reflect value choices. These choices must be transparent, consistent with the goal and scope of the assessment, and traceable for accountability and reproducibility. Currently, no overview of the weighting used in studies related to European livestock production is available. Therefore, in this review we focused on the weighting methods used in studies assessing the social impact of European livestock production.

The research question in our study was: What weighting methods are used in studies assessing the social impact of livestock production in Europe?

1.1.3. Consequential Life Cycle Assessment

To better shape the future of farming and food in Europe, the European Commission introduced the vision for agriculture and food (European Commission, 2025). In the suggested framework, four priority areas were identified, i.e. attractiveness - to make farming a viable appealing career; competitiveness – to strengthen the sector's competitive position in global markets; future-proofing - embracing innovation and sustainability for long-term resilience; connection - to foster fair living and working conditions in rural areas. Under these priority areas, various areas of action were proposed, among which a) "launch a long-term strategy on livestock" is proposed to tackle the pressure from the impact of climate change to global competition and higher energy prices; and b) "offer a voluntary benchmarking for on-farm sustainability" contributes to the transition of Europe's agricultural sector to a low-carbon economy. Such areas of action, however, require a holistic understanding of the input and outputs relating to the livestock sector, and their impacts.

Life Cycle Assessment (LCA) is a well-known methodology to estimate the potential environmental burdens of products or services throughout their life cycle (ISO, 2006). Currently two main approaches are available, consequential LCA (C-LCA) and attributional LCA (A-CLA). A-LCA aims to determine the environmental loads attributed to the processes directly used or physically connected with the product used. However, this approach does not address in detail the consequences of implementing such strategies. C-LCA is used to overcome this disadvantage. The UNEP-SETAC Life Cycle Initiative, supported by the United Nations (UNEP-SETAC, 2011), establishes that "the consequential approach attempts to provide information on the environmental burdens that occur, directly or indirectly, as a consequence of a decision".

Regarding livestock production, the dominant method to evaluate environmental impacts are A-LCA-based. To date, little information is available regarding the advances of C-LCA methods in evaluations of current EU livestock systems. To better inform future policy making, evidence-based knowledge is needed for evaluating the consequences of the current livestock systems, i.e., using C-LCA. In this review, therefore, we focus on the development of environmental C-LCA methods for farm-to-fork evaluations of European livestock systems.

1.2. Research objective and questions

The research objective for TCA is to give an overview of existing use of TCA for European livestock production and the urge for the development of new modules within TCA methodology. The research questions for this part are: How is TCA used to measure the sustainability of European livestock production, what opinion do experts have on the use of TCA and is there an urgency to develop a TCA methodology for direct impact of livestock production on biodiversity? The research objective for the part on S-LCA was to assess the weighting methods applied in literature on the social impact of livestock production in Europe. This part aimed to answer the research question: What weighting methods are used in studies assessing the social impact of livestock production in Europe? The research objective for the part C-LCA was to show an overall picture of C-LCA of European livestock systems, and the advances of the C-LCA methodology. This part aims to answer the following questions: 1) What is the current status of C-LCA studies of European livestock systems, especially regarding which topics were most studied, and which systems are included; 2) Which approaches were used to develop scenarios; Which models or methods were applied; 3) Which environmental impact categories are more important for stakeholders in Europe; Which methods of presentation/reporting are most appropriate for communication of impacts and trade-offs; 4) How do the studies include uncertainty analysis; 5) How do studies deal with the constrained by-products and marginal products.

1.3. Reader guide

Chapter 1 gives an overview of the background of the study and the research objectives. The main objective is to give an overview of the TCA methods for European livestock systems. TCA is based on LCAs, S-LCAs and C-LCAs. In this study, an overview is given of the current state of the art of these approaches. This is based on literature reviews for TCA, S-LCA and C-LCA and a Delphi approach for TCA which are described in Chapter 2. The results of the reviews and the results of the Delphi approach for TCA are described in Chapter 3. Chapter 4 contains the discussion and Chapter 5 the conclusions.

2. Methods

2.1. Literature review

The Preferred Reporting Items for Systematic reviews and Meta-Analyses 2020 statement (hereafter referred to as PRISMA 2020), as described by Page et al. (2021), was applied for the literature review. Deliverable 1.3 of STEP UP gives a detailed description of all the three literature searches that have been performed including inclusion/exclusion criteria; information sources; search strategy; when searches were executed and the search string, study selection processes (i.e., which process was followed to select relevant studies); a PRISMA diagram; data collection processes and data items. This is given in D1.3 for TCA, S-LCA and C-LCA.

2.1.1. Literature review on TCA

The papers/articles/studies for the literature review and data collection were retrieved from three online databases: Scopus, Web of Science, and Pubmed. In total 234 studies were identified with the defined search strings in Table 2. Studies were excluded if they were from before 2010, not journal articles or conference papers, and not in English. The search was conducted in August and September 2024.

Table 2: Search string (search terms and fields) used in the literature review on TCA in European livestock production for the databases Scopus, Web of Science and Pubmed

Database	Search string
Scopus	TITLE-ABS-KEY(("True Cost Accounting" OR "True Price" OR "External Costs" OR "Hidden costs" OR "True Costs" OR "societal costs" OR "damage costs" OR "abatement costs") AND ("Social" OR "health" OR "economic " OR "environmental" OR "ecological " OR "climate") AND ("livestock" OR " dairy cows" OR " beef sucklers" OR "fattening cattle" OR "finishing cattle" OR "sheep dairy" OR "sheep meat" OR "goats" OR " pig" OR " laying hens" OR " broilers" OR " milk" OR "eggs" OR " pork" OR " meat" OR " cheese " OR " mutton" OR " veal" OR " wool" OR " leather" OR "dairy")) AND PUBYEAR > 2009
Web of Science	(TI=(("True Cost Accounting" OR "True Price" OR "External Costs" OR "Hidden costs" OR "True Costs" OR "societal costs" OR "damage costs" OR "abatement costs") AND ("Social" OR "health" OR "economic " OR "environmental" OR "ecological " OR "climate") AND ("livestock" OR " dairy cows" OR " beef sucklers" OR "fattening cattle" OR "finishing cattle" OR "sheep dairy" OR "sheep meat" OR "goats" OR " pig" OR " laying hens" OR " broilers" OR " milk" OR "eggs" OR " pork" OR " meat" OR " cheese " OR " mutton" OR " veal" OR " wool" OR " leather" OR "dairy")) OR (AB=(("True Cost Accounting" OR "True Price" OR "External Costs" OR "Hidden costs" OR "True Costs" OR "societal costs" OR "damage costs" OR "abatement costs") AND ("Social" OR "health" OR "economic " OR "environmental" OR "ecological " OR "climate") AND ("livestock" OR " dairy cows" OR " beef sucklers" OR "fattening cattle" OR "finishing cattle" OR "sheep dairy" OR "sheep meat" OR "goats" OR " pig" OR " laying hens" OR " broilers" OR " milk" OR "eggs" OR " pork" OR " meat" OR " cheese " OR " mutton" OR " veal" OR " wool" OR " leather" OR "dairy")))OR (AK=(("True Cost Accounting" OR "True Price" OR "External Costs" OR "Hidden costs" OR "True Costs" OR "societal costs" OR "damage costs" OR "abatement costs") AND ("Social" OR "health" OR "economic " OR "environmental" OR "ecological " OR "climate") AND ("livestock" OR " dairy cows" OR " beef sucklers" OR "fattening cattle" OR "finishing cattle" OR "sheep dairy" OR "sheep meat" OR "goats" OR " pig" OR " laying hens" OR " broilers" OR " milk" OR "eggs" OR " pork" OR " meat" OR " cheese " OR " mutton" OR " veal" OR " wool" OR " leather" OR "dairy")))) AND PY=(2010-2024)
Pubmed	(("True Cost Accounting" OR "True Price" OR "External Costs" OR "Hidden costs" OR "True Costs" OR "societal costs" OR "damage costs" OR "abatement costs") AND ("Social" OR "health" OR "economic " OR "environmental" OR "ecological " OR "climate") AND ("livestock" OR " dairy cows" OR " beef sucklers" OR "fattening cattle" OR "finishing cattle" OR "sheep dairy" OR

	"sheep meat" OR "goats" OR " pig" OR " laying hens" OR " broilers" OR " milk" OR "eggs" OR " pork" OR " meat" OR " cheese " OR " mutton" OR " veal" OR " wool" OR " leather" OR "dairy")) AND (2010:2024[pdat])

Figure 1 shows how the 234 identified papers ended up in 50 papers that were included in the literature review. Following the PRISMA 2020 method, the identified papers have been equally divided between two reviewers who worked independently through the screening process. Studies were excluded when TCA was not applied, when livestock was not involved, when the regional scope was outside Europe and when the article was not written in English. After screening and excluding, 50 articles were left for data collection and were included in the analyses (see flow diagram, Figure 1).

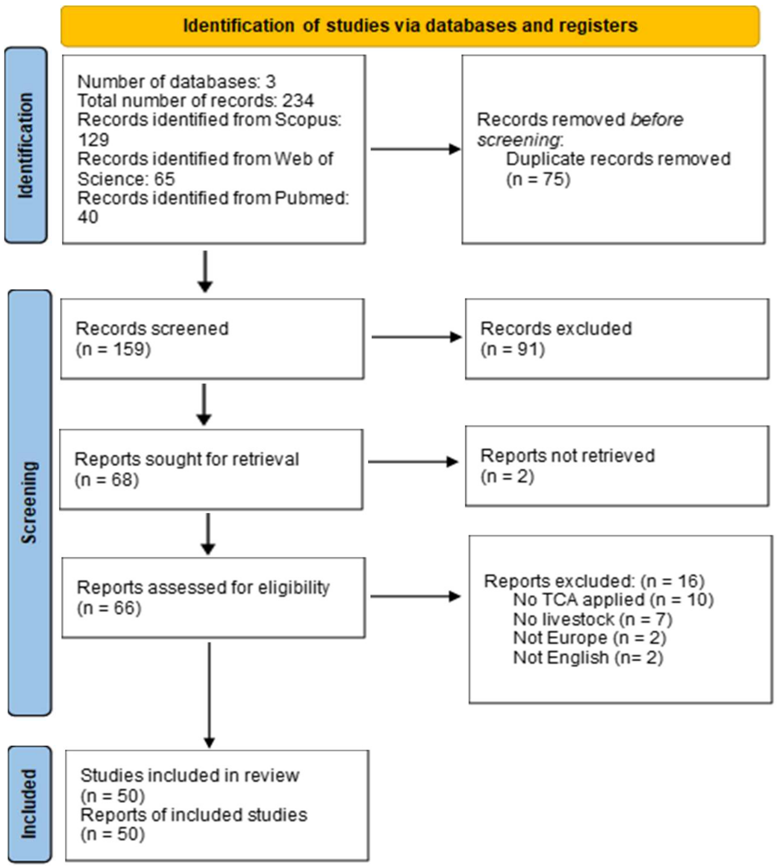


Figure 1: PRISMA flow diagram for scientific TCA studies applied in livestock in Europe

The 50 included articles were read, and the following variables have put in the database (Excel sheet):

- Document information (author, title, year of publication, quality of publication);
- Focus of the study (system boundary, production system, animal species, scope, product (if applicable), country/region where study is applied;
- Data (externality, impact category, impact on, (sub)indicator, method and model used to quantify externality, valuation method, valuation data sources, monetisation factor (value, unit, scope), year of data, data quality (sample size, sensitivity analysis, data source)
- Results (external cost – value, external cost – unit)
- Discussion on uncertainty of method, models and data.

2.1.2. Literature review on weighting methods in S-LCA

The literature review on weighting methods used in social life cycle assessments (S-LCA) of European livestock production was combined with the literature reviews of Task 1.3 in STEP UP, that had the aim of identifying indicators applied in literature. Therefore, the search terms in this deliverable are broader than just weighting methods. For this deliverable, we extracted data about the applied weighing methods from retrieved studies.

In the literature review, we searched the databases Scopus, Web of Science, CAB Abstracts, and Google Scholar following the PRISMA 2020 method (Table 3). Topic specific search terms included Social LCA, S-LCA, S LCA, Social Life Cycle Assessment, Social impact assessment, or Social assessment. This was combined with search terms for animal types/products and countries in Europe. We searched the title, abstract, and key words, where available in the databases' search engines. Studies were excluded if they were from before 2000, not journal articles or conference papers, and not in English. The search was conducted in May 2024. Studies on animal health/welfare without a link to S-LCA or social impact assessment were also excluded.

Table 3: Search string (search terms and fields) used in the literature review on social impact

	Scopus	Web of Science	CAB Abstracts	Google Scholar
Terms	("Social LCA" OR "S-LCA" OR "S LCA" OR "Social Life Cycle Assessment" OR "Social impact assessment" OR "Social assessment") AND ("Livestock" OR "Beef" OR "Goat" OR "Poultry" OR "Suckler cow" OR "Sheep" OR "Dairy" OR "Cattle" OR "Chicken" OR "Hog" OR "Broiler" OR "Milk" OR "Egg" OR "Pork" OR "Layer" OR "Pig" OR "Piglet" OR "Sow" OR "Calf" OR "Calves" OR "Hen" OR "Mutton" OR "Veal" OR "Steer" OR "Duck" OR "Turkey" OR "Meat" OR "Cheese") AND ("Albania" OR "Andorra" OR "Austria" OR "Belarus" OR "Belgium" OR "Bosnia and Herzegovina" OR "Bulgaria" OR "Croatia" OR "Cyprus" OR "Czech Republic" OR "Denmark" OR "Estonia" OR "Finland" OR "France" OR "Germany" OR "Greece" OR "Holy See" OR "Hungary" OR "Iceland" OR "Ireland" OR "Italy" OR "Latvia" OR "Liechtenstein" OR "Lithuania" OR "Luxembourg" OR "Malta" OR "Moldova" OR "Monaco" OR "Montenegro" OR "Netherlands" OR "North Macedonia" OR "Norway" OR "Poland" OR "Portugal" OR "Romania" OR "San Marino" OR "Serbia" OR "Slovakia" OR "Slovenia" OR "Spain" OR "Sweden" OR "Switzerland" OR "Ukraine" OR "United Kingdom" OR "Europe" OR "EU" or "Russia" OR "European Union")			
Fields	TITLE-ABS-KEY	TI	AB	TITLE-ABS-KEY

In total, 140 records were retrieved, of which 12 were duplicates (Figure 2). After screening title and abstract, 83 records were excluded that did not concern the social impact of European livestock production. Assessments of the retrieved 45 reports resulted in further exclusion of 35 reports, because they did not concern S-LCA or social impact assessment of European livestock. Two reports were added (one published just after the search was conducted, one was not found with the search string but did include a social impact assessment). Thus, 12 reports were included in the final review.

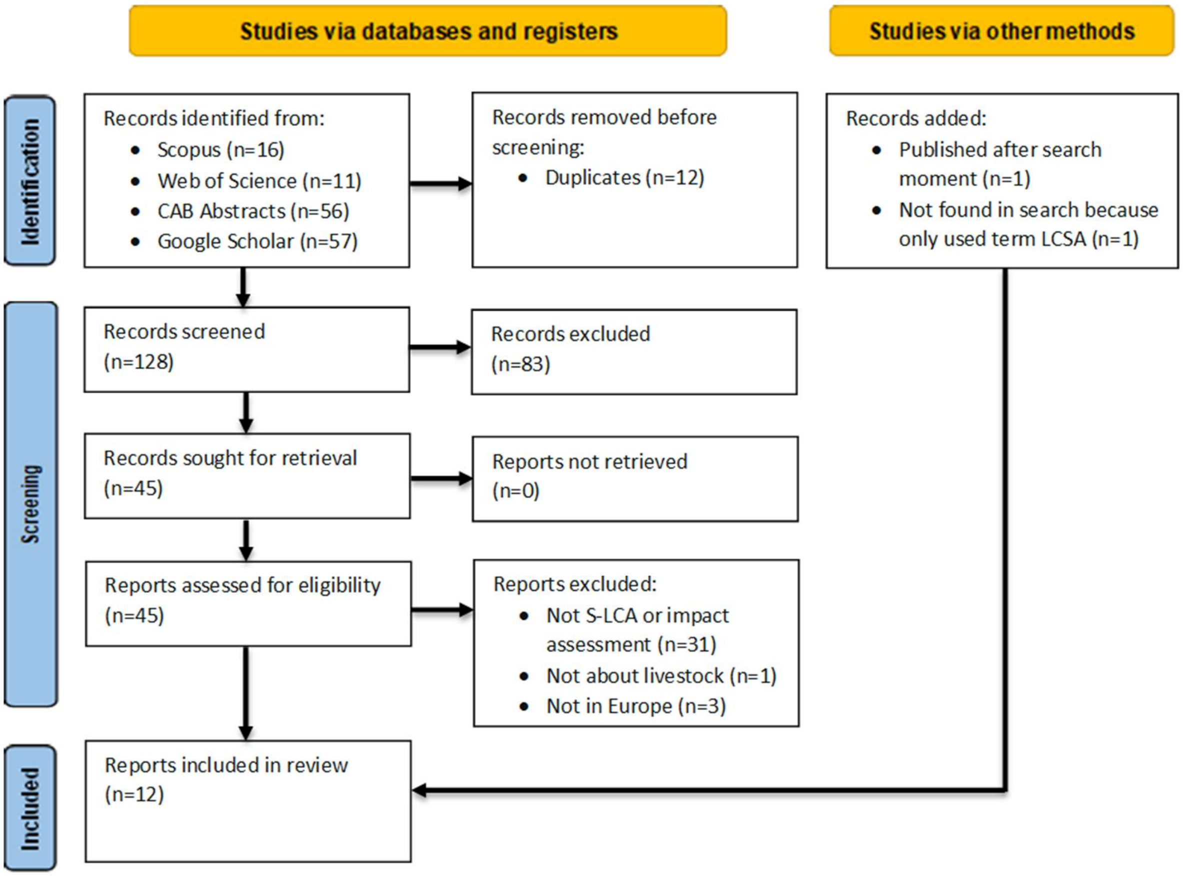


Figure 2: Search results for the literature review on social life cycle assessment of European livestock production

2.1.3. Literature review on C-LCA of European livestock production

The literature search and extraction of information for C-LCA were carried out in a systematic and thorough manner following the PRISMA 2020 framework (Page et al., 2021). Two databases, Web of Science and Scopus, were used to carry out the literature search. The literature search follows the combination of search terms as outlined in Table 4, i.e., Level 1 AND Level 2 AND Level 3. Within each level, different terms are combined using the OR operator. The number of references is recorded for each database.

Table 4: Search string (search topics and terms) used in the literature review on consequential life cycle assessment

Level	Topic	Terms
1	Region	EU OR Euro* OR Austria OR Belgium OR Bulgaria OR Croatia OR Cyprus OR Czech Republic OR Denmark OR Estonia OR Finland OR France OR Germany OR Greece OR Iceland OR Hungary OR Ireland OR Italy OR Latvia OR Lithuania OR Luxembourg OR Liechtenstein OR Malta OR Netherlands OR Norway OR Poland OR Portugal OR Romania OR Slovakia OR Slovenia OR Spain OR Sweden OR Switzerland OR UK OR United Kingdom OR Great Britain OR England OR Scotland OR Wales OR Northern Ireland
2	System	livestock OR animal OR bull* OR beef* OR beef cattle OR fattening cattle OR finishing cattle OR veal OR dairy* OR ovine OR lamb OR sheep OR goat OR swine OR pig* OR finishing pigs OR growing-finishing pigs OR broilers OR laying hens OR poultry OR livestock production OR farming systems OR production systems OR livestock systems OR feedlot system OR food systems OR forage-based livestock production OR conventional farming OR organic farming OR agricultur* OR future farming OR intensive farming OR extensive farming
3	Method	LCA OR life cycle assessment OR life cycle analysis OR consequential LCA OR consequential life cycle assessment OR social LCA OR life cycle sustainability assessment OR life cycle sustainability analysis OR LCSA OR rebound

Records were filtered for years using automated tools where available and the number of excluded records were noted. Afterwards, references for each search and database were included in an Excel sheet and duplicates were removed and counted.

A first screening based on title and abstract eliminated all references that did not fulfil the following inclusion criteria: a) Published between 2012 and 2025, b) English language publication, c) Original article, peer-reviewed article published in a scientific journal, d) Focus of the analysis on overall EU/European level, e) Covering one of the main species covered by STEP-UP, i.e., cattle, pig, sheep, goat, poultry, and f) Using Environmental LCA.

Reasons for not including references were noted and counted in the Excel Sheet. Unclear or borderline cases were included in the first screening round. The second screening round includes full-text items of the remaining references and further eliminates references that do not meet the inclusion criteria. Unclear cases were highlighted for comparison with a second reviewer and in extreme cases were discussed in a group.

References were grouped by a) LCA methods, b) species/systems, and c) indicators.

The PRISMA 2020 method was used for data extraction (Figure 3). Two investigators extracted data from the screened sources independently using a coding system. Discrepancies were resolved in discussions. Eventually, data was presented in a narrative summary relating to the review questions. Data from the included articles were extracted to Excel.

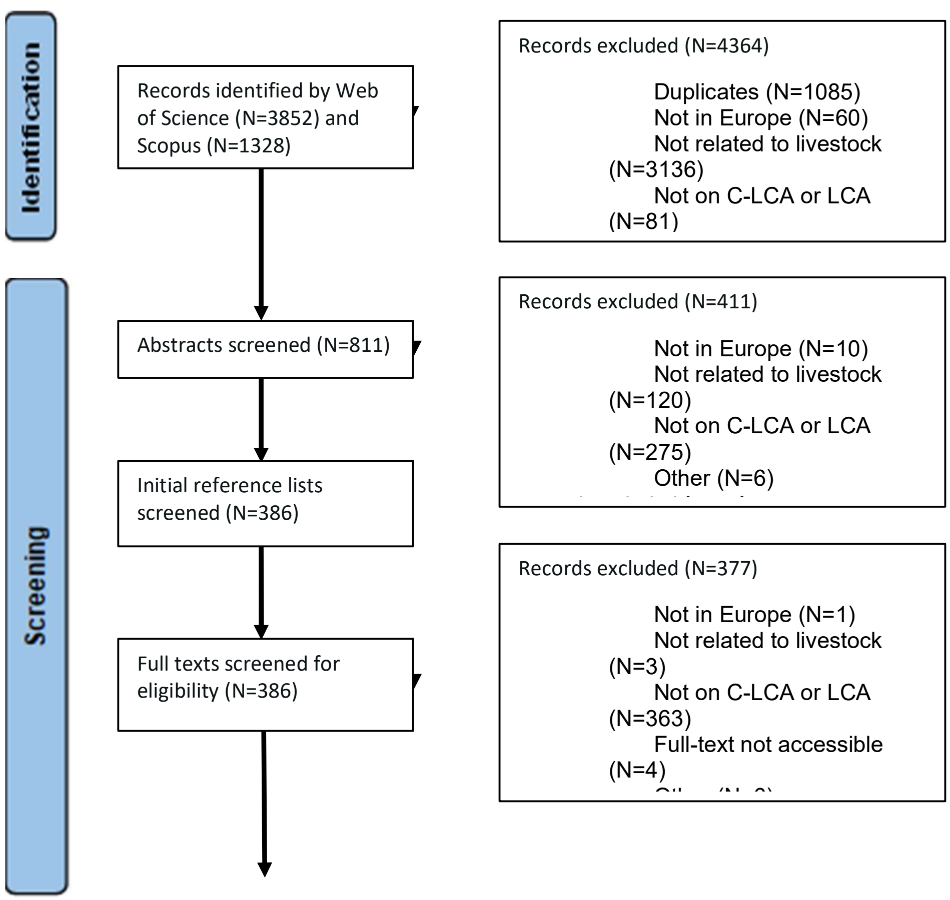


Figure 3: Search results for the literature review on consequential life cycle assessment (C-LCA) of European livestock production

2.2. Delphi approach on the application of TCA in European livestock

The method defined by Spranger et al. (2022) was followed to systematically report about the process for conducting a Delphi approach. Based on the results of the literature review regarding the application of TCA in European livestock production, we used the Delphi approach to get expert insights on following subjects:

- Which externalities for livestock production systems in Europe are regarded far more important than other externalities (i.e. prioritisation)
- Which externalities should be considered when measuring sustainability for livestock production systems in Europe
- The importance of measuring the direct impact of livestock production systems on biodiversity;
- The applicability of a proposed methodology to approach the direct impact of livestock production systems in Europe for light, medium, and heavy measure packages.

The Delphi approach was used to speed up the discussion about the mentioned subjects and to obtain a consensus about the mentioned subjects. This was realised by asking the same questions in two rounds. In the first round, experts were unaware of the opinion and arguments of other experts. In the second round, they could form their opinion, also based on the opinion of others and arguments given by other experts.

Experts were selected based on the networks of team members in STEP UP. The criteria for selecting experts were their expertise about livestock production systems, about impact of livestock systems on biodiversity, and/or about TCA. The experts were all active in research, agrifood industry, governments, or non-governmental organisations (NGOs). About 40 experts were directly approached by email to ask if they were willing to cooperate in a Delphi approach by filling in the online questionnaire twice in the period April-May 2025. Twenty-five persons agreed to cooperate, 20 persons started the questionnaire, and 14 persons completed the questionnaire twice. The 25 persons that agreed to cooperate were invited for each round and got also a reminder to fill in the questionnaire. The online questionnaire was closed on the 1st of June 2025.

The questionnaire was structured according to the subjects described above. In the first block some characteristics of the experts were asked, such as in which sector they are occupied and what their expertise is. The questionnaire was developed in SurveyLet software. The results of the 14 respondents that completed the two Delphi rounds showed that the differences in opinion are minor between the two rounds. So, only the results of round two are described in this publication.

2.3. Approach to monetise direct impacts of livestock production systems on biodiversity in TCA

The literature review on TCA shows that little attention is paid to the direct impact of livestock production on biodiversity. The Delphi approach shows that the experts are of the opinion that this impact is among the top four of the most important externalities related to European livestock production. In the present TCA approaches of CE Delft, True Price, Sustainability Impact Metrics, Environmental Priority Strategies (EPS), Shadow Prices of Impact Quantities - Food System (SPIQ-FS), Value Balancing Alliance, Methoden

Konvention, no module is available to estimate the direct impact of food production on biodiversity. Only indirect impacts such as the impact of climate change, nitrogen deposition, land use on biodiversity are considered.

To gain insights on the direct impact of livestock production, an abatement cost approach was used. For three measurement packages, the changes in benefits and/or costs have been estimated including the expected direct impact of these measures on biodiversity. The measurement packages are characterised as light, medium and heavy, given an indication of the severity of the measures for husbandry practices and often also an indication of the additional costs to implement these measures.

3. Results

3.1. TCA and European livestock systems

3.1.1. Literature review

The number of studies that were published increased after 2019. Most studies have been published in 2020 and 2023 (eight each).

The scope of most of the 50 assessed studies applied TCA at farm level (22 studies), followed by product, region and country (each 8). Only a few studies (4) applied TCA at EU level. In cases where the scope was product based, most studies included meat (7) and dairy (9) in their analyses, including both fresh and highly processed products.

Regarding the geographical distribution, Germany (either the whole country or only certain federal states) was considered in most articles (13 studies). Four studies each considered the EU-27 as a whole, the Netherlands, Denmark, and Ireland. France, Italy and Belgium were each considered in three studies.

In most studies, the system boundary was a farm-to-farm gate (22 studies). Fifteen studies use cradle-to-farmgate. Most of the 50 TCA studies consider multiple animal species (29), while the remaining studies focus on only one species. Dairy cattle is the most assessed animal species (32 studies), followed by pigs (20), beef cattle (14), poultry (10) and sheep or goat (2). Nine studies assessed the whole agricultural or livestock sector and did not specify the animal species under consideration.

In the 50 identified TCA studies, we distinguished social and environmental externalities. Nearly all studies (47 out of 50) consider only environmental externalities, while two studies considered only social externalities. One study considered both social and environmental externalities. Regarding the environmental externalities, climate change was considered by most studies (22), followed by acidification (17) and eutrophication (13). Biodiversity and ecosystems were assessed in only two studies.

There were two major types of methods that have been applied for the estimation and calculation of the monetary value of the externalities:

1) Studies that estimate an “own” abatement cost curve, based on the data that had been gathered in a particular study (28 studies), and
2) Studies that use available monetisation factors for the calculation of the monetary value of an externality (22 studies).

Besides the outcomes of the literature review which was done in T1.3 of STEP UP and is described in D1.3, a small additional review has been made with a specific focus on the crosspoint of biodiversity, economic valuation and livestock systems. With the following Scopus search strategy “(“economic value” OR “economic valuation” OR “economical value” OR “economical valuation” OR “monetary value” OR “monetary valuation” OR “financial value” OR “financial valuation” OR “commercial value” OR “commercial valuation” OR “fiscal value” OR “fiscal valuation”) AND (biodiversity OR “biological diversity”) AND (livestock* OR cattle OR diary OR cattle OR sheep OR herd* OR pig* OR swine*)”, 103 papers were found. When adding the “in title only” constraint, zero papers were found. After reviewing the papers from this search and searching with similar keywords in other databases, only two papers were found that focus (at least somewhat) on each of the three required themes. The paper by Baltussen et al. (2016) aimed to assess the socio-economic and environmental effects of livestock production systems in Tanzania. The direct impact on biodiversity is assessed qualitatively, but no economic valuation is done. In the policy recommendations of the paper, it is suggested to do so in the future. The paper by Maher et al. (2021), who looked at the economic valuation of ecosystem services provided by beef cattle, including the ecosystem services related to the conservation of biodiversity. None of these papers is strongly relevant for setting up a TCA methodology for biodiversity impact of livestock systems, indicating that there is a gap in the literature on this topic.

3.1.2. Delphi approach

3.1.2.1. Prioritising externalities within TCA for European livestock production systems

The first group of questions in the Delphi approach was related to the importance of different externalities for livestock production systems in Europe. Table 4 contains the list of all externalities that was formulated in the HE project FOODCoST. All respondents were asked to score the importance of the externalities for European livestock production from 1 to 22 (from most important- least important). In Table 4, the most important externalities are highlighted in green, and the least important externalities in yellow. As shown in Table 4, there are nine environmental externalities, four of which belong to the most important externalities according to the respondents. More than half of the respondents scored these externalities in the top four. For climate change, all respondents scored this externality in the top four. The other externalities are acidification and eutrophication, direct effects on biodiversity and ecosystems, and land use and land transformation. The high ranking of direct effects on biodiversity and ecosystems is surprising since this is one of the externalities that still lacks a methodology in LCA and TCA (see 3.11).

Economic externalities such as income transfers, monopoly power effects on markets and institutional structure, and spillovers are regarded as least important externalities by about half of the respondents (bottom top 4 score). Also, consumer rights are regarded as one of the least important externalities by the respondents.

The remarks/ comments given by the respondents confirm the results as presented in Table 5. There was one exception: animal welfare was often mentioned in the remarks/ comments but ended up in the top 4 only 5 times. Animal welfare is number five on the list of most important externalities.

Table 5: List of all externalities in HE FOODCoST project grouped in three capitals (environmental, social and economic) used in STEP-UP Delphi approach

Externalities	Capital		
	Environmental	Social	Economic
Acidification and eutrophication	X		
Animal welfare		X	
Climate change	X		
Consumer rights		X	
Direct effects on biodiversity and ecosystems	X		
Equity, living income			X
Food safety		X	
Food security		X	
Food waste effects on market			X
Health effects of diets		X	
Income transfers			X
Infectious diseases		X	
Labour rights and conditions		X	
Land use and land transformation	X		
Local community rights		X	
Monopoly power effect on market and institutional structure			X
Noise, smell, visual intrusion	X		

Non-renewable resource depletion	X		
Particulate matter	X		
Spillovers (knowledge, infrastructure, human capital)			X
Toxicity	X		
Water stress	x		
Total externalities	9	8	5

The 22 externalities are categorized in three capitals: environmental, social, and economic (see table 5). We asked the respondents about the importance of these three categories. They agreed that the environmental externalities related to livestock production systems in Europe are more important than the social externalities (including animal welfare) and economic externalities. One of the respondents refers to a Joint Research Centre study on a farming practices evidence library (https://datam.jrc.ec.europa.eu/datam/mashup/JRC_FP_EVIDENCE_LIBRARY/index.html) mainly containing details of environmental externalities.

3.1.2.2. Use of TCA for European livestock production systems

If using a TCA analysis, the respondents are of the opinion that not all 22 externalities should be part of the analysis. This can make the TCA analysis too complex. However, they are not clear about how to measure sustainability: should the 5 most important externalities be considered in all TCA analysis (see results in 3.1.2.1) or should the 5 most important externalities per species be taken into account. Of course, the aim of the study, including its (geographic) scoping, will often decide which externalities are taken into account and which externalities are not.

The respondents agree on the fact that a lack of data is a bad reason to leave an externality out of the analysis. Also, externalities should not be selected because data are available. If externalities are important, data should be collected. For livestock production systems in Europe, data of direct impacts on biodiversity and ecosystems are lacking. All respondents (somewhat) agree that the importance of externalities differs between livestock species, between livestock production systems, and between geographic regions. However, this does not mean that, e.g., the impact of extensive grazing in the UK and Ireland on biodiversity is small (respondents declare that extensive grazing results in a green deserts). Most respondents also conclude that differing importance does not mean that certain externalities should (not) be considered.

3.1.2.3. TCA & Biodiversity

3.1.2.3.1. Importance of biodiversity in TCA

In this section participants were asked to share their view on how direct impact of livestock production systems on biodiversity can be included in the TCA methodology.

The first 3 questions were about **the importance of biodiversity in TCA and the availability with relevant knowledge**. We can conclude that most of the participants (86%) found it important to express the direct impact of livestock systems on biodiversity in monetary values, and that the majority (54%) agree that currently we lack the required knowledge to do so for all types of livestock systems in Europe.

3.1.2.3.2. Feasibility of measures

In the following section we asked participants about the **perceived feasibility of three proposed measures** (table 6). Measures indicated as ‘light’ have almost no impact on husbandry practices and low costs. ‘High’ measures have considerable impact on husbandry practices and high additional costs.

Table 6: The three examined measures used to assess the impacts of livestock production on biodiversity

Package	Measures	Applied on % of total grassland
Light	1. Extensively grazed grassland (max 3 cows per hectare), grazing from 1 May until 15 June	20%
Medium	1. Extensively grazed grassland (max 3 cows per hectare), grazing from 1 May until 15 June	25%
	2. Grass clover, resting period from 1 April until 15 June	25%
Heavy	1. Extensively grazed grassland (max 1.5 cows per hectare), grazing from 1 May until 1 July	40%
	2. Grass clover, resting period from 1 April until 15 June	30%
	3. Puddle/swampy grassland for meadow birds from 15 February until 15 June	10%

It can be concluded that it is unclear whether the measures explored can be applied to livestock systems across European countries universally, while local (farm-level) conditions and the different animal species need to be considered when designing measures to improve feasibility. The heavier the approach, the less uniformly it can be implemented, according to the expert opinions (see Appendix 1 for graphs per question).

According to the expert answers, long-term contracts and guidance on implementation would be needed the most to implement the proposed measures in practice. Interestingly, only 36% of the respondents chose higher compensation as a need, implying that the financial compensation is a less pressing requirement for implementation than the stability of contracts and the required knowledge and guidance.

In the following question, respondents were asked to share their opinion on additional measures. There are also other measures which can be implemented by farmers to improve biodiversity, such as: belated mowing, maintaining a higher water level, landscape elements, and meadow bird nest management. However, the costs of implementation and the impact of these measures on biodiversity ((Potentially Disappeared Fraction (PDF) score) are unknown. These (additional) measures cannot therefore be included in TCA analysis.

Half of the respondents believe that these additional measures should also be added to the TCA methodology, even if more research is needed on their effects before this can be done. One of the respondents added an open answer, which became available as an option to select for other participants. In the end, 45% of respondents chose this answer, indicating that they believe 'that other measures, beyond those included in Table 6, might have more evidence to support their implementation'. In one way or another, it means all respondents believe that additional measures should be added to the TCA methodology.

3.1.2.3.3. Data availability

To be able to complete a TCA analysis for assessing the direct impacts of livestock systems on biodiversity, data needs to be available. Fifty percent of respondents (strongly) disagree with the statement that data is available per EU region about how selected measures affect the PDF score of species. Ten percent somewhat disagree, while 20% remain neutral, and 20% agree somewhat. It can be concluded that the respondents are rather negative about data availability on how measures affect PDF scores.

Nobody voted on either 'strongly disagree' or 'strongly agree' on the statement "*The effects of implementing the measures, on the income of farmers, are known across the EU regions*". The answers are spread across the scale, but more people disagree than agree; 50% (somewhat) disagree, while 42% (somewhat) agrees.

Nobody voted on either 'strongly disagree' or 'strongly agree' on the statement "*Farmers are willing to share data to calculate the impact of their livestock system on biodiversity (using TCA)*". However, respondents were agreeing more than disagreeing. Fifty-eight percent voted '(somewhat) agree', while 8% voted 'disagree'. Most respondents believe that farmers would be willing to share data to be used for TCA, but a large part (one third) of the respondents remained neutral about this statement, showing that there is no strong certainty in the opinions.

Once again, nobody voted on either 'strongly disagree' or 'strongly agree' on the statement "*Farmers are willing to share their level of income before and after implementing the measures, across the EU*". Twenty-seven percent of respondents neither agreed or disagreed with this statement, and another 27% (somewhat) agreed. 45% voted '(somewhat) disagree'. Opinions on this statement are spread and there is no strong consensus, although respondents disagree more than they agree.

There was a strong consensus on the statement "*The relation between the cost of implementing measures at livestock farms and their effect on biodiversity needs to be estimated per type of livestock system in Europe*"; 14% strongly agreed, 79% agreed, and 7% somewhat agreed. No respondent stayed neutral or disagreed. According to the experts the relation between the costs of measures and their effect on biodiversity need to be estimated per different type of livestock system in Europe.

Table 7 : he three examined measures packages used to assess to decrease the direct negative the impacts of livestock production on biodiversity and the estimated cost (in Euro per ha per year)

Package	**Measure**	**Costs (euro /ha/year)[1]**
Light	1. Extensively grazed grassland (max 3 cows per hectare), grazing from 1 May until 15 June	€400-700
Medium	1. Extensively grazed grassland (max 3 cows per hectare), grazing from 1 May until 15 June 2. Grass clover, resting period from 1 April until 15 June	€400-700 €1,000-1,700
Heavy	1. Extensively grazed grassland (max 1.5 cows per hectare), grazing from 1 May until 1 July 2. Grass clover, resting period from 1 April until 15 June 3. Puddle/ swampy grassland for meadow birds from 15 February until 15 June	€700-820 €1,200-1,700 €1,000-3,500

1 Costs vary depending on soil type -peat/sandy/ clay soil

There was a strong consensus in the answers; all respondents agreed (36% agreed somewhat, 50% agreed, while 14% strongly agreed) with the statement "*According to compensation fees from Dutch agri-environmental schemes, the costs of the measures are shown in the table 7. These costs can be obtained/estimated for other EU countries as well*". According to experts, it is possible to estimate the costs of measures proposed for other EU countries.

Overall, it can be concluded that participants agree that data on the costs of measures and their effects on PDF scores is currently not sufficiently available, but that farmers would be willing to share data to be able to calculate the biodiversity impacts of their products. They are more negative about the willingness of farmers to share income data. All experts agreed that it would be possible to calculate the costs of measures per EU country (as is done in the Netherlands), and that the TCA method should be made livestock system specific.

3.1.2.3.4. Potential ways of implementation of TCA for biodiversity

There are several potential scenarios regarding the use of TCA for biodiversity (e.g., changing product prices based on TCA outcomes, new EU subsidies). In this section questions were asked about the **favourability and likelihood of different scenarios** (See Appendix 1 for details).

It can be concluded that experts foresee a combination of market- and government-driven implementation with a mix of incentives, in which long-term contracts should ideally play an important role. According to them, the government should take the leading role. The main hurdles for biodiversity TCA implementation mentioned by the respondents are the lack of awareness and responsibility in society and the food sector, the economy's current short-term view, the lack of required data, and the complexity of generalisation across landscapes when it comes to biodiversity measures.

3.1.3. Case study on monetising biodiversity

Introduction

The influence of livestock production on biodiversity is twofold: on one hand, livestock production contributes to a loss of biodiversity through effects like habitat conversion, eutrophication and acidification and spread of invasive species (Maxwell et al., 2016 and Leip et al., 2015). These effects represent the external costs of livestock production for society. On the other hand, livestock farming plays an important role in conserving or even enhancing biodiversity through supporting types of ecosystems (Teillard et al., 2016 and Sala et al., 2017). The positive effects represent the environmental benefits of livestock production for society. True Cost Accounting (TCA) aims to internalise (monetise) these external effects by measuring and valuing the environmental costs as well as benefits.

In current literature, the monetisation of the impact of human activity on biodiversity is based on the costs implied for restoring habitats or ecosystems (De Bruyn et al., 2023 and Galgani et al., 2021). These methods, however, are restricted to a limited number of types of ecosystems and refer to a general context. The valuation in a context with specific regional (or national) circumstances regarding biodiversity and livestock production systems is missing. This case study offers a method to fill this gap. The method comprises seven steps that will be described in further detail below.

Dutch dairy farms

The developed method for monetising the impact of livestock production systems on biodiversity is applied to conventional intensive dairy farms in the Netherlands on three different types of soils: peat soil, sandy soil, and clay soil. Measures to mitigate biodiversity loss are supposed to be represented by agri-environmental schemes for dairy farms. The reason for selecting intensive farms is that these farms apply no or only a limited number of biodiversity measures and can therefore serve as a baseline in this case study. The figures and results of the three Dutch dairy farms are used to illustrate the seven steps of the method.

Seven step approach

Figure 4 gives an overview of the seven steps of the method for monetising the impact of livestock production systems on biodiversity. In the following, the steps are described in further detail and are illustrated with the results of Dutch dairy farms.

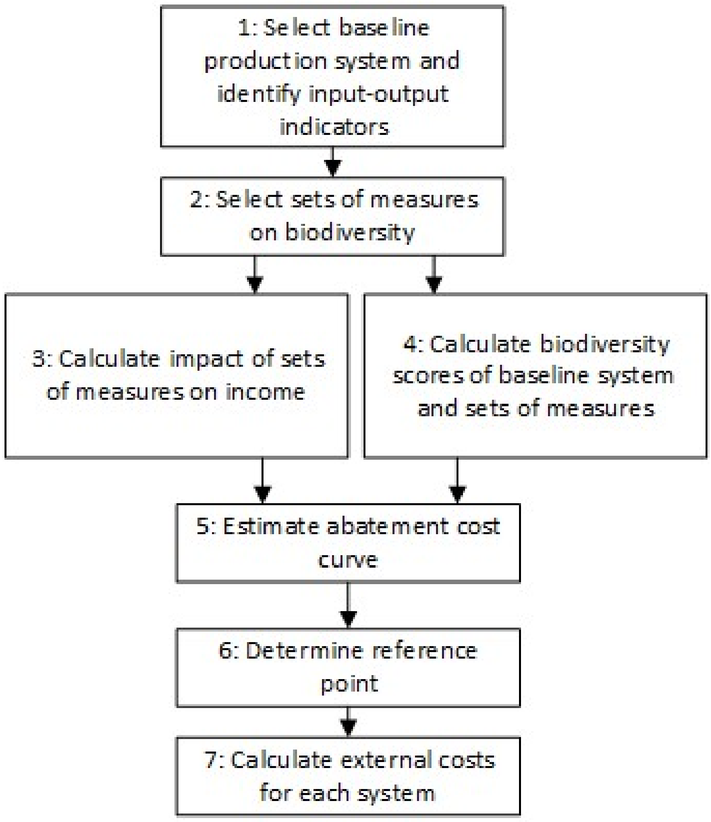


Figure 4: Seven steps for approach for monetising the impact of livestock production systems on biodiversity

- **Step 1: Select base line production system and identify input-output indicators**

The selected production system should be specified for a country, region, and system type. Here, we selected conventional dairy farms in the Netherlands on three different types of soil. The selection of the production system is followed by the identification of input and output indicators. Examples of input indicators are number of cows and hectares of grass- and arable land, milk production per cow, and use of fertiliser. Examples of output indicators are total milk production, gross margin, and farm income. The input and output characteristics of the conventional Dutch dairy farms on the three different types of soils are summarised in table 8.

Table 8: Input and output indicators of selected Dutch dairy production systems

Item		**Conventional intensive dairy farms** 1)		
		Peat soil	**Sandy soil**	**Clay soil**
Farm structure	# dairy cows	140	164	137
	# calves and heifers	66	77	64
	ha grassland	58	56	63
	ha arable land	7	11	9
Productivity	Milk yield (kg/cow/year)	8,800	9,400	8,600
Intensity	Livestock units/ha	2.5	3.0	2.5
Manure application	kg N/ha/year	232	226	236
Fertilizer application	kg N/ha/year	157	139	224
Feed (crude protein (CP) level)	gr CP/kg DM	165	160	160
Grazing	# hours	1,015	720	955
Groundwater level	cm below surface	60	n.a.	n.a.

Total revenues	Euro/farm/year	611,502	705,069	581,550
	Euro/ha/year	9,127	10,847	8.077
Revenues from agri-environmental schemes	Euro/farm/year	5,034	770	1,870
	Euro/ha/year	77	11	26
Total costs	Euro/farm/year	491,502	607,624	508,406
	Euro/ha/year	7,336	9,348	7.061
Farm income	Euro/farm/year	120,001	97,445	73,143
	Euro/ha/year	1,791	1,499	1,016

1) Farms are included in the Farm Accountancy Data Network (FADN)

Source: Jongeneel et al. (2024)

The numbers in table 8 show that the farm intensity (expressed in livestock unit/ha) is highest on sandy soil. The intensity of the farms on all three soil types lies above the Dutch average of 2.2 livestock units per hectare (Wageningen Economic Research, 2024). Income per ha is higher on peat soil (1,719 Euro/ha/year) than on sandy soil (1,499 Euro/ha/year) and on clay soil (1,016 Euro/ha/year). The contribution of agri-environmental schemes to total revenues is relatively small on all three types of soil: 0.1% on sandy soil, 0.3% on clay soil, and 0.8% on peat soil.

- **Step 2: Select sets of measures on biodiversity**

The set of measures can be derived from studies that aim to analyse the impact of measures on biodiversity. The collected data should indicate farm level costs of implementing biodiversity measures in the production systems selected in step 1. In this case study, the biodiversity measures are obtained from agri-environmental schemes developed for Dutch farming systems. The schemes differ between regions, depending on the agreements made between the beneficiary (farmer collectives) and the government. The compensation fee for agri-environmental schemes is based on the income foregone (income that would have been generated without an agri-environmental scheme) and the cost incurred of applying a scheme, e.g., additional labour costs (Polman, 2024).

In this case study, three different sets of measures are used: light, medium, and heavy. Heavy measures imply more restrictions on land use, which is usually associated with higher costs or foregone income and thus with a higher compensation fee. The sets of measures in this case study are based on the measures in the agri-environmental scheme that are frequently applied by farmers (Visser and Kleyheeg, 2025). The sets of measures are summarized in Table 9.

Table 9: Overview of sets of measures applied for all farm types

Category	Measure	Rate of implementation (% of grassland area) [1]	Compensation fee [2] (euro/ha/year)
Light	Extensively grazed grassland: grazing from 1 May until 15 June, min. 1 and max. 3 livestock units (LU) per ha	20%	504 (peat soil) 433 (sandy soil) 700 (clay soil)
Medium	Extensively grazed grassland: grazing from 1 May until 15 June, min. 1 and max. 3 LU per ha	30%	504 (peat soil) 433 (sandy soil) 700 (clay soil)
	Grass clover, resting period 1 April to 15 June, 4 indicator species	20%	1.375 (peat and sandy soil) 1.675 (clay soil)
Heavy	Extensively grazed grassland: grazing from 1 May until 1 July, min. 1 and max. 1.5 LU per ha (peat and sandy soil) [3]	50%	705 (peat soil) 820 (sandy soil) 700 (clay soil)

	Extensively grazed grassland: grazing from 1 May until 15 July, min. 1 and max. 3.0 LU per ha (clay soil)		
	Grass clover, resting period 1 April to 15 June, 4 species	50%	1.375 (peat and clay soil) 1.307 (sandy soil)
	Hedgerow (landscape elements)	0,1%	23.500

1) The percentages are based on expert opinion.
2) Information obtained from farmer collective Rijn & Gouwe Wiericke (peat soil), farmer collective Brabant (sandy soil), and farmer collective Rivierenland (clay soil).
3) Not available for clay soil

- **Step 3: Calculate impact of sets of measures on income**

There are two widely used approaches for calculating external costs and benefits of livestock production systems: the damage costs approach and the abatement costs approach (Sundqvist et al., 2004; De Bruyn et al., 2023). Damage costs reflect the burden (financial and non-financial) caused by biodiversity loss and borne by those who are affected by it. Abatement costs refer to the costs and the foregone benefits (due to lower productivity) incurred by adopting biodiversity measures. For this case study, the abatement costs approach is preferred above the damage cost approach. Damage costs are difficult to assess for biodiversity, and data about the damage (in monetary terms) associated with biodiversity loss is limited, especially the damage that can solely be assigned to specific livestock production systems.

In this case study, the abatement costs are derived from the compensation fee provided in the agri-environmental schemes presented in Step 2 (Table 9). The costs of the measure per farm are calculated by multiplying the compensation fee per hectare with the number of hectares on which the measure is applied. Subsequently, the average income per hectare under the different scenarios (sets of measures) is calculated for each type of soil. The results are shown in Table 10.

Table 10: Average income level (in Euro/ha/year) of conventional intensive dairy farms on three types of soil per scenario (set of biodiversity measures)

	Conventional intensive dairy farm		
	peat soil	**sandy soil**	**clay soil**
Conventional	1,499	1,791	1,016
Conventional + light	1,209	1,719	754
Conventional + medium	1,041	1,414	602
Conventional + heavy	571	745	178

- **Step 4: Calculate biodiversity score for baseline system and sets of measures**

There are three major groups of indicators that measure biodiversity: genetic diversity, species diversity, and landscape diversity. Studies that focus on the biodiversity in food production systems mainly use species diversity as an indicator to measure biodiversity (Kok et al., 2020). In this case study, we also use species diversity, measured with the PDF indicator (Potentially Disappeared Fraction of species). A PDF calculation has already been applied in studies concerning agricultural production systems and biodiversity, and hence a certain amount of data is available.

The PDF indicator uses characterization factors that express the relative diversity loss for different agricultural practices (e.g. organic, intensive, extensive) and land uses (De Schryver et al., 2010). The biodiversity score of a livestock production system is calculated by multiplying the characterization factor of a particular land use type with the number of hectares of the corresponding land use type. Subsequently, the weighted average is calculated based on the total number of hectares, according to the following equation:

$$PDF_i = \frac{\sum_{j=1}^{n} (CF_{j,i} * A_{j,i})}{\sum_{j=1}^{n} A_{j,i}}$$

Where:
PDF_i = PDF score of livestock production system *i*.
$CF_{j,i}$ = characterization factor expressing PDF of plant species richness of land use type *j* in livestock production system *i*.
$A_{j,i}$ = area occupied (in m^2) by land use type *j* in livestock production system *i*.
The PDF has a value between 0 and 1, where 0 reflects that all original species are still present and 1 that all original species have disappeared, so a higher value indicates a lower score on biodiversity.

The characterisation factors for the PDF in this case study are obtained from Kok et al. (2020). The area occupied is calculated from the hectares per farm provided in Table 8 and the rate of implementation of the biodiversity measures provided in Table 9. The results of the PDF-score are provided in Table 11.

Table 11: PDF score of selected farm types per scenario

	Conventional intensive dairy farm		
	sandy soil	**sandy soil**	**sandy soil**
Conventional	0.17	0.20	0.18
Conventional + light	0.11	0.16	0.12
Conventional + medium	0.06	0.13	0.08

- **Step 5: Estimate abatement cost curve**

The estimation of the abatement cost curve is based on the production costs and biodiversity scores that have been determined in Step 3 and 4. Figure 5 provides an example of an abatement cost curve for a dairy farming system with abatement costs in Euro/ha/year on the y-axis and the PDF-score on the x-axis. Conventional farming (without any set of measures) causes the highest abatement costs per ha per year and it is connected to the highest PDF-score (= lowest level of biodiversity).

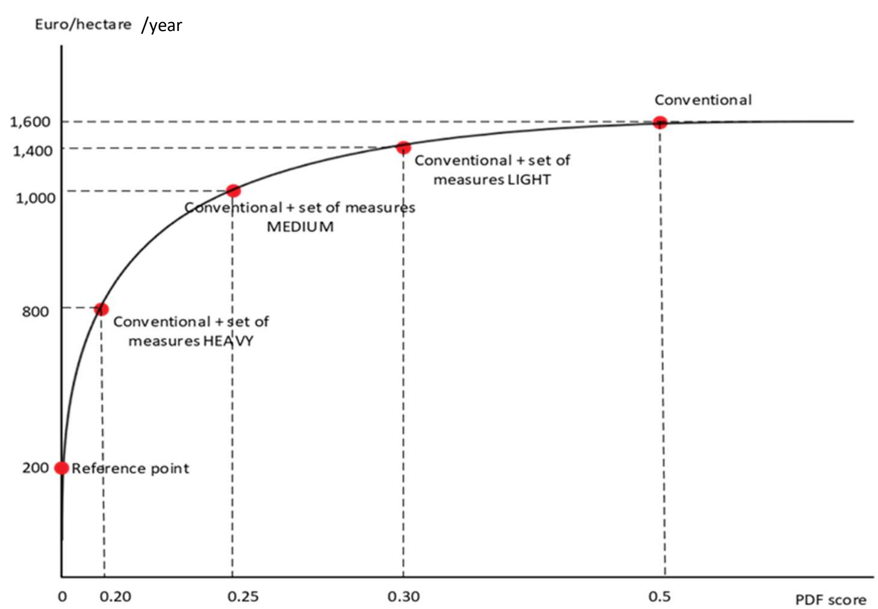


Figure 5: Example of an abatement cost curve for a dairy farming system in the Netherlands

- **Step 6: Determine reference point**

The reference point represents the situation where external costs are zero, which means that there are no societal costs due to biodiversity loss. One option for the reference point is pristine nature, which is reflected by a PDF-score of 0, implying that the richness of species does not change. It can be argued that livestock production is always associated with some degree of biodiversity loss and that hence a reference point of pristine nature is not achievable. In this case study, a sensitivity analysis is applied to analyze how a higher value of the reference point affects the external costs of biodiversity. Figure 6 illustrates the case for the Dutch dairy farm on sandy soil with a PDF of 0.1 as a reference point. In this case, abatement costs in Euro/ha/year become negative for a PDF below 0.05. This implies that if a livestock farming system is located on this part of the abatement cost curve, the system would generate external benefits. This is not the case when the reference point is set to PDF of 0.1, where the abatement cost curve stays above zero (negative externalities).

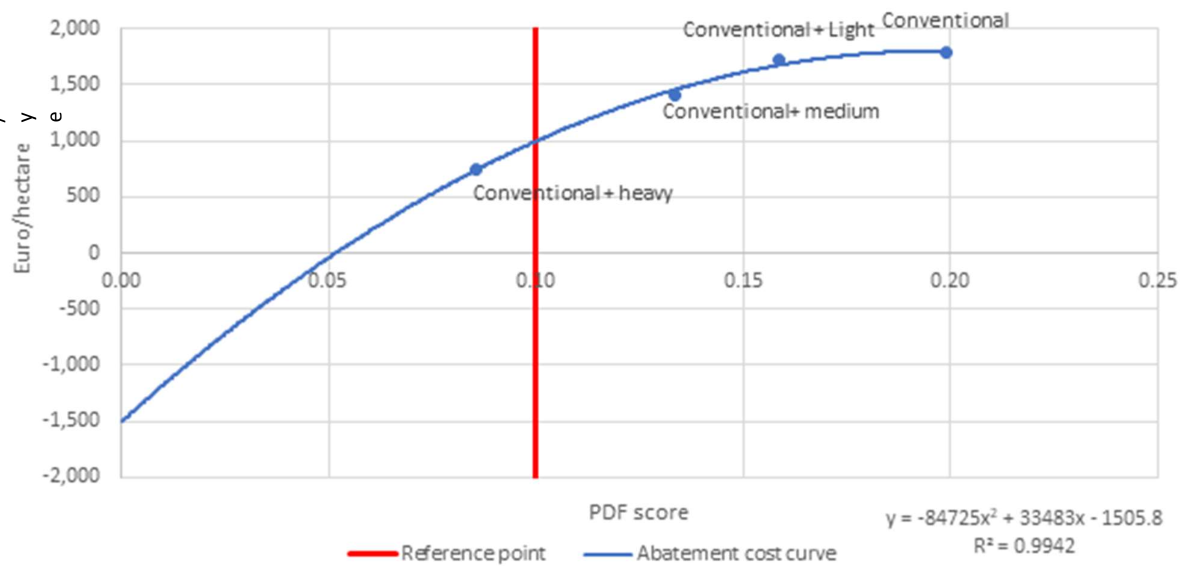


Figure 6: Abatement cost curve for a conventional intensive dairy farm on sandy soil

- **Step 7: Estimate external costs on biodiversity**

The external costs are the difference between the costs at the chosen reference point and the costs of the production system under consideration, as shown in Figure 5. Negative external costs reflect a net benefit. Table 12 shows the calculated abatement costs (Euro/ha/year) for our case study of the Dutch dairy farms on three types of soil and three reference points for the PDF indicator.

Table 12: External costs on biodiversity for different scenarios and reference points for PDF

	Abatement costs in euro/hectare/year		
	R = 0	***R = 0.05***	***R = 0.10***
Peat soil farm			
Conventional	1,664	813	264
Conventional + light	1,456	606	56
Conventional + medium	1,042	192	-358
Conventional + heavy	867	17	-533

Sandy soil farm			
Conventional	2,718	1,565	727
Conventional + light	2,752	1,418	580
Conventional + medium	2,377	1,223	386
Conventional + heavy	1,779	626	-212
Clay soil farm			
Conventional	1,786	929	349
Conventional + light	1,604	746	167
Conventional + medium	1,275	417	-162
Conventional + heavy	1,020	163	-417

The results in the table show that the choice of the reference point has a strong effect on the value of the abatement costs. External costs are lower when using a higher reference point, such as 0.05 or 0.10. At a reference point of 0.10, the abatement costs are negative for a conventional system with a medium and heavy set of biodiversity measures on peat and clay soil and for a conventional system with a heavy set of measures on sandy soil. These situations imply a net benefit to biodiversity.

3.2. S-LCA literature review

The retrieved 12 studies for S-LCA showed the application of weighting at three levels: multiple inventory indicators into an indicator, multiple indicators into an impact subcategory, and multiple impact subcategories into social impact (Table 13). We discuss these three levels in more detail below.

Table 13: Overview weighting methods used in the literature on the social impact of European livestock production

Study	S-LCA method RS/IP[1]	Inventory indicators into indicator	Indicators into impact subcategory	Impact subcategories into social impact
Tallentire et al. (2019)	RS	No (only 1 inventory indicator per indicator)	Equal weighting	No (results on impact subcategory level)
Aranda et al. (2021)	RS	No (only 1 inventory indicator per indicator)	No (results on indicator level)	No (results on indicator level)
Chen and Holden (2017)	RS and IP	No (only 1 inventory indicator per indicator)	RS: No (only 1 indicator per impact subcategory) IP: unequal weighting (reference flow)	No (results on impact subcategory level)
Chen and Holden (2018)	RS	No (only 1 inventory indicator per indicator)	Equal weighting	No (results on impact subcategory level)
Zhu et al. (2023)	Not indicated	No (only 1 inventory indicator per indicator)	No (results on indicator level)	No (results on indicator level)
Kokemohr et al. (2022)	Not indicated	No (only 1 inventory indicator per indicator)	No (results on indicator level)	No (results on indicator level)
Neugebauer et al. (2018)	Not indicated	No (nothing quantified)	No (nothing quantified)	No (nothing quantified)
Valente et al. (2023)	RS	Did not explicitly mention inventory indicators	Equal weighting	No (results on impact subcategory level)

Lillywhite et al. (2012)	Not indicated	No (nothing quantified)	No (nothing quantified)	No (nothing quantified)
Scherer et al. (2018)	Not indicated	Unequal weighting (complex formula; no source)	No (results on indicator level)	No (results on indicator level)
Møller et al. (2024)	RS	No (only 1 inventory indicator per indicator)	Equal weighting (majority of impact subcategories) Unequal weighting: (1) health and safety (one part sickness absence + mental health, other part occupational accidents; based on indicator robustness), (2) animal welfare (produced protein in reference flow)	No (results on impact subcategory level)
Zira et al. (2020)	RS	No (only 1 inventory indicator per indicator)	Equal weighting	Unequal weighting (expert opinion using Analytical Hierarchical Process)

[1] RS = reference scale method; IP = impact pathway method.

Weighting multiple inventory indicators into an indicator

Of the twelve studies, only one applied weighting multiple inventory indicators into an indicator. It used a complex formula to aggregate multiple inventory indicators (stocking density, days on pasture, life duration, moral value) into animal welfare, although details on the formula's design or rationale were not provided. It provided the data prior to weighting separately, but did not apply sensitivity analysis on the value of the used weights. Eight studies used only one inventory indicator per indicator, thus having no need for weighting. Two studies, both conference papers, presented a list of indicators to be assessed in a future project without a quantitative assessment. Finally, one study did not explicitly mention inventory indicators, so it was not possible to deduce if they used weighting.

Weighting multiple indicators into an impact subcategory

At the level of weighting multiple indicators into an impact subcategory, five studies applied equal weighting, and two studies applied unequal weighting. For unequal weighting, the reference flow was used to set weighting factors, or the authors set the weighting factors (Møller et al., 2024). The two studies with unequal weighting applied that only to a part of the impact subcategories assessed. Møller et al. (2024) applied equal weighting for most impact subcategories, but for the health and safety impact subcategory they used unequal weighting based on the level of robustness and relevance (mental health and sickness absence together were one part, occupational accidents the other part), and for animal welfare impact subcategory indicators based on the distribution of produced protein in the reference flow. Chen and Holden (2017) used the reference flow as weighting factor for the impact subcategories they assessed using the impact pathways (IP) method, whereas they only had one indicator per impact subcategory assess using the reference scale (RS) method. Four studies only presented results at indicator level, so they did not aggregate to impact subcategory level. Finally, two studies, both conference papers, only presented a list of indicators to be assessed in a future project without a quantitative assessment.

Only two studies offered partial justification for their decisions. Møller et al. (2024) used the reference flow to set weighting factors based on the logic that more working hours would result in more time to be exposed to social impact. Valente (2023) used equal weighting, indicating that they considered this to be no weighting, which they applied because of the lack of comparability across indicator results and the difficulty of making scientifically robust trade-offs. All studies that applied weighting provided the data prior to weighting separately, but none applied sensitivity analysis on the value of the used weights.

Weighting multiple impact subcategories into social impact

Only one study (Zira et al., 2020) applied weighting multiple impact subcategories into an overall social impact score. They used unequal weighting with expert-based weights for each impact subcategory obtained using the Analytic Hierarchy Process. Expert input was collected through structured questionnaires targeting stakeholder and subsystem combinations. Weights were then applied to calculate the Social Risk Time (SRT) which links the social risk to the functional unit by factoring in exposure, and the Social Hotspot Index (SHI) which relates the SRT to the worst possible situation for the system. Zira et al. (2020) provided the data prior to weighting separately, but did not apply sensitivity analysis on the value of the used weights. Nine studies did not aggregate impact subcategories into social impact; they only presented results at indicator or the impact subcategory level. Finally, two studies, both conference papers, only presented a list of indicators to be assessed in a future project without a quantitative assessment.

Summary

Weighting was applied at three levels, multiple inventory indicators into an indicator, multiple indicators into an impact subcategory, and multiple impact subcategories into social impact. Weighting multiple indicators into an impact subcategory was used the most, weighting multiple inventory indicators into an indicator and multiple impact subcategories into social impact were only applied in study each. Two types of indicator weighting were used: equal weighting and unequal weighting. For equal weighting, studies applied the average. Most studies using unequal weighting applied weighted average, except for one study that used mathematical formulas to weigh different inventory indicators into indicators for animal welfare. Weights for unequal weighting were based on stakeholder values, the reference flow, or were reported without a source. Most studies did not report a justification for the selected weighting method, although both UNEP guidelines (UNEP, 2020) and the ISO-standards for social life cycle assessment (ISO, 2024) stress the need to provide this. All studies provided the data prior to weighting separately. None of the studies applied sensitivity analysis on the value of the used weights, which is advised by the UNEP guidelines and ISO-standards.

3.3. C-LCA literature review

Twenty-three studies were included (Table 14). Among the included studies, four livestock species identified in the STEP-UP project were studied, including cattle (dairy cows, beef cattle), pigs, poultry, and sheep. A wide range of countries were included, especially the livestock intensive regions, e.g., Belgium, Italy, the Netherlands, France, Germany, Denmark, Spain and the UK. A wide range of topics were studied, including manure management (N=9; ten Hoeve et al., 2014; Styles et al., 2016; Willeghems et al., 2016; Lijó et al., 2018; Beyers et al., 2022; Styles et al., 2022; Beyers et al., 2023a; Mediboyina and Murphy, 2024; Santolin et al., 2024), alternative feeding strategies (N=5; Karlsson et al., 2015; Negro et al., 2017; Salemdeeb et al., 2017; van Zanten et al. 2018; Beyers et al., 2023b), and policy change (Styles et al., 2018; Salou et al., 2019).

Other topics include assessing the environmental impacts of the production cycle, e.g., milk production (Dalgaard et al., 2014), biogas production (van Stappen et al., 2016); or changing processes of production, e.g., bedding material (Yesufu et al., 2020), replacing fossil energy use (e.g., for milk production, Kimming et al., 2015); or developing a new system (e.g., farm conversation from silage-based to grass-based system, (Nguyen et al., 2013); use poorly drained land for livestock production (Sharma et al., 2018;). We also found a study evaluating the environmental impacts of diet changes from animal-based products to plant-based products (Costa et al., 2023).

Approaches to develop scenarios

Based on the rationales for developing scenarios, we categorised six different approaches for scenario development (Table 13), including technical-based approaches (N=9), management-based approaches (N=5), factorial approaches (N=5), policy-based approaches (N=2), optimisation approaches (N=1), and a combined approach (N=1).

Technical information of the process of a technique or a system was used to build scenarios. The assumptions (e.g., for marginal producers) were made depending on the geographical location and the specific techniques or systems tested (e.g., biomass waste-to-energy technology in Mediboyina and Murphy, 2024), while considering other factors (e.g., market constraints and marginal suppliers in Santolin et al., 2024). Technical-based approaches were mainly applied by studies evaluating the environmental impacts of livestock waste management strategies, e.g., slurry treatment (ten Hoeve et al., 2014, Beyers et al, 2023a) and for producing mineral fertilisers (ten Hoeve et al., 2014; Lijó et al., 2018; Beyers et al., 2023a; Santolin et al., 2024) or biogas (for cogeneration heat and power, Styles et al., 2016; Lijó et al., 2018; Mediboyina and Murphy, 2024). Evaluation of environmental impacts of different animal feeding strategies is another topic in which technical-based approaches were applied (Negro et al., 2017; Beyers et al., 2023b). In one study, scenarios were developed to use waste as potential animal feed (Salemdeeb et al., 2017). This technical-based approach was applied to develop scenarios using different techniques to process food waste, among which using waste as feed (i.e., conversion into dry pig feed, conversion into wet pig feed) was especially interesting for livestock production.

Management-based approaches were also applied to develop scenarios. During scenario development, extra or new processes were created in the production cycle, or different management or utilisation approaches were applied. In Karlsson et al. (2015), three scenarios were developed based on different faba beans utilisation methods (i.e., current use as protein feed, biorefinery processing, and roughage feed). In van Stappen et al. (2016), a farm-scale biogas plant is assumed to be installed, scenarios were developed based on the assumptions about the use of the biogas plant co-products and the pre-installation uses of the agro-industrial feedstock. In another study, substrate available at the farm (manure with mixed-in bedding material) was used to produce biogas and rapeseed oil to eliminate the fossil energy use at farm, resulting in the changing of the management strategies (Kimming et al., 2015). Another example is van Zanten et al. (2018). In their study, diet substitution scenarios were developed to replace soybean meal with rapeseed meal in finishing-pig diets, or with waste-fed larvae meal in growing-pig diets. The system boundary was therefore expanded from pig production to the production of feed ingredients. Management-based approaches can also be more complex. In Yesufu et al. (2020), scenarios were developed considering management decisions (e.g., farmer decisions, bedding substitutions) and the resulting consequences (i.e., indirect land use change (iLUC) for buying extra concentrate feed, type of avoided electricity generation, different rates of digestibility of the displaced pasture).

We also identified studies using a factorial approach. This approach usually comes with a fuller or complete storyline. In Styles et al. (2022), for example, two stylised national scenarios are evaluated to assess the comparative greenhouse gas (GHG) emission mitigation efficacy of four categories of anaerobic digestion feedstock, and three decarbonisation (prevailing technology) contexts per feedstock are defined. In Costa et al. (2023), scenarios of individual diet substitutions were developed based on the assumption that consumers were willing to change their diets, and a wider assessment of consumption changes. In Sharma et al. (2018), alternative ways (i.e., pasture-base milk production, suckler beef and sheep production) of using poorly drained farmland were defined. In Dalgaard et al. (2014), scenarios of the actual milk production situation were modelled. In another early study (Nguyen et al., 2013), scenarios of farm conversion were developed, based on the assumption of an increase in preference for grass-based milk in France.

Policy can also be a main driver for developing scenarios. In Salou et al. (2019), scenarios were developed based on the changes of agricultural markets corresponding to EU27 policy application, i.e., dairy quota removal and implementation of a grass premium in the EU27. The same approach was also applied in Styles et al. (2018), in which they developed different farm typologies, i.e., dairy intensification scenarios because of policy change. Moreover, an optimisation approach was applied in Willeghems et al. (2016). Their study applied a manure allocation model - the model was used to minimise either the economic cost or the carbon footprint of manure allocation in Belgium.

Scenarios can also be developed by combining different approaches. In Beyers et al. (2022), technique-based approaches and factorial approaches (i.e., considering regions) were applied. Their study was conducted to evaluate whether the implementation of slurry acidification as an emission mitigation technology is sensible in areas of high pig density in Denmark, Limburg, and Catalonia. The three regions were chosen based on their relevance to Europe's intensive pork production and their trade, regional distinctiveness, degree of technological establishment and urgency of reducing agricultural emissions to comply with international emission reduction targets.

Approaches to build inventories

Different approaches were applied to feed the data into inventory for C-LCA modelling, including dealing with the by-products and identifying the marginal products. Usually, a mix of different approaches were applied to build inventories, including data from different databases, e.g., Ecoinvent; expert-knowledge-based estimations, experiment-based data, survey; and modelling-derived data.

Ecoinvent is the most common database used for building inventories and was applied in most included studies (Table 13) to identify the marginal products or suppliers (Figure 7). Apart from Ecoinvent, other databases are available to identify marginal-products at different geographical levels, e.g., FAO (Styles et al., 2018), EU (Dalgaard et al., 2014), or governmental legislation or recommendations (Willeghems et al., 2016).

Definition	Example-dairy systems in UK[1]
• **Determining product:** A product for which a change in demand will affect the production volume of the activity.	• **Determining product**: Milk produced from the dairy systems.
• **Dependent co-product (or by-product):** A product for which a change in demand does not affect the production volume of the co-producing activity.	• **Dependent co-product (or by-product)**: Dairy beef (culled milking cows, dairy bull calves, heifers) produced from the dairy systems.
• **Marginal suppliers (or marginal products):** The suppliers that will change their production capacity in response to an accumulated change in demand for the product.	• **Marginal suppliers (or marginal products)**: Beef produced in Brazil - the assumption was made that the increased beef production in some scenarios (compared to the baseline scenario) substitutes extensive beef production in Brazil– the world's largest, and growing, exporter of beef (based on FAO Statistics).

[1]*Styles et al. (2018) was used as an example. In the study, different farm scenarios were developed to represent different levels of intensification for UK dairy farms.*

Figure 7: Some key concepts in C-LCA modelling.

Expert-based estimation, data from previous carried-out experiments, data from first-hand survey are important sources of data for building inventories, especially when the data needed is not available in the available databases, or the available databases could not reflect the local scenario.

Modelling can also provide data for inventories, e.g., economic modelling. In Costa et al. (2023), for example, an economic farm emission model was applied; through a comparative static linear optimisation model, farm management decisions were assessed and optimised with the aim of maximising the total gross margin (i.e. the objective function) of the farm. The main results of the optimisation process were included in the inventories. In Salou et al. (2019), an economic model (i.e., MATSIM-LUCA) was used to model agricultural markets in 2030 under the developed scenarios; the output of the economic model was used to build the consequential life cycle inventory. In Willeghems et al. (2016), the use of a manure allocation model allowed the optimal spatial manure allocation to be determined (i.e., either based on economic or environmental optimisation), which further allows the LCA calculations to determine the environmental impact of each manure management strategy. One limitation, however, is that the model ignores part of the reality, by making simplified assumptions about the processed manure transport destinations.

Selection of impact categories for life cycle impact assessment

Most included studies carried out life cycle impact assessment (LCIA) at mid-point level, with different methodologies applied (Table 13), including IPCC methodologies (2006, 2007), ReCiPe (Goedkoop et al., 2009), CML 2001, and ILCD methods (European Commission, 2010). In addition, we found models or approaches developed for specific impact categories and indicators. In Willeghems et al. (2016), for example, a consequential footprint approach was developed. In ten Hoeve et al. (2014), carbon sequestration was calculated using the simple, dynamic C-Tool model (Hutchings, 2010). In Nguyen et al. (2013), effects on on-farm soil carbon were predicted with the RothC model and on global land use change (LUC) with models of global agricultural markets. Salou et al. (2019) applied MATSIM-LUCA model - a partial equilibrium model of global agricultural markets-, to assess market effects and land use change impacts of policy instrument changes and to identify the processes affected. In Dalgaard et al. (2014), iLUC was assessed by an iLUC model developed by Schmidt et al. (2012).

Other specific models or approaches were developed to assess the processes that were not assessed. For example, for modelling the waste management technologies, EASETECH LCA-model were applied (Negro et al., 2017), which was specifically developed for the modelling of waste and energy technologies (Clavreul et al., 2014). Different from typical waste management LCAs, the authors used a “zero-burden” approach, i.e., the activities related to the generation of the orange peel waste (used as animal feed) were not included, as they were the same for all the investigated waste management scenarios (Negro et al., 2017). Another study modelled waste management strategies using a hybrid LCA approach, which combines conventional process-based LCA and an input-output based LCA (Salemdeeb et al., 2017). The input-output approach was used to estimate upstream-processes that are not modelled using conventional LCA, e.g., the manufacture of electronic products, therefore, to reduce the truncation error in conventional LCA (Salemdeeb et al., 2017). In another study (Costa et al., 2023), to model the potentially important “what if” LUC effects for scenarios of soymilk and pea protein ball production, the authors applied a “carbon opportunity cost” approach proposed by Searchinger et al. (2018). In van Zanten et al. (2018), to assess the environmental consequences of using co-products in livestock feed, the authors developed their own framework (van Zanten et al., 2014) - the net environmental impact can therefore be calculated (i.e. environmental benefits minus the environmental costs).

Uncertainty analysis

In LCA modelling studies, statistical comparison of different scenarios is possible when the range of uncertainty is available. Most included studies carried out uncertainty analyses (N=18, out of 23 studies). Among the studies that carried out uncertainty analysis, Tier 2 and Tier 3 approaches were identified. The Monte Carlo method is the most popular Tier 2 approach, while the most common Tier 3 approaches include sensitivity analysis and/or scenario analysis. We also identified studies combining sensitivity analysis with uncertainty analysis (Styles et al., 2016; van Stappen et al., 2016; Beyers et al., 2022).

Table 14: Extracted information for the literature review on consequential life cycle assessment of European livestock production

No.	Author	Topic	Approach to develop scenarios	Impact categories	Methodology of the LCIA	Approach to build inventories	Uncertainty analysis
1	Mediboyina and Murphy (2024)	Waste manage ment	Technical-based approach	At midpoint level	ReCiPe 2016	Ecoinvent process; Industry-specific datasets	None
2	Santolin et al. (2024)	Waste manage ment	Technical-based approach	At endpoint level	ReCiPe 2016	Ecoinvent process; Expert knowledge	Uncertainty analysis (Monte Carlo Method)
3	Costa et al. (2023)	Diet change of human (from animal-based to plant-based)	Factorial approach (using economic modelling)	At midpoint level	European Commission Product Environmental Footprint (PEF) guidelines (2018); Land occupation: calculated in the respective life cycle inventories; Land use change: “Carbon opportunity cost” approach proposed by Searchinger et al. (2018)	Ecoinvent process; Linear optimisation model, i.e. economic farm emission model; Literature; FAO statistics	Uncertainty analysis (error propagation)
4	Beyers et al. (2023a)	Waste manage ment	Technical-based approach	At midpoint level	Environmental Footprint 3.0 methodology	Experiment-based data; Literature; Mass balancing; Ecoinvent process	Scenario analysis
5	Beyers et al. (2023b)	Alternat ive feeding	Technical-based approach	At midpoint level	Environmental Footprint 3.0 methodology	Ecoinvent process	Scenario analysis
6	Styles et al. (2022)	Waste manage ment	Factorial approach	At midpoint level	IPCC (2007); Land occupation: measured as m^{2}.year; CML (2010).	Ecoinvent process; FAO statistics; Literature	Scenario analysis
7	Beyers et al. (2022)	Manure manage ment	Combined approach, technical-based and factorial (i.e. regions) approach	At midpoint level	ReCiPe 2016 midpoint methodology	Ecoinvent process	Uncertainty analysis (Monte Carlo Method); Sensitivity analysis: variation analysis.
8	Yesufu et al. (2020)	Farm manage	Combined approach,	At midpoint level	CML (2010); IPCC (2006)	Ecoinvent;	Scenario analysis

		ment (i.e., changin g bedding material)	considering management and technical changes			Previous studies from the authors; Literature; Data obtained from industry; Data from governmental organisations	
9	Salou et al. (2019)	Policy change	Policy-based approach (with economic modelling)	At midpoint and endpoint level	IPCC (2013); CML-IA baseline v3.02; Total cumulative energy demand (CED)—v1.09; USEtox (consensus only) v1.04; ReCiPe Endpoint methodology	Ecoinvent process	None
10	Lijó et al. (2018)	Waste manage ment	Technical-based approach	At midpoint level	ReCiPe 2008; IPCC (2006)	Experiment-based data; Ecoinvent process	Scenario analysis
11	Sharma et al. (2018)	Alternat ive land use	Factorial approach	At midpoint level	CML 2001	OECD/FAO datasets; Data from governmental and European level datasets; Literature	Sensitivity analysis
12	Styles et al. (2018)	Policy change	Policy-based approach	At midpoint level	IPCC Tier 1 approach; iLUC emissions for mid-case scenarios - crop-specific land footprint and iLUC CO2 factor derived for biofuel emissions calculations (Overmars, Stehfest, Ros & Prins, 2011).	FAO statistics; Literature	Scenario analysis
13	van Zanten et al. (2018)	Alternat ive feeding	Management -based approach (combined with system expansion)	At midpoint level	Framework developed by the authors (van Zanten et al., 2014)	Expert knowledge; Literature	Scenario analysis
14	Salamdeeb et al. (2017)	Waste manage ment / alternat ive feeding	Technical-based approach	At midpoint level	Hybrid LCA approach, i.e. combining conventional process-based LCA and an input-output based LCA developed by the authors, including below methods: IPCC 2007, WMO 1999, USEtox, Dreicer, ReCiPe midpoint, CML, Humbert, Accumulated Exceedance.	Data from governmental organisations; Literature; Data from FAO and USDA; Ecoinvent process; Direct communication with industry and government	Sensitivity analysis (Monte Carlo Method)
15	Negro et al. (2017)	Alternat ive feeding	Technical-based approach (with system expansion)	At midpoint level	EASETECH LCA-model (Clavreul et al., 2014)	Experimental data; Ecoinvent process; Expert-knowledge; Literature	Uncertainty analysis (Monte Carlo Method); Scenario analysis

16	Willeghems et al. (2016)	Manure management	Optimisation approach	At midpoint level	Consequential footprint approach developed by the authors	Literature; Data from governmental legislation recommendations	None
17	Styles et al. (2016)	Manure management	Technical-based approach	At midpoint level	CML (2010); IPCC (2006)	Experimental data; LCAD EcoScreen tool; Data collected from survey	Uncertainty analysis; Scenario analysis
18	van Stappen et al. (2016)	Biogas production	Management-based approach	At midpoint level	ILCD method	Expert knowledge; Literature	Uncertainty analysis (Monte Carlo Method); Scenario analysis
19	Karlsson et al. (2015)	Alternative feeding	Management-based approach	At midpoint level	Authors' own approach	Literature; FAO statistics; Ecoinvent process	Sensitivity analyses
20	Kimming et al. (2015)	Farm management (i.e. replacing fossil energy use at farm)	Management-based approach	At midpoint level	IPCC (2006); Calculation of the actual use (i.e. energy use)	Literature; Ecoinvent process	Sensitivity analysis
21	Dalgaard et al. (2014)	Milk production	Factorial approach	At midpoint level	IPCC (2007); iLUC model (version 3) developed by Schmidt et al. (2012)	Literature; Expert knowledge; Data from governmental organisation (i.e. EU commission)	None
22	ten Hoeve et al. (2014)	Manure management	Technical-based approach (with system expansion)	At midpoint level	ReCiPe 2008	Expert knowledge; Literature; Regional standards	Sensitivity analysis
23	Nguyen et al. (2013)	Farm management (i.e. farm conversion)	Factorial approach (with economic modelling)	At midpoint level	CML 2001	Literature; Ecoinvent process	None

Summary

To sum up, the included studies cover a wide range of livestock species, regions, and topics. Different approaches were used to develop scenarios, among which the technical processes and management strategies were the most considered factors. Depending on the specific goal, either one or more approaches could be used. In terms of building inventories, a mix of different sources of data were used, among which Ecoinvent is the most common database. Experiment-based data, expert-based estimation, or data from surveys could support the inventory building, especially where databases are not available. Moreover, different types of models can also provide data for inventories. Regarding the LCIA, most studies carried out the impact assessment at mid-point level. To evaluate the uncertainty of the results, further developments in uncertainty analysis are needed. Most of the included studies applied uncertainty analyses, using either Tier 2 (e.g., Monte Carlo methods) or Tier 3 approaches (e.g., sensitivity analysis, scenario analysis).

4. Discussion

4.1. TCA

In the literature of TCA studies a wide range of indicators are used, depending on the externality(ies) addressed. Most of the reviewed TCA studies mention environmental issues, where climate change, acidification and eutrophication are most frequently addressed. Social impacts are rarely considered. Biodiversity is regarded as important by experts (see results of Delphi approach) but is still scarcely addressed in the TCA literature. The reason for this may be the lack of data and knowledge with respect to the dose-response relationship in ecosystems and its effect on biodiversity. For instance, the effect of externalities of livestock systems on biodiversity may be positive or negative, depending on the livestock system and ecosystem(s) considered. To fill this gap a first attempt is made in this publication to propose a methodology to measure the direct impact of livestock production systems in the Netherlands on biodiversity (see section 3.1.3).

In the reviewed TCA studies, we find marginal abatement costs and marginal damage costs, either based on "own" data (e.g., regional data generated with technical-economic models of dairy farms in Germany showing the relation between lower nitrogen emission and additional costs for these farms per reduction level) and based on calculations with an available monetisation factor. Sometimes, market prices are used as a monetisation factor. Marginal abatement costs and marginal damage costs vary widely, depending on the section of the marginal cost/damage curve and other circumstances the study is placed in. The use of marginal abatement costs or marginal damage costs should be preferred, since market prices rarely reflect the marginal cost of an externality.

Issues considering data quality and the use of models increases the necessity to execute sensitivity analyses to interpret and discuss the impact of data quality and models on the results. Often this is not done in literature so far.

Experts have a clear view on what type of externalities should be considered in a TCA-based analysis. Given the current state of art of research there is a strong focus on environmental issues. Some of the social issues like animal welfare are also regarded as important. Economic externalities such as monopoly power, income transfers, and spillovers are regarded as less important for performing a TCA for European livestock. Although there is no module for monetising the direct impact of European livestock on biodiversity, nor the availability of data, most experts see this issue as very important for TCA. In this study an approach is given for monetising the direct impact of livestock production in the dairy sector in the Netherlands. The experts do agree that such an approach could work for other regions, however region and species-specific measurement approaches should be adapted, and the monetisation factor will depend on these elements.

For many of the issues raised in the Delphi approach there is consensus. However, on some issues there is far more discussion. The number of experts were low, the response time was rather short, and the questionnaire was relatively long. This can influence the extent to which respondents were willing to reconsider their opinion based on arguments given by others. The difference in results of the two Delphi rounds are minimal.

4.2. S-LCA

Our review of weighting methods used in S-LCA studies on European livestock production found that seven out of twelve studies applied weighting at one or more of the following levels: inventory indicators to indicators, indicators to impact subcategories, and impact subcategories to overall social impact. Five of the seven applied equal weighting and four applied unequal weighting. Weights for unequal weighting were based on stakeholder values (Zira et al., 2020), on indicator robustness (Møller et al., 2024), on the reference flow (Chen and Holden, 2017; Møller et al., 2024) or presented a formula without a source (Scherer et al., 2018). Hardly any studies provided a justification for the selected weighting methods, and none applied a sensitivity analysis.

UNEP (2020) describes four methods for weighting in S-LCA: Equal weights (equal importance to all indicators), expert or stakeholder values (based on expert or stakeholder preferences), most robust indicators prioritised (higher weights to indicators considered more robust and relevant), and worse performance prioritised (a weight of 1 to the worst-performing indicator and 0 to others) (Table 15). These options differ in their transparency, robustness, and normative stance. Our literature review showed that many of the studies applied equal weighting. The United Nations Environment Programme (UNEP, 2020) cautions that applying equal weighting can create a false perception of objectivity and might not sufficiently reflect real-world concerns. Several studies applied unequal weighting, with weights based on stakeholder values or indicator robustness. Thus, three of the four methods have been used in studies on European livestock production: equal weights, expert and stakeholder values, and most robust indicators, with the majority using equal weights. The weighting approach 'Worse performance prioritised' was not used in the analysed studies on European livestock production.

Table 15: Overview of approaches for weighting of indicators in social life cycle assessments (UNEP, 2020)

Weighting approach	Description	Pros	Cons	When to apply
Equal weights	Assigns equal value to all indicators	Simple, easy to communicate	False sense of neutrality	When indicators are robust and equally relevant
Expert or stakeholder values	Weights are based on stakeholder input or expert judgment	Integrates stakeholder perspectives	Time-consuming, depends on quality of stakeholder process	When stakeholder perspectives are crucial
Most robust indicators	Higher weights are given to more robust or reliable indicators	Prioritises reliable and robust data	Potential subjectivity in defining reliability and robustness	When indicators vary in data quality and relevance
Worse performance prioritised	Worst-performing indicator is fully weighted, others receive no weight	Avoids diluting negative impacts	May present an unbalanced view	When identifying and addressing negative performances

An important issue is the role of subjectivity in weighting. Weighting inherently involves value judgments, irrespective of which weighting method is selected (UNEP, 2020). Only two studies provide explicit justifications for the selected weighting method (Zira et al., 2020; Møller et al., 2024). Zira at al. (2020) used stakeholder values and Møller et al. (2024) adapted weights between indicators, based on data availability, indicator robustness, and contextual relevance. Even though ISO (2024) and UNEP (2020) emphasise the need for justification and transparency of the used weighting method, most reviewed studies do not provide this. This also prevents identification of guidelines for selecting the best weighting method to be used in studies to assess the social impact of European livestock production. Future studies should include the rationale for their weighting method choice.

None of the studies address the uncertainty associated with weighting. Do Carmo et al. (2017) developed a method for incorporating uncertainty into weighting based on Monte Carlo simulations. Their method involves randomly varying the value judgments of experts and aggregating the results into stochastic scores. The method enables sensitivity analysis of the influence of weighting assumptions and supports a more robust interpretation of results. While this approach increases the transparency and reliability of outcomes, it also introduces complexity and case-specificity. Future studies should include assessments of uncertainty in the applied weighting method.

In this study, we focused on weighting as the process of assigning value-based importance to inventory indicators, or impact subcategories to aggregate them into the next higher level of assessment. It is important to distinguish this from other practices aggregating inventory data across countries or animal species, sometimes also referred to as "weighting" in literature. For example, Zira et al. (2020) used mass allocation to aggregate inventory data across countries, which is a method of distributing inventory flows rather than applying value-based preferences. Tallentire et al. (2019) and Aranda et al. (2021) refer to "risk weighting", while in-fact both used predefined characterisation values that express the level of risk and are part of the impact assessment step, rather than part of a normative weighting process. Such applications of "weighting" refer to aggregation or characterisation of factors, which was outside the scope of our analysis.

4.3. C-LCA

As the number of C-LCA studies focusing directly on livestock production is limited, we expanded our inclusion criteria and included studies that addressed part of the livestock production cycle within the system boundaries. Studies that utilise livestock waste / by-products were therefore included.

Among the included studies, studies that directly evaluate livestock systems were underrepresented. More C-LCA studies are therefore needed to assess livestock production system directly. Current studies mainly focus on manure management and feeding strategies. A broader range of topics could therefore be covered, e.g. housing, management protocols, alternative production systems, etc.

Developing scenarios and building inventories

Among the included studies, technical and management-based approaches were the most applied methods for the development of scenarios. When developing a completely new scenario, however, the approach might depend on the goal of the study, e.g., whether the study aims to explore the impacts of policy changes; or an ‘ideal’ situation; or if the study aims to optimise the management processes. In such cases, approaches such as the factorial approach, policy-based approach, or optimisation approach might be more appropriate. If necessary, different approaches can be combined. One common issue with developing scenarios is making simplified assumptions. This might be because of the complexity of the scenarios (Nguyen et al., 2013; Styles et al., 2018; Salou et al., 2019; Costa et al., 2023), or due to limitations of the model (Willeghems et al., 2016).

After building scenarios, it is important to build a robust life cycle inventory. C-LCA expands the system boundaries, to reflect the direct and indirect changes associated with a particular intervention, in terms of stages and scales of production elsewhere (Yang, 2016). To avoid the need for co-product allocation, system expansion involves including the functions or products related to the original systems and treating the co-products as part of the overall system (Weidema and Schmidt, 2022). Different approaches were applied to feed the data into an inventory for C-LCA modelling, including dealing with the by-products and identifying the marginal products.

Ecoinvent is dominant among different databases. Although a powerful database, the users should be aware of its limitations. In Satolin et al. (2024), for example, the authors questioned the classification defined by Ecoinvent, as constrained markets might differ between regions, e.g., animal manure. Constrained markets therefore should be decided based on real-world conditions. When choosing databases, the users should be also aware of the geographical suitability, as using a global dataset for country or region-specific assessments might affect the results (Dalgaard et al., 2014; Costa et al., 2023). But this might also be an advantage, as demonstrated by Styles et al. (2022) - the modelling was based in the UK, but the use of (adapted) marginal processes from Ecoinvent allowed the results to be generalisable across other industrialised countries.

Therefore, the choice should be made with a clear idea of how to interpret the results. Whenever possible, it is important to use updated data inventories (Salamdeeb et al., 2017). In addition, regional C-LCA databases should be developed for livestock production.

The selection of impact categories

Regarding the LCIA methodologies, though many methodologies are available, the selected one should be suitable for the geographic scope. In Beyers et al. (2023b), for example, the Environmental Footprint 3.0 methodology was selected for the life cycle impact assessment (Fazio et al., 2018), because it has been developed for Europe and allows for straightforward normalisation and weighting.

Most of the included studies applied midpoint impact assessments. In general, midpoint indicators focus on specific environmental problems, e.g., climate change or acidification, while endpoint indicators assess the overall environmental damage, such as impacts on human health, ecosystems, or resource depletion. In livestock-related C-LCA studies, most evaluate the direct environmental impact, midpoint impact categories are therefore more suitable. When available, however, recommendations from literature should also be considered. For example, Salou et al. (2019) selected the impact categories based on the recommendations from the International Reference Data System (JRC and IES 2010) and from the authors of previous studies (Salou et al., 2017) - they included both midpoint and endpoint impact categories for the impact assessments.

Depending on the technique being tested and the topic of the study, either a detailed list or a short list of impact categories could be selected. In Salemdeeb et al. (2017), for example, 12 mid-point impact categories were assessed. According to the authors, these impact categories include a diverse set of environmental and human health indicators to give a multi-criteria assessment of the impacts of their tested food waste disposal technologies. While in Karlsson et al. (2015), only three impact categories were selected because they best represent the environmental benefits of Faba beans (i.e., as protein feed). In another study evaluating the environmental impacts of diets changes from animal-based products to plant-based products (Costa et al., 2023), the authors chose five categories out of the 16 environmental impact categories recommended by the method (i.e., European Commission Product Environmental Footprint guidelines, European Environmental Bureau, 2018), which covers the dominant environmental impacts incurred by agricultural systems in relation to planetary boundary exceedances (Steffen et al., 2015). So far, it is difficult to give recommendations regarding the choice of impact categories. This is due to the inconsistency of the selection of impact categories among studies, and the underrepresented number of the C-LCA studies evaluating directly on livestock systems. For future C-LCA studies evaluating directly on livestock systems, we recommend selecting impact categories from midpoint level as a starting point, and tailor their choice to the topic and the tested scenarios. This, however, depends on the availability of the data. In Negro et al. (2017), for example, the environmental impacts due to capital goods were not included because of a lack of data.

Uncertainty analysis

It is important to include uncertainty analysis in C-LCA modelling, as uncertainty is one of the main issues affecting the reliability of LCA results (McKone et al., 2011). Common sources of uncertainties in LCA studies include model, scenario, and parameter uncertainty (Lloyd and Ries, 2007). In C-LCA, specific sources of uncertainty relate to the definition of market-mediated substitution scenarios (Bamber et al., 2020). Depending on the specific contexts, the relative importance of the sources of uncertainty varies in different studies (Bamber et al., 2020). To determine the confidence levels of the C-LCA results, it is therefore important to quantify the uncertainties.

Uncertainty analysis aims to quantify the uncertainty in the output of a model due to uncertainties in the input values. A tiered approach was usually applied to assess uncertainties, i.e. following a Tier 1 (simple), Tier 2 (more refined), or Tier 3 (detailed) approach. In the included studies, tier 2 and tier 3 approaches were identified. The Monte Carlo method is a common Tier 2 approach for uncertainty analysis - using random sampling to explore the uncertainty in model inputs and assess how the output is affected, e.g. in Santolin et al. (2024). In addition, Monte Carlo methods can be included into Tier 3 uncertainty analysis (Negro et al., 2017). It is noted that Monte Carlo methods aim at analysing the parameter uncertainty (Bamber et al., 2020). Besides Monte Carlo methods, error propagation can be assessed differently, e.g., in Costa et al. (2023), aggregate errors were calculated as the square root of the sum of squared errors across major contributory processes. Self-defined approaches were also available, e.g., in styles et al. (2016), uncertainty ranges were calculated excluding and including highly uncertain iLUC burdens for all crops and feedstocks diverted from animal feed.

Sensitivity analysis is a common Tier 3 approach for uncertainty analysis, which focuses on identifying which input parameters are most influential. This can be performed by analysing the impact of changing uncertain or highly influential parameters, e.g., the choice of marginal technologies (Karlsson et al., 2015; Negro et al., 2017), alternative energy sources and dietary components (Beyers et al., 2023b); or by selecting context processes, e.g., different Ecoinvent processes for potassium fertiliser provision (Beyers et al., 2023a), differential decarbonisation pathways across food production, waste management and energy generation (Styles et al., 2022). In terms of the range of changes, decisions can be made depending on the specific contests. In Sharma et al. (2018), a 10% adjustment of the parameters was applied in the context of global marginal markets. While in ten Hoeve et al. (2014), the lowest and highest reasonable values from the literature were chosen for the sensitivity analyses. Specific types of sensitivity analysis may be chosen, e.g. a variation analysis could be conducted to test how alternative assumptions would affect the results (Beyers et al., 2022).

Scenario analyses (tier 3 approach) can also be applied for determining uncertainty (Styles et al., 2016; van Stappen et al., 2016; Styles et al., 2018; Lijó et al., 2018; van Zanten et al., 2018). Alternative scenarios are developed in this context. This approach differs from the commonly-applied sensitivity analysis approach, as scenario analysis explores a range of possible outcomes by analysing how different combinations of variables affect the model, while sensitivity analysis usually focuses on changing one variable at a time. In scenario analysis, many alternative scenarios could be developed. The terms (i.e., sensitivity analysis, scenario analysis), however, might be mix-used. In Yesufu et al. (2020), for example, the authors applied sensitivity analysis, in which 34 scenario permutations were analysed to represent combinations of substitutions and alternative scenarios. Following our definition, the 'sensitivity analysis' should be 'scenario analysis'. It is therefore important to understand the specific context to avoid the confusion.

Among the included studies, Montel Carlo methods, sensitivity analysis, and scenario analysis were the most applied methods for uncertainty analysis. These studies carried out uncertainty analysis targeting the parameter and scenario uncertainty, but did not address the model uncertainty. For future studies, we recommend carrying out uncertainty analysis at least using a tier 2 approach (e.g., Monte Carlo method) to address the parameter uncertainty. Depending on the specific studies, tier 3 approaches could give more detailed information on, e.g. which variable causes highest uncertainty (i.e., sensitivity analysis), which combinations of variables cause highest uncertainty (i.e., scenario analysis). Regarding the specific sources of uncertainties in C-LCA, suggestions were provided from the literature, e.g. to look to other fields such as economics (Bamber et al., 2020). To date, no consensus has been reached regarding the methodologies for quantifying model and scenario uncertainties. Efforts should be made to develop such methods, e.g. in LCA software.

4.4. Overarching topics

Although the above discussion focuses on different dimensions of sustainability, some overarching topics can be identified. First, studies often included only a limited selection of sustainability issues in their analysis, often based on data availability and perceived relevance. This resulted in studies including different impact categories, hampering an effective comparison. A predefined list of impact categories, indicators and externalities that each study should include, could help overcome such issues. Second, uncertainty and sensitivity analysis are often lacking in the selected studies. Studies often used “most-likely” or “average” values of input variables, or weighting factors, without considering the possible uncertainty associated with their adoption. An uncertainty or sensitivity analysis should be part in each study addressing the sustainability impact of livestock production to allow for better-informed decision making.

5. Conclusions

5.1. TCA

True Cost Accounting (TCA) is a methodology in development. This also holds for its application in European Livestock production. The number of scientific publications is limited but starkly increasing in recent years. TCA is mostly applied for dairy systems with climate change, acidification, and eutrophication as main externalities. Social and economic externalities are hardly researched. Many studies are about estimating abatement cost curves, estimating the relation between increase of sustainability and increase in cost of production to realise the increased sustainability.

In the Delphi approach the same externalities as in the literature were mentioned by experts to focus on in TCA analysis. The experts mentioned one additional issue: the direct impact of a livestock production system on biodiversity. According to our knowledge, no module has been developed within the TCA-community until now for this issue. This is one of the reasons we developed a module for the direct impact of livestock production systems on biodiversity, based on an abatement cost curve approach. The module was developed for three dairy systems in the Netherlands. Experts think that this methodology could also be applied to other livestock systems in Europe. However, the approach needs to be adapted to specific circumstances, and there is some doubt if the knowledge and/or data are available to apply this methodology for other livestock production systems. Experts believed data availability should not hinder the development of such a methodology, given the importance of biodiversity in livestock production.

5.2. S-LCA

Studies on the social impacts of European livestock production apply different weighting methods using both equal and unequal weights. They present the data prior to weighting but fail to report a justification of their weighting method choice and/or fail to perform a sensitivity analysis on the applied weights. Future studies should address these shortcomings. This could also aid in the development of guidelines for selecting weighting methods in studies assessing the social impact of European livestock production.

5.3. C-LCA

By carrying out literature search in a systematic manner, this study provided an overall picture of C-LCA of European livestock systems, and the advances of the C-LCA methodology. Among the included studies, different approaches were applied for developing scenarios, various sources of data were used for building inventories, and most studies carried out impact assessments at the mid-point level. The main conclusions were as follows:

- C-LCA studies assessing livestock systems directly are under-represented.
- Scenario development to date has focused on technical processes and management decisions, other approaches could be applied, e.g., optimisation approaches, factorial approaches, or policy-based approaches, for developing more future-oriented scenarios.
- A robust life cycle inventory requires careful selection of the most updated data from different data sources, and the choice of data from databases and literature should be suitable for the studied geographical scope.
- The selection of impact categories indicators should directly consider the goal(s) of the data interpretation and the overarching study.

- Uncertainty analysis is necessary in C-LCA modelling, to quantify the variability and uncertainty related to the results, to allow for a more informed decision-making.

Based on the conclusions, we recommend future studies assess livestock production systems directly, for example, changing different processes of the production cycle. To obtain a robust result, it is important to build a detailed scenario, by applying (a mix of) different approaches. Moreover, future studies should use updated data for building inventories, select appropriate impact categories that match the goal of the study, and include uncertainty analysis where possible.

5.4. HE STEP-UP

For the HE STEP-UP the conclusions above do imply that a full assessment of all possible externalities is impossible given the lack of methodologies, lack of data and lack of weighting the externaliities. On the other hand there is agreement about the most important externalities that should be included and for these externalities methodologies and data are available or can be developed as shown by the case of direct impact of livestock production systems on biodiversity. The research further shows that attention is needed for explaining weighting externatlities and for uncertainty analysis.

References

Aranda, J., Zambrana-Vásquez, D., Del-Busto, F., & Cárez, F. (2021). Social impact analysis of products under a holistic approach: A case study in the meat product supply chain. Sustainability, 13(21), 12163. https://doi.org/10.3390/su132112163.

Baltussen, W., T. Achterbosch, E. Arets, A. de Blaeij, N. Erlenborn, V. Fobelets, P. Galgani, A. De Groot Ruiz, R. Hardwicke, S.J. Hiemstra, P. van Horne, O. A. Karachalios, G. Kruseman, R. Lord, W. Ouweltjes, M. Tarin Robles, T. Vellinga, L. Verkooijen (2016). Valuation of livestock eco-agri-food systems: poultry, beef and dairy. Wageningen, Wageningen University & Research, True cost & True Price, publication 2016-023. https://doi.org/10.18174/389545

Bamber, N., Turner, I., Arulnathan, V., Li, Y., Ershadi, S. Z., et al. (2020). Comparing sources and analysis of uncertainty in consequential and attributional life cycle assessment: review of current practice and recommendations. The International Journal of Life Cycle Assessment, 25, 168–180. https://doi.org/10.1007/s11367-019-01663-1

Bare, J. C., Hofstetter, P., Pennington, D. W., & De Haes, H. A. U. (2000). Midpoints versus endpoints: The sacrifices and benefits. *The International Journal of Life Cycle Assessment*, *5*, 319-326. https://doi.org/10.1007/BF02978665

Beyers, M., Coudron, C., Ravi, R., Meers, E., & Bruun, S. (2023b). Black soldier fly larvae as an alternative feed source and agro-waste disposal route–A life cycle perspective. *Resources, Conservation and Recycling*, *192*, 106917. https://doi.org/10.1016/j.resconrec.2023.106917

Beyers, M., Duan, Y. F., Jensen, L. S., & Bruun, S. (2022). Effect of natural and regulatory conditions on the environmental impacts of pig slurry acidification across different regions in Europe: a life cycle assessment. *Journal of Cleaner Production*, *368*, 133072. https://doi.org/10.1016/j.jclepro.2022.133072

Beyers, M., Ravi, R., Devlamynck, R., Meers, E., Jensen, L. S., & Bruun, S. (2023a). Constructed wetlands and duckweed ponds as a treatment step in liquid manure handling—A life cycle assessment. *Science of the Total Environment*, *889*, 163956. https://doi.org/10.1016/j.scitotenv.2023.163956

Broeren, M. L., Zijp, M. C., Waaijers-van der Loop, S. L., Heugens, E. H., Posthuma, L., Worrell, E., & Shen, L. (2017). Environmental assessment of bio-based chemicals in early-stage development: a review of methods and indicators. *Biofuels, Bioproducts and Biorefining*, *11*, 701-718. https://doi.org/10.1002/bbb.1772

Chen, W., & Holden, N.M. (2017). Social life cycle assessment of average Irish dairy farm. The International Journal of Life Cycle Assessment, 22, 1459-1472. https://doi.org/10.1007/s11367-016-1250-2.

Chen, W., & Holden, N.M. (2018). Tiered life cycle sustainability assessment applied to a grazing dairy farm. Journal of Cleaner Production, 172, 1169–1179. https://doi.org/10.1016/j.jclepro.2017.10.264

Clavreul, J., Baumeister, H., Christensen, T. H., & Damgaard, A. (2014). An environmental assessment system for environmental technologies. *Environmental modelling & software*, *60*, 18-30. https://doi.org/10.1016/j.envsoft.2014.06.007

Costa, M. P., Saget, S., Zimmermann, B., Petig, E., Angenendt, E., Rees, R. M., ... & Styles, D. (2023). Environmental and land use consequences of replacing milk and beef with plant-based alternatives. *Journal of Cleaner Production*, *424*, 138826. https://doi.org/10.1016/j.jclepro.2023.138826

Dalgaard, R., Schmidt, J., & Flysjö, A. (2014). Generic model for calculating carbon footprint of milk using four different life cycle assessment modelling approaches. *Journal of Cleaner production*, *73*, 146-153. https://doi.org/10.1016/j.jclepro.2014.01.025

De Bruyn., S., de Vries., J., Juijn., D., Bijleveld., M., van der Giesen., C., Korteland., M., van Santen., W., & Pápai., S. (2023). Environmental Prices Handbook 2023 (Methodical substantiation of key figures used for valuation of emissions and environmental impacts, Issue. https://cedelft.eu/publications/environmental-prices-handbook-2023/

De Schryver, A.M., Zelm, R. van, Huijbregts, M.A.J. and Goedkoop, M. (2010). In Sonesson, U., Berlin, J. and Ziegler, F., Addressing land use and ecotoxicology in Life cycle Assessments of food production technologies. In: *Environmental Assessment and Management in the Food Industry,* pp 399-411, Woodhead Publishing.

Do Carmo, B.B.T., Margni, M., & Baptiste, P. (2017). Addressing uncertain scoring and weighting factors in social life cycle assessment. *The International Journal of Life Cycle Assessment*, 22(10), 1609–1617. https://doi.org/10.1007/s11367-017-1275-1

European Commission (2010). International Reference Life Cycle Data System (ILCD) Handbook- General Guide for Life Cycle Assessment - Provisions and Action Steps. Publications Office of the European Union, Luxembourg. https://publications.jrc.ec.europa.eu/repository/handle/JRC58190

European Commission (2025). Vision for Agriculture and food-ensuring the future of our farmers and food. https://agriculture.ec.europa.eu/overview-vision-agriculture-food/vision-agriculture-and-food_en

European Environmental Bureau (2018). The EU product environmental footprint (PEF) methodology - what can it deliver and what not. An NGO viewpoint 1–10. https://eeb.org/wp-content/uploads/2020/11/The-EU-Product-Environmental-Footprint-Methodology.pdf

Fazio, S., Biganzoli, F., De Laurentiis, V., Zampori, L., Sala, S., & Diaconu, E. (2018). Supporting information to the characterisation factors of recommended EF Life Cycle Impact Assessment methods, EUR 29600 EN, Publications Office of the European Union, Luxembourg. https://publications.jrc.ec.europa.eu/repository/handle/JRC114822

Galgani, P., Woltjer, G., de Adelhart Toorop, R. and de Groot Ruiz, A. (2021). Valuation framework for true price assessment of agri-food products. Version 1 – May 2021. PPS "Echte en eerlijke prijs voor duurzame producten". valuation_framework_for_true_price_assessment_of_-wageningen_university_and_research_588067.pdf

Goedkoop, M., Heijungs, R., Huijbregts, M., De Schryver, A., Struijs, J., & Van Zelm, R. (2009). ReCiPe 2008. A life cycle impact assessment method which comprises harmonised category indicators at the midpoint and the endpoint level, 1, 1-126. https://www.rivm.nl/sites/default/files/2018-11/ReCiPe%202008_A%20lcia%20method%20which%20comprises%20harmonised%20category%20indicators%20at%20the%20midpoint%20and%20the%20endpoint%20level_First%20edition%20Characterisation.pdf

IPCC (2006). IPCC Guidelines for National Greenhouse Gas Inventories. IGES, Japan. https://www.ipcc-nggip.iges.or.jp/public/2006gl/

IPCC (2007). Climate Change 2007. IPCC Fourth Assessment Report. The Physical Science Basis. http://www.ipcc.ch/ipccreports/ar4-wg1.htm.

ISO (2006). ISO 14040 - Environmental management - Life cycle assessment - Principles and framework. International Organization Standardization.

ISO (2024). ISO 14075:2024. Environmental management — Principles and framework for social life cycle assessment. International Organization for Standardization, Geneva, Switzerland.

Jongeneel, R., Van Asseldonk, M. Daatselaar, C., Greijdanus, A., Helming, J., Vissers, L. (2024). Uitwerking bedrijfstypen voor duurzame landbouw: melkveehouderij en akkerbouw. Wageningen, Wageningen Economic Research, Rapport 2024-001. 138 blz.; 4 fig.; 68 tab.; 27 ref.

JRC and IES (2010). International reference life cycle data system (ILCD) handbook: general guide for life cycle assessment—detailed guidance. Publications Office of the European Union. https://publications.jrc.ec.europa.eu/repository/handle/JRC58190

Karlsson, H., Ahlgren, S., Strid, I., & Hansson, P. A. (2015). Faba beans for biorefinery feedstock or feed? Greenhouse gas and energy balances of different applications. *Agricultural Systems*, *141*, 138-148. https://doi.org/10.1016/j.agsy.2015.10.004

Kimming, M., Sundberg, C., Nordberg, Å., Baky, A., Bernesson, S., & Hansson, P. A. (2015). Replacing fossil energy for organic milk production–potential biomass sources and greenhouse gas emission reductions. *Journal of Cleaner Production*, *106*, 400-407. https://doi.org/10.1016/j.jclepro.2014.03.044

Kok, A., de Olde, E. M., de Boer, I. J. M., & Ripoll-Bosch, R. (2020). European biodiversity assessments in livestock science: A review of research characteristics and indicators. Ecological Indicators, 112, 105902.

Kokemohr, L., Escobar, N., Mertens, A., Mosnier, C., Pirlo, G., Veysset, P., & Kuhn, T. (2022). Life cycle sustainability assessment of European beef production systems based on a farm-level optimization model. Journal of Cleaner Production, 371, 134552. https://doi.org/10.1016/j.jclepro.2022.134552.

Leip, A., Leach, A., Musinguzi, P., Davis, K.F., Yu, K., Herrero, M., Billen, G., Garnier, J., Grizzetti, B., Lassaletta, L., Reis, S. (2015). Impacts of European livestock production : nitrogen, sulphur, phosphorus and greenhouse gas emissions, land-use, water eutrophication and biodiversity. Environ. Res. Lett. 10, 1–13. https://doi.org/ 10.2340/16501977-0484.

Lillywhite, R.D., Keeling, C., Courtney, P., Lampkin, N., Pearce, B., Rayns, F., Reed, M., Schmutz, U., Watson, C., & Williams, A. (2012). Assessing the economic, environmental and social characteristics of UK farming systems. IFSA 2012 Proceedings. https://ifsa.boku.ac.at/cms/fileadmin/Proceeding2012/IFSA2012_WS6.1_Lillywhite.pdf.

Lijó, L., Frison, N., Fatone, F., González-García, S., Feijoo, G., & Moreira, M. T. (2018). Environmental and sustainability evaluation of livestock waste management practices in Cyprus. *Science of the Total Environment*, *634*, 127-140.

Lloyd, S. M., Ries, R. (2007). Characterizing, propagating, and analyzing uncertainty in life-cycle assessment: a survey of quantitative approaches. Journal of Industrial Ecology, 11, 161–179.

Maher, A. T., Quintana Ashwell, N. E., Maczko, K. A., Taylor, D. T., Tanaka, J. A., Reeves, M. C. (2021). Valuation of beef cattle ecosystem services. An economic valuation of federal and private grazing lands ecosystem services supported by beef cattle ranching in the U.S. Oxford University Press. American Society of Animal Science.

Maxwell, S.L., Fuller, R.A., Brooks, T.M., Watson, J.E.M. (2016). Biodiversity: the ravages of guns, nets and bulldozers. Nature 536, 143–145. https://doi.org/10.1038/ 536143a

McKone, T.E., Nazaroff. W.W., Berck. P., Auffhammer, M., Lipman, T., et al. (2011). Grand challenges for life-cycle assessment of biofuels. *Environmental Science & Technology,* 45, 1751–1756.

Mediboyina, M. K., & Murphy, F. (2024). Environmental Assessment of a Waste-to-Energy Cascading System Integrating Forestry Residue Pyrolysis and Poultry Litter Anaerobic Digestion. *Energies, 17*, *1511.*

Møller, H., Rydhmer, L., Christensen, T., Poulsen, L.K., & Olsen, H.F. (2024). Social life cycle assessment in current and future Norwegian livestock production. The International Journal of Life Cycle Assessment. https://doi.org/10.1007/s11367-024-02345-3.

Negro, V., Ruggeri, B., Fino, D., & Tonini, D. (2017). Life cycle assessment of orange peel waste management. *Resources, Conservation and Recycling*, *127*, 148-158. https://doi.org/10.1016/j.scitotenv.2018.03.299

Neugebauer, S., Fischer, D., Bach, V., & Finkbeiner, M. (2018). Social indicators for meat production – addressing workers, local communities, consumers and animals. ResearchGate. https://www.researchgate.net/publication/273631163_Social_indicators_for_meat_production_-_addressing_workers_local_communities_consumers_and_animals.

Nguyen, T. T. H., Corson, M. S., Doreau, M., Eugène, M., & van der Werf, H. M. (2013). Consequential LCA of switching from maize silage-based to grass-based dairy systems. *The International Journal of Life Cycle Assessment*, *18*, 1470-1484. https://doi.org/10.1007/s11367-013-0605-1

Page, M. J., McKenzie, J. E., Bossuyt, P. M., Boutron, I., Hoffmann, T. C., Mulrow, C. D., ... & Moher, D. (2021). The PRISMA 2020 statement: an updated guideline for reporting systematic reviews. *bmj*, 372. https://doi.org/10.1016/j.jclinepi.2021.03.001

Polman, N. (2024). Personal communication, November 11, 2024.

RIVM (2011). LCIA: the ReCiPe model. Dutch National Institute of Public Health and the Environment. https://www.rivm.nl/en/life-cycle-assessment-lca/recipe

Sala, O.E., Yahdjian, L., Havstad, K. and Aguiar, M.R. (2017). Rangeland ecosystem services: nature's supply and humans' demand. In: Briske, D.D. (Ed). Rangeland systems: processes, management and challenges. Cham, Switzerland: Springer.

Salemdeeb, R., Zu Ermgassen, E. K., Kim, M. H., Balmford, A., & Al-Tabbaa, A. (2017). Environmental and health impacts of using food waste as animal feed: a comparative analysis of food waste management options. *Journal of cleaner production*, *140*, 871-880. https://doi.org/10.1016/j.jclepro.2016.05.049

Salou, T., Le Mouël, C., Levert, F., Forslund, A., & van Der Werf, H. M. (2019). Combining life cycle assessment and economic modelling to assess environmental impacts of agricultural policies: the case of the French ruminant sector. *The International Journal of Life Cycle Assessment*, *24*, 566-580. https://doi.org/10.1007/s11367-018-1463-7

Santolin, J., Vlaeminck, S. E., Appiah-Twum, H., Van Winckel, T., & Spiller, M. (2024). Consequential LCA of NPK fertilizers from microbial, animal, plant, and mineral origin highlights resource constraints and environmental impacts. *Journal of Cleaner Production*, *457*, 142312. https://doi.org/10.1016/j.jclepro.2024.142312

Scherer, L., Tomasik, B., Rueda, O., & Bauer, C. (2018). Framework for integrating animal welfare into life cycle sustainability assessment. *International Journal of Life Cycle Assessment, 23*, 1476–1490. https://doi.org/10.1007/s11367-017-1420-x

Schmidt, J.H., Reinhard, J., Weidema, B.P. (2012). A model of indirect land use change. In: Extended Abstract from Presentation at the 8th International Conference on LCA in the Agri-food Sector, 1-4 Oct 2012, St. Malo, France.

Searchinger, T. D., Wirsenius, S., Beringer, T., & Dumas, P. (2018). Assessing the efficiency of changes in land use for mitigating climate change. *Nature*, *564*(7735), 249-253. https://doi.org/10.1038/s41586-018-0757-z

Sharma, P., Humphreys, J., & Holden, N. M. (2018). Environmental impacts of alternative agricultural uses of poorly drained farm land in Ireland. *Science of the Total Environment, 637*, 120-131. https://doi.org/10.1016/j.scitotenv.2018.04.315

Spranger, J., Homberg, A., Sonnberger, M., & Niederberger, M. (2022). Reporting guidelines for Delphi techniques in health sciences: a methodological review. *Zeitschrift für Evidenz, Fortbildung und Qualität im Gesundheitswesen*, *172*, 1-11. https://doi.org/10.1016/j.zefq.2022.04.025

Steffen, W., Richardson, K., Rockström, J., Cornell, S. E., Fetzer, I., Bennett, E. M., ... & Sörlin, S. (2015). Planetary boundaries: Guiding human development on a changing planet. *science*, *347*(6223), 1259855. DOI: 10.1126/science.1259855

Styles, D., Dominguez, E. M., & Chadwick, D. (2016). Environmental balance of the UK biogas sector: An evaluation by consequential life cycle assessment. *Science of the Total Environment*, *560*, 241-253. https://doi.org/10.1016/j.scitotenv.2016.03.236

Styles, D., Gonzalez-Mejia, A., Moorby, J., Foskolos, A., & Gibbons, J. (2018). Climate mitigation by dairy intensification depends on intensive use of spared grassland. *Global change biology*, *24*, 681-693. https://doi.org/10.1111/gcb.13868

Styles, D., Yesufu, J., Bowman, M., Williams, A. P., Duffy, C., & Luyckx, K. (2022). Climate mitigation efficacy of anaerobic digestion in a decarbonising economy. *Journal of Cleaner Production*, *338*, 130441. https://doi.org/10.1016/j.jclepro.2022.130441

Sundqvist, T., Söderholm, P., and Stirling, A. (2004). Electric power generation: valuation of environmental costs. Encyclopedia Energy, 229–243. doi: 10.1016/B0-12-176480-X/00543-X

Tallentire, C. W., Edwards, S. A., Van Limbergen, T., & Tuyttens, F. A. M. (2019). The challenge of incorporating animal welfare in a social life cycle assessment model of European chicken production. *International Journal of Life Cycle Assessment, 24*, 1093–1104. https://doi.org/10.1007/s11367-018-1565-2

ten Hoeve, M., Hutchings, N. J., Peters, G. M., Svanström, M., Jensen, L. S., & Bruun, S. (2014). Life cycle assessment of pig slurry treatment technologies for nutrient redistribution in Denmark. *Journal of Environmental Management*, *132*, 60-70. https://doi.org/10.1016/j.jenvman.2013.10.023

Teillard, F., Anton, A., Dumont, B., Finn, J.A., Henry, B., Souza, D.M., Manzano P., Milà i Canals, L., Phelps, C., Said, M., Vijn, S., White, S. (2016). A review of indicators and methods to assess biodiversity – Application to livestock production at global scale. Livestock Environmental Assessment and Performance (LEAP) Partnership. FAO, Rome, Italy.

UNEP (2020). Guidelines for Social Life Cycle Assessment of Products and Organizations 2020. Benoît Norris, C., Traverso, M., Neugebauer, S., Ekener, E., Schaubroeck, T., Russo Garrido, S., Berger, M., Valdivia, S., Lehmann, A., Finkbeiner, M., Arcese, G. (eds.). United Nations Environment Programme (UNEP), Paris, France. https://www.lifecycleinitiative.org/wp-content/uploads/2021/01/Guidelines-for-Social-Life-Cycle-Assessment-of-Products-and-Organizations-2020-22.1.21sml.pdf.

UNEP-SETAC (2011). Global guidance principles for life cycle assessment databases a basis for greener processes and products. https://www.lifecycleinitiative.org/wp-content/uploads/2012/12/2011%20-%20Global%20Guidance%20Principles.pdf

Valente, C., Danielsen, R., Woodhouse, A., Johnsen, F.M., & Forsberg, E.-M. (2023). Social performance and impact assessment of an autonomous system in the meat processing sector. The International Journal of Life Cycle Assessment, 28(8), 2012–2026. https://doi.org/10.1007/s11367-023-02256-9.

Visser, T., and Kleyheeg, E. (2025). Ecologische evaluatie Agrarisch Natuur en Landschapsbeheer. (Rapport / Wageningen Environmental Research; No. 3422). Wageningen Environmental Research. https://doi.org/10.18174/689914

van Stappen, F., Mathot, M., Decruyenaere, V., Loriers, A., Delcour, A., Planchon, V., ... & Stilmant, D. (2016). Consequential environmental life cycle assessment of a farm-scale biogas plant. *Journal of environmental management*, *175*, 20-32. https://doi.org/10.1016/j.jenvman.2016.03.020

van Zanten, H. H., Bikker, P., Meerburg, B. G., & de Boer, I. J. (2018). Attributional versus consequential life cycle assessment and feed optimization: alternative protein sources in pig diets. *The International Journal of Life Cycle Assessment*, *23*, 1-11. https://doi.org/10.1007/s11367-017-1299-6

van Zanten, H. H., Mollenhorst, H., de Vries, J. W., van Middelaar, C. E., van Kernebeek, H. R., & de Boer, I. J. (2014). Assessing environmental consequences of using co-products in animal feed. *The International Journal of Life Cycle Assessment*, *19*, 79-88. https://doi.org/10.1007/s11367-013-0633-x

Wageningen Economic Research (2024). Livestock units per hectare increases again. https://agrimatie.nl/PublicatiePage.aspx?subpubID=2523&themaID=2755&indicatorID=2767&sectorID=2245

Weidema, B. P., Schmidt, J. (2022). Consequential modelling in life cycle inventory analysis. https://lca-net.com/publications/show/consequential-modelling-in-life-cycle-inventory-analysis/

Yang, Y. (2016). Two sides of the same coin: consequential life cycle assessment based on the attributional framework. *Journal of Cleaner Production*, *127*, 274-281. https://doi.org/10.1016/j.jclepro.2016.03.089

Yesufu, J., McCalmont, J. P., Clifton-Brown, J. C., Williams, P., Hyland, J., Gibbons, J., & Styles, D. (2020). Consequential life cycle assessment of miscanthus livestock bedding, diverting straw to bioelectricity. *Global change biology bioenergy, 12*, 39-53. https://doi.org/10.1111/gcbb.12646

Zhu, L., Schneider, K., & Oude Lansink, A. (2023). Economic, environmental, and social inefficiency assessment of Dutch dairy farms based on the dynamic by-production model. European Journal of Operational Research, 310(3), 1417–1433. https://doi.org/10.1016/j.ejor.2023.05.032.

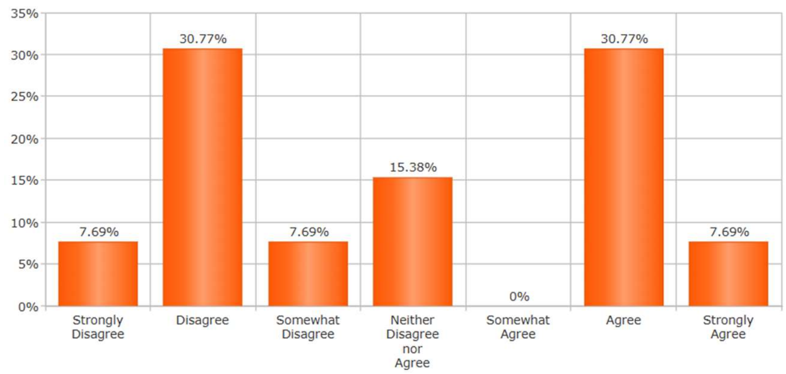
Zira, S., Röös, E., Ivarsson, E., & others. (2020). Social life cycle assessment of Swedish organic and conventional pork production. *International Journal of Life Cycle Assessment, 25*, 1957–1975. https://doi.org/10.1007/s11367-020-01811-y

Appendix 1 – Detailed results of TCA & Biodiversity

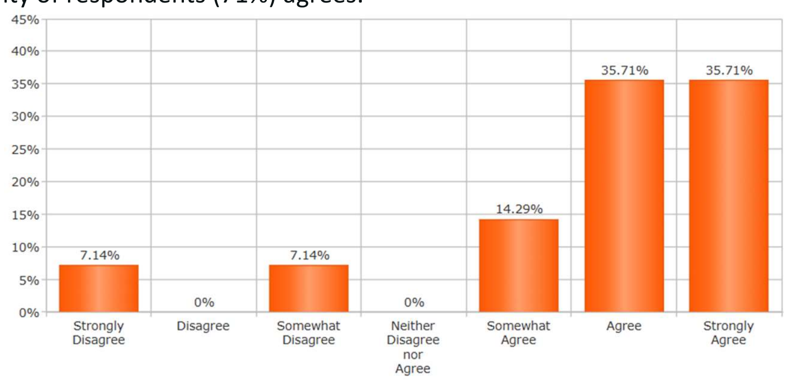
1. Questions on feasibility per measure package

Results feasibility 'light' package

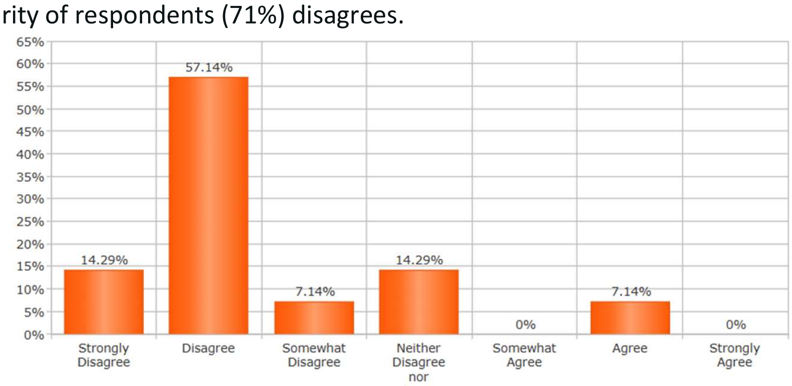
- Q1: *"The light measures package can be applied to livestock systems across all of Europe universally"*
  The respondents have strongly varying views on this statement, no consensus was reached.



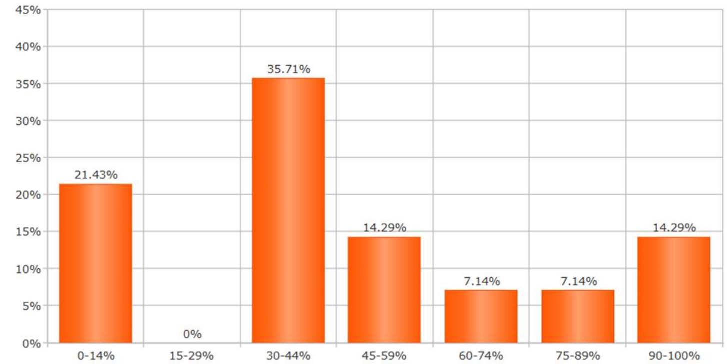
- Q2: *"The feasibility of the light measures package to improve biodiversity depends on local (farm-level) conditions"*
  The vast majority of respondents (71%) agrees.



- Q3: *"The light measures package can be applied to livestock systems for all animal species (cows, pigs, goats, chickens, etc.)"*
  The vast majority of respondents (71%) disagrees.

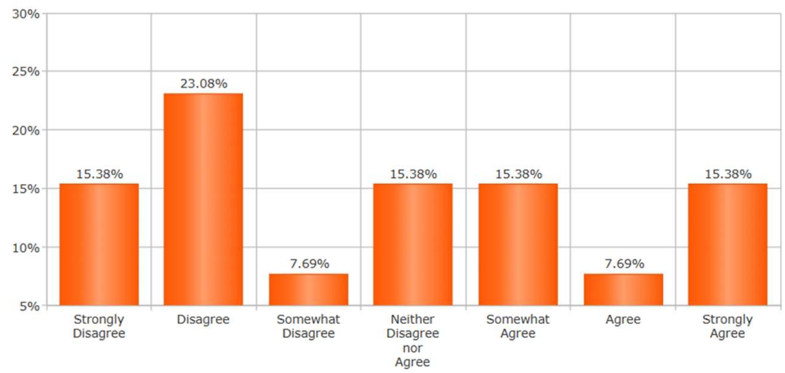


- Q4: *"On what percentage of livestock farms in Europe is it feasible to implement the light measures package?"*
  The respondents have strongly varying views on this question, no consensus was reached.

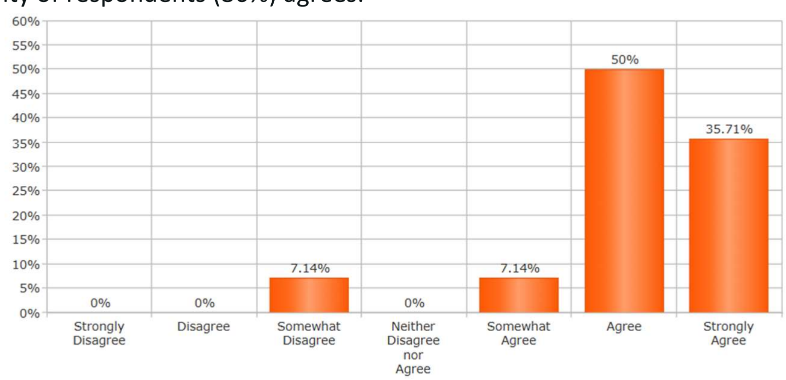


Results feasibility 'medium' package

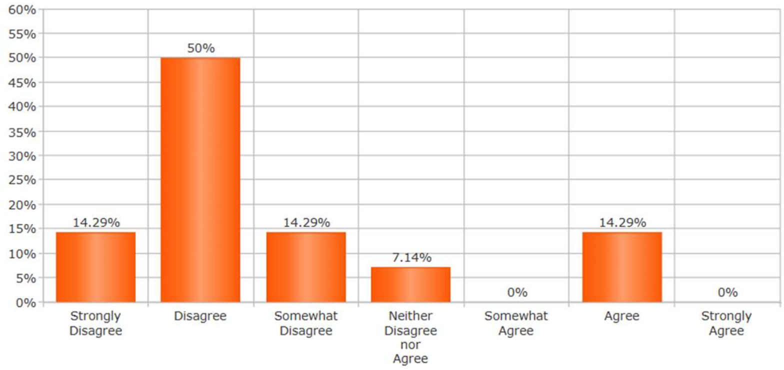
- Q1: *"The medium measures package can be applied to livestock systems across all of Europe universally"*
  The respondents have strongly varying views on this statement, no consensus was reached.



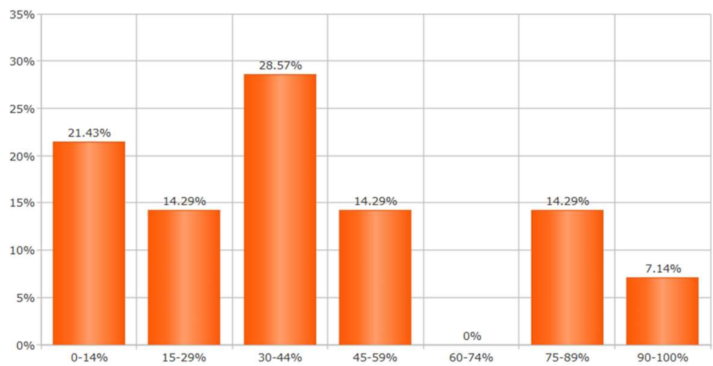
- Q2: *"The feasibility of the medium measures package to improve biodiversity depends on local (farm-level) conditions"*
  The vast majority of respondents (86%) agrees.



- Q3: *"The medium measures package can be applied to livestock systems for all animal species (cows, pigs, goats, chickens, etc.)"*
  The majority of respondents (64%) disagrees.

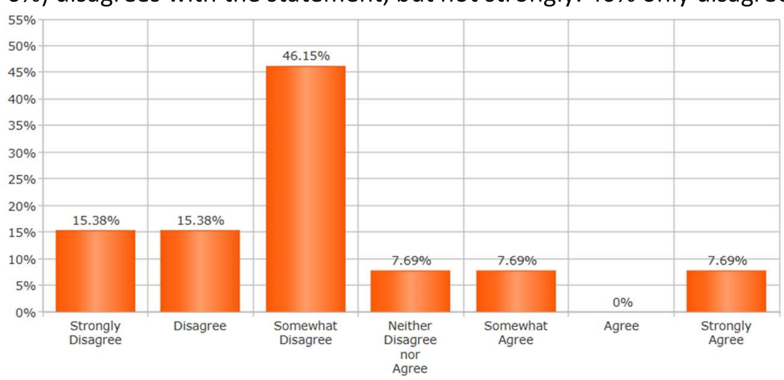


- Q4: *"On what percentage of livestock farms in Europe is it feasible to implement the medium measures package?"*
  64% of the respondents agree that the medium measure package could be implemented on <44% of European livestock farms.

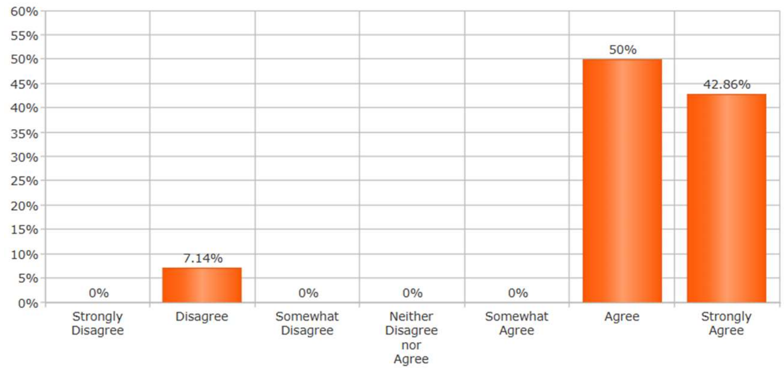


Results feasibility 'heavy' package

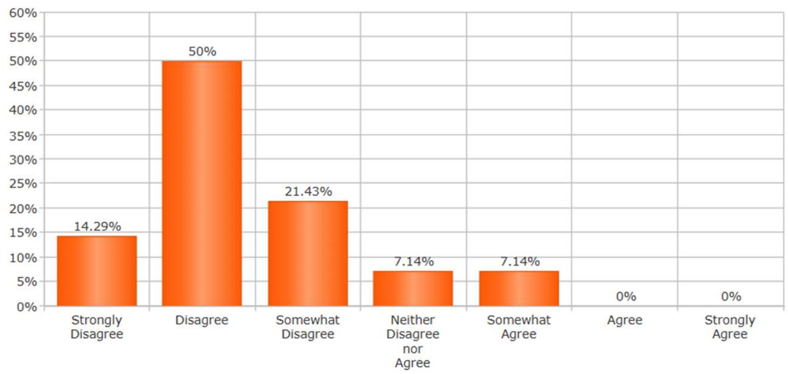
- Q1: *"The heavy measures package can be applied to livestock systems across all of Europe universally"*
  The majority (76%) disagrees with the statement, but not strongly. 46% only disagrees somewhat.



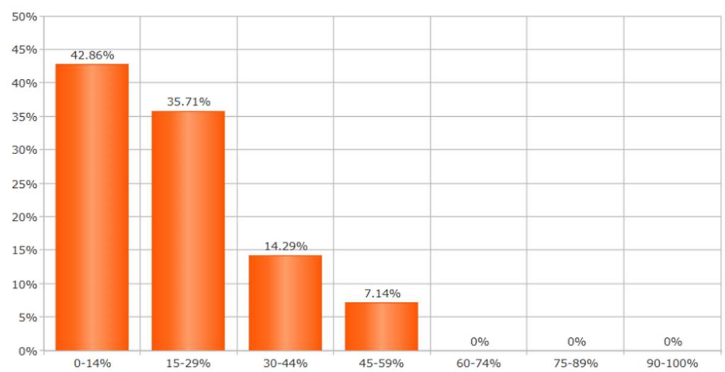
- Q2: *"The feasibility of the heavy measures package to improve biodiversity depends on local (farm-level) conditions"*
  The vast majority of respondents (93%) agrees.



- Q3: *"The heavy measures package can be applied to livestock systems for all animal species (cows, pigs, goats, chickens, etc.)"*
  The vast majority of respondents (64%) disagrees.

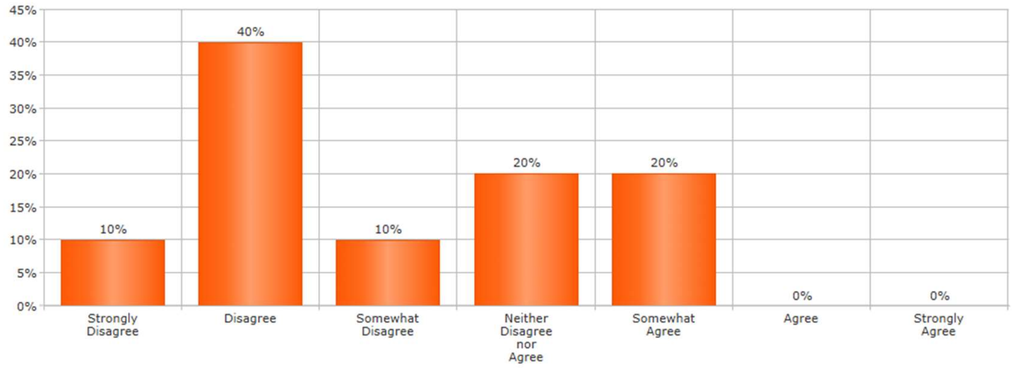


- Q4: *"On what percentage of livestock farms in Europe is it feasible to implement the heavy measures package?"*
  All of the respondents agree that the heavy measure package could be implemented on <59% of European livestock farms. Besides, 79% of the respondents agree that it could be implemented on <29% of the farms.

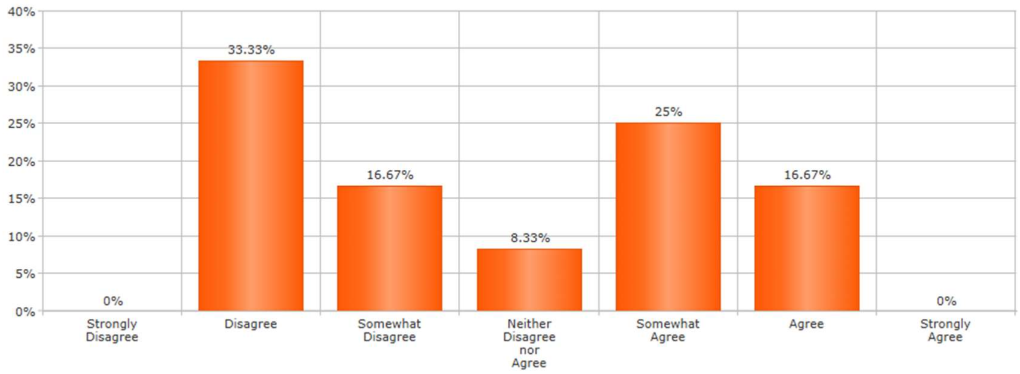


2. Questions on data availability

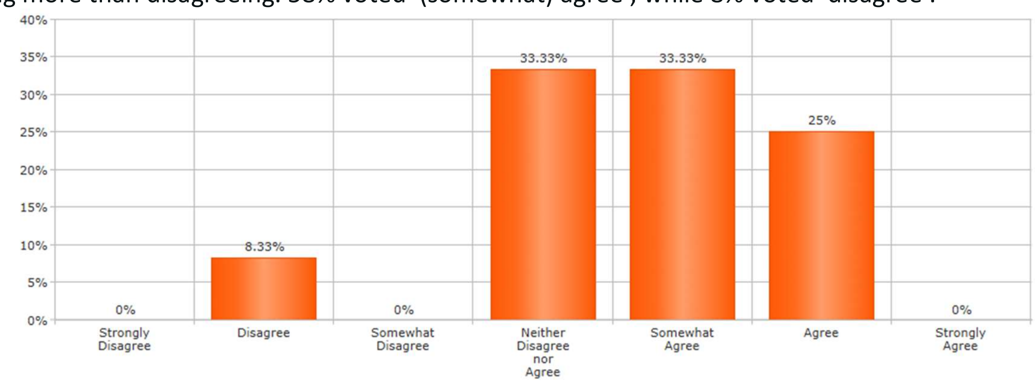
Q1: *"Data is available per EU region about how the selected measures affect the potentially disappeared fraction (PDF) score of species. (PDF is a measure for biodiversity and indicates the percentage or fraction of species that are no longer found due to a man-made impact of some kind)."*
50% of respondents (strongly) disagree with this statement, and 10% somewhat disagree, while 20% remain neutral, and 20% agree somewhat.



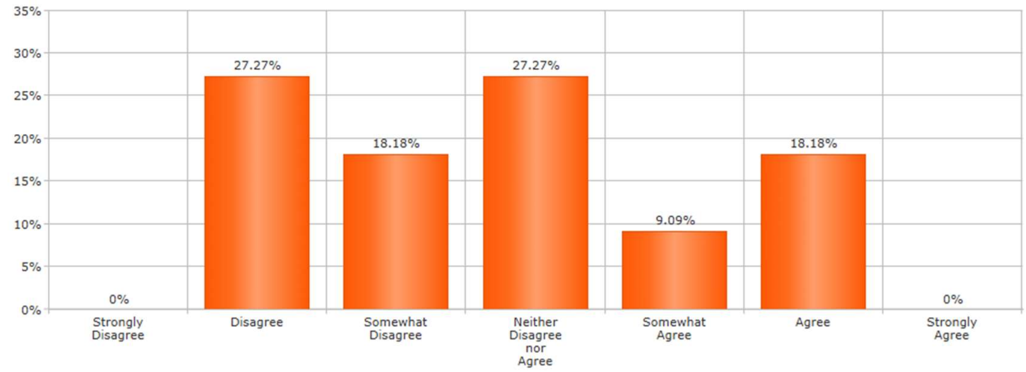
Q2: *"The effects of implementing the measures, on the income of farmers, are known across the EU regions"*
Nobody voted on either 'strongly disagree' or 'strongly agree' on this statement. The answers are spread across the scale, but more people disagree than agree; 50% (somewhat) disagree, while 42% (somewhat) agrees.



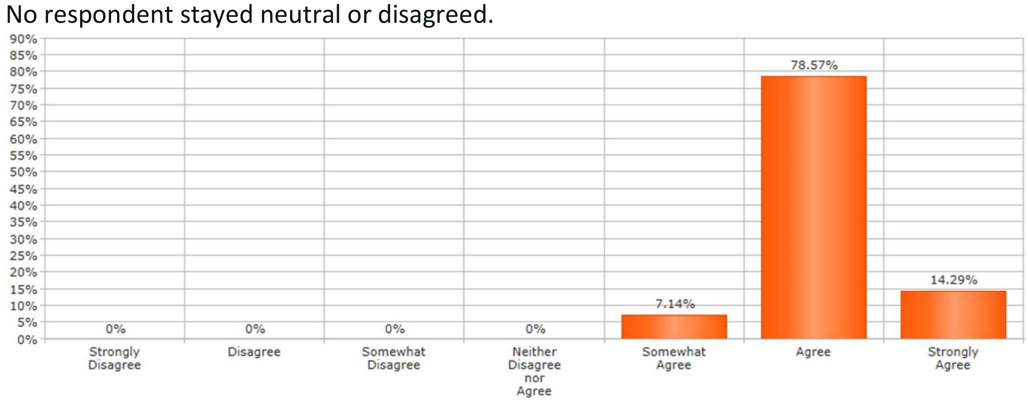
Q3: *"Farmers are willing to share data to calculate the impact of their livestock system on biodiversity (using TCA)"*
Nobody voted on either 'strongly disagree' or 'strongly agree' on this statement. However, respondents were agreeing more than disagreeing. 58% voted '(somewhat) agree', while 8% voted 'disagree'.



Q4: *"Farmers are willing to share their level of income before and after implementing the measures, across the EU"*
Once again, nobody voted on either 'strongly disagree' or 'strongly agree' on this statement. 27% of respondents neither agreed or disagreed with this statement, and another 27% (somewhat) agreed. 45% voted '(somewhat) disagree'.



Q5: *"The relation between the cost of implementing measures at livestock farms and their effect on biodiversity needs to be estimated per type of livestock system in Europe"*
There was a strong consensus on this statement; 14% strongly agreed, 79% agreed, and 7% somewhat agreed. No respondent stayed neutral or disagreed.

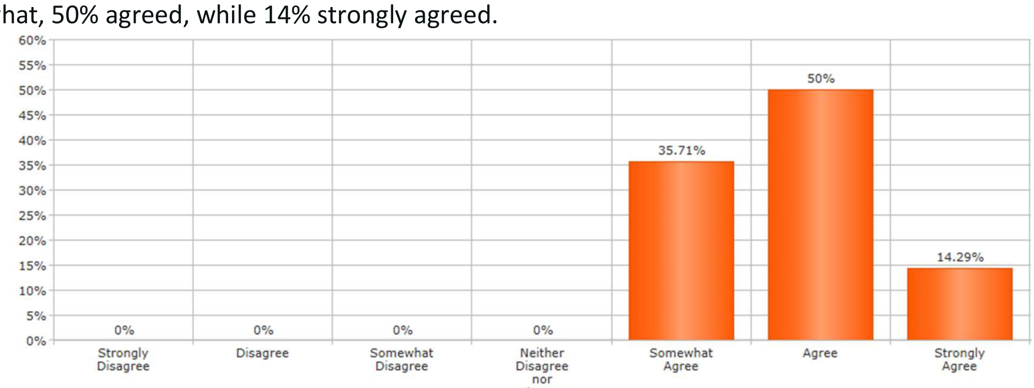


Q6: "*According to compensation feed form Dutch agri-environmental schemes, the costs of the measures are shown in the table below. These costs can be obtained/estimated for other EU countries as well"*

Package	Measure	Costs (euro/ha)
Light	1. Extensively grazed grassland (max 3 cows per hectare), grazing from 1 May until 15 June	€400-700
Medium	1. Extensively grazed grassland (max 3 cows per hectare), grazing from 1 May until 15 June	€400-700
	2. Grass clover, resting period from 1 April until 15 June	€1.000-1.700
Heavy	1. Extensively grazed grassland (max 1.5 cows per hectare), grazing from 1 May until 1 July	€700-820
	2. Grass clover, resting period from 1 April until 15 June	€1.200-1.700
	3. Puddle/swampy grassland for meadow birds from 15 February until 15 June	€1.000-3.500

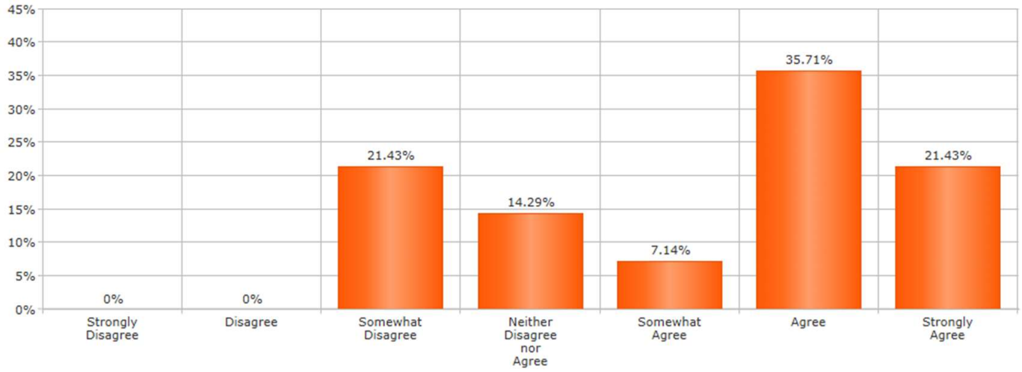
** Costs vary depending on soil type - peat/sandy/clay soil*

There was a strong consensus in the answers; all respondents agreed with the statement. 36% agreed somewhat, 50% agreed, while 14% strongly agreed.

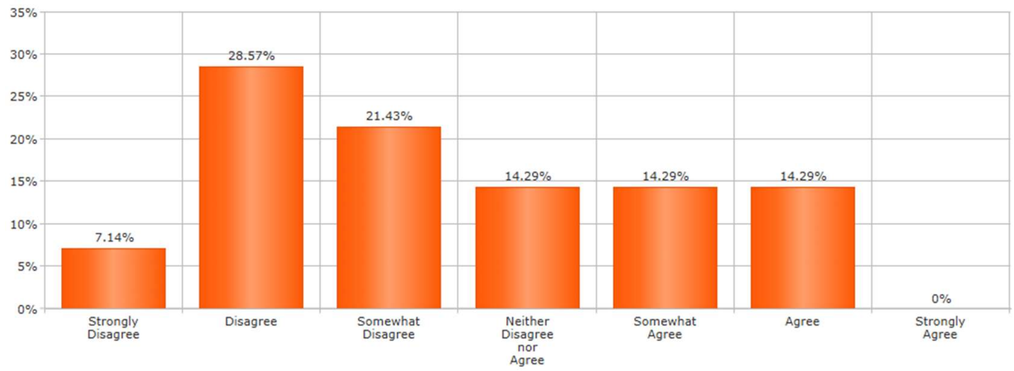


3. Potential ways of implementation of TCA

Q1: *"The best option is to make the implementation government-driven (public). EU or national bodies give subsidies for implementing the measures and/or use regulation to stimulate implementation"*
57% of respondents (strongly) agree with this statement, while 21% somewhat disagree.



Q2: *"The best option is to make the implementation market-driven (private). Products coming from farms which have implemented the measures will be sold for a higher price to the customer (e.g. by using labelling)"*
57% of respondents (strongly/somewhat) disagree with this statement, while 28% (somewhat) agree.



Q3: *"The best option is to do the implementation through a combination of public and private incentives"*
29% of respondents strongly agrees with this statement, and another 43% (somewhat) agrees, meaning that 72% agrees in total. 21% of respondents (somewhat) disagree.