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Review of life-cycle assessments of livestock production: perspectives for application to environmental impact assessment in developing countries

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Contents

Abstract

This review draws on Life-Cycle Assessments (LCA) of livestock value chains. The current state of livestock LCAs is summarized, with an emphasis on limitations and lessons for a developing country context. Of the 149 LCAs reviewed, 19 incorporated developing countries. Key messages are: LCAs can be conducted for livestock value chains in developing countries; and, lessons can be learnt to improve the rigor of alternative methodologies including modeling, indicator specification, allocation of impact and incorporating sensitivity analysis. Further, results from existing LCAs provide a point of reference for future LCAs and sustainability assessments in developing countries.

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Introduction

There is a sustained need for effective environmental assessment methodologies and frameworks for livestock production. This is particularly the case in a development context, where progress can be rapid and environmental safeguards weak.

Life-Cycle Assessment (LCA) provides a rigorous framework to assess a product or system against a range of environmental impact categories from the 'cradle to the grave'. LCA has been increasingly applied to agricultural products, including those from livestock. A limited number of published LCAs have assessed livestock in developing countries.

Defined by ISO 14040 and 14044, LCA sets out a clear method for analysis, including goal and scope definition, Life-Cycle Inventory (LCI), Life-Cycle Impact Assessment (LCIA) and sensitivity/uncertainty analysis (ISO 2009).

As a data intensive and complex methodology, LCA may not be suited to some developing country contexts. In these cases, the method employed can be enhanced from an understanding of existing livestock LCAs.

This review seeks to: summarize the current state (level of activity, range of impact categories, geographical spread) of LCA application to livestock production and products; summarize the current state of LCA application for livestock in developing countries; identify limitations for LCA application in a development context; identify lessons learnt by LCA practitioners applicable to researchers assessing the sustainability of livestock production in a developing country context.

Materials and methods

Literature has been collected from journals and institutions using search terms that relate to the LCA methodology, the livestock sector, sub-sectors, products, co-products and waste streams. Further, literature has been sought to support a critique of various LCA elements.

In total 201 livestock related LCAs were identified. The full text of 149 of these could be accessed through Scopus, ScienceDirect and other online sources. For all articles the sub-sector of focus was noted; further analysis was undertaken drawing on full text publications.

This review summarizes published works by each core element of an LCA. Elements are defined as: goal and scope, LCI, LCIA, sensitivity analysis and results from LCAs. Drawing from the results of LCAs, the review discusses the dominant sources of impact, comparing LCAs, mitigation and trade-offs.

Table 1: Summary of livestock LCAs in developing countries

Study	Country	Industry/Product(s)	Functional unit	Value Chain length	Impact categories	Sensitivity
Bennett et al. 2006	Argentina	Poultry	1kg LW	Cradle to plant door	GWP; ODP; HTP; FWAETP	No
de Léis et al. 2014	Brazil	Dairy	1kg ECM	Cradle to farm gate	GWP	Yes
(Ruviaro et al. 2014)	Brazil	Beef	1kg LWG	Cradle to farm gate	GWP	Yes
Alvarenga et al. 2012	Brazil	Broiler chickens	tonne of feed	Cradle to gate	GWP; AD; AP; EP; ODP; HTP; MAETP; TETP; POCP; LC	No
Gerbens-Leenes et al. 2013	Brazil, China, Netherlands, USA	Poultry, pork, beef	l of water type per kg of product	Feed production and herd management	Water footprint	No
Huang et al. 2014	China	Dairy	1kg FPCM	Cradle to packaged milk	H_20-e	Yes
Liang et al. 2013	China	Livestock	Average number of livestock	Husbandry and waste	GWP	No
Xie et al. 2011	China	Dairy	1000 l of milk	Packaging	Human health; EQ; AD	No
Opio et al. 2013	Global	Ruminant livestock	1kg CW or 1kg FPCM	Cradle to retail	GWP	Yes
FAO 2010	Global	Dairy	kg FPCM	Cradle to retail	GWP	Yes
Hagemann et al. 2011	38 countries, including 12 developing	Milk	kg FPCM	Cradle to gate	GWP	No
Zervas & Tsiplakou 2012	Global	Small ruminants and all livestock	LW	Cradle to grave	GWP	No
Daneshi et al. 2014	Iran	Dairy	1kg FPCM	Cradle to packaged milk	GWP	No
Alqaisi et al. 2013	Jordan	Dairy	kg FPCM	Cradle to gate	GWP	No
Weiler et al. 2014	Kenya	Livestock	1kg Milk	Cradle to farm gate	GWP	Yes

Bartl et al. 2011	Peru	Milk	kg FPCM or 1 animal	Feed production and herd management	GWP; AP; EP	Yes
Djekic et al. 2014	Serbia	Dairy	1kg dairy product	Cradle to packaged product	GWP; AP; EP; ODP; POCP; HTP	No
Tongpool et al. 2012	Thailand	Poultry - broiler	tonne of feed	Cradle to packaged feed	GWP; ODP; HTP; AD; POCP; PM; AP; EP; TETP; +3 others	No
Phong 2010	Vietnam	Agriculture/aquaculture	Kcal	Cradle to farm gate	GWP; EP; AP	No

Functional unit abbreviations	**Impact category abbreviations**	EP= Eutrophication potential
FPCM= Fat and protein corrected milk ECM= Energy corrected milk Kcal= kilocalorie M^3= Cubic metres Ha= Hectares SW=Slaughter weight LW= Live-weight LWG= Live weight gain CW= Carcass weight HSCW = Hot Standard Carcass Weight	HTP= human toxicity potential (HTP) FWAETP= fresh water aquatic ecotoxicity potential AP= acidification potential MAETP= Marine aquatic ecotoxicity potential POCP= Photochemical Ozone Creation Potential EQ= Ecosystem quality RD= Resource depletion NREU= Non-renewable energy use LC= Land competition ODP= Ozone depletion potential	AD= Abiotic depletion TETP= Terrestrial ecotoxicity GWP= Global Warming Potential LU= Land use H20-e= water depletion normalised by scarcity EF= Ecological footprint PM= Particulate matter formation

System boundaries, inventory, impact assessment and sensitivity

Researchers have utilized the LCA methodology to address questions on the environmental impact of livestock production. Figure 1 shows a marked increase in the number of livestock related publications this decade; of all articles identified, 159 were published from 2010 to 2014. Subsectors of focus include beef, sheep, poultry and pig. Dairy has received the highest amount of research attention, accounting for 92 of the 201 publications identified.

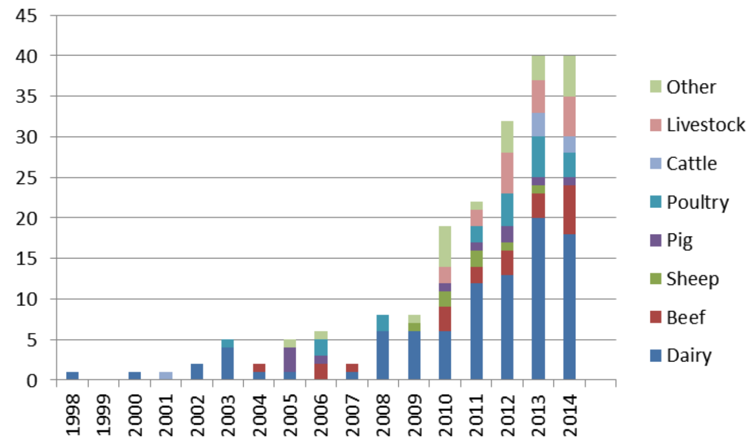

Figure 1: Publications by year and sub-sector n=201

The majority of livestock LCAs have been conducted in OECD countries. There are 19 studies that assess developing country[1] value chains, these are summarized in table 1 (refer to the Supplementary Information for a summary table of all studies).

LCA element 1: Goal and scope

The ISO standard for LCA requires practitioners to provide clear goals and a well-defined scope. This element is the basis for the Life-Cycle Inventory (LCI), and the impact categories assessed.

The LCAs reviewed in this study had a range of goals, from comparing products or systems, to challenging LCA methodology. The primary purposes are summarized in table 2.

Table 2: summary of primary LCA purpose*

Purpose category	Number of obs.
Improve LCA methodology	17
Quantify impact	39
Quantify marginal impact	1
Economic and social impact of mitigation	2
Footprinting	5
Hotspot identification	11

[1] Developing countries as defined by the World Bank

Global benchmarking	1
Compare products or systems	60
Mitigation options	19
Environmental trade-offs	1

*These categories reflect the primary goal that was stated, not the range of goals pursued in each study.

These goals incorporated a range of impact categories, with Global Warming Potential (GWP), Acidification Potential (AP) and Eutrophication Potential (EP) being the most common. Ninty-one studies assessed multiple impact categories, four of which assessed over 10 (summarized in supplementary information). Impact categories are discussed further in the Life-Cycle Impact Assessment (3.3. LCIA) section.

System boundaries

The scope of an LCA needs to be comprehensively defined to allow for peer review and comparison. The system boundaries describe the length of the value-chain assessed and the factors included/excluded from analysis. Regarding value-chain length, Nijdam et al. (2012, p. 762) summarized the prevailing trend in livestock LCAs: *"Although a full life cycle assessment should cover 'cradle to grave', most of the studies cover only the chain from 'cradle to farm gate'"*. Thirteen of the reviewed LCAs assessed from cradle to grave/consumption, with a further eleven assessing from cradle to port, retailer or packaged product. The prevalence of partial LCAs of livestock does allow for in-depth analysis of individual stages of the chain, but loses part of the power of an LCA. Spoilage due to on-farm practices, for example, can increase the environmental burden per unit of milk consumed and result in environmental impacts at the processor level.

Factors associated with the value-chain scope can be excluded if justified by an LCA practitioner. Grown and imported feed, animal husbandry, mortality, transport, electricity and capital infrastructure are all factors that need clear system boundaries. The defined system boundaries can have a significant impact on estimated environmental impact and comparability.

Functional unit

This is the unit that the environmental impacts are ascribed to. A detailed functional unit improves the clarity of LCA results and can provide a more accurate representation of the impacts. For LCAs assessing dairy, impact per kilogram of Fat and Protein Corrected Milk (FPCM) was a common unit of measurement, other functional units are summarized in table 1 and appendix table A1.

A functional unit can allow for comparison with other studies, however the variability in functional units hampers this (Reckmann et al. 2012; Yan, 2011). Further, the functional unit is often not suited to comparison between products; One litre of FPCM for example is not necessarily nutritionally equivalent to 1 kg of beef.

There has also been some debate about the relevance of area as a functional unit. Yan et al. (2011 P 373) argue that the "real reductions in impact need to be balanced against demand for products", of which area is neither a function nor measure.

LCA element 2: Life cycle inventory

The underlying data and parameters of an LCA are referred to as a Live-Cycle Inventory (LCI). A LCI for livestock generally includes farm and/or processor level data, assumed values for parameters, emission factors and modeling specifications.

Livestock related LCAs highlight the two drawbacks of the data intensive nature of the methodology. Firstly, the lack of available inventory data limits impact categories that can be assessed (Daneshi et al. 2014; Dolman et al. 2012; Castanheira et al. 2010; Thomassen et al. 2008).

Secondly, the use of default inventory data *"based on very simplified models of complex systems"*) can produce misleading results (Flysjö, et al., 2011, P. 466; Nijdam et al. 2012; O'Brien et al. 2012). This is particularly a challenge when LCI values are not clearly summarized, as in the case of some of the assessed LCAs.

LCA element 3: Life cycle impact assessment

Central to an LCA, Life-Cycle Impact Assessment is the process of utilizing inventory data to generate environmental impact indicators. Many of the impact categories utilized in the reviewed articles are listed in Table 2.

Table 3. Impact categories in reviewed LCAs

Impact category
Abiotic depletion
Acidification potential
Biodiversity
Ecosystem quality
Eutrophication potential
Fresh water aquatic ecotoxicity potential
Global Warming Potential
Particulate matter
Human toxicity potential (HTP)
Land competition
Land use
Marine aquatic ecotoxicity potential
Non-renewable energy use
Nutrient balance
Ozone depletion potential
Photochemical Ozone Creation Potential
Resource depletion
Soil acidification
Terrestrial ecotoxicity
Water depletion

Current and emerging impact categories

There is a continuum of acceptance of impact categories represented in livestock related LCAs. Atmospheric categories are accepted as adequate mid-point indicators, whereas location specific categories have been recently developed, are being improved or are emerging as new categories.

Modeling the processes and flows of Green-House Gasses (GHGs) and converting GHGs to GWP as a mid-point indicator is widely accepted. The marginal impact on the concentration of GHGs is adequate as an environmental indicator because there are related global thresholds and reduction targets.

There are different models available to estimate the output of GHGs. The accuracy ruminant emissions in livestock LCAs (following IPCC guidelines) has been criticized as being too simplistic. This is especially the case for developing countries where other, more accurate models exist and are in ongoing development (Herrero et al. 2013). Further, the treatment of Land Use Change (LUC) differs between studies, where using PAS2050 or iLUC alters the results substantially (Dalgaard et al. 2014). The LEAP guidelines (2014) recommend impacts from LUC to be reported separately to the rest of the activities – making this facet of LCA more transparent.

Other impact categories where the location of emission/use is relevant includes: Eutrophication potential, acidification potential, ecotoxicity and water use. These mid-point indicators are rarely extended into end-point impact (Röös et al. 2013). There have been, however, rigorous debates on communicating the impacts associated with water depletion. Water use normalized by a local water stress index (WSI) removes some of the ambiguity in interpretation associated with volumetric water use (Ridoutt & Pfister 2010; Ridoutt et al. 2010). Several researchers have called for impact on water availability to be incorporated into more studies (Picasso, 2014; Reckmann et al. 2012). It should be noted that there are models available for extending eutrophication and acidification to end-point impact, such as ReCiPe (LEAP 2015).

A comprehensive measure for soil impacts is being debated in the literature. Garrigues et al. (2012) suggest developing a 'mid-point indicator' which would then inform an endpoint indicator called 'damage to ecosystem diversity'. Garrigues et al. (2012), Peters et al. (2011) and Yan et al. (2011) also stress the importance of developing the soil impact category for livestock LCAs. Current compaction indicators designed for crop production, for example, could be extended to incorporate livestock sources of impact (Garrigues et al. 2012); and micro nutrients can be assessed in an LCA framework (Peters et al. 2011).

Four of the 149 LCAs incorporated biodiversity (namely: Picasso 2014; Mueller et al. 2014; Binder et al. 2012; Haas et al. 2001). This is a complex and data intensive impact category. Most methods for assessing biodiversity use Species-Area Relationships (LEAP 2015). The LEAP review (2015) identifies four available methods for producing a biodiversity indicator: ReCiPe's Biodiversity loss indicator, Ecological Damage Potential, species richness and ecosystem productivity, and Mean Species Abundance (MSA - demonstrated in De Baan et al. 2013). Several authors are advocating for biodiversity to be incorporated into more livestock related LCAs (Dolman et al. 2012; Yan et al. 2011)

Other categories that have been proposed include: antibiotic use (Reckmann et al., 2012) and phosphorous loss (Yan et al. 2011).

Further, there is a need to incorporate a wide range of environmental impact categories in any given LCA so the trade-offs between them can be investigated (Picasso et al., 2014; de Boer et al. 2011; Ridoutt et al. 2011).

Social and economic impact categories

Several studies have called for greater integration of social and economic assessments along with environmental factors (Picasso et al. 2014; Weiler et al. 2014; Binder et al. 2012; Yan et al. 2011). Binder et al. (2012) assert that decision makers are poorly equipped without such a comprehensive assessment.

Fifteen studies did incorporate environmental impact categories along with the impact category that largely has economic implications: abiotic depletion. One novel approach of incorporating economic aspects was termed 'Life Cycle Costing', coupled with LCA (Asselin-Balençon & Jolliet 2014).

One interesting case where the lines between environmental and social aspects are burred is found in Weiler et al. (2014). In this study, environmental impact was allocated to social systems such as status, liquidity and substitutes to finance and insurance. While not explicitly quantifying the impacts across the lifecycle, this does raise some insights into the social trade-offs with environmental mitigation options.

Allocation and system expansion

When a functional unit relates to one of many goods produced by a system, the estimated impact per unit is not immediately apparent. In such cases, the environmental impact of the functional unit can simply be accepted as overstated and assigned solely to the functional unit as in Flysjö et al. (2012); impact can be allocated to co-products based on bio-physical or economic basis; or, the system boundaries can be expanded to conduct a consequential analysis.

Eight of the 149 reviewed studies used a Consequential LCA (CLCA). CLCA asks the question: what is the environmental impact of the co-product if it had to be produced elsewhere and then sold in the same marketplace? This is the preferred method of ISO 14044, where the environmental benefit of this co-product, if any, is then subtracted from the total impact and assigned to the functional unit (Avadí & Fréon 2013; Eady et al. 2012; O'Brien et al. 2012; Yan et al. 2011). This is a complex modeling process that requires insights into how agents (supermarkets, feed traders etc.) will act in hypothetical situations, for which economic models can be used (Nguyen et al. 2013). This modeling also requires additional LCI parameters, as studies on production systems often far away from the primary study location must be undertaken.

Multiple CLCA studies, according to their calculations, noted that attributional LCA (ALCA) impact estimates are overstated. Cederberg et al. (2003) found that biogenic emissions should be lower for the Swedish dairy industry, when the beef industry is considered. Lehuger et al. (2009 P. 624) found that *"four out of 10 [impact categories] were improved[/lessened] with system expansion".* Flysjö et al. (2011) found that system expansion resulted in a 63–76% lower footprint for Swedish and New Zealand dairy production (compared to 100% allocation to milk).

The implementation of CLCA, however, has its limitations. It is data intensive and complex to model (Thoma et al. 2013), *"particularly for livestock"* (Eady et al. 2012, P. 148). The complexity of modelling also introduces another element of uncertainty into the results that needs to be accounted for. These reasons give an insight into why the majority of studies utilized ALCA methods.

An ALCA works to allocate emissions to various goods based on, depending on the relevance, bio-physical relationships or by economic values (Eady et al. 2012; O'Brien et al. 2012). Goods can include feed for animal production versus human food as well as milk, eggs, meat, skins, hides, and fibre. Allocation methods can influence the estimated impact considerably (Flysjö et al. 2011; Cederberg et al. 2003).

The LEAP guidelines offer specific recommendations for allocation in livestock LCAs. For small ruminants, biophysical allocation is recommended on farm and economic allocation between fibre and meat. For poultry, system expansion between eggs and meat is recommended. For feed it is recommended to use biophysical allocation when inputs are not attributed to a specific crop, or using economic allocation or crop area.

The LEAP guidelines also provide detail for allocation for transport, processing, manure and fertilizers.

The LEAP guidelines and ISO standard allows for allocation to multiple products, but does not set limits on what can and can not be allocated to. de Vries and de Boer (2010) and Weiler et al. (2014) raise concerns of allocation in developing country contexts which have multiple functions. Weiler et al. (2014) found that the GHG estimates using economic allocation was higher at 2 kg CO_2-e compared to 1.6 kg CO_2-e for when non-market goods are allocated emissions. The inclusion of non-market goods and farmer centered valuations are a pertinent issues for livestock LCAs in developing countries and globally.

LCA element 4: Sensitivity / uncertainty analysis

A sensitivity analysis assesses the impact of an LCA component on the results. One third of the reviewed LCAs incorporated a sensitivity / uncertainty analysis (Refer to table A1 in the appendix for a summary of components assessed). Many of the sensitivity analyses indicated the most influential inputs, parameters and design features and presented the overall uncertainty on the results. The aim of these analyses is to provide decision makers with a more transparent source of information.

Some studies utilized Monte Carlo simulations (MCS) to characterize the uncertainty. Chen et al (2014) notes two limitations with using MCS. Firstly that the mean and distribution of each parameter in question needs to be known, and secondly that correlations between variables need to be investigated.

Source of impact, LCA comparison, mitigation and trade-offs

Through chain – source of impact

From the 24 LCAs assessing pre and post-farm gate activities, those activities pre-farm gate were generally the largest contributor to impact categories. Table 3 summarizes the percentage of impact attributable to pre-farm gate activities, by study and impact category; the majority of studies attributed over 70% of 'impact' to pre-farm activities.

In the case of dairy, Fantin et al. (2012) state that: "raw milk production at farms dominates the whole life cycle for all impact categories"; Yan et al (2011) stated that 80% of GHG emissions from European dairy is primary production related; For other livestock products, Roy et al. (2012, P.221) reaffirm that "the production stage is the main contributor [to GHGs] in the life cycle of meat [(chicken, pork and beef)]".

The dominance of pre-farm gate activities should not detract from the value of conducting through chain assessments. As mentioned in discussion on system boundaries, an assessment concluded at the farm gate assumes that the remaining value-chain components are effective.

The lesson here is that modeling and inventory specification on-farm will be a significant portion of the overall output for many impact categories (Kim et al. 2013; Fantin et al. 2012; Roy et al. 2012; Yan et al. 2011; Cederberg, 2009), greater allocation of effort may be justified for this stage of the chain if post farm gate functions are deemed efficient.

Table 4. Impact pre-farm gate for through chain studies (percent of total impact category)

	Begtsson, Seddon, 2013	Berlin, 2002	Davis et al., 2010	Fantin et al., 2012	Ridoutt, Pfister, 2010	Thevenot et al., 2013	Verge et al., 2013	Verge et al., 2013
	Chicken	Cheese	Pork chop (conventional)	Milk	Pasta sauce / Peanut M&Ms	Chicken	Milk	Yogurt
GWP	81.39	94.38	56.35^	85	-	89.67	86.9	72.2
Acidification	-	98.98	-	92	-	97.73	-	-
Eutrophication	-	99.36	96.44	97	-	98.22	-	-
POCP	-	93.7	-	84	-	-	-	-
Ozone layer depletion	-	-	-	62	-	-	-	-
Water depletion / footprint*	75.08	-	-	-	97	-	-	-
Abiotic depletion	80.84	-	34.64ł	-	-	-	-	-
Ecopoints	87.12	-	-	-	-	-	-	-

*Stress-weighted, including grey water in Ridoutt et al. (2010)

^GWP: 13% of emissions at processor and 13% at household in Davis et al. (2010)

ł Abiotic depletion: 19% of impact at processor, packaging 14%, household 23%.

Comparison between systems and products

Many LCAs aim to compare systems within a subsector. A smaller portion of studies, however, compare impact categories between products. Several studies that do compare products, do so by harmonizing multiple LCAs.

Harmonizing LCAs is challenging due to variations in system boundaries, functional units, inventories utilized, the impact categories investigated and the method of allocation (Fantin et al., 2012; Bengtsson et al., 2013; Reckmann et al., 2012; Yan et al., 2011).

For chicken, Bengtsson et al. (2013) identified a range for GWP between 2000 and 5480 kgCO_2 eq/t of liveweight across eight studies.

de Vries and de Boer (2010) compared the impact categories from 16 LCAs on pork, chicken, beef, milk and egg. All studies are compared against common functional units – protein and daily intake. Ranges for land use, energy use, GWP, acidification and eutrophication were summarised. There was a strong overlap between GHG emissions (per kg of protein) for all products except beef, which had a lower bound of almost twice the emissions of other products.

Röös et al. (2013) analyzed 23 LCAs on pork, chicken and beef. Impact categories included: GWP, MJ primary energy, area in m^2, acidification and eutrophication.

Schmidinger & Stehfest (2012) also incorporated non-livestock products into their comparison. One of their findings was that *"soybased products like tofu can be more than half as high as those of intensive chicken breeding"* (Schmidinger & Stehfest 2012, P 970).

The LEAP guidelines aim to standardize livestock LCAs and the claims drawn from them. Guidelines include sections for system boundaries, co-product allocation, land use change and sensitivity analysis. As more LCAs follow these guidelines comparability will improve.

Mitigation

Some studies suggested system changes to mitigate environmental impacts, where many instances were confined to the farm. Some suggested that intensification could reduce GHG emission intensity (Weiler et al. 2014; Flysjo et al. 2011); Others focused on mitigation through manure management (Delgaard et al. 2014; Styles et al. 2014).

Trade-offs between impact categories

The trade-off between impact categories is an important consideration in the overall environmental benefit of mitigation activities (de Boer et al. 2011). Röös et al. (2013) did assess the relationship between impact categories; Findings varied between monogastrics and ruminants; Interventions on the carbon footprint of monogastrics did not negatively affect other impact categories; The case of ruminants was more complicated and variable. Studies such as Röös et al. (2013) though, are not common.

Lessons for a developing country setting

Despite challenges, LCAs can be conducted in a developing country context. In cases where limitations do not allow for an LCA, alternative methodologies can be strengthened from LCA principles. Limitations in developing countries precluding LCA could include a lack of accurate data for direct or indirect activities, lack of modeling of specific systems, limitation in expertise, time or financial constraints.

Existing livestock LCAs have addressed many challenges common to all environmental assessment frameworks. Lessons that can be drawn on in a developing country context relate to: models, system boundaries, data inventory, indicator design, allocation of impact, sensitivity analysis and transparency.

i. Existing LCAs provide for a wealth of models and indicators relating to the relationship between complex biophysical processes and environmental impacts. Some of these models and indicators could be transferrable to a developing country context.

ii. 'System boundaries' is an important concept for any environmental impact assessment. Clarity on what is outside the scope of analysis and why provides greater transparency for peers and target audiences and allows areas to be improved on in the future.

iii. The availability and accuracy of data is a limitation in a developing country context. Ideally locally specific data should be sourced and in some instances, over several years. In the case that this is not possible, results need to be presented with relevant caveats. This is particularly the case for pre-farm gate data, due to the share of burden for many impact factors

iv. The LCA methodology does not yet cater for all livestock related environmental impact categories. In particular, soil and biodiversity impact categories are under active development. Integrating social and economic aspects into LCA does not appear to have a strong basis in literature or standards as yet.

v. The LEAP guidelines can increase consistency of impact allocation and reporting between LCAs. There is still need, however, to provide guidelines on multi-functional systems in developing countries.

vi. The largest source of impact often comes from on-farm activities. While losing some of the benefit of undertaking an LCA, it can be justified to analyze up to the farm gate.

vii. Sensitivity analysis of various components of an environmental assessment allows for future improvement and transparency. In instances where Monte Carlo simulations are undertaken, assumptions need to be stated.

viii. Existing impact assessments and mitigation proposals can be assessed in developing country contexts.

viii. Trade-offs between impact categories need to be considered when assessing the environmental benefit of an intervention.

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Annex 1: Components considered in sensitivity analyses

Study	Sensitivity component
Adom et al., 2013	Mill inputs
Bartl et al., 2011	Allocation choices
Basset-mens et al., 2006	Crop yields, feed ratios
Battini et al., 2014	Manure storage
Belflower et al., 2012	Management changes
Berlin, 2002	System boundaries and allocation
Binder et al., 2012	Changes to sustainability ranges - ie. parameters
Casey et al., 2006	Emission factors
Chen et al., 2014	Manure management, animal housing and leachate
Dalgaard et al., 2014	Beef system, crop yields; milk yield
de Boer et al., 2012	Effect of crop yields and root depth on water requirements
de Leis et al., 2014	Feed quality parameters
De vries et al, 2012	Minimum and maximum values for LUC, higher fugitive methane emissions from the digestion facility, a higher electric efficiency of the biogas engine, and increased NFRV of the digestates.
Dudley et al., 2014	Land use change, soil emissions, soil carbon, enteric fermentation, manure methane emissions, dry matter intake, crop yield, animal mass
Eide et al., 2003	Amount of cleaning chemical used
FAO, 2010	Herd and feed characteristics
Flysjö et al., 2012	Emission factors
Guerci et al., 2014	Allocation and land use change
Huang et al., 2014	Allocation (economic and biophysical), farm type compared to average farm
Ledgard et al., 2011	Including customer travel
Lehuger et al., 2009	Cropping techniques
Leinonen et al., 2012	Activity data
Leinonen et al., 2013	Uncertainty analysis
Lijo et al., 2014	Methane losses, production of heat and energy
Mogensen et al., 2014	Emission factors and assumptions
Nguyen et al., 2013	Prices
Nielsen and Høier, 2009	Assumptions
O'Brien et al., 2011	Country specific emission factors
O'Brien et al., 2012	Biophysical v economic allocation
Ogino et al., 2013	N excretion rate, N2O emission factor from waste water, emissions from feed and supplements
Opio et al., 2013	Parameters and emission factors; soy production scenarios; land use change
Pelletier et al., 2010	Modeling SOC
Picasso et al., 2014	Rate of soil sequestration
Prapaspongsa et al., 2010	Manure dry matter, manure storage and application conditions, marginal electricity suppliers

Roer et al., 2013	Emission factors for livestock and land
Ross et al., 2014	IPCC coefficients and EFs
Rotz et al., 2010	Activity data
Ruviaro et al., 2014	Feed quality parameters and intake
Samuel-Fitwi et al., 2013	Energy sources
Sandars et al., 2003	Key variables
Sanders and Webber, 2014	Energy and transport
Schader et al., 2014	Milk yield, concentrates
Sonesson & Berlin 2003	Assumptions
Styles et al., 2014	Ranking of feedstock options
Thevenot et al., 2013	Emission factors for ammonia emissions
Thoma et al., 2013	Products loss/waste at consumer stage
Thomassen et al., 2008	Market situations
van der Werf et al., 2005	Calculation methods
Van Middelaar et al., 2013	Carbon payback period after conversion from grassland
Zehetmeier et al., 2014	Parameters or variables that are important contributors to GHG emissions and show a high degree of variability

Annex 2: Summary of livestock LCAs assessed

Study	Country	Industry/Product(s)	Functional unit	Value Chain length	Impact categories	Sensitivity
Bennett et al. 2006	Argentina	Poultry	1kg LW	Cradle to plant door	GWP; ODP; HTP; FWAETP	No
Gollnow et al. 2014	Australia	Dairy	1kg FPCM	Cradle to farm gate	GWP	No
Williams et al. 2014	Australia	Dairy	1l FPCM	Cradle to farm gate	GWP	No
Bengtsson & Seddon 2013	Australia	Poultry	ton of roast chicken breast fillet	Cradle to consumption point	Eco-points: AD; AP; TETP; MAETP; EP; GWP; HTP; ionizing radiation; land transformation and use; ODP; POCP; respiratory effects; and water depletion	No
Ridoutt et al. 2013	Australia	Beef	kg LW	Cradle to farm gate	GWP; consumptive water use; LU	No
Eady et al. 2012	Australia	Sheep mixed	tonne grain, kg greasy wool, animal	Cradle to farm gate	GWP	No
Peters et al. 2011	Australia	Red meat	1 kg of HSCW meat	On farm (gate to gate)	Nutrient balance; soil acidification	No
Ridoutt et al. 2011	Australia	Beef	1kg LW	Cradle to farm gate	GWP; H2O-e	No
Ridoutt et al. 2010	Australia	Dairy	tonne of SMP delived to Japan	Cradle to port	H2O-e	No
Ridoutt & Pfister 2010	Australia	Lamb	kg lamb at retail	Cradle Australia to retailer in USA	H2O-e	No
Biswas et al. 2010	Australia	Sheep	1kg meat / wool	Cradle to farm gate	GWP	No
Peters et al. 2010	Australia	Red meat	1 kg of HSCW meat	Cradle to processing gate	Transferred water; net water use	No
Peters et al. 2010	Australia	Red meat	1 kg of HSCW meat	Cradle to farm gate	GWP; total energy; waste	No
Wood et al. 2006	Australia	Conventional v organic	Dollars of sales	Cradle to farm gate	GWP; water use; land disturbance; total energy use	No

Functional unit abbreviations	Impact category abbreviations	
FPCM= Fat and protein corrected milk	HTP= human toxicity potential (HTP)	EP= Eutrophication potential
ECM= Energy corrected milk	FWAETP= fresh water aquatic ecotoxicity potential	AD= Abiotic depletion
Kcal= kilocalorie	AP= acidification potential	TETP= Terrestrial ecotoxicity
M^3= Cubic metres	MAETP= Marine aquatic ecotoxicity potential	GWP= Global Warming Potential
Ha= Hectares	POCP= Photochemical Ozone Creation Potential	LU= Land use
SW=Slaughter weight	EQ= Ecosystem quality	H20-e= water depletion normalised by scarcity
LW= Live-weight	RD= Resource depletion	EF= Ecological footprint
LWG= Live weight gain	NREU= Non-renewable energy use	PM= Particulate matter formation
CW= Carcass weight	LC= Land competition	
HSCW = Hot Standard Carcass Weight	ODP= Ozone depletion potential	

Study	Country	Industry/Product(s)	Functional unit	Value Chain length	Impact categories	Sensitivity
Meul et al. 2014	Belgium	Dairy	1kg FPCM	Cradle to farm gate	GWP; AP; EP	No
de Léis et al. 2014	Brazil	Dairy	1kg ECM	Cradle to farm gate	GWP	Yes
Ruviaro et al. 2014	Brazil	Beef	1kg LWG	Cradle to farm gate	GWP	Yes
Alvarenga et al. 2012	Brazil	Broiler chickens	tonne of feed	Cradle to farm gate	GWP; AD; AP; EP; ODP; HTP; MAETP; TETP; POCP and LC	No
Gerbens-Leenes et al. 2013	Brazil, China, Netherlands, USA	Poultry, pork, beef	l of water type per kg of product	Feed production and herd management	Water footprint	No
Hünerberg et al. 2014	Canada	Beef	1kg LW	Cradle to farm gate	GWP	No
Zhang et al. 2013	Canada	Dairy	disposal of 1100 tonnes of organic waste	Manure management	GWP; AP; EP; AD	No
Beauchemin et al. 2010	Canada	Beef	kg of beef	Cradle to farm gate	GWP	No
Beauchemin et al. 2011	Canada	Beef	kg of beef	Herd	GWP	No
Vergé et al. 2013	Canada	Dairy	% of annual emissions by product	Cradle to packaged product	GWP	No
Huang et al. 2014	China	Dairy	1kg FPCM	Cradle to packaged milk	H20-e	Yes
Luo et al. 2014	China	Pig	Annual production	Farm and manure management	GWP; EP; AP	No
Liang et al. 2013	China	Livestock	Average number of livestock	Husbandry and waste	GWP	No
Yang et al. 2012	China	Pig biogas and aquaculture	MJ	Pigsty, fishpond, biodigestor	GWP	No

Functional unit abbreviations	Impact category abbreviations	
FPCM= Fat and protein corrected milk ECM= Energy corrected milk Kcal= kilocalorie M^3= Cubic metres Ha= Hectares SW=Slaughter weight LW= Live-weight LWG= Live weight gain	HTP= human toxicity potential (HTP) FWAETP= fresh water aquatic ecotoxicity potential AP= acidification potential MAETP= Marine aquatic ecotoxicity potential POCP= Photochemical Ozone Creation Potential EQ= Ecosystem quality RD= Resource depletion NREU= Non-renewable energy use	EP= Eutrophication potential AD= Abiotic depletion TETP= Terrestrial ecotoxicity GWP= Global Warming Potential LU= Land use H20-e= water depletion normalised by scarcity EF= Ecological footprint PM= Particulate matter formation

CW= Carcass weight HSCW = Hot Standard Carcass Weight	LC= Land competition ODP= Ozone depletion potential	

Study	Country	Industry/Product(s)	Functional unit	Value Chain length	Impact categories	Sensitivity
Zhong et al. 2013	China	Pig manure	Ton dry solids	Manure management	GWP	No
Xie et al. 2011	China	Dairy	1000 l of milk	Packaging	Human health; EQ; AD	No
Dalgaard et al. 2014	Denmark and Sweden	Dairy	1kg ECM	Cradle to farm gate	GWP	Yes
Kristensen et al. 2011	Denmark	Dairy	kg FPCM	Cradle to farm gate	GWP	No
Oxenboll et al. 2011	Denmark	Poultry	Relative difference	Cradle to farm gate	GWP; AP; EP	No
Prapaspongsa et al. 2010	Denmark	Pig manure	1 ton of raw pig manure	manure management system	GWP; EP; PM	Yes
Nielsen & Høier 2009	Denmark	Dairy	1000kg mozzarella cheese	Cradle to processed product	GWP; AP; EP; AD; LU; POCP	Yes
Katajajuuri et al. 2014	Finland	Poultry	1,000 kg of sliced broiler chicken fillet	Cradle to retailer	GWP	No
Virtanen et al. 2011	Finland	Multiple food	% of daily consumer impact	Cradle to grave	GWP	No
Chen & Corson 2014	France	Dairy	1000 l milk sold, ha of land	On-farm	GWP; EP; AP	Yes
Nguyen et al. 2013	France	Dairy	1t FPCM	Cradle to farm gate	GWP; land use	Yes
Lehuger et al. 2009	France	Dairy	tonne of feed	Cradle to feed fed	GWP;TETP; MAETP; EP; HTP; TETP; POCP; AP; LU	Yes
Basset-mens et al. 2006	France	Pig	1kg LW; Ha land	Cradle to farm gate	GWP; AP; EP	Yes
van der Werf et al. 2005	France	Pig feed	1000 kg of pig feed	Feed production to pigs mouth	GWP; AP; TETP; EP; NREU; LU	Yes
van der Werf et al. 2009	France	Dairy	1000 l milk sold, ha of land	On-farm	GWP; EP; AP	No

Functional unit abbreviations	**Impact category abbreviations**	
FPCM= Fat and protein corrected milk ECM= Energy corrected milk Kcal= kilocalorie M^3= Cubic metres Ha= Hectares SW=Slaughter weight LW= Live-weight LWG= Live weight gain CW= Carcass weight HSCW = Hot Standard Carcass Weight	HTP= human toxicity potential (HTP) FWAETP= fresh water aquatic ecotoxicity potential AP= acidification potential MAETP= Marine aquatic ecotoxicity potential POCP= Photochemical Ozone Creation Potential EQ= Ecosystem quality RD= Resource depletion NREU= Non-renewable energy use LC= Land competition ODP= Ozone depletion potential	EP= Eutrophication potential AD= Abiotic depletion TETP= Terrestrial ecotoxicity GWP= Global Warming Potential LU= Land use H20-e= water depletion normalised by scarcity EF= Ecological footprint PM= Particulate matter formation

Study	Country	Industry/Product(s)	Functional unit	Value Chain length	Impact categories	Sensitivity
Prudêncio da Silva et al. 2014	France and Brazil	Poultry	1 tonne of chicken	Cradle to packaged product	GWP; AP; EP; TETP; LU; total energy	No
Nguyen et al. 2012	France, Brazil, Malaysia	Poultry feed	1 kg of feed	Feed production	GWP; AP; EP; LU; TETP; EN	No
Zehetmeier et al. 2014	Germany	Beef	1kg FPCM	Cradle to farm gate	GWP; LU	Yes
Michel et al. 2010	Germany	Manure	Ha	Cradle to manure management	GWP; AP; EP; NREU; ground water pollution	No
Haas et al. 2001	Germany	Cattle	Ha	Undefined	GWP; NREU; AP; EP; HTP; biodiversity; landscape image; animal welfare	No
Daneshi et al. 2014	Iran	Dairy	1kg FPCM	Cradle to packaged milk	GWP	No
O'Brien et al. 2014	Ireland	Dairy	1kg FPCM	Cradle to farm gate	GWP	No
O'Brien et al. 2012	Ireland	Dairy	tonne of FPCM sold, tonne of milk solids sold, on-farm area occupied, total farm area occupied	Cradle to farm gate	GWP; EP; AP; LU; NREU	Yes
O'Brien et al. 2011	Ireland	Dairy	Ha p.a	Cradle to farm gate	GWP	Yes
Casey & Holden 2006	Ireland	Beef	liveweight per year	Cradle to farm gate	GWP	Yes

Study	Country	Industry/Product(s)	Functional unit	Value Chain length	Impact categories	Sensitivity
Battini et al. 2014	Italy	Dairy biodigestor	1kg FPCM	Cradle to farm gate	GWP	Yes
Guerci et al. 2014	Italy	Dairy	1kg FPCM	Cradle to farm gate	GWP	Yes
Lijó et al. 2014	Italy	Pig biodigestor	100 kWh	Biomass production to manure management	GWP; AP; EP ODP; POCP; NREU	Yes
Torquati et al. 2014	Italy	Dairy	kWh	Farm and manure management	GWP	No
Guerci et al. 2013	Italy	Dairy	1kg FPCM	Cradle to farm gate	GWP; AP; EP; LU; NREU	No
Fantin et al. 2012	Italy	Dairy	1 l of packaged milk	Cradle to distribution centre	GWP; ODP; POCP; AP; EP; NREU; hazardous and non-hazardous waste	Yes
Ogino et al. 2013	Japan	Pig	one marketed pig	Cradle to farm gate	GWP; AP; EP	Yes
Oishi et al. 2013	Japan	Cattle	kg of total weight output of live calves and culled cows from birth to culling	Cradle to farm gate	GWP; EP; AP	No
Ogingo et al. 2008	Japan	Dairy	1kg FCM	Cradle to farm gate	GWP; AP; EP; NREU	No
Ogingo et al. 2007	Japan	Beef	1 beef calf	Cradle to farm gate	GWP; AP; EP; total energy	No
Ogino et al. 2004	Japan	Beef	Finished cattle	Fattening system and inputs	GWP; AP;EP	No
Roy et al. 2012	Japan	Meat	kg meat / 1g protein / MJ of energy	Cradle to grave	GWP	No
Alqaisi et al. 2013	Jordan	Dairy	kg FPCM	Cradle to gate	GWP	No
Weiler et al. 2014	Kenya	Livestock	1kg Milk	Cradle to farm gate	GWP	No
Baek et al. 2014	Korea	Dairy	1kg FPCM	Cradle to farm gate	GWP	No
Dolman et al. 2014	Netherlands	Dairy	1kg FPCM	Cradle to farm gate	GWP; AP; EP; LU; NREU	No
Dekker et al. 2013	Netherlands	Eggs	Per kg of egg	Cradle to farm gate	GWP; AP; EP; LU; energy use; nutrient balance	No
Van Middelaar et al. 2013	Netherlands	Dairy	ton of FPCM	Cradle to farm gate	GWP	Yes
De Boer et al. 2012	Netherlands	Dairy	kg FPCM	Cradle to farm gate	HH; EQ; RD	Yes
Dolman et al. 2012	Netherlands	Pig	100 kg SW	Cradle to farm gate	LU; NREU; GWP; EP; AP	No

Functional unit abbreviations	**Impact category abbreviations**	
FPCM= Fat and protein corrected milk ECM= Energy corrected milk Kcal= kilocalorie M^3= Cubic metres Ha= Hectares SW=Slaughter weight LW= Live-weight LWG= Live weight gain CW= Carcass weight HSCW = Hot Standard Carcass Weight	HTP= human toxicity potential (HTP) FWAETP= fresh water aquatic ecotoxicity potential AP= acidification potential MAETP= Marine aquatic ecotoxicity potential POCP= Photochemical Ozone Creation Potential EQ= Ecosystem quality RD= Resource depletion NREU= Non-renewable energy use LC= Land competition ODP= Ozone depletion potential	EP= Eutrophication potential AD= Abiotic depletion TETP= Terrestrial ecotoxicity GWP= Global Warming Potential LU= Land use H20-e= water depletion normalised by scarcity EF= Ecological footprint PM= Particulate matter formation

Study	Country	Industry/Product(s)	Functional unit	Value Chain length	Impact categories	Sensitivity
De Vries et al. 2012	Netherlands	Manure	1 ton untreated liquid manure	Manure management	GWP, AP; EP; AD; PM	No
De Vries et al. 2012	Netherlands	Pig manure	1 ton substrate	Manure management and application	GWP; AD; EP; AP; LU; PM	Yes
van Middelaar et al. 2011	Netherlands	Cheese	kg cheese / m2 land	Cradle to retailer	GWP; LU; NREU	Yes
Thomassen et al. 2009	Netherlands	Dairy	kg of FPCM	Cradle to farm gate	GWP; EU; NREU; EP; AP	No
Thomassen et al. 2008	Netherlands	Dairy	kg of FPCM leaving the farm gate	Cradle to farm gate	Land use; energy use; GWP; AP; EP	No
Thomassen et al. 2008b	Netherlands	Dairy	kg FPCM	Cradle to farm gate	LU; NREU; GWP; AP; EP	Yes
Zonderland-Thomassen et al. 2014	New Zealand	Beef and sheep	1kg LW	Cradle to farm gate	H2O-e; EP	No
Zonderland-Thomassen & Ledgard 2012	New Zealand	Dairy	kg FPCM	Cradle to farm gate	Water footprint	No
Ledgard et al. 2011	New Zealand	Lamb	kg of NZ lamb purchased in the UK	Cradle to grave	GWP	Yes
Flysjö et al. 2012	New Zealand and Sweden	Dairy	kg FPCM	Cradle to farm gate	GWP	Yes
Roer et al. 2013	Norway	Cattle	kg FPCM and 1 kg carcass	Cradle to farm gate	GWP; AD; MAETP; EP; HT; ODP; LU; AP; TETP	Yes
Ellingsen & Aanondsen 2006	Norway	Cod Poultry comparison	0.2 kg fillets	Cradle to consumer	GWP; AP; EP; total energy use; TETP; MAETP	No
Eide et al. 2003	Norway	Dairy	10,950 cleans of dairy equipment in year	Chemical production to usage	GWP; NREU; POCP	Yes

Study	Country	Industry/Product(s)	Functional unit	Value Chain length	Impact categories	Sensitivity
Eide 2002	Norway	Dairy	1000l milk	Cradle to grave	GWP; EP; AP; ODP; POCP; Ecotoxicity; total energy use	No
Flysjö et al. 2011	NZ + Sweden	Dairy	1kg ECM	Cradle to farm gate	GWP	No
Bartl et al. 2011	Peru	Milk	kg FPCM or 1 animal	Feed production and herd management	GWP; AP; EP	Yes
González-García et al. 2014	Portugal	Poultry	168.4 g of protein	Cradle to slaughterhouse gate	GWP; AP; EP; POCP; AD; NREU	No
Castanheira et al. 2010	Potugal	Dairy	tonne of milk	Cradle to farm gate	GWP; AP; EP; AD; POCP	No
Thévenot et al. 2013	Reunion Island	Poultry	tonne of packed whole chickens	Cradle to packaged product	GWP; AP; EP	Yes
Djekic et al. 2014	Serbia	Dairy	1kg dairy product	Cradle to packaged product	GWP; AP; EP; ODP; POCP; HTP	No
Devers et al. 2013	South Africa	Pork	1kg CW	Cradle to farm gate	GWP; AP; EP	No
Ripoll-Bosch et al. 2013	Spain	sheep	kg LW	Cradle to farm gate	GWP	No
Bayo et al. 2012	Spain	Pig manure	1m3 of pig slurry	Manure and land management	GWP; AP; EP	No
Del Prado et al. 2013	Spain	Dairy	kg of FPCM	Cradle to farm gate	GWP	No
Meneses et al. 2012	Spain	Dairy	m3 of biogas	Waste management	GWP; EP; AP; TETP; MAETP; radiation; ODP; AD	No
Iribarren et al. 2011	Spain	Dairy	l of raw milk	Cradle to farm gate	AP; EP; GWP; LC; NREU	No
Joy et al. 2011	Spain	Lamb	kg lamb meat	Cradle to farm gate	GWP	No
Hospido et al. 2003	Spain	Dairy	1l milk	Cradle to packaged product	GWP; ODP; AP; EP; POCP; AD	No
Davis et al. 2010	Spain and Sweden	Meat v legumes	Meal	Cradle to plate	GWP; EP; AP; LU; NREU	No
Mueller et al. 2014	Sweden	Dairy	1 l of milk	Cradle to farm gate	Biodiversity	No
Berlin et al. 2008	Sweden	Dairy	1kg consumed product	Cradle to consumed product	GWP; EP; EN; POCP	No

Functional unit abbreviations	Impact category abbreviations	
FPCM= Fat and protein corrected milk	HTP= human toxicity potential (HTP)	EP= Eutrophication potential
ECM= Energy corrected milk	FWAETP= fresh water aquatic ecotoxicity potential	AD= Abiotic depletion
Kcal= kilocalorie	AP= acidification potential	TETP= Terrestrial ecotoxicity
M^3= Cubic metres	MAETP= Marine aquatic ecotoxicity potential	GWP= Global Warming Potential
Ha= Hectares	POCP= Photochemical Ozone Creation Potential	LU= Land use
SW=Slaughter weight	EQ= Ecosystem quality	H20-e= water depletion normalised by scarcity
LW= Live-weight	RD= Resource depletion	EF= Ecological footprint
LWG= Live weight gain	NREU= Non-renewable energy use	PM= Particulate matter formation
CW= Carcass weight	LC= Land competition	
HSCW = Hot Standard Carcass Weight	ODP= Ozone depletion potential	

Study	Country	Industry/Product(s)	Functional unit	Value Chain length	Impact categories	Sensitivity
Davis & Sonesson 2008	Sweden	Chicken dinner	Meal	Cradle to prepared meal	GWP; AP; EP; ODP	No
Cederberg & Stadig 2003	Sweden	Dairy and beef	1kg ECM / bone-free meat	Cradle to farm gate	GWP; EP; AP; LU; pesticide use; energy use	No
Berlin et al. 2007	Sweden	Dairy	% of waste	Processor to packaged	GWP; EP; AP; POCP	No
Sonesson & Berlin 2003	Sweden	Dairy	Scenario / year	Farm gate to grave	GWP; AP; EP; POCP; NOx; Use of net energy; primary energy carriers	Yes
Berlin 2002	Sweden	Cheese	kg of packaged cheese	Cradle to packaging	GWP; AD; AP; EP; POCP; MAETP; ETEP	Yes
Cederberg & Mattsson 2000	Sweden	Dairy	tonne FPCM	Cradle to farm gate	GWP; AD; LU; human health; AP; EP; POCP	No
Mogensen et al. 2014	Sweden and Denmark	Cattle	1kg CW	Cradle to farm gate	GWP	Yes
Schader et al. 2014	Switzerland	Dairy	Ha cultivated / 1kg FPCM	Cradle to farm gate	GWP	Yes
Binder et al. 2012	Switzerland	Dairy	1kg milk	Milk value chain	GWP; biodiversity; social; economic	Yes
Tongpool et al. 2012	Thailand	Poultry - broiler	tonne of feed	Cradle to packaged feed	GWP; ODP; HTP; AD; POCP; PM; AP; EP; TETP; +3 others	No
Leinonen et al., 2013	UK	Poultry	tonne of product	Cradle to feed fed	GWP; EP; AP	Yes

Mezzullo et al. 2013	UK	Cattle	m3 biogas	Manure management	Carcinogens; respiratory inorganics; GWP; radiation; ODP; TETP; MAETP; AP; UP; NREU	No
Bell et al. 2011	UK	Dairy	Ha and FPCM	Cradle to farm gate	GWP; LU	No
Webb et al. 2014	UK	Livestock	CW; million eggs; 1l milk	Cradle to farm gate	GWP; LU	No
Sandars et al. 2003	UK	Pork	1000kg of pork	Manure management and application	GWP; smog; EP; AP	Yes

Functional unit abbreviations	**Impact category abbreviations**	EP= Eutrophication potential
FPCM= Fat and protein corrected milk	HTP= human toxicity potential (HTP)	AD= Abiotic depletion
ECM= Energy corrected milk	FWAETP= fresh water aquatic ecotoxicity potential	TETP= Terrestrial ecotoxicity
Kcal= kilocalorie	AP= acidification potential	GWP= Global Warming Potential
M^3= Cubic metres	MAETP= Marine aquatic ecotoxicity potential	LU= Land use
Ha= Hectares	POCP= Photochemical Ozone Creation Potential	H20-e= water depletion normalised by scarcity
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LWG= Live weight gain	NREU= Non-renewable energy use	
CW= Carcass weight	LC= Land competition	
HSCW = Hot Standard Carcass Weight	ODP= Ozone depletion potential	

Study	Country	Industry/Product(s)	Functional unit	Value Chain length	Impact categories	Sensitivity
Ross et al. 2014	UK	Dairy	1kg ECM	Cradle to farm gate	GWP	Yes
Styles et al. 2014	UK	Dairy biodigestor	DM codigested	Feed, animal, manure	GWP; AP; EP	Yes
Leinonen et al. 2012	UK	Poultry	1,000 kg of eggs	Cradle to farm gate	GWP; AP; EP; AD; LU; pesticide use	Yes
O'Brien et al. 2014	UK, Ireland, US	Dairy	1kg ECM	Cradle to farm gate	GWP	No
Picasso et al. 2014	Uruguay	Red meat	1kg LW	Cradle to farm gate	GWP; EP; TETP; AD; biodiversity; soil erosion	Yes
Pelletier et al. 2013	USA	Eggs	Tonne of liquid egg	Cradle to processing	GWP	No
Adom et al. 2013	USA	Dairy feed	kg of milled dairy feed	Feed production	GWP	Yes
Belflower et al. 2012	USA	Dairy	cow and FPCM	Cradle to farm gate	GWP; AP; erosion; EP	Yes
Rotz et al. 2010	USA	Dairy	kg FPCM	Cradle to farm gate	GWP	Yes
Zabaniotou & Kassidi 2003	USA	Poultry	50,000 egg cartons	Egg carton manufacture	GWP; AP; EP; ODP; POCP; winter smog; heavy metals; Carcinogenic substances; Nutrient enrichment	No
Ghafoori et al. 2006	USA	Beef/biodigestor	1 MWh	Feed, animal, manure	GWP	No
Stone et al. 2012	USA	Pig	1 pig	Cradle to farm gate	GWP; EP; AP; TETP	No
Coats et al. 2013	USA	Manure	Percent change	Manure management	GWP	No
Nutter et al. 2013	USA	Dairy	1KG fluid milk	Processing to distribution	GWP	No
Kim et al. 2013	USA	Dairy	kg moisture free cheese	Cradle to grave	GWP; EN; EP; HTP; TETP; LU; POCP; Water use	No
Asselin-Balençon & Jolliet 2014	USA	Dairy biodigestor	1l milk	Cradle to farm gate	GWP	No

Functional unit abbreviations	Impact category abbreviations	
FPCM= Fat and protein corrected milk ECM= Energy corrected milk Kcal= kilocalorie M^3= Cubic metres Ha= Hectares SW=Slaughter weight LW= Live-weight LWG= Live weight gain CW= Carcass weight HSCW = Hot Standard Carcass Weight	HTP= human toxicity potential (HTP) FWAETP= fresh water aquatic ecotoxicity potential AP= acidification potential MAETP= Marine aquatic ecotoxicity potential POCP= Photochemical Ozone Creation Potential EQ= Ecosystem quality RD= Resource depletion NREU= Non-renewable energy use LC= Land competition ODP= Ozone depletion potential	EP= Eutrophication potential AD= Abiotic depletion TETP= Terrestrial ecotoxicity GWP= Global Warming Potential LU= Land use H20-e= water depletion normalised by scarcity EF= Ecological footprint PM= Particulate matter formation

Study	Country	Industry/Product(s)	Functional unit	Value Chain length	Impact categories	Sensitivity
Stackhouse-Lawson et al. 2012	USA	Beef	Production system	Cradle to farm gate	GWP	No
Venczel & Powers 2010	USA	Manure	600 cows per day	Animal to manure management	GWP	No
Pelletier et al. 2010	USA	Beef	1kg LW	Cradle to farm gate	GWP; EP; EF; total energy use	Yes
Dudley et al. 2014	USA	Beef	1kg LW	Cradle to farm gate	GWP	Yes
Thoma, Popp, et al. 2013	USA	Dairy	1kg milk	Cradle to grave	GWP	Yes
Sanders & Webber 2014	USA	Beef	1kg beef / wheat	Cradle to food preparation	GWP	Yes
Phong 2010	Vietnam	Agriculture/aquaculture	Kcal	Cradle to farm gate	GWP; EP; AP	No
Opio et al. 2013	Global	Ruminant livestock	1kg CW or 1kg FPCM	Cradle to retail	GWP	Yes
FAO 2010	Global	Dairy	kg FPCM	Cradle to retail	GWP	Yes
Zervas & Tsiplakou 2012	Global	Small ruminants and all livestock	LW	Cradle to grave	GWP	No
de Vries & de Boer 2010	Meta analysis	Multiple livestock	kg of edible product	Not detailed	GWP; LU; NREU; EP; AP	No
Röös et al. 2013	Meta analysis	Meat	kg of bone free meet	Various	GWP; AP; EP; LU	No
Ercin et al. 2012	Various	Soy, Animal	150g paddy, litre of milk	Cradle to grave	Volumetric water	No
Nijdam et al. 2012	Multiple	Animal products	kg of protein	Cradle to farm gate	LU	No
Weiss & Leip 2012	Europe	Livestock	kg meat	Cradle to farm gate	GWP (including LULUC)	No

Functional unit abbreviations	Impact category abbreviations	
FPCM= Fat and protein corrected milk ECM= Energy corrected milk Kcal= kilocalorie M^3= Cubic metres Ha= Hectares SW=Slaughter weight LW= Live-weight LWG= Live weight gain CW= Carcass weight HSCW = Hot Standard Carcass Weight	HTP= human toxicity potential (HTP) FWAETP= fresh water aquatic ecotoxicity potential AP= acidification potential MAETP= Marine aquatic ecotoxicity potential POCP= Photochemical Ozone Creation Potential EQ= Ecosystem quality RD= Resource depletion NREU= Non-renewable energy use LC= Land competition ODP= Ozone depletion potential	EP= Eutrophication potential AD= Abiotic depletion TETP= Terrestrial ecotoxicity GWP= Global Warming Potential LU= Land use H20-e= water depletion normalised by scarcity EF= Ecological footprint PM= Particulate matter formation

Annex 3: Supplementary references

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