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Stockholm Environment Institute
Linnégatan 87D, Box 24218
104 51 Stockholm
Sweden
Tel: +46 8 30 80 44
Web: www.sei-international.org

Director of Communications: Robert Watt
Editors: Tom Gill, Andy Mash
Layout/graphics: Richard Clay

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1 INTRODUCTION

Livestock is one of the fastest growing sub-sectors of agricultural production. It contributes around 40% of the gross domestic product (GDP) of global agriculture. Moreover, about half the world's farmers obtain part of their income and livelihood from livestock-related activities, of whom 1 billion live in developing countries (WB, 2009).

Often, livestock husbandry can increase the efficiency of food production by converting biomass that is inedible for humans, for example from crop residues and pasture, into high nutrition food produce. At the same time, it can provide large amounts of valuable organic fertilizer. Consequently, livestock production can contribute to economic growth and poverty reduction and, if correctly managed, play an important role in developing sustainable agricultural production systems. It is also crucial for maintaining ecological values. For example, grazing areas in Sweden not only generate animal feed, but also sustain other ecosystem services such as culturally desirable open landscapes and biodiversity-rich meadows (Eriksson, Cousins and Bruun, 2002; Pykälä, 2000).

The demand for food from animal sources is expected to double by 2050 (IAASTD, 2008), driven by population growth, urbanization and rising incomes (Delgado, Rosegrant, Steinfeld, Ehui and Courbois, 1999). Demand in developing countries will account for the major part of the increase in both production and consumption of animal products (Alexandratos, 2009). As a result, competition for land and water is likely to be fierce, with potentially profound outcomes for both the environment and food security (Herrero et al., 2010).

Furthermore, it will be imperative to limit agricultural expansion into vulnerable ecosystems to avoid irreversible changes in the resilience of agro-ecosystems (Naylor, 2009; Rockstrom et al., 2009). Thus, a large part of the demand must be met by the "sustainable intensification" of agriculture (Tilman, Balzer, Hill and Befort, 2011), that is, producing more food without using more bio-resources, land, water and other inputs (Herrero et al., 2010).

There are many frameworks and methods for evaluating the environmental sustainability of farm systems. These include the Response Inducing Sustainability Evaluation (RISE) tool (Grenz, Thalmann, Stämpfli, Studer and Häni, 2009; Häni et al., 2003; Häni, Pintér and Herren, 2006; Häni, Stämpfli, Keller and Menzi; Häni, Stämpfli, Tello and Braga, undated) and Sustainable Performance Assessment (SPA) (Elferink, Kuneman and Visser, 2012; Kuneman et al., 2014). However, few of these initiatives are concerned solely with livestock systems, and these tend to focus on one or two areas rather than address all potential livestock-related environmental impacts. Hence, to fully capture these impacts, a multidimensional framework is needed to underpin environmental impact assessments of livestock production, and of livestock value chains.

In the context of agriculture, an impact assessment can be broadly defined as an analysis of the effects of change in agriculture and livestock systems, which can be studied at a number of different scales and in a number of different ways (Thornton, Kristjanson and Thorne, 2003). Impact assessments have received growing attention in the past decade, largely because funding opportunities for agricultural research have changed drastically, as have the expectations of the results (Thornton, 2006; Thornton et al., 2003). Thus, there is an increased demand for *ex-ante* assessments, which can deliver a benchmark for livestock production systems under development. In relation to *ex-post* and status quo assessments, *ex-ante* assessments can help policymakers and decision makers, as well as investment agents involved in new interventions and modes of production, determine the impacts and trade-offs as well as the co-benefits of proposed developments. Monitoring and evaluation frameworks are also useful tools for assessing agricultural production systems, although more as a tool for analysing progress during and after a particular development. Such activities allow for corrective action where development is moving in an undesired direction. Monitoring and evaluation are also most useful when used by farmers, farming communities, protection agencies and private sector actors.

Thus, *ex-ante* assessments are more practical if a framework is intended to deliver results that can be used to identify desirable outcomes and trade-offs. *Ex ante* assessments are also of most use for policymakers and decision makers rather than farmers or scientists. A rapid assessment framework that can deliver an *ex-ante* description of the situation at hand would be relevant for decision makers dealing with a sector that is being intensified and experiencing a flow of new innovations.

Livestock systems are highly complex and will influence ecosystems in a range of ways, both directly and indirectly (van Mil, Foegeding, Windhab, Perrot and van der Linden, 2014). Therefore, *ex-ante* assessments of agriculture (and also *ex-post* assessments) require a combination of different models and methods in order to deliver useful information about the impacts of proposed changes in systems of agricultural production (Thornton and Herrero, 2001).

This study reviews the currently available tools for and approaches to assessing the environmental impacts of livestock production systems. The review aims to identify the key parameters included in a sustainability or impact assessment method, and whether these parameters differ between different sectors and objectives.

2 RATIONALE AND STRUCTURE OF ENVIRONMENTAL IMPACT ASSESSMENT FRAMEWORKS

In recent decades there has been a steady increase in the number of approaches used to assess the environmental impact and sustainable performance of agricultural production (van der Werf and Petit, 2002). This is an important development because it generates new support tools that can aid decision makers and policymakers at multiple scales (van der Werf, Tzilivakis, Lewis and Basset-Mens, 2007). In particular, the environmental impact of livestock production has gained increased attention in research and in the media. For example, the number of documents on Google Scholar for "livestock and environment" increased by around 80% in the 15 years since 2000 compared to the 15 years before 2000 (Google, 2014), and the number of documents found for "livestock environmental assessment" increased from 32,000 to 174,000 over the same period.

According to Petit and Van der Werf (2003; van der Werf et al., 2007) the frameworks and methodologies for assessing the environmental impacts of agricultural production systems are generally structured around five main methodological steps: (1) definition of the overall objective of the method; (2) definition of environmental objectives; (3) definition of systems to be analysed; (4) construction or identification of indicators for each environmental objective; and (5) calculation of results. In each step, but in particular for steps one to four, choices must be made about how the methodology should be used and developed (van der Werf et al., 2007).

For the purposes of this study, we have modified Petit and Van der Werf's five steps as follows:

- Scope of the study (Section 4.1) – general objective of the method (revised step 1)
- Environmental objective (Section 4.2) – impact dimensions and indicator selection (revised steps 2 and 4)
- System definition (Section 4.3) – spatial and temporal boundaries (revised step 3)
- Data collection and analysis, and results calculation (Section 4.4) (revised step 5)
- Presentation of results (Section 4.5) (additional step)

Assessment tools for livestock and agricultural production systems and their associated value chains differ in a number of aspects. These include the general objectives and aims, target audiences, environmental issues addressed and indicators selected, as well as the spatial and temporal scales covered. There are also many environmental impacts that are associated with livestock, aquaculture and agricultural production. In *Livestock's Long Shadow*, Steinfeld et al. (2006) highlight six key impacts. We extend these to seven below, since very different indicators and measures apply to greenhouse gas (GHG) emissions and energy use, which are thus best considered separately. These impacts are widely used in assessment tools and in the literature. They are: (1) greenhouse gas emissions; (2) energy use; (3) water usage and pollution; (4) biodiversity loss; (5) nutrient cycling, mainly of nitrogen and phosphorous; (6) land use; and (7) land cover change. In recent years, life cycle assessment methodologies (LCAs), which aim to cover the complete product value-chain, have become increasingly popular for assessing the environmental impacts of livestock products (Fraval, 2014). Since LCAs include the entire value-chain, they also give rise to further impact dimensions that cover transportation, processing, consumption, losses and reuse along the product value chain. Thus, in this review we also include the impact dimensions of: (8) waste products and emissions; and (9) eco-toxicity (see Table 1).

3 METHODOLOGY

Because most methodologies do not just deal with livestock systems, we also reviewed methodologies that deal with agricultural production more broadly, as long as these methodologies substantially cover or consider livestock production. Due to the broad scope of these methodologies, for simplicity we labelled all the tools and initiatives in this study "frameworks".

We identified a large number of frameworks by searching the Scopus, Science Direct and Google Scholar databases. We used the search words and phrases "environmental impact assessments" and "sustainability assessments" of both agriculture and livestock production systems. From the first screening, 50 frameworks were selected for further study based on whether they include all or some of five selected criteria: (1) indicator selection; (2) temporal and spatial scales; (3) target audience; (4) timeframe for assessment; and (5) the type of environmental impact covered. Where we excluded frameworks, we did so on the basis of lack of information, or where they did not consider the environmental aspect of sustainability or did not target livestock systems. Appendix 1 presents the 50 frameworks reviewed.

Nine frameworks were selected for more in-depth review, on the basis that they could provide guidance for building a new framework that covers the multidimensional environmental impacts associated with livestock production systems. The nine frameworks are all relatively rapid assessment tools, cover multiple environmental impact dimensions that are measured by selected indicators, cover multiple temporal and spatial scales, and target a broad audience. To be included in the in-depth review, the frameworks had to fulfill at least two of these selection criteria. Table 2 lists the nine frameworks that were reviewed in-depth.

This report includes results from all 50 of the frameworks studied, unless otherwise stated. We analysed the frameworks in terms of the structure of their methods, and separated them into three broad categories:

- *General frameworks*, which include several environmental dimensions and aim to assess the entire environmental impact of analysed production;
- *Dimension-specific frameworks*, which focus on analysing a specific environmental impact or dimension such as biodiversity; and
- *Modelling frameworks*, which distinguish themselves from other frameworks in that their methodology relies mainly on modelling for data collection, not on gathering data through measurements, surveys or interviews.

Close study was made of the background information on each of the frameworks, including manuals, websites and documents describing their application. The frameworks were further evaluated on the basis of a number of attributes, which are described in more detail below.

3.1 Overall objectives of the frameworks

The big discrepancies between the different frameworks analysed in this review mean that the frameworks can be categorized in numerous ways. In this study we categorized the frameworks into those that have either a focus on "sustainability", or an emphasis on "environmental impact or resource use". This distinction was made based on both the description and the formulation of the general aim of each analysis. In general, frameworks that seek to assess sustainability tend to have a broader aim than those which focus on assessing environmental impact or resource use. Sustainability assessments call for the inclusion of global processes and resources, such as biodiversity and fossil fuels (van der Werf and Petit, 2002). The frameworks categorized as focusing on environmental impact or resource use are narrower in scope, aim to assess the impact of a particular agricultural system and tend to focus more on monitoring and evaluation.

It should be noted that the search terms used to identify methodologies were broad in scope, and it is therefore not possible to draw any general conclusions about whether frameworks set out to assess either sustainability or environmental impact. However, studying the aim of a framework provides information on its overall structure, and also allows the framework outputs to be assessed in relation to the general objective. In this way, such an approach can contribute conclusions about framework structure and development. The results of this review are presented in sections 4.1 to 4.5, and are organized in line with the attributes for analyse described in sections 3.1 to 3.5.

3.2 Environmental objectives

The environmental "objectives" of the frameworks usually consist of a set of environmental impacts that describe what the analysis aims to cover. The various frameworks use a number of different terms for these objectives, including "themes", "categories of environmental impact" or "environmental impact dimensions" (van der Werf and Petit, 2002).

For the purpose of this study we use the term environmental impact dimensions, since this refers more to the processes involved than the formulation of objectives. The environmental impact dimensions are described in section 3.2.1 and then measured by a number of key indicators, which are described below.

3.2.1 Environmental impact dimensions

We analysed the frameworks on the basis of how many of the nine key environmental impact dimensions they include for analysis. We categorized the frameworks according to the structure proposed by Van der Werf and Petit (2002), in which the authors suggest a division between objectives according to whether they are input-related, emissions-related or system state-related.

Table 1 shows that five of the nine environmental impact dimensions are categorized as input-related, because they result from inputs to livestock systems. Two impact dimensions are emissions-related. The dimensions of soil health and biodiversity stock are system state-related, because they relate to a state, or a shift in state, already established before the analysis takes place. This does not imply that system states are static; for example, soil health or biodiversity will be affected by inputs and emissions over time that will affect their state (or "health"). Such feedback-loops and interactions should be acknowledged when interpreting results.

It should also be noted that the environmental impact dimensions can be an aggregation of indicators, and thus could be categorized in different ways that are suitable for a specific framework and analytical scope.

3.2.1 Environmental impact indicators

It is difficult to measure the environmental impacts of agricultural production because agricultural systems having profound effects on other sectors and ecosystems. Measurement becomes even more challenging when trying to assess which impacts result from livestock production alone, because livestock directly affects ecosystems via animal husbandry, as well as via agricultural production of animal feed. It is usually not possible to directly measure such impacts, because most result from a number of interlinked activities and ecosystem processes. Impacts are also affected by the baseline state of a system and how that system would tend to react to a number of different circumstances, as well as current conditions such as whether it is a dry or a wet year. Such interrelationships have proved difficult to assess and predict. Indicators are chosen in order to simplify complex relationships

Table 1: The nine selected environmental impact dimensions sorted into categories of; input related, emissions-related and system state-related.

Input-related dimensions	Emission-related dimensions	System state-related dimensions
Water (quantity)	GHG emissions	Soil health
Land use	Waste products and emissions	Biodiversity stock
Nutrient cycling (input of fertilizers)		Water (quality)
Energy use		Nutrient cycling (flux balance)
Eco-toxicity		

and enable a quantitative measure or indication of a relationship in terms of impacts (Halberg, Verschuur and Goodlass, 2005). Furthermore, indicators used in an *ex-ante* assessment can be used *ex-post* to measure how well objectives have been attained, thus supporting monitoring and evaluation if the methodology is implemented (van der Werf and Petit, 2002).

Many of the frameworks that aim to assess all of the environmental impact dimensions associated with agricultural production build on existing methodologies and models. The Pressure-State-Response (PSR) categorization of environmental impacts and associated indicators, developed in the 1970s by the Organisation for Economic Co-operation and Development (OECD) to structure their work on environmental policies and reporting (OECD, 2003), was later developed into the DPSIR framework (driving-forces/pressures/states/impacts/response) (Smeets and Weterings, 1999). This approach to categorizing indicators has been influential in recent decades, because of the simple and illustrative structure of the indicators that is comprehensible to both scientists and stakeholders, and because it is human-centric, implies causal relationships and enables linkages or interactions in the system to be isolated while maintaining their relevance to the larger system structure (OECD, 2003).

Indicators can also be of a different sort, depending on the aim of the framework or how the methodological steps are defined and organized. This review categorizes indicators into either *process-oriented* or *product-oriented*, following Halberg et al. (2005). Process-oriented indicators use a land-based approach, generally calculated as environmental impact per hectare of land, and only account for on-farm emissions and not the environmental impacts associated with the production of the inputs, for example chemical fertilizers. Product-oriented and life cycle-oriented indicators include the global aspects of environmental impact and the entire value chain, as a measure of impact per production unit or kilogram of a product.

Another division by which indicators are analysed in this study has been developed by Van der Werf and Petit (Halberg et al., 2005; van der Werf and Petit, 2002). In this scheme, indicators are categorized according to whether they are *means-based* (i.e. related to farming production practices) or *effect-based* (i.e. related to the effects of practices on the state of a system or on emissions into the environment) (van der Werf and Petit, 2002). The advantages of selecting effect-based indicators is that they relate more directly to a framework's environmental objectives and that the best option for achieving the objectives is left up to the end-user. However, one disadvantage of effect-based indicators is that they have a much higher data requirement compared to means-based indicators. Effect-based indicators also require much more time for data collection and analysis (van der Werf and Petit, 2002), whereas the data required to measure means-based indicators are generally easy to obtain. The major disadvantage of means-based indicators (in addition to their weaker connection to the framework objectives) is that they should not be used to guide changes in environmental impact, because indicators have been used to determine environmental impact which is itself subject to change (Payraudeau and van der Werf, 2005).

3.3 System definition

We also reviewed the frameworks in terms of how they set the boundaries for analysis. The frameworks vary a great deal in how they do this. Our focus was on boundaries of scale, both temporal and spatial.

Spatial scales
We categorized the reviewed frameworks according to four spatial scales: the farm/field, landscape, regional and global scales. We also took into account whether they aimed to assess multiple scales and, if so, which scales these were (e.g. farm to landscape scale or farm to global scale).

Temporal scales
We divided the temporal coverage of the frameworks into three time perspectives: short (<1 year), medium (1–10 years) or long (>10 years).

3.4 Data collection and analysis

There is great variation in the methods for data collection chosen by the frameworks, depending on the scope of the study and the following attributes which were reviewed for each framework:

Time required
Frameworks differ in the time required to gather data and perform analyses. We categorized the frameworks under the periods "weeks", "months" or "years", based on the information available in the methodology description.

Audience
We also categorized the frameworks according to their target audiences. These can be farmers, scientists, consumers, producers, practitioners or policymakers and decision makers.

Skills required
We found differences among the frameworks in the kind of skills required to apply the methods. Some frameworks require expert knowledge, such as skills for operation and implementation, while others have prerequisites in terms of data input into models. In some cases, specialist communication skills are required to reach the target audience.

The means of data collection are partly covered in the different attributes of system definition described above. However, some attributes of data collection are also related to indicator selection and the methods used to assess them. Therefore, the in-depth review of nine selected frameworks further examined the methods used by their selected indicators to analyse and estimate results for each of the nine environmental impact dimensions.

3.5 Presentation of framework results

The results generated by the frameworks in our analysis can be presented in a number of ways. This review analysed whether the frameworks use charts/figures, tables, numbers or indexes, or a combination of these. It is also noted whether they supplement their results with a report, or any kind of follow-up document, for their intended audience.

4 OVERVIEW OF ASSESSED FRAMEWORKS

Of the 50 frameworks in this review, 28 are categorized as general frameworks, 10 as dimension-specific (i.e. covering a single environmental impact dimension) and 12 as modelling frameworks (see **Appendix 1** on the 50 reviewed frameworks). **Table 2** presents the organization behind the framework, its aim, purpose and application, for the nine in-depth reviews.

Just over half of the frameworks (26) are applied to case studies in developing countries. Only three frameworks state in their title or primary aim that their focus is on livestock. Of those three, one is indicator-specific and two are modelling frameworks. However, 16 of the frameworks already have known applications to livestock systems. Six are designed for global or national studies, and are thus not applicable to livestock systems alone. Two of the frameworks are theoretical and have not yet been applied. The remaining 26 have been applied in several cases. However, it is not possible to determine whether any of these 26 frameworks were applied strictly to livestock systems or whether they examine livestock together with other types of agriculture production.

Table 2: The nine frameworks that were reviewed in-depth

Framework	Organization and/or date established	Aim or purpose	Application
Vital Signs – African monitoring systems (Scholes, Palm and Andelman, 2013; VitalSigns, 2014)	Conservation International (CI), the Council for Scientific and Industrial Research (CSIR) in South Africa, and the Earth Institute (EI) at Columbia University	To ensure that improvements in food production also support livelihoods that are resilient, and healthy natural ecosystems.	Initially launched in five African countries – Tanzania, Ethiopia, Ghana, Uganda and Mozambique.
Response-Inducing Sustainability Evaluation (RISE) (Grenz et al., 2009; Häni et al., 2003; Häni et al., 2006; Häni, Stämpfli, Keller, et al., undated; Häni, Stämpfli, Tello, et al., undated)	Bern University of Applied sciences. Partnered with Nestlé, the Research Institute of Organic Agriculture, the Danone Fonds pour l'Ecosystème, the Swiss Federal Office for Agriculture and Energy and Capacity Building International (GIZ)	Indicator- and interview-based method for assessing the sustainability of farm operations.	RISE has been used in 40 countries on more than 1400 farms, both agriculture and dairy.
AgBalance (AgBalance, 2012; Schoeneboom, Saling and Gipmans, 2012)	BASF	AgBalance is a tool designed to assess the sustainability of agricultural products and processes.	Unknown amount of applications but built on several hundreds of previous case studies.
Life-Cycle Assessment (LCA) (Bauman and Tillman, 2004; Cederberg, Flysjö and Ericson, 2007; Cederberg, Henriksson and Berglund, 2013; De Boer, 2003; De Boer et al., 2011; De Boer et al., 2012; De Vries and De Boer, 2010; Flysjö, Cederberg, Henriksson and Ledgard, 2012; Fraval, 2014; Thomassen, Dalgaard, Heijungs and De Boer, 2008; Vellinga et al., 2013)	Ian Boustead published the first book on LCA work in 1979.	A holistic method for evaluating environmental impact during the entire life cycle of a product, considering two types of environmental impacts: (1) use of resources; and (2) emission of pollutants.	Unknown. Standardized method. 70 articles on livestock-related LCAs have been identified (Fraval, 2014)

World Agricultural Watch (WAW) (CIRAD, 2011; FAO, 2012b; George, Bosc, Even, Belieres and Bessou, 2012)	FAO, Agricultural reséarch for development (CIRAD), and the French Government, with the participation of the International fund for agricultural development (IFAD)	The main goal is to bring the dynamics and relative performances of different types of agriculture into the policy debate in terms of production and economic, social and environmental sustainability at the local and global levels, while taking anticipated changes into account.	Farms in Vietnam, Mali and Madagascar
Environmental sustainability index (ESI) (Esty, Levy, Srebotnjak and de Sherbinin, 2005, 2005a, 2005b, 2005c)	Yale Centre of environmental law and policy, Center for International Earth Science Information Network (CIESIN)	The Environmental Sustainability Index (ESI) is a measure of overall progress towards the environmental sustainability of national environmental stewardship based on a compilation of indicators derived from underlying datasets.	Global assessments, applied to all nations
Sustainable performance assessment (SPA) (Elferink et al., 2012; Kuneman et al., 2014; SAI, 2010)	Sustainable Agriculture Initiative, 2010	A blueprint for a set of indicators on chosen sustainability issues, aims to indicate to farmers the impacts of their farming practices to help them improve the sustainability of their farming.	Not applied yet
MESMIS (López-Ridaura, van Keulen, van Ittersum and Leffelaar, 2005a, 2005b; López-Ridaura, Masera and Astier, 2002; Speelman, López-Ridaura, Colomer, Astier and Masera, 2007)	Interdisciplinary group for rural technology	A systemic, participatory, interdisciplinary and flexible framework for evaluating sustainability, offering guidelines on the selection of specific environmental, social and economic indicators focused on the important characteristics that steer systems performance,	More than 20 case studies in Mexico and Latin America.
GAIA (CLM, 2012, 2014)	CLM, 2012	A yardstick to make biodiversity measurable and comparable.	Unknown. Free online access webtool

4.1 Scope of the study: general objective of the method

The results indicate that 30 (60%) of the frameworks have a stronger emphasis on assessing environmental impact than assessing sustainability. Only 12 of the frameworks (24%) state that assessing sustainability is their general aim, compared to 32 (64%) that focus on environmental impact or assessment of resource use. Nine of the frameworks did not have a clear aim to examine either sustainability or environmental impact, but rather emphasized resource-use efficiency, building knowledge, or a specific environmental dimension such as biodiversity.

4.2 Environmental objectives

Each individual framework formulates environmental objectives differently, but the formulations tend to be defined by which environmental impacts are measured, and by which indicators. For clarification, in this review the methodological choices on environmental objectives are divided into two separate sections – impact dimensions and indicator selection.

4.2.1 Impact dimensions

Apart from the single-dimension frameworks, only the Sustainable Performance Assessment (SPA) and Sustainable assessment of food and agriculture systems (SAFA) initiatives in this review clearly state why certain objectives are chosen, and why others, related to the identified key areas of environmental impact, are excluded from the analysis (Elferink et al., 2012; FAO, 2012a, 2013b, 2014c, 2014d; Kuneman et al., 2014). Some frameworks begin by developing their methodology focused on a single environmental impact dimension, for example GHG emissions as in the case of the FAO initiative behind the Global livestock environment assessment model (GLEAM) (Gerber et al., 2013; MacLeod, Gerber, Mottet, et al., 2013; Macleod, Gerber, Vellinga, et al., 2013; Opio et al., 2013), but aim to include further multiple dimensions in the next phase of the initiative.

Single-dimension methodologies include the Gaia Yardstick of Biodiversity (CLM, 2012, 2014), the Water Footprint (Hoekstra, 2010) and the Ex-Ante Carbon Balance Tool (EX-ACT) (Branca, Gorin and Tinlot, 2012; FAO, 2014a). Methodologies that aim to cover multiple, or all identified, environmental impacts associated with agricultural systems include the Sustainable Performance Assessment (SPA) (Elferink et al., 2012; Kuneman et al., 2014) and the FieldPrint Calculator (FieldtoMarket, 2012, 2014).

Table 3 illustrates how many frameworks cover each category of environmental impact dimensions. A number of frameworks cover only one of these types of environmental impact dimension, while others cover two or all three. In general, which dimension a framework covers is closely related to the structure of its methodology. For example, Input-Output Analysis (IOA) (Goodlass, Halberg and Verschuur, 2003; Halberg et al., 2005; Oosterhaven and Stelder, 2008; Rueda-Cantuche, Beutel, Neuwahl, Mongelli and Loeschel, 2009) will only cover the first two categories of objectives. The Environmental Management for Agriculture (EMA) framework does not include emissions-related objectives in the analysis (Lewis and Bardon, 1998), while Life Cycle Assessment (LCA) analysis does not define the objectives of analysis according to the state of the analysed system (Fraval, 2014).

Furthermore, 34 (68%) of the frameworks cover multiple dimensions, but only seven cover all nine. Water use is the most-covered environmental impact dimension, analysed by 33 (66%) of the frameworks. The next most-covered dimension is soil health, covered by 30 (60%) of the frameworks, followed by GHG emissions, covered by 29 (58%).

Three dimension-specific frameworks focus on GHG emissions, compared to two on biodiversity, one on water and one on energy. The dimensions of eco-toxicity, and waste products and emissions are included in significantly fewer frameworks than the other dimensions: only 13 and 10 do so, respectively.

4.2.2 Indicator selection

Methodologies that assess multiple indicators commonly group them into ecological, economic or social indicators, or indicator categories. Moreover, indicator categories center around the environmental impact dimensions of livestock or agricultural production, that is, land use, land cover change, nutrient cycling, water usage and pollution, energy usage, GHG emissions and biodiversity loss. These indicator categories are further divided into specific sub-categories, such as soil management, crop productivity and nitrogen and phosphorous balances. Sub-categories are more variable between frameworks than the more general indicator categories, and depend on the scale and scope of the analysis.

Table 3: Number of frameworks that cover environmental impact dimensions, categorized as emissions-related (ER), inputs-related (IR) and system state-related (SSR), and the number of frameworks that cover different combinations of categories.

The table also shows the number of frameworks that cover each of the nine categories of environmental impact dimensions.

Categories	Emissions-related (ER)	Input-related (IR)	Systems state-related (SSR)	Only ER	Only IR	Only SSR	ER+IR	IR+SSR	ER+SSR	All
Number of frameworks	30	37	35	3	2	4	4	9	0	23
Impact dimensions	GHG emissions	Water use	Soil health	Nutrient cycling	Energy use	Bio-diversity stock	Land use	Eco-toxicity	Waste products and emissions	All
Number of frameworks	29	33	30	26	24	25	28	10	13	7

New assessment frameworks frequently make use of the driving-force, pressure, state, impact, response (DPSIR) analysis framework (OECD, 2001, 2003). In this review, eight of the analysed frameworks (16 %) use the DPISR categorization of indicators. The LCA methodology, recently used to develop an ISO standard for assessment of environmental impact (ISO, 2014), is also frequently used in developing new frameworks, or integrated into frameworks that rely on a combination of different methods. AgBalance uses a "full LCA" for analysis (Schoeneboom et al., 2012), while trade-off analysis (TOA) also builds on the LCA methodology for assessment (Stoorvogel, Antle, Crissman and Bowen, 2004; Stoorvogel, Antle, Crissman and Bowen, 2001). This review found that an additional seven frameworks include aspects of LCA analysis in their proposed methodology without naming them as LCA-assessments.

Moreover, in their indicator selection, 26 of the methods use process-based indicators while 13 use product-based ones. Five frameworks use both types of indicator.

As described above, indicators can be categorized into means-based or effect-based (van der Werf and Petit, 2002), and frameworks can measure one or both types of indicator. For example, the EX-ACT only uses effect-based indicators, while EMA only focuses on farming practices, thus only measuring means-based indicators (Branca et al., 2012; FAO, 2014a; Lewis and Bardon, 1998). In this review, the majority (41 or 82%) of frameworks use effect-based indicators, while 23 (46%) use means-based. It should be noted that of those which use means-based indicators, most cover both types and only one framework uses means-based indicators alone. There is a full list of frameworks and indicators measured in **Appendix 1.**

4.3 System definition: spatial and temporal boundaries

The results of this review indicate that the methods that focus on a specific scale mostly examine the farm, regional and/or global scales, or product assessments (see **Figure 1**). Some assessment tools are targeted for use at the national or global scales, for example the Environmental Sustainability Index (ESI) or the World Agricultural Watch (WAW) (Esty et al., 2005c; George, Bosc, Even, Belieres and Bessou, 2012). Others have been developed to focus on facilitating farm management, for example the RISE tool (Grenz et al., 2009; Häni et al., 2003; Häni et al., 2006; Häni, Stämpfli, Keller and Menzi, undated; Häni, Stämpfli, Tello and Braga, undated) and Sustainable Performance Assessment (SPA) (Elferink et al., 2012; Kuneman et al., 2014). Another group tries to assess the environmental impact of a product, for example the Fieldprint calculator (FieldtoMarket, 2012, 2014) and most LCA analysis frameworks (Fraval, 2014).

We identified a large variation between the 48 frameworks that provided information on coverage or spatial scale. The most frequently covered scale was that of the field and farm, which was the focus of 34 frameworks (71%). Most frameworks covered

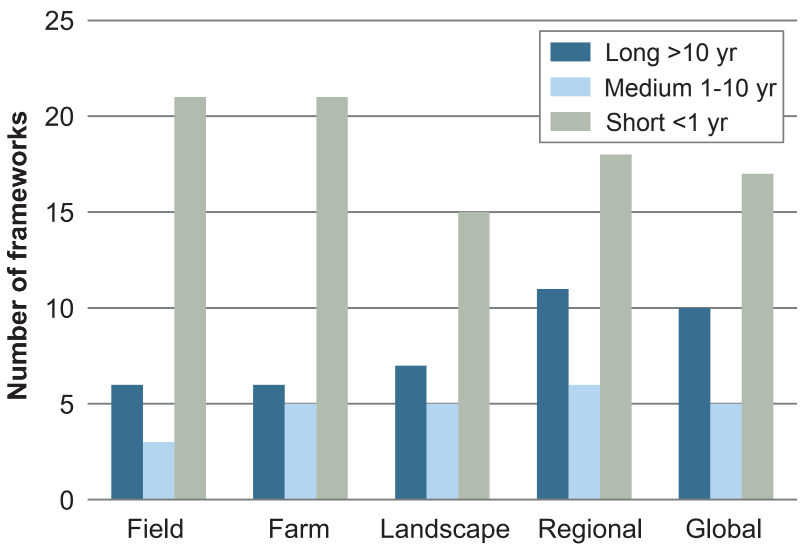

Figure 1: Number of frameworks covering different spatial and temporal scales scale (n=48, two of the frameworks do not provide information on coverage of scales)

multiple scales (37 or 77%). Almost one-third of the frameworks state that they include all spatial scales in their analysis, from field to global.

The coverage of temporal scales is illustrated in **Figure 1** and **Table 4**. Most frameworks focus on short time scales, but about a quarter cover multiple temporal scales, thereby aiming to capture both short- and long-term impacts. However, many of the frameworks do not discuss how they aim to cover different temporal scales or how the selection of scale has been made. This review also considers the timescale of an environmental impact in terms of indicators. For example, impacts linked to GHG emissions always take place over a longer period compared with other impacts. Thus, we assume that frameworks that include GHG emissions cover longer temporal scales.

Figure 1 shows that the landscape scale is the least covered spatial scale, and the least frequently covered timeframe for analysis is the medium term, from 1–10 years. It can also be seen that the long-term temporal scale is covered less frequently for the field scale than for the global and regional scales. Moreover, the applicability of frameworks in this review shows that only one-fifth of the selection, 11 frameworks, set out to measure systems ex-ante.

4.4 Data collection and analysis, and results calculation

More than half of all the frameworks (54 %) require expert knowledge for their use, and the most common audience is policymakers and decision makers, targeted by around 60% of the frameworks. Farmers are the target audience of almost 30 %, followed by scientists and conservation agents. Twelve of the 50 frameworks were web-based, making them easy to access and use for the general public and non-expert users. This also allows for methods, such as RISE (Grenz et al., 2009; Häni et al., 2003; Häni et al., 2006; Häni, Stämpfli, Keller, et al., undated; Häni, Stämpfli, Tello, et al., undated), to use crowd sourcing and aggregate data entries from individual farmers in a specific region. **Table 5** illustrates the differences between the nine methodologies reviewed in-depth in terms of how they vary in data intensity, required practitioner skill, time needed for analysis and the target audience.

The next sections describe the most commonly used methodologies and indicators in the reviewed frameworks, and rely on results from the entire selection of 50 frameworks. For a full list of the in-depth methodology review see **Table 6**.

Table 4: Temporal scales addressed in the reviewed frameworks, including multiple scales

Number of framework	Short term (<1 yr.)	Medium term (1–10 yr.)	Long term (>10 yr.)
Total	31	9	14
Percentage*	62%	18%	28%

* Percentages do not add up to 100% because frameworks were included under every category that applied to them: short, medium and long term, to indicate the coverage of each spatial category.

For a full record of the indicators used by the different frameworks see **Appendix 1**.

4.4.1 GHG emissions

The main types of emissions that livestock contribute to global warming are linked to land use and land cover change (36 %), enteric fermentation (25%) and manure management (31 %) (Steinfeld et al., 2006). Most methods and models for calculating GHG emissions per production unit are built up around and use calculations based on the guidelines for national greenhouse gas inventories developed by the International Panel on Climate Change (IPCC, 2006). These methods and models are categorized into tiers numbered from one to three, where tier one is the most detailed. The frameworks in this review mostly use tier-two values that require less time for data collection and analysis but provide a measure with a level of detail that is locally relevant. The impact dimension "GHG emissions" is one of the most covered dimensions, and three of the frameworks focus on this dimension alone. GHG emissions are commonly analysed for the entire value chain, since they are emitted at all steps of the production chain. The two most commonly used indicators for GHG emissions are: GHG emissions in CO_2-equivalents per kg of product, and manure management.

4.4.2 Energy use

In livestock production, energy use can be divided into: direct energy use, including the use of non-renewable energy (e.g. oil and natural gas) and electricity; and indirect energy use, for the production of mineral fertilizers and purchased feeds (Vayssières, Vigne, Alary and Lecomte, 2011). Other indirect energy uses, such as for the production of pesticides and machinery, are generally not considered (Vigne, Vayssieres,

Table 5: The nine frameworks reviewed in-depth, listed according to their data intensity, skill requirements, time consumption and target audience

No.	Framework	Data intensity	Skill requirements	Time consumption	Audience
1.	Vital Signs – African monitoring systems (Scholes et al., 2013; VitalSigns, 2014)	Uses data from observation, monitoring and census systems, which have their own sampling frames. Sampling in four "Tiers" from coarse to very detailed	Not high. Very well-defined sampling methods in protocols	Sampling is conducted from very short to very long time intervals. However, the design of sampling relies on repetition of sampling every 1–2 or 3–5 years	Environmental/ agri- policymakers and decision makers
2.	Response-Inducing Sustainability Evaluation (RISE) (Grenz et al., 2009; Häni et al., 2003; Häni et al., 2006; Häni, Stämpfli, Keller, et al., Undated; Häni, Stämpfli, Tello, et al., Undated)	Requires secondary "background data". gathered from surveys/ interviews	Requires experts to conduct assessment. A trained analyst must complete an in-depth farm assessment	Four hours. Requires training beforehand.	Farmers
3.	AgBalance (AgBalance, 2012; Schoeneboom et al., 2012)	Based on a huge data set gathered during 15 years of Eco-efficiency assessments. Uses data from scientific, expert or governmental sources, together with field studies	Requires experts to conduct assessment	Builds on 15 years of gathered background data. Additional time for data gathering and analysis	Farmers, policymakers and decision makers, food-chain industry, scientists
4.	LCA for agriculture (Bauman and Tillman, 2004; Cederberg et al., 2007; Cederberg et al., 2013; De Boer, 2003; De Boer et al., 2011; De Boer et al., 2012; De Vries and De Boer, 2010; Flysjö et al., 2012; Fraval, 2014; Thomassen et al., 2008; Vellinga et al., 2013)	High level of requirements: Ideally, primary data over 2–3 years throughout the chain, supplemented by secondary data and emission factors	Requires experts to conduct assessment	Minimum of several months to meet ISO standard requirements	Private sector, policy and decision makers, environmental markets
5.	World Agricultural Watch (WAW) (CIRAD, 2011; FAO, 2012b; George, Pierre-Marie et al., 2012)	Relies on inputs from several existing statistical datasets	Requires experts to conduct assessment	Less than 5 years	Decision makers and stakeholders
6.	ESI (Esty et al., 2005, 2005a, 2005b, 2005c)	Heavy requirement of input data from existing databases	Considerable conceptual and analytical processing precedes the calculation of the ESI scores and rankings	Standardized method like LCA. Data gathering, calculation and scoring require some significant time and personnel.	National policymakers
7.	Sustainable performance assessment (SPA) (Elferink et al., 2012; Kuneman et al., 2014; SAI, 2010)	Minimum data intensity to make an estimation based on each indicator	Not high. Described for farmers to use	Data gathering requires time. Yet to be pilot tested (2012–2013)	Farmers, companies, practitioners

8.	MESMIS (López-Ridaura et al., 2002; López-Ridaura, van Keulen, et al., 2005a, 2005b; Speelman et al., 2007)	Requires background data from existing statistical databases, as well as surveys, interviews and field work	Requires skills in linear modelling	Time period of at least two years for measurements. Data calculation and analysis require some additional time	Scientists, policy-makers
9.	GAIA (CLM, 2012, 2014)	Farmers knowledge about local flora, fauna, management practices, natural vegetation	No particular experience. Web-based survey developed for farmers	Very short time requirement, assuming that background data are available	Farmers

Lecomte and Peyraud, 2012). The energy consumption takes place during the transportation, cleaning and processing of livestock products but is also largely consumed during the production of animal feed, mostly for irrigation and particularly for the production of non-organic fertilizers (Gerber et al., 2013).

Different methodological approaches exist for assessing energy, for example simple Energy Assessments (EA) (Pimentel, 1992) that consider use of fossil energy and successfully link energy use to environmental impact, such as natural resource depletion. In Ecological Footprints, energy is a sub-indicator, represented as land. This approach successfully raises awareness of resource use for a wider audience, but fails to raise the issue of how to improve energy use efficiency (Vigne et al., 2012).

There are also methods that calculate the entire environmental impact of processes in energy terms. Emergy analysis considers total energy use for certain production or human benefit, as emergy fluxes into natural resources, e.g. the amount of solar, wind and water energy required to produce the same resources. This method separates renewable and non-renewable resources and thus identifies whether processes rely heavily on non-renewable resources. However, the environmental impact of renewable energy is not quantified (Vigne et al., 2012). Exergy analysis assesses the environmental impact of livestock entirely in flows of energy. All inputs and outputs are recalculated as energy flows and assessed as the balance of energy inputs and outputs to the system. Compared to other input-output balance methods, exergy assessments can also capture whether the energy output is degraded in relation to the energy input, and thus has a lower value. For example, if energy is emitted in terms of heat, there has been a loss in energy quality compared to the system input; but if all energy has been embedded in human-edible livestock products, the energy net loss will be lower (Apaiah, Linnemann and van der Kooi, 2006; Ertesvag, 2005).

Various models can be used to predict energy use throughout the value chain. These are often based on IPCC Tier 2 calculations (IPCC, 2006), but also use modelling such as the "greenhouse gases regulated emissions and energy use in transportation" model (GREET), and the "revised universal soil loss equation" (RUSLE2), which assess energy use in agricultural practices such as tillage, equipment operation and manure management. The energy requirements for irrigation practices can be calculated based on secondary data and user inputs on the frequency and methods of irrigation.

Frameworks tend to define their indicators in terms of either energy use per kilogram of product, or energy use per hectare. Energy use per product is the most common indicator, because energy is covered primarily by methods that take a value-chain perspective – which generally assesses impacts per product. Most methodologies also divide energy into renewable and non-renewable in order to capture impacts that correspond only to the share of non-renewable energy.

4.4.3 Water

Despite the fact that it is the dimension covered by the largest number of frameworks, there is no real consensus in the literature on how to address the impact dimension of water. This review distinguishes between assessments of water quality and quantity as they use different indicators and methods.

For water quantity, the frameworks use the indicators of cubic metre of water input per kilogram of product produced, and irrigation water per hectare or kilogram of product. Water requirements are measured using models such as the FAO CropWat (FAO, 2014b) or tailored models such as LPJmL and SWAT (Bondeau et al., 2007; Faramarzi, Abbaspour, Schulin and Yang, 2009; Garg, Karlberg, Barron, Wani and Rockstrom, 2012; Gassman, Reyes, Green and Arnold, 2007; Gerten et al., 2005; Schuol, Abbaspour, Srinivasan and Yang, 2008; Schuol, Abbaspour, Yang, Srinivasan

Table 6: Methodology description by environmental impact dimension for in-depth review of nine selected frameworks

Key: FM= field measurement, E= Erosion, SOC/SOM= Soil organic carbon/matter, SD= Secondary data, NB= Nutrient balance, ENU= Energy use, BD= Biodiversity, SPR= Species richness, MN=Management, GWP= Global warming potential, CB= Consumer benefit, DM= Damage functions, CF= Characterization factors, LUC=Land use change

Framework/ Impact dimension	GHG emissions	Water quantity and quality	Soil health	Nutrient cycling	Energy usage	Biodiversity stock	Land use	Eco-toxicity potential	Waste emissions and products
Vital Signs (Scholes et al., 2013; Vital-Signs, 2014)	FM and modelling	FM	FM	FM	FM	FM	FM and remote sensing		
RISE (Grenz et al., 2009; Häni et al., 2003; Häni et al., 2006; Häni, Stämpfli, Keller, et al., Undated; Häni, Stämpfli, Tello, et al., Undated)	FAO Ex-Act (which builds on e.g. IPCC, 2006)	Quantity: FAO LocClim, Water footprint and own developed methodology. Water stress: Global Water Tool Quality: Risk assessment	E: CORINE rapid assessment. SOM: balance based on VDLUFA method		Energy intensity, direct energy only (energy density figures from SD)	IP-Suisse BD scores.	Land classification according to official Swiss system. Prod: SD	PAN, Ecotoxnet, FOAG rating. Rating of eco- and human-toxicity of active ingredients. Modified Environmental Impact Quotient	Disposal quality for differed kinds of waste
AgBalance (AgBalance, 2012; Schoeneboom et al., 2012)	Air mass of emissions per CB. GHG emissions adjusted as defined by IPCC (2006)	Quality: CV approach Quantity: Pfister, Köhler and Hellweg method assesses CWU (excluding green water) (Pfister, Koehler and Helweg, 2009)			Total primary ENU required for CB.	Relative function from the BD state indicator and others	Model of DM and generic CF for calculating impacts from land occupation and LUC	European risk ranking system (EURAM) – a scoring system based on the principles of environmental risk assessment	
Life-Cycle Assessment (LCA) (Bauman and Tillman, 2004; Cederberg et al., 2007; Cederberg et al., 2013; De Boer, 2003; De Boer et al., 2011; De Boer et al., 2012; De Vries and De Boer, 2010; Flysjö et al., 2012; Fraval, 2014; Thomassen et al., 2008)	IPCC Tier 2 (IPCC, 2006)	Quantity: FAO CropWat	Roth-C model, FM of pH, score based on anti-E MN	NB of farm input and output	IPCC Tier 2	Questionnaire on BD improving MN on farm	For crops: inverse of yield. For animal feed: inverse of yield of ingredients	Risk score = exposure/toxicity or maximum acceptable conc. Simple version uses environmental impact score as totalized impact on people and environment	
World Agricultural Watch (WAW) (CIRAD, 2011; FAO, 2012b; George, Pierre-Marie et al., 2012)	IPCC Tier 2, SD (IPCC, 2006)	Only measures irrigation from input of SD	E: RUSLE2 and WEPS 1.0. SOC: RUSLE2 (SCI)		RUSLE2, GREET SD		Direct from input data. Planted area/unit of production		

Environmental sustainability index (ESI) (Esty et al., 2005, 2005a, 2005b, 2005c)	SD. IPCC Tier 2 (IPCC, 2006)	Quality: Critical volumes or critical limits. Quantity: FAO CropWat	Roth-C model, FD, score-based anti-erosion measures	NB of farm inputs and outputs	Total ENU by SD. IPCC Tier 2	Questionnaire on BD improving MN on the farm	For crops: inverse of yield. For animal feed: inverse of yield of ingredients	Calculated using the European Union law classifications for hazardous materials Risk score = exposure/toxicity or maximum acceptable conc. Simple version uses environmental impact score as total impact on people and environment
Sustainable performance assessment (SPA) (Elferink et al., 2012; Kuneman et al., 2014; SAI, 2010)	SD. IPCC Tier 2 (IPCC, 2006)	Only measures irrigation from input of SD.	E: RUSLE2 and WEPS 1.0. SOC: RUSLE2 (SCI)		RUSLE2, GREET and calculated SD		Direct from input data. Planted area/unit of production	
MESMIS (López-Ridaura et al., 2002; López-Ridaura, van Keulen, et al., 2005a, 2005b; Speelman et al., 2007)		FM and sampling	FM sampling		FM sampling	Surveys of flora	FM and sampling	
GAIA (CLM, 2012, 2014)						Measures SPR, composition and farm MN		

and Zehnder, 2008). These tailored models aim to model process-oriented water flows within a defined area. However, there is an ongoing debate on how to deal with the enormous amount of water that is evapotranspired over agricultural land and grassland used for fodder and grazing. The approach of Hoekstra and Chapagain, to include all water, is widely applied, but it has several limitations. For instance, it has been criticized for making generalizations about water resource use (Perry, 2014; Ridoutt, Sanguansri, Nolan and Marks, 2011), and a better approach for freshwater appropriation in biomass systems may be required (Ridoutt and Pfister, 2010, 2013). Others argue that only liquid freshwater appropriation is important, because this is what has trade-off value for alternative uses. This is for example the approach taken in LCA assessments, where water use is measured by indicators related to local water stress, using a local-specific water stress index to spatially connect the calculations to the local importance of water use (De Vries and De Boer, 2010; Ridoutt, Eady, Sellahewa, Simons and Bektash, 2009; Ridoutt and Huang, 2012; Ridoutt and Pfister, 2010, 2013; Ridoutt, Sanguansri, Freer and Harper, 2012; Ridoutt et al., 2011; Zonderland-Thomassen and Ledgard, 2012).

Water quality is most commonly assessed in terms of pesticide use, fertilizer use and the nutrient balance associated with production. Assessments tend to use a “critical amount” approach, which aims to identify the critical amount of water pollution that is acceptable for a certain species, or that does not exceed regulations, based on maximum emission concentrations (MECs) or maximum accepted concentrations (MACs). MECs and MACs consider the risks that chemicals in use pose to the environment and humans, combined with the emitted quantity. By including indicators on both the application of chemicals and the critical amount of pollution for a specific area, both the amount of pollution and the environmental impact of emissions are included in the analysis (Elferink et al., 2012; Kuneman et al., 2014).

Indicators vary a lot for water quality, but the most common one is water quality or the potential risk to water quality (Elferink et al., 2012; Grenz et al., 2009; Häni et al., 2003; Häni et al., 2006; Häni, Stämpfli, Keller et al., undated; Häni, Stämpfli, Tello, et al., undated). Water quality indicators aims to capture pollution from pesticides and other chemical uses, and the potential risk of eutrophication caused by leakages of nitrogen and phosphorous from manure application to nearby water bodies and resources.

4.4.4 Biodiversity

While there is common agreement that agriculture and livestock production have impacts on the status of biodiversity, there is no consensus in the literature on how to deal with measuring biodiversity loss, or how to accredit such loss to the actual practice of agriculture. Methods for assessing the indicators vary from simple modelling to indicator-specific frameworks that identify biodiverse habitats, such as Habitat Hectares (DSE, 2004; Parkes, Newell and Cheal, 2003), or monitor biodiversity status, for example the TEAM monitoring method which uses remote sensing methods such as GIS (TEAM, 2008). More simple methods aim to derive the biodiversity status of a farm based on the environmental baseline and composition of the landscape, for example the GAIA biodiversity yardstick (CLM, 2012, 2014). There are also indicator-specific, regional to global methods such as GLOBIO 3, which assesses multiple environmental dimensions as drivers of biodiversity loss (Alkemade, Reid, van den Berg, de Leeuw and Jeuken, 2012). The large discrepancy between methods and models makes results difficult to compare and patterns hard to distinguish in this environmental impact dimension.

Biodiversity is also the impact dimension that is measured by the largest number of indicators for each framework. Indicators for biodiversity vary a lot between frameworks because they use proxies for biodiversity, and assume relationships between a production system and the protection of species, habitats and resilience. Examples of indicators for biodiversity include: (i) share of protected areas; (ii) share of protected species; (iii) species composition; (iv) canopy cover; and (v) different kinds of biodiversity protection measures.

4.4.5 Soil quality and land use

Frameworks generally measure soil quality using indicators of soil organic matter, pH, soil erosion and nutrient balance in soils. Data for these indicators are very locality specific and normally gathered at the farm/field scale. They require intense data collection to reveal aggregated impacts beyond the farm level. If the time and scope of the framework do not allow for field measurements, previously developed models and secondary data can be consulted. Measurements of soil organic matter can, for example, be provided by models oriented to soil-physical and chemical processes, such as the Rothamstead Carbon model (RothC) which measures carbon turnover in soils, and VDLUFA, a humus balance model that calculates the soil organic matter balance in the soil (Coleman and Jenkinson, undated; Kolbe, 2005). Erosion is most commonly calculated based on the universal soil-loss equation, RUSLE/USLE. Another method for assessing erosion and erosion risk is by monitoring the erosion during a farm visit, which is applied for example in VitalSigns Tier 2b (Scholes et al., 2013).

Estimates of soil health can also provide assessments of erosion by calculating an erosion-prevention score based on soil type and measures of erosion, as suggested in the Sustainable Performance Assessment (Elferink et al., 2012; Kuneman et al., 2014), or based on expert consultations, as in RISE (Grenz et al., 2009; Häni et al., 2003; Häni et al., 2006; Häni, Stämpfli, Keller, et al., undated). Some methods measure all kinds of soil parameters and nutrients, which is both time-consuming and complex. Thus, most methodologies that aim for a rapid assessment rely on secondary data and/or modelling, and focus on nitrogen and phosphorous balances in the soil.

Land use is, in general, illustrated by estimates of how much land is dedicated to specific production. For process-oriented indicators and results, the total area cultivated for associated production is calculated. For land use and land cover change, most frameworks use remote-sensing approaches.

The wide variety of methods means that there is wide variety in the selection of indicators. However, frameworks measure land use most frequently by land use per kilogram of product. Besides land use, other indicators include field size and cropping patterns for production.

4.4.6 Nutrients

The most common assessment method for nutrient inputs is based on the rate of application of different nutrients per hectare of arable land, information that can often be gathered directly from farmers. A more precise measure would be to calculate nutrient application per kilogram of product, which relates the application rate to the efficiency of production (Elferink et al., 2012; Kuneman et al., 2014). The most commonly used methods are nutrient balancing methods based on farm inputs and outputs, as described by FAO (Roy, Misra, Lesschen and Smaling, 2003). This method is more specific than considering only the application rate of nutrients, because it also accounts for the accumulation of soil organic matter and modelled or actual losses of nutrients to the environment (Elferink et al., 2012; Kuneman et al., 2014).

The same variation in how the different frameworks approach nutrient balances is found in in how much detail they measure the balance, as well as in the background data used, what input-output data are taken into account and which nutrients are to be assessed. For rapid assessments, calculations are limited to nitrogen and phosphorous balancing, but more detailed nutrient balancing methodologies also include potassium and other minerals. For example, a nutrient balance will include inputs such as fertilizers, soil, irrigation water, nitrogen from atmospheric deposition, and the amount of nitrogen fixated by legumes. Outputs in turn include farm products leaving the farm, removed crop residues and manure.

Depending on the level of detail, frameworks will rely on the modelling of existing data, gathered in field experiments or from surveys and interviews during farm visits.

For indicator selection, nutrients are generally captured in terms of the surplus or deficit of nitrogen and phosphorous in kilograms per hectare, or product. Many also include indicators such as manure management and manure application.

4.4.7 Eco-toxicity potential

Toxicity potential is generally assessed based on data gathered from a local/regional database on the toxicity potential of different pesticides and other chemicals. For example, the RISE method uses data from the Pesticide Action Network (PAN) and Ecotoxnet for rating assessment. The eco- and human-toxicity of the active ingredients of applied pesticides and chemicals are then estimated as well as a modified Environmental Impact Quotient, to give an indication of the eco-toxicity of the chemicals used in the analysed system (Häni et al., 2003).

The SPA uses two different methods depending on data availability. The more data intensive approach is the risk score, which is a ratio of exposure divided by toxicity or maximum acceptable concentration of chemicals. Exposure is determined on the basis of a number of climatic factors as well as the method and frequency of application of each chemical. The simpler version is based on an environmental impact score, which means the totalized impact on people and the environment, based on the behaviour of chemicals by ranking them on a number of different factors such as run-off potential and LD50 (the lethal dose for 50% of a species). Online databases are the main source for these characteristics of chemicals, and also provide information by region (Elferink et al., 2012; Kuneman et al., 2014). The AgBalance assessment uses the European risk ranking system (EURAM), which is a scoring system based on the principles of environmental risk assessment (Esty et al., 2005a, 2005b; Schoeneboom et al., 2012).

Indicators for eco-toxicity are generally in the form of ratings for eco-toxicity, or potential risk scores in number form (e.g. 1–5) or of qualitative descriptions such as low, medium or high.

4.4.8 Waste

Waste is generally divided into different waste categories in order to identify disposal quality, or how difficult the waste is to dispose of, as well as categories that identify how much waste is reused and recycled in the system. Examples of different categories might be: "hazardous waste", "non-hazardous waste" and "recycle and reuse", as used in the RISE method (Grenz et al., 2009; Häni et al., 2003; Häni et al., 2006; Häni, Stämpfli, Keller, et al., undated; Häni, Stämpfli, Tello, et al., undated).

The most commonly used indicators for waste products are: hazardous waste, municipal waste and recycling. Waste management is also an indicator that is widely used between methodologies because it can have profound effects on other environmental impact dimensions, such as water quality and eco-toxicity, due to leakages.

4.5 Presentation of results

The reviewed frameworks provide outputs in a range of formats, such as reports, tables, diagrams or a combination each. **Table 7** shows that the majority (66 %) of frameworks present results in the form of a table, in most cases complemented either by a detailed report (30 %) or a summary chart (17 %). Eight frameworks present results only in table form, while five only use graphics and three only publish reports. In general, there is a wide variation in how the results are visualized. The most popular tools for illustrating results, besides a report and tables, are graphics. The most popular of these are spider charts showing the differences between multiple impact dimensions in the same graph, which are used by 18 % of the frameworks. Another graphic that stands out is the use of "traffic lights", which are used to give an indication of "good or bad" for one or several impact dimensions. Traffic lights do not show the differences between different impact dimensions, however, and were used by only 6% of the frameworks.

Most of the methodologies that are not modelling frameworks (20 of the 38, or 53%) use a scoring approach in their analysis and presentation of results. Many methodologies choose to score their outcomes by assigning indicators with a score from 0 to 100. Others, such as RISE and IDEA, do so in the form

Table 7: Types of output by frequency among the 50 reviewed frameworks

Output type	Percentage
Report and table	30%
Table only	16%
Table and other chart	12%
Spider or traffic light diagram only	2 %
Other chart only	10%
Report and spider or traffic light diagram	6%
Report only	6%
Report, table and spider or traffic light diagram	8%
Report and other chart	2%
No output	8%

of a "good or bad" approach, for example a red light or similar graphic indicator (Grenz et al., 2009; Häni et al., 2003; Häni et al., 2006; Häni, Stämpfli, Keller, et al., undated; Häni, Stämpfli, Tello, et al., undated; Zahm, Viaux, Giradin, Vilain and Mouchet, 2006). Others, including the Environmental sustainability index (ESI), use a single score as the outcome (Esty et al., 2005b, 2005c). However, results are normally presented using more than one explanatory tool, graphic, table, report or equivalent, as shown in **Table 7** and **Table 8**. **Table 8** lists the outputs of the nine in-depth reviewed frameworks in terms of how the results are illustrated and communicated to the target audience.

Table 8: Description of the outputs of the nine in-depth reviewed frameworks by type of illustration and additional information provided to end-users

Framework	Output illustration	Output description
Vital Signs – African monitoring systems (Scholes et al., 2013; VitalSigns, 2014)	Measurements are presented in an open-access online dashboard	Decision-support for indicators of: sustainability, resilience, food security, water scarcity, climate security, biodiversity security and livelihoods
Response-Inducing Sustainability Evaluation (RISE) (Grenz et al., 2009; Häni et al., 2003; Häni et al., 2006; Häni, Stämpfli, Keller, et al., Undated; Häni, Stämpfli, Tello, et al., Undated)	Sustainability polygon. Degree of sustainability in a "traffic-light" illustration	A RISE feedback report in the form of a farm profile, or sustainability polygon, a table of parameter scores followed by further explanatory information on the indicators, their meanings and calculation
AgBalance (AgBalance, 2012; Schoeneboom et al., 2012)	Sustainability spider chart	Four separate layers are generated: (1) provision of absolute figures (litre of water per MJ energy) or scores; (2) results calculated for the 16 indicator categories; (3) an assessment of the economic, ecological and social contribution to the overall sustainability of each alternative; and (4) benchmarks for the sustainability of each alternative against other practices.
Life Cycle Assessment (LCA) (Bauman and Tillman, 2004; Cederberg et al., 2007; Cederberg et al., 2013; De Boer, 2003; De Boer et al., 2011; De Boer et al., 2012; De Vries and De Boer, 2010; Flysjö et al., 2012; Fraval, 2014; Thomassen et al., 2008; Vellinga et al., 2013)	Detailed publications with results summarized in tables and graphs. Infographics used to communicate to the public	An impact assessment of the ISO standard for the entire product cycle given for the impact categories: land use, energy use, climate change, eutrophication and acidification
World Agricultural Watch (WAW) (CIRAD, 2011; FAO, 2012b; George, Pierre-Marie et al., 2012)	Reports, policy briefs, database for stakeholders	Policy briefs formulated to support evidence for decision makers at the national level, including information on: (1) agricultural transformation; (2) historical development of transformation within the country; (3) current status of and forecasts for transformation and impacts; and (4) key considerations and development options for local agricultural practices

Environmental sustainability index (ESI) (Esty et al., 2005, 2005a, 2005b, 2005c)	Environmental sustainability index score	Global datasets developed from ESI analysis e.g. Anthropogenic biomes, an archive of census-related products, climate effects on food supply, compendium of environmental sustainability indicators, an environmental performance index and an environmental sustainability index
Sustainable Performance Assessment (SPA) (Elferink et al., 2012; Kuneman et al., 2014; SAI, 2010)	For each issue SPA describes - the output indicator (kg CO2/unit) - data the farmer needs to put in (kg fertilizer) - background data needed - calculation rules (boundaries, formulae)	Seven fact sheets on climate change and energy, water use, nutrient efficiency, soil quality, biodiversity, pesticides and land use. Each chapter or factsheet also briefly outlines why these data and methods were chosen
GAIA (CLM, 2012, 2014)	Pie charts for: (1) productive areas under targeted nature management; (2) area of non-productive elements in the field; (3) area of natural resources.	Farm score for biodiversity themes. Scores are defined for six themes and for their effect on 11 categories of flora and fauna
MESMIS (López-Ridaura et al., 2002; López-Ridaura, van Keulen, et al., 2005a, 2005b; Speelman et al., 2007)	Amoeba diagrams (radial diagrams, tradeoff curves)	Places the results by indicator and system into a single table or matrix, using the original units of each indicator; determines thresholds or baseline values for each indicator; builds indices for each indicator, according to baseline values or thresholds; places all indicators together, using graphs and tables; examines the connections or relationships between indicators, including positive and negative feedback.

5 DISCUSSION

This literature review of environmental impact assessment frameworks for livestock and agriculture reveals that surprisingly few of them either examines livestock and agriculture separately, or focus solely on livestock production systems. We identified and refined nine key environmental impact dimensions and five main methodological steps. The development of the frameworks centers around various important choices and selections that define their structure in terms of scope, boundaries, target audience and scale of analysis. This review found that the selection of which environmental impact dimensions to cover, and of which indicators to measure and by what methods, varies greatly between frameworks. The frameworks also use different ways of presenting results and generate a wide range of tools and measures for doing so.

We found that, in the process of developing a framework for environmental assessment, the scope and general objective set the foundation for the method. However, the general objective tends to consider broad concepts and can be formulated in a way that has implications for the direction of the framework that are not explicitly stated in the general objective. We found that frameworks such as LCA and EMA (Fraval, 2014; Lewis and Bardon, 1998), which aim to assess environmental impacts, also reported all the categories required for sustainability assessments, and can thus be said to assess sustainability as well as the stated environmental impact, or vice versa (van der Werf and Petit, 2002). The divergence between the stated aims of frameworks and their titles also reinforces the point that it is somewhat difficult to distinguish between environmental impacts and sustainability assessments.

In general, results indicate that it is hard to draw any conclusions about the overall structure of frameworks by only reviewing the methodological aim, and that the formulation of the aim does not play a significant role in the framework of the structure.

The environmental objectives of a framework drive the selection of environmental impact dimensions and the selection of indicators. The frameworks vary widely in how they formulate environmental objectives, and the formulation also connects back to what is stated in the general objective since this will ultimately decide if the framework achieves what it sets out to do. For example, if the general objective of a framework is to assess sustainability or environmental impact, the environmental objectives will be formulated differently than if the general objective is to assess environmental impact, in order to deliver targeted results that allow the framework to be successful.

In general, we found little explanation for why environmental impact categories and indicators were selected, verifying the findings of Van der Werf and Petit (2002). Many tools do not include an explicit rationale for indicator selection, environmental impacts or preferred methods (Halberg et al., 2005). This makes comparing the results from different methods problematic, and makes it difficult for practitioners to make informed choices between available methods for analysis, or on improving existing tools and methods.

Two new impact categories were also identified in addition to the ones outlined by Steinfeld et al. (2006): eco-toxicity, and waste emissions and products. The inclusion of the latter reflects recent attempts to include the entire value chain of a product, rather than only focusing on the production stage. The number of LCA analyses that use a value-chain perspective is increasing, and 57 studies were published between 2000 and 2013 that focus on livestock and aquaculture production (Fraval, 2014)

The frameworks also differ in terms of whether they choose to include all, or focus on one or a few, of the impacts. Once again, they do not provide a rationale for which impacts are excluded or included. Reasons for selection vary from the previous focus of analysis of the framework developer, to the aim of performing a full-scale analysis or the need to develop a method to assess multiple impact dimensions rather than a single dimension.

On which impact dimensions are most important, our results differ from other reviews. For example, Van der Werf and Petit (2002) conducted a review that found that “energy consumption” (framed as use of non-renewable energy) was the most prominently assessed environmental impact dimension, followed by “landscape quality” and “biodiversity”. While soil quality is the impact category with least coverage in their results, it is one of the most important impacts in this review. This may be the result of recent scientific as well as public trends, where assessment methodologies and focuses tend to follow the interests of the public and policymakers at the time of assessment. The increased popularity of a value-chain approach and Life-Cycle Assessments (Fraval, 2014) has resulted in two new impact categories being commonly addressed: waste products and emissions, and eco-toxicity. Another example of frameworks following public and academic trends is that GHG emissions were not identified as significantly important by Van der Werf and Petit in 2002, but have since gained more attention in the debate on livestock, and also on agricultural production in general. This trend accelerated after the publication of *Livestock's Long Shadow*, which stated that 18% of global GHG emissions can be attributed to livestock production (Steinfeld et al., 2006).

Although some frameworks analyse the same environmental impact dimensions, they can still use widely different indicators for analysis. There are a number of variations of the same indicator, or rather attributes are added to indicators that are related to the system definition for a specific method. Thus the unit by which indicators are measured also varies, and these variations are also a result of the framework scale as well as the target audience.

There is no universal list of indicators that is applicable to all agricultural and livestock situations, although there have been numerous attempts to develop such a list in the past (Esty et al., 2005c; Halberg et al., 2005; OECD, 2001, 2003; Zahm et al., 2006). However, several frameworks use pre-existing ways of categorizing indicators, and this report shows a few examples of these that are widely used, for example the Pressure-State-Response categorization (OECD, 2003) or the indicators developed for LCA assessments (Fraval, 2014).

Halberg et al. (2005) argue that most indicators used for environmental impact assessment of agriculture are process-based, and this is verified in our results. In recent years, methods of assessment of the environmental impacts of all kinds of production have increasingly moved towards including the whole value-chain of production. These types of assessment use product-oriented indicators, or both process- and product-based indicators, rather than focus on the process. In this review, 13 frameworks use product-based indicators, of which six assess both indicator types.

Biodiversity was the impact dimension with the greatest variety of different assessment methods and measures. This is likely to be a reflection of the multiple linkages between production, consumption and biodiversity loss, and the dependence on local scale activities to relate these linkages to each other, which makes it challenging to link consumption and production to changes in biodiversity. Perhaps there are also delays between agricultural production activities and changes in ecosystems, which mean that farmers do not get feedback in time, and that effects might accumulate before they are detected. This applies not only to biodiversity, but also to other impact dimensions such as water use, land use, land-cover change and GHG emissions. It is usually difficult to provide evidence for links between human activity and environmental impacts before an impact has taken place, and this is particularly true for agriculture and, within agriculture, especially livestock, because impacts have to be connected only to the particular parts of agriculture associated with livestock keeping and the production of animal fodder. Thus, there is a need for further research to capture livestock and agricultural production effects on ecosystem functioning (MEA, 2005). Framework developers could benefit greatly from consulting on methods that aim only to measure one environmental impact dimension, as well as multidimensional frameworks to develop appropriately detailed and cost-efficient ways to capture impacts in their assessments.

There are a number of methods available for measuring the environmental impact dimensions associated with livestock. The challenge is to match them properly to the scale of analysis. An environmental impact assessment of livestock value-chains should deliver results that mirror the objectives and expected outcomes of such a framework. Thus, a simply designed framework cannot rely on costly, labour-intensive and time-consuming methods of measurement and highly detailed outcomes and results. Our results show that most frameworks rely on a number of different methods that are combined to capture several dimensions and value-chain steps. This presents a challenge in terms of matching different methods with different input and output data, to generate results that are both easy to analyse and comparable.

Multidimensional frameworks that aim to be holistic, rapid and simple to use, depend strongly on secondary data. The collection of secondary data depends on availability, as well as the time allocated for data collection, and may limit the cases where the framework can be applied. We found that frameworks did not generally estimate how much time was required for gathering and preparing secondary data, with the exception of RISE and SPA (Elferink et al., 2012; Grenz et al., 2009; Häni et al., 2003; Häni, Stämpfli, Keller, et al., undated; Kuneman et al., 2014). The time needed for data collection and analysis can vary a lot, depending on whether, for example, a practitioner can rely on a statistical source such as FAOSTAT, or needs to search for data from local sources. Moreover, many frameworks use primary data collection methods, such as field measurements and household surveys, which generally require a lot of time for collection, as well as personnel and data analysis.

We identified that the majority of frameworks aim to assess environmental impacts at multiple scales, both temporal and spatial. However, when looking at timescales, most frameworks only cover a short timescale of less than one year. In addition, many of the frameworks are assumed to take a long-term perspective as a result of including GHG emissions in their analysis, although other impacts are not measured over the long term. Thus, there is possibly an even greater emphasis on the short term among the reviewed frameworks than our results show, because temporal scales are not presented according to impact dimension. Thus, if a framework measures all impact dimensions over the short term (except for GHG emissions, and the impact of such which always take place over the long term), the framework would still be assumed to cover long-term temporal scales. It might be better to consider GHG emissions separately from other indicators to enable stronger results on temporal scales in this type of review.

One way of covering multiple temporal and spatial scales is by up-scaling or downscaling results from one scale to make them relevant at another. This is the preferred method of many of the frameworks, since it does not require data to be covered for all scales of analysis but allows data from one scale to be used for others. However, we found that the frameworks that use this method do not clearly describe their methods of up-scaling, such as aggregation, or the assumptions that are required to use aggregation or a competing method. As a consequence, it has not been possible to capture how frameworks deal with the up- and downscaling of data in this literature review. For a framework to be both rapid and able to deal with complexity, it needs a clear methodology for up-scaling so that it does not require new data for all scales of assessment. Thus, the component of up- and downscaling needs further review to identify a proper methodology to meet the need for a rapid environmental assessment at multiple scales.

Another important finding of this review is that policymakers, as well as decision makers in general, are the most commonly targeted audience. However, most frameworks do not perform *ex-ante* analysis, and thus would have to inform policymakers at the same time as production is taking place, or after it has taken place. Naturally, it is desirable for decision makers to be able to take to preventive action on environmental impacts before a process has begun or an intervention has been adopted, but the lack of *ex-ante* analysis makes it difficult for them to do so. To properly inform policymakers and decision makers, the focus must shift towards *ex-ante* assessments to deliver targeted results, thereby enabling timely and informed decision-making to mitigate environmental impacts from the start of a process (Thornton, 2006; Thornton and Herrero, 2001).

Finally, it is important for any assessment method to produce an outcome that is visually clear and informative for its target audiences. Thus, it is preferable to use outputs that can be easily compared with other methods. In this review, most frameworks used reports and tables to present their outputs. However, many also used complementary graphics tools. Of these, spider charts were the most popular, used by almost one-fifth of the frameworks, often combined with a more informative report as feedback to the end-user. It is often useful for end-users to be given outputs that are complemented by a report containing further recommendations and explanations of what the output means. However, the frameworks generally provided little by way of rationale for the choices made regarding the presentation of results.

Thus, the last methodological step, presentation of framework results and communicating them with stakeholders, comes with a number of important choices for the developer of a framework. It is important that the presentation of results connects back to the previous steps of the methodology in order to achieve the stated objectives and deliver results to the target audience. This step also calls for a balance between detail and communication. In our review we identified a number of ways to deliver results in an informative and pedagogical way, normally in combination with different measures. For example, graphics, tables and reports are commonly combined in various ways in order to present the findings.

6 CONCLUDING REMARKS

Given the expected ongoing increase in the demand for and production of livestock products and their associated impact on the environment, there is a need for effective methods of assessment that focus on livestock value chains and their environmental impact. This review assessed 50 frameworks that consider the environmental impact of livestock, of which only three state that they focus solely on livestock production. There is also a need for *ex-ante* assessments that can indicate what is happening in the landscape, and what the potential risk areas are for environmental degradation, of a planned intervention, project or product.

In order to provide useful results, environmental assessments of livestock value chains need to be holistic. This means that they need to capture all the key environmental impacts of livestock production, rather than focusing on one or a few, and measure such impacts at multiple temporal and spatial scales.

Finally, assessment methods need to be rapid and provide results in a cost-efficient manner if they are to assist with policymaking and decision-making, and to prevent environmental degradation before the impact has already happened. Our results indicate that the reviewed frameworks do not capture the entirety of the impacts caused by livestock production. There needs to be an increased understanding of the links between livestock value chains and local, regional and global landscapes for there to be a realistic chance that the projected increases in livestock production can be sustainable.

Frameworks tend to form their indicators and environmental impact dimensions around the most serious environmental impacts of livestock and agricultural production. However, the methods for assessing impacts differ. For example, for measuring biodiversity frameworks use widely different indicators and methods. A majority of frameworks aim to assess multiple scales and target policymakers, decision makers and farmers, but there is a lack of frameworks that cover larger spatial scales over a longer-term perspective.

This review has revealed a number of gaps and limitations in existing frameworks. The most surprising finding is that the frameworks provide little information on their methodological choices, regarding which environmental impact dimensions they choose to cover, and by which indicators and methods they intend to measure them. Most of the frameworks in this review provided only limited information on the methods used for assessments, how their indicators were identified, and the methods used for up-scaling the results to multiple scales.

We conclude that for a framework to be successful in assessing the environmental impacts of livestock value chains, it should include:

- A clearly defined aim and purpose.
- A set of measurable objectives that cover multiple spatial and temporal scales. These should not be so few that they do not satisfactorily capture the aim and purpose (and thus generate new objectives), but few enough to enable implementation of the methodology.
- Indicators to measure these objectives.
- A clear and visible presentation of the outputs that is comparable with other assessments, easy to comprehend and informative for the target audience as well as other interested and affected parties.
- Finally, and most importantly, frameworks should provide clear information on the chosen focus of the assessment method, why the environmental impact dimensions have been chosen, the methods and indicators that will be used to measure them and, crucially, why these indicators and methods were selected. Answering these questions will make frameworks more applicable and more usable, and generate results that are easier to compare. The latter point also allows for improvement, since more users will be able to apply and verify the framework – and thus more easily suggest improvements.

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Appendix 1: Frameworks listed by category: (i) general; (ii) indicator-specific; and (iii) modelling, as well as by owner/developer, aim/purpose and application.

Framework	Organization and/or date established	Aim/purpose	Application
I. General frameworks 28			
Trade-off analysis (TOA) (Antle, Diagana, Stoorvogel and Valdivia, 2010; Classens et al., 2012; Stoorvogel, Antle and Crissman, 2004; Stoorvogel, Antle, Crissman and Bowen, 2001; Stoorvogel, Antle, Crissman, et al., 2004)	Michigan State University and Wageningen University.	A policy decision support system, focused on economics, designed to quantify trade-offs between key sustainability indicators under alternative policy and technology scenarios.	Have been applied to several East African Dairy Development projects, e.g. in Kenya
Vital Signs – African monitoring systems (Scholes et al., 2013; VitalSigns, 2014)	Conservation International (CI), the Council for Scientific and Industrial Research (CSIR) in South Africa and the Earth Institute (EI), Columbia University	The aim is to ensure that improvements in food production also support livelihoods that are resilient, and healthy natural ecosystems.	Initially launching in five African regions: Tanzania, Ethiopia, Ghana, Uganda and Mozambique.
Response-Inducing Sustainability Evaluation (RISE) (Grenz et al., 2009; Häni et al., 2003; Häni et al., 2006; Häni, Stämpfli, undated; Keller, et al.; Häni, Stämpfli, Tello, et al., undated)	Bern University of Applied sciences. Partners with Nestlé, Research Institute of Organic agriculture, the Danone Fonds pour l'Ecosystème, the Swiss Federal Office for Agriculture and Energy and Capacity Building International (GIZ)	Indicator and interview-based method for assessing the sustainability of farm operations.	RISE has been used in 40 countries on more than 1400 farms, both agriculture and dairy.
AgBalance (AgBalance, 2012; Schoeneboom et al., 2012)	BASF	AgBalance is a tool designed to assess sustainability in agricultural products and processes.	Unknown amount of applications but built on several hundreds of previous case studies
Life-Cycle Assessment (LCA) (Bauman and Tillman, 2004; C Cederberg et al., 2007; C. Cederberg et al., 2013; De Boer, 2003; De Boer et al., 2011; De Boer et al., 2012; De Vries and De Boer, 2010; Flysjö et al., 2012; Fraval, 2014; Thomassen et al., 2008; Vellinga et al., 2013)	Ian Boustead published the first book on LCA in 1979	A holistic method of evaluating environmental impact during the entire life cycle of a product, considering two types of environmental impacts: (1) use of resources; and (2) emission of pollutants.	Unknown. Standardized method. 70 articles on livestock-related LCAs have been identified (Fraval, 2014).
World Agricultural Watch (WAW)(CIRAD, 2011; FAO, 2012b; H. B. George, Pierre-Marie et al., 2012)	Food and agricultural organization, Agricultural reséarch for development (CIRAD), the French Government, with the participation of the International fund for agricultural development (IFAD)	The main goal is to bring the dynamics and relative performances of different types of agriculture into the policy debate in terms of production and economic, social and environmental sustainability at the local and global levels, while taking anticipated changes into account.	Farms in Vietnam, Mali and Madagascar
Environmental sustainability index (ESI) (Esty et al., 2005, 2005a, 2005b, 2005c)	Yale Centre of environmental law and policy, Center for International Earth Science Information Network (CIESIN)	The ESI is a measure of overall progress towards the environmental sustainability of national environmental stewardship based on a compilation of indicators derived from underlying datasets.	Global assessments, applied to all nations
Input and output accounting systems (IOAS) (Goodlass et al., 2003; Halberg et al., 2005; Oosterhaven and Stelder, 2008; Rueda-Cantuche et al., 2009)	First developed by Leontief in the 1930s	Initially to allow tracing of monetary flows for all goods and services between sectors and industries within an economy, directly and indirectly. Can be used for material flows as well as economic.	The basis for the design of many other frameworks, e.g. EMA, AI, Energy and Exergy analysis.

Sustainable value chain analysis (SVCA) (Bonney, Clark, Collins, Dent and Fearne, undated; Fearne et al., 2009; Fraval, Marks, Fearne and Ridoutt, 2010)	University of Tasmania, University of Queensland	An assessment of the relationships between the different stakeholders which, coupled with the effective flow of information, enables the economic (and environmental) optimization of material flows – allocating time, people and technology appropriately and with minimal impacts on the environment.	Four or five case studies in Australia? (SF)
Sustainable performance assessment (SPA) (Elferink et al., 2012; Kuneman et al., 2014; SAI, 2010)	Sustainable Agriculture Initiative. 2010	A blueprint for a set of indicators on chosen sustainability issues; aims to indicate to farmers the impacts of their farming practices to help them improve the sustainability of their farming.	Not yet applied
Fieldprint calculator 2.0 (FieldtoMarket, 2012, 2014)	Field to market	An educational resource and simple tool to get producers to think about their operations and how practices relate to natural resource management and sustainability.	Unknown. Free online access web-tool
Eco-efficiency analysis (BASF, 2014; Saling et al., 2002)	BASF. 1996	Aims to compare similar products or processes by examining the entire product life cycle	More than 450 analyses using the system
Participatory action research (Francis and Sibanda, 2001; Kummu et al., 2012; Parfitt, Barthel and Macnaughton, 2010)	Coined in 1946 by Kurt Lewin	Aims to produce knowledge and action directly useful to interested and affected parties through research, adult education or sociopolitical action. Participation and action form the basis of the method.	Several case studies, for example one on dairy farming in Zimbabwe
Sustainability assessment of food and agriculture (SAFA) (FAO, 2013a, 2013b, 2014c, 2014d)	FAO	A holistic global framework for the assessment of sustainability along food and agricultural value chains that seeks to harmonize approaches within the food value chain, and to spread best practices	Unknown
IDEA (Indicateurs de Durabilité des Exploitations Agricolas) (Vilain, 2003; Zahm et al., 2006)	Vilain et al. 2003	Aims to preserve: natural resources such as water, air, soil and biodiversity; and social values that are characteristic of a certain degree of socialization and are implicit in sustainable agriculture.	65 farms were surveyed between 1998 and 2002
Unilever Sustainable Living Plan (USPL) (Unilever, 2012a, 2012b, 2014)	Unilever	Sets out to decouple growth from environmental impact, while at the same time increasing positive social impacts.	For example, the whole dairy sector in Australia
MESMIS (López-Ridaura et al., 2002; López-Ridaura, van Keulen, et al., 2005a, 2005b; Speelman et al., 2007)	Interdisciplinary framework on rural technology	A systemic, participatory, interdisciplinary and flexible framework for evaluating sustainability, offering guidelines in the selection of specific environmental, social and economic indicators, focused on the important characteristics that steer the performance of systems	More than 20 case studies in Mexico and Latin America.
Pressure State Response framework (PSR) and Driving Force/ Pressure State/ Impact Response (DPSIR) (OECD, 2001, 2003)	The Organization for Economic Co-operation and Development, 1970	Developed by the OECD to structure its work on environmental policies and reporting. PSR highlight cause-effect relationships and assist policymakers and decision makers to see environmental, economic and other issues as interconnected.	Unknown. Applied by a number of methodologies
System of Integrated Environmental and Economic Accounting (SEEA, undated)	United Nations Environment Programme, 1993	Conceptual framework that describes interactions between the economy and the environment, and stocks and changes in stocks of environmental assets. It provides a structure for comparing and contrasting source data and allows the development of multiple aggregates, indicators and trends on environmental and economic issues.	Several national case studies, for example in South Africa, the Philippines, China, Australia and the Netherlands
Global dairy agenda of action (FAO, undated; GDAA, 2014)	Livestock dialogue	The purpose of the agenda is to inform, guide and catalyse continuous improvement in livestock production towards more efficient use of natural resources. The initial focus is around land, water, nutrients and greenhouse gas emissions.	Case studies, for example in the Dutch and New Zealand dairy systems
EIA (Environmental Impact Assessment) (Aucamp, 2009)	Obtained formal status in 1969, with the enactment of the National Environmental Policy Act in the USA	Assesses the environmental impacts of new, localized pollution sources, e.g. industry or highways.	Unknown. Standardized methods like LCA. Numerous case studies
Agro-environmental indicators (Agro-Eco method, AEI) (Giradin, Bockstaller and Van der Werf, 2000; van der Werf and Petit, 2002)		The aim is to characterize the environmental impact of farming systems from a set of indicators	Indicators are established with data from a network of 17 arable farms in the Rhine plain, France and Germany

EP (Ecopoints) (van der Werf and Petit, 2002)	The Swiss Ministry of the Environment	Assigns scores to farmers' production practices and landscape maintenance, any process or product.	Unknown
Environmental management for agriculture (EMA) (Lewis and Bardon, 1998; van der Werf and Petit, 2002)	Agriculture and the Environment Research Unit (AERU) at the University of Hertfordshire	Computer-based informal environmental management system for agriculture. The main objective is to allow measurement and monitoring of environmental performance	More than 5000 purchases of the software
Hot spot analysis (Lam, 2013; Liedtke, Baedeker, Kolberg and Lettenmeier, 2010)	Wuppertal institute	The main objective is to identify central peaks of resource use or sustainability issues along the whole value chain quickly and reliably; life-cycle phase-specific	Several product chain studies, for example on cream cheese and milk production.
Gold standard (GSF, 2014)	Worldwide Fund for Nature	To demonstrate that carbon markets can deliver capital efficiently to greenhouse gas mitigation projects as well as substantial co-benefits	800 Gold Standard low carbon projects have been listed, predominantly in China, India, Turkey and Africa
Integrated systems approach (Castellini et al., 2012)	University of Perugia, 2012	A bio-economic model combining on-farm data recording with multi-criteria decision analysis (MCDA)	Unknown
Economics of Ecosystems and Biodiversity (TEEB) (de Groot, Fisher and Christie, 2010; TEEB; Wittmer et al., 2013)	The economics of ecosystems and biodiversity	A global initiative focused on drawing attention to the economic benefits of biodiversity, including the growing cost of biodiversity loss and ecosystem degradation. TEEB presents an approach that can help decision makers recognize, demonstrate and capture the values of ecosystem services and biodiversity.	Initiated national studies in 19 countries
II. Environmental dimension-specific frameworks 10			
GAIA (CLM, 2012, 2014)	CLM. 2012	A yardstick to make biodiversity measurable and comparable.	Unknown. Free online access web-tool
Tropical Ecology Assessment and Monitoring (TEAM) (Chawla et al., 2012; Meyer et al., 2010; TEAM, 2008)	Team network	The mission is to generate real-time data to monitor long-term trends in tropical biodiversity and ecosystem services through a global network of field stations, providing an early warning system on the status of biodiversity and ecosystem services to effectively guide conservation action.	TEAM scientists have collected over 1 million camera trap photographs
Emergy analysis (Castellini, Bastianoni, Granai, Bosco and Brunetti, 2006; Vayssières et al., 2011; Vigne et al., 2012)	Unknown	To quantify the energy value of both direct energy and material resources. This means that all the required inputs of material, information and labour are aggregated using emergy equivalents	Unknown
(Extended) Exergy analysis (Apaiah et al., 2006; Ertesvag, 2005)	Unknown	Provides a method for evaluating the maximum work extractable from a substance relative to a reference state based on the first and second law of thermodynamics.	Unknown
Habitat hectares (DSE, 2004; Parkes et al., 2003)	Victoria Department of Natural Resources. 2000	Aims to assess how natural a site is in comparison to the same vegetation type in the absence of major ecosystem changes. The approach also intends to provide a clear focus for discussions on management activities for practical improvement.	A number of programmes, including Victoria's 'Bush Tender'
Cool Farm Tool, Carbon Trust Footprint calculator (CFI, 2014; Whittaker, McManus and Smith, 2013)	Unilever and University of Aberdeen	The Cool Farm Institute's mission is to enable millions of growers globally to make more informed on-farm decisions that reduce their environmental impact. Focused on greenhouse gases in the first phase, the Institute provides the Cool Farm Tool as a quantified decision support tool that is credible and standardized.	Unknown. Free online access web-tool
Climate change, agriculture and food security program (CCAFS) smallholder GHG quantification protocol (Rosenstock, Rufino, Butterbach-Bahl and Wollenberg, 2013)	Consultative Group on International Agricultural Research (CGIAR)	Aims to improve quantification of baseline emission levels and support mitigation decisions	Unknown
Sustainable Rural Livelihood (SRL) (Scoones, undated)	IFAD	Improved understanding of the livelihoods of poor people. Draws on the main factors that affect poor people's livelihoods and the typical relationships between these factors, with a focus on sustainability as a key factor in overcoming poverty	Many case studies in developing nations, e.g. Bangladesh, Yemen, Sudan and India
Globio 3 (Alkemade et al., 2012)	International Livestock Research Institute (ILRI), University of Edinburgh	The GLOBIO3 model has been developed to assess human-induced changes in biodiversity in the past, present and future at the regional and global scales	Global study by Alkemade et al., 2009

Ex-Ante Carbon balance Tool (EX-ACT) (Branca et al., 2012; FAO, 2014a)	FAO	Aims to provide ex-ante measurements of the impact of agriculture and forestry development projects on greenhouse gas emissions and carbon sequestration	More than 20 case studies in both developing and developed regions
III. Modelling frameworks (12)			
Water footprint (Chapagain and Hoekstra, 2003, 2004, 2008; Chapagain, Hoekstra and Savenije, 2006; Chapagain, Hoekstra, Savenije and Gautam, 2006; Hoekstra, 2003a, 2003b, 2009, 2010; Hoekstra and Chapagain, 2007a, 2007b; Hoekstra, Chapagain, Aldaya and Mekonnen, 2011; Mekonnen and Hoekstra, 2011, 2012)	Water footprint network	To calculate the water footprint of a product/nation/person	Unknown. Free online access web-tool
Global livestock environmental assessment model (GLEAM) (Gerber et al., 2013; MacLeod, Gerber, Mottet, et al., 2013; Macleod, Gerber, Vellinga, et al., 2013; Opio et al., 2013)	FAO 2013	Help improve understanding of livestock greenhouse gas (GHG) emissions along supply chains, and to identify and prioritize areas for intervention to reduce sector emissions. In its current form, the model only quantifies GHG emissions, but was developed with the intention of including other environmental categories such as nutrient, water and land use.	Currently run for global GHG emissions
Material Flow Analysis (MFA) (Bello Bugallo, Stupak, Cristóbal Andrade and Torres López, 2012; Littleboy, Freebairn and Silburn, 1999)	Unknown	To build volume indicators to assess environmental resource extraction (the input side) and emissions and waste (the output side)	Unknown. Used in numerous methodologies
SWAT (Garg et al., 2012; Gassman et al., 2007; Schuol, Abbaspour, Srinivasan, et al., 2008; Schuol, Abbaspour, Yang, et al., 2008)	U.S. Department of Agriculture, Agricultural research service, and Texas AgriLife Research	Developed to simulate the quality and quantity of surface and ground water and predict the environmental impact of land use, land management and climate change. Can be used to assess soil erosion, non-point source pollution and regional watershed management	Unknown. Free online access web-tool
NUANCES framework (Rufino et al., 2011; Rufino et al., 2007; Tittonell, Corbeels, van Wijk and Giller, 2010; Tittonell et al., 2009; van Calker, Berentsen, Giesen and Huirne, 2008; van Wijk et al., 2009)	Wageningen University	Overall aim to increase understanding of the tactical and strategic decisions farmers make in allocating resources, and the underlying trade-offs where the immediate needs of the family may often override the possibility of investing in the longer-term sustainability of the farm	Unknown
COMPASS (Groot, Rossing, Dogliotti and Tittonell, undated)	Wageningen University	Developed to support experiential learning and decision-making in participatory settings.	Mainly applied in Europe but work in sub-Saharan Africa is in preparation
LPJ (Bondeau et al., 2007; Gerten et al., 2005; Rost et al., 2008; Rost et al., 2009)	Potsdam Institute for Climate Impact Research	LPJ is a dynamic global simulation model of vegetation biogeography and vegetation/soil biogeochemistry. Taking climate, soil and atmospheric information as inputs, it dynamically computes spatially explicit transient vegetation composition in terms of plant functional groups, and their associated carbon and water budgets.	Used in a number of global studies
Ecological footprint (CFSE, 2014; Hoekstra, 2009)	Global footprint network	Assesses the area of productive land (BPA) and water ecosystems required to produce the resources that the population consumes and to assimilate the wastes that the population produces	Unknown. Free online access web-tool
LUCIA (Marohn, Siripalangkanont, Berger, Lusiana and Cadish, 2010)	Marohn 2008	Built for the Uplands Program to address environmental impacts caused by land use change in small mountainous catchments of (sub) tropical regions.	Validation has been carried out of yield data in Ban Tat and a previous version of the hydrological sub model
SEAMLESS (Alkan Olsson et al., 2009; Ewert et al., 2006; Geniaux, Bellon, Deverre and Powell, 2009; van Ittersum et al., 2008)	The SEAMLESS Association	Aims to deliver an integrated framework for making integrated assessments of agricultural systems at multiple scales in order to provide analytical capabilities on the environmental, economic, social and institutional aspects of agriculture; and to develop a component-based system that allows reuse for upcoming problems while using software that facilitates reuse and linkage of the components	Unknown

Integrated modelling of global environmental Change (IMAGE) (Alkemade et al., 2012; Bouwman and Goldewijk, 2006)	The IMAGE model has its beginnings in the mid-1980s	The core application is the development and analysis of scenarios for global environmental change. The design of scenario assumptions and their translation into model inputs are therefore just as important as the actual software.	The IMAGE model has been applied to a variety of global studies.
IMPACT (González-Estrada et al., 2008; Herrero et al., 2007; Waithaka, Thornton, Herrero and Shepherd, 2006; Zingore et al., 2009)	ILRI, University of Edinburgh; started in the 1990s	An integrated platform for animal crop-systems designed to investigate the impacts of different interventions on farmers' livelihoods (incomes and food security) and the trade-offs of resource use. It computes nutrient balances, food security, incomes and cash flows, and labour use efficiency.	Has been applied in Africa, Asia and Latin America. An abridged version has been applied to farms in Asia and East Africa as part of CCAFS.

Appendix 2: Full list of indicators, measured by environmental dimension, for the 50 reviewed frameworks

Framework	Water		Soil use	Land use	Energy consumption	GHG emissions/air quality	Biodiversity and plant protection	Nutrient flows (nitrogen and P)	Eco-toxicity potential	Waste
	Quantity	Quality								
General frameworks										
TOA (Antle et al., 2010; Classens et al., 2012; Stoorvogel, Antle and Crissman, 2004; Stoorvogel et al., 2001; Stoorvogel, Antle, Crissman, et al., 2004)	Volumetric water content at plant wilting point	Degradation as well as absorption and lateral water flow	Soil organic matter	Management decisions		Average methane efficiency (L/kg milk)				
	Volumetric water content at field capacity	Monitoring programme of pesticide concentrations in the vadose zone	Soil erosion	Land use		Average total methane emissions per farm (L/year)				
	Average water use efficiency (m3/kg product)	Ground water and streams throughout the study area	Nutrients	Fertilizer use						
	Average total water use per farm (m3/year)			Pesticide application						
Vital Signs (Scholes et al., 2013; VitalSigns, 2014)	Adequacy of water supply for ecosystems	Percentage of farmers with clean water for agriculture	Nutrient and acidity in soils	Grown crops	Farm machinery usage	Changes in soil carbon stocks	Biodiversity health index	Manure management		
	Soil cover and structure that allow movement and infiltration of water	Runoff of sediments and nutrients into water bodies	Soil organic matter	Field size		Nitrous oxide from nitrogen fertilizer application	Species abundance and health			
	River water depth		Top-soil losses	Harvest patterns		Methane emissions from soil flooding	Canopy cover			
				Grazing (past and present)						

Framework	Water		Soil use	Land use	Energy consumption	GHG emissions/air quality	Biodiversity and plant protection	Nutrient flows (nitrogen and P)	Eco-toxicity potential	Waste
	Quantity	Quality								
RISE (Grenz et al., 2009; Häni et al., 2003; Häni et al., 2006; Häni, Stämpfli, Keller, et al., Undated; Häni, Stämpfli, Tello, et al., Undated)	Water management	Risks to water quality	Soil organic matter	Soil management	Energy usage and management	GHG balance, storage of farm manure	Plant protection management	Nitrogen balance	Eco and human toxicological risks	Type and quantity of waste
	Water supply	Water quality	Soil reaction	Crop productivity	Energy consumption per ha/workforce	Storage of farm manure	Ecological priority areas	Phosphorous balance		On-farm and off-farm waste disposal and recycling
	Water use intensity	Stability of water quality	Soil pollution	Herd management	Degree of self-sufficiency for energy consumption		Intensity of agricultural production	Nitrogen and phosphorus self-sufficiency		Environmental hazard of waste
	Water productivity		Soil erosion	Crop rotation	Share of sustainable energy carriers		Landscape quality	Ammonia emissions		Waste management
	Water quantity		pH	Crop husbandry			Diversity of agricultural production	Input of nitrogen and phosphorus		
	Stability of water quantity		Moisture	Size of plots			Size of plots	Manure storage and application		
			Soil compaction				Weed control			
			Nutrients				Surface without high biodiversity			
			Salinity				Risk potential of pesticides used			
			Tillage-related risks				Proportion of intensively used agricultural land			
			Nutrient mining				Eco and human toxicological risks			
AgBalance (AgBalance, 2012; Schoeneboom et al., 2012)	CWU in points/consumer benefits (not including green water)	Total emissions released into water	Soil organic matter	Land use in n2/consumer benefits	Primary energy consumption (MJ/CB) for the complete product life cycle	Global warming potential (kg/CB) for the entire life cycle	Number of endangered species	Nitrogen balance	Eco-toxicity points /consumer benefits	Solid waste emissions (kg/consumer benefits) categorized as municipal, hazardous, construction and mining
		Environmental impact of emitted chemicals,	Nutrient balance	Farming intensity	Non-renewable energy	GHG emissions	Biodiversity increasing services	Phosphorous balance	Terrestrial eco-toxicity	
			Potential for soil compaction	Crop rotation	Renewable energy	GHG emissions resulting from indirect land use	Availability of protected zones	Nitrogen surplus		
			Soil erosion			Photochemical ozone creation	Farming intensity and crop rotation	Phosphorous surplus		
						Ozone depletion potential	Nitrogen surplus			
							Potential for intermixing (decrease factor)			

Framework	Water		Soil use	Land use	Energy consumption	GHG emissions/air quality	Biodiversity and plant protection	Nutrient flows (nitrogen and P)	Eco-toxicity potential	Waste
	Quantity	Quality								
LCA (Bauman and Tillman, 2004; C Cederberg et al., 2007; C. Cederberg et al., 2013; Imke J. M. De Boer, 2003; I. J. M. De Boer et al., 2011; Imke J. M. De Boer et al., 2012; De Vries and De Boer, 2010; Flysjö et al., 2012; Fraval, 2014; Thomassen et al., 2008; Vellinga et al., 2013)	Water stress index	Fresh water aquatic eco-toxicity potential	Land use	Land competition	Non-renewable energy use	Global warming potential				
		Acidification potential,				Ozone depletion potential				
		Marine aquatic ecotoxicity potential				Photochemical ozone creation potential				
		Eutrophication potential								
WAW (CIRAD, 2011; FAO, 2012b; H. B. George, Pierre-Marie et al., 2012)	Water area formally established as protected	Water quality	Soil quality	Land cover and land use	Energy consumption	Climate change impact due to activities of the agricultural holding during one year	Important forest and rate of deforestation	Nitrogen and phosphorus emissions potential		
	Potential for irrigation					Manure management and storage	Land established as protected area	Manure storage and application		
						Nitrogen and phosphorus emissions potential	Fragmentation (agriculture, forestry pasture)			
						Air quality	Plant protection			
							Plant protection activities of the holding during one year			
							Conservation of indigenous plants and breeds			
							Agricultural conservation practices			

Framework	Water		Soil use	Land use	Energy consumption	GHG emissions/air quality	Biodiversity and plant protection	Nutrient flows (nitrogen and P)	Eco-toxicity potential	Waste
	Quantity	Quality								
ESI (D. C Esty et al., 2005b)	Fresh water availability per capita	Dissolved oxygen concentration	Salinization	Percentage of total land area (including inland waters) with very low anthropogenic impact	Energy efficiency	Carbon emissions per million USD GDP	Percentage of country's territory in threatened ecoregions			Waste recycling rates
	Internal groundwater availability per capita	Electrical conductivity	Nutrient depletion	Percentage of total land area with very high anthropogenic impact	Hydropower and renewable energy production as percentage of total energy consumption	Carbon emissions per capita	Threatened bird species as percentage of known breeding bird species in each country			Solid waste generation
	Percentage of country under severe water stress	Phosphorous concentration	Desertification			Nitrogen oxide gases	Threatened amphibian species as percentage of known amphibian species			Hazardous waste generation
		Water quality				Volatile organic compounds	National biodiversity index			Land fill volume
		Suspended solids					Annual average forest cover change rate			Unsafe disposal of waste
		Fertilizer consumption per hectare of arable land								
		Pesticide consumption per hectare of arable land								
IOAS (Goodlass et al., 2003; Niels Halberg et al., 2005; Oosterhaven and Stelder, 2008; Rueda-Cantuche et al., 2009)			Pesticide use: treatment frequency index and environmental impact points		Direct energy use in megajoule or megajoule/ha	Kg carbon dioxide emissions/ kg product		Nitrogen and phosphorus surplus, nitrate leakage		
			Treatment frequency index		Total energy use megajoule/ha product	Megajoule input in CO2-equivalent		Efficiency: % input-output		
			Environmental impact points					Nitrate leakage		
SVCA (Bonney et al., 2009; Fearne et al., 2009; S Fraval et al., 2010)	Contribution to water scarcity	Acidification, water pollution	Acidification	Land competition	Energy consumption	Carbon emissions	Loss of biodiversity	Eutrophication	Human toxicity	Waste management
				Loss of life support function of land		Stratospheric ozone depletion,	Deforestation		Eco-toxicity	
						Photo-oxidant formation				

Framework	Water		Soil use	Land use	Energy consumption	GHG emissions/air quality	Biodiversity and plant protection	Nutrient flows (nitrogen and P)	Eco-toxicity potential	Waste
	Quantity	Quality								
SPA(Elferink et al., 2012; Kuneman et al., 2014; SAI, 2010)	Water requirement m3/kg product	Potential risk score per ha	pH	Land used for crop production in m2/kg of product	Energy and fuel use	Emission of greenhouse gases in CO2-eq/kg of product	Biodiversity score,. between 1 and 100 based on detailed survey	Surplus/deficit nitrogen and phosphorus in kg/ha	Potential risk score per ha	
	Irrigation efficiency m3/m2	Potential risk score per kg of product	Organic matter balance	Land used for off-farm fodder in m2/kg of production	Energy production on farm			Surplus/deficit nitrogen and phosphorus in kg/kg product	Potential risk score per kg of product	
		Impact score per ha	Reduced erosion risk						Impact score per ha	
		Impact score per kg of product							Impact score per kg of product	
Fieldprint calculator 2.0 (FieldtoMarket al, 2012, 2014)	Irrigation water applied		Soil erosion per unit of production	Land use per unit of production	Energy use per unit of production	GHG emissions per unit of production				
	Per acre irrigation water applied,		Per acre soil erosion, total soil erosion	Total land use (planted acres)	Per acre energy use, total energy use	Per acre GHG emissions				
	Total irrigation water applied					Total GHG emissions				
Eco-efficiency (BASF, 2014; Saling et al., 2002)				Land use	Energy consumption	GHG emissions			Toxicity potential	
PAR (Francis and Sibanda, 2001; Kummu et al., 2012; Parfitt et al., 2010)	Participatory method with no information on indicators used for analysis									

Framework	Water		Soil use	Land use	Energy consumption	GHG emissions/air quality	Biodiversity and plant protection	Nutrient flows (nitrogen and P)	Eco-toxicity potential	Waste
	Quantity	Quality								
SAFA(FAO, 2013a, 2013b, 2014c, 2014d)	Water conservation target	Clean water target	Soil improvement practices	Land conservation and rehabilitation plan	Renewable energy use target	GHG reduction target	Landscape/marine habitat conservation plan	Nutrient balances		Renewable and recycled materials
	Water conservation practices	Water pollution prevention practices	Soil physical structure	Land conservation and rehabilitation practices	Energy-saving practices	GHG mitigation practices	Ecosystem-enhancing practices			Waste reduction target
	Ground and surface water withdrawals	Concentration of water pollution	Soil chemical quality	Net loss/gain of productive land	Energy consumption	GHG balance	Structural diversity of ecosystems			Waste reduction practices
		Wastewater quality	Soil biological quality	Land use and land cover change	Renewable energies		Ecosystem connectivity			Waste disposal
			Soil organic matter content				Species conservation target			Food loss and waste reduction
							Species conservation practices			
							Diversity of production			
							Wild genetic diversity enhancing practices			
							Agro-biodiversity in situ conservation			
							Locally adapted varieties/breeds			
							Genetic diversity in wild species			
							Saving of seeds and breeds			
IMAGE (Bouwman and Goldewijk, 2006)	Water supply and demand			Land allocation	Energy supply and demand	Carbon dioxide, methane, nitrous oxide		Nitrogen and phosphorus emissions from point and non-point sources		
						Ozone depletion – halocarbons		Nitrogen and phosphorus balances		
				Changes in land use	Bioenergy	Non methane volatile organic compounds and sulphur dioxide				

Framework	Water		Soil use	Land use	Energy consumption	GHG emissions/air quality	Biodiversity and plant protection	Nutrient flows (nitrogen and P)	Eco-toxicity potential	Waste
	Quantity	Quality								
IDEA (Vilain, 2003; Zahm et al., 2006)		Effluent processing, water resource protection	Organic matter management	Cropping patters			Diversity of annual or temporary crops	Fertilization		
			Fertilization	Fodder area management			Diversity of perennial crops			
			Effluent processing	Dimension of fields			Diversity of associated vegetation			
			Soil resource protection,	Stocking rate			Animal diversity			
							Enhancement and conservation of genetic heritage			
USPL (Unilever, 2012b, 2014; Unliever, 2012)	Water use		Soil health and fertility		Energy use		Biodiversity loss	Nutrient balances	Pest management	
			Soil loss							
MESMIS (López-Ridaura et al., 2002; López-Ridaura, van Keulen, et al., 2005a, 2005b; Speelman et al., 2007)		Pesticide leaching	Soil organic matter content	Producers and area cultivated per system			Number of species	Nutrient balances		
		Nitrogen lost by leaching	Nutrient content				Type of biodiversity conservation management			
		Use of fertilizers	Erosion levels				Number of managed species			
		Biocides sprayed	Agrochemical usage							
			Crop diversity							
			Area of soil eroded							
			Nitrogen fixed by leguminous species							
			Characteristics of soils							
SEAMLESS (Alkan Olsson et al., 2009; Ewert et al., 2006; Geniaux et al., 2009; van Ittersum et al., 2008)	Water use	Nitrate leaching	Pesticide use	Area of farm	Energy use due to mineral fertilizer	Nitrous oxide emissions	Crop diversity	Use of mineral Phosphorous		
	Water surface runoff	Pesticide leaching	SOM-balance	Share of grassland in forage area	Energy use due to farming practices	Ammonia emissions	Net deforestation	Nitrate leaching		
	Water use by irrigation	Percentage of area with high leaching	Soil erosion	Stocking rate in the total forage area		Global warming potential	Animals exceeding carrying capacity	Phosphorous leaching		
				Stocking rate in the total grassland area			Area of conservation	Nitrogen and phosphorus balance		
				Area with conservation tillage				Nitrogen and phosphorus application		

Framework	Water		Soil use	Land use	Energy consumption	GHG emissions/air quality	Biodiversity and plant protection	Nutrient flows (nitrogen and P)	Eco-toxicity potential	Waste
	Quantity	Quality								
PSR (OECD, 2001, 2003)	Intensity of use of water resources,	Concentration of pollutants in environmental media	Erosion risks	Change in land use		Carbon dioxide, methane, nitrous oxide, chlorofluorocarbon emissions	Status of wildlife and ecosystems and of natural resource stocks	Nitrogen and phosphorus balances	Exceeding critical loads	Generation of waste (municipal, industrial, hazardous)
	Frequency, duration and extent of water shortages	Exceeding critical loads	Degree of top soil losses			Chlorofluorocarbon emissions	Habitat alteration and land conversion from natural state	Nitrogen and phosphorus from fertilizer use and livestock	Concentration of pollutants in environmental media	Waste minimization
			Rehabilitated areas				Percentage threatened or extinct species,			
							Percentage protected areas			
SEEA (SEEA, undated)	Water use intensity	Water treatment		Land conversion	Energy efficiency	GHG emissions	Threat to biodiversity	Nutrient balances		
					Renewable energy					
Global dairy agenda of action (FAO; GDAA, 2014)	Water availability	Water quality	Soil quality				Direct biodiversity threats			Waste generation
			Soil retention				Indirect biodiversity threats			Reuse and recycling
EIA (Aucamp, 2009)	Water use	Quality of surface water	Soil quality	Land use	Energy use	GHG emissions	Biodiversity loss	Nutrient balances		
AEI (Giradin and Bockstaller, 2000; H. M. G van der Werf and Petit, 2002)	DPSIR structure indicators to assess farming practices									
EMA (Lewis and Bardon, 1998; H. M. G van der Werf and Petit, 2002)	Water quantity	Water quality	Soil fertility		Energy		Conservation, e.g. hedgerows		Pesticide application	Waste
			Erosion							
			Fertilizer application							
Hot spot analysis (Lam, 2013; Liedtke et al., 2010)	Hot spots and cold spots for water use	Hot spots and cold spots for water pollution		Hot spots and cold spots for land use	Hot spots and cold spots for energy use		Hot spots and cold spots for biodiversity			Hot spots and cold spots for waste emissions
Gold standard (GSF, 2014)	Water quantity	Water quality	Soil condition		Access to affordable and clean energy services	CO2-equivalent emissions	Biodiversity			
		Other pollutants								
Integrated systems approach (Castellini et al., 2012)	There were six indicators for each of the following dimensions: economic, social, environmental and quality. The environmental indicators were estimated using life cycle assessment (LCA), ecological footprints and emergy analysis									

Framework	Water		Soil use	Land use	Energy consumption	GHG emissions/air quality	Biodiversity and plant protection	Nutrient flows (nitrogen and P)	Eco-toxicity potential	Waste
	Quantity	Quality								
TEEB (de Groot et al., 2010; TEEB; Wittmer et al., 2013)	Water regulation, water flow		Erosion regulation, soil protection	Land cover change			Species richness			Waste assimilation
							Species diversity			
							Beta-diversity			
							Threatened species			
Environmental dimension specific										
GAIA (CLM, 2012, 2014)							Area of natural reserves			
							Productive areas under targeted nature manage-ment			
							Area of small non-productive elements in the field			
							Wet elements			
							Herbaceous ele-ments			
							Wooden elements			
							Green elements on the farm			
TEAM (Chawla et al., 2012; Meyer et al., 2010; TEAM, 2008)							Species diversity			
							Abundance			
							Habitats			
Emergy analysis (Castellini et al., 2006; Vayssières et al., 2011; Vigne et al., 2012)					Energy balance by emergy					
(Extended) Exergy analysis (Apaiah et al., 2006; Ertesvag, 2005)					Energy balance by exergy					
Habitat hectares (DSE, 2004; Parkes et al., 2003)							Habitat structure and health			
Cool farm tool (CFI, 2014; Whittaker et al., 2013)						GHG emissions				
(Rosenstock et al., 2013)						GHG emissions				
SRL (Scoones)	Categorizes indicators as: natural resource base sustainability, covering soil fertility, vegetation cover and ability to recover from disturbance									
Globio 3 (Alkemade et al., 2012)							Species composition in disturbed and undisturbed areas			
							Land use			
EX-ACT (Branca et al., 2012; FAO, 2014a)						GHG emissions				

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Water footprint (Chapagain and Hoekstra, 2003, 2004, 2008; Chapagain, Hoekstra and Savenije, 2006; Chapagain, Hoekstra, Savenije, et al., 2006; Hoekstra, 2003a, 2003b, 2009, 2010; Hoekstra and Chapagain, 2007a, 2007b; Hoekstra et al., 2011; Mekonnen and Hoekstra, 2011, 2012)	Blue water footprint	Grey water footprint								
	Green water footprint									
Modelling frameworks										
GLEAM (Gerber et al., 2013; MacLeod, Gerber, Mottet, et al., 2013; Macleod, Gerber, Vellinga, et al., 2013; Opio et al., 2013)						GHG emissions				
MFA (Bello Bugallo et al., 2012; Littleboy et al., 1999)					Energy consumption per capita	Total Carbon dioxide emissions of area				
SWAT (Garg et al., 2012; Gassman et al., 2007; Schuol, Abbaspour, Srinivasan, et al., 2008; Schuol, Abbaspour, Yang, et al., 2008)	Water flows in watershed									
NUANCES (Rufino et al., 2011; Rufino et al., 2007; Tittonell et al., 2010; Tittonell et al., 2009; van Calker et al., 2008; van Wijk et al., 2009)										
COMPASS (Groot et al.)	Water balance		Soil carbon					Nutrient balances		
			Soil erosion							
			Nutrient dynamics							
LPJmL (Bondeau et al., 2007; Gerten et al., 2005; Rost et al., 2008; Rost et al., 2009)	Consumptive water use									
Ecological footprint (CFSE, 2014; Hoekstra, 2009)				Land surface of assessed farm	Energy as land equivalent, carbon sink as Land equivalent					
				Land surface needed to produce ingredients for concentrate feeds						
LUCIA (Marohn et al., 2010)						GHG emissions				

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IMPACT (González-Estrada et al., 2008; Herrero et al., 2007; Waithaka et al., 2006; Zingore et al., 2009)				Land management		Climate				
				Livestock management						

SEI - Headquarters
Stockholm
Sweden
Tel: +46 8 30 80 44
Executive Director: Johan L. Kuylenstierna
info@sei-international.org

Visitors and packages:
Linnégatan 87D
115 23 Stockholm, Sweden
Letters:
Box 24218
104 51 Stockholm, Sweden

SEI - Africa
World Agroforestry Centre
United Nations Avenue, Gigiri
P.O. Box 30677
Nairobi 00100
Kenya
Tel: +254 20 722 4886
Centre Director: Stacey Noel
info-Africa@sei-international.org

SEI - Asia
15th Floor
Witthyakit Building
254 Chulalongkorn University
Chulalongkorn Soi 64
Phyathai Road, Pathumwan
Bangkok 10330
Thailand
Tel: +(66) 2 251 4415
Centre Director: Eric Kemp-Benedict
info-Asia@sei-international.org

SEI - Oxford
Florence House
29 Grove Street
Summertown
Oxford, OX2 7JT
UK
Tel: +44 1865 42 6316
Centre Director: Ruth Butterfield
info-Oxford@sei-international.org

SEI - Stockholm
Linnégatan 87D, 115 23 Stockholm
(See HQ, above, for mailing address)
Sweden
Tel: +46 8 30 80 44
Centre Director: Jakob Granit
info-Stockholm@sei-international.org

SEI - Tallinn
Lai str 34
10133 Tallinn
Estonia
Tel: +372 627 6100
Centre Director: Tea Nõmmann
info-Tallinn@sei-international.org

SEI - U.S.
Main Office
11 Curtis Avenue
Somerville, MA 02144
USA
Tel: +1 617 627 3786
Centre Director: Charles Heaps
info-US@sei-international.org

Davis Office
400 F Street
Davis, CA 95616
USA
Tel: +1 530 753 3035

Seattle Office
1402 Third Avenue, Suite 900
Seattle, WA 98101
USA
Tel: +1 206 547 4000

SEI - York
University of York
Heslington
York, YO10 5DD
UK
Tel: +44 1904 32 2897
Centre Director: Lisa Emberson
info-York@sei-international.org

Stockholm Environment Institute

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