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# Guidelines for LCA application on Mediterranean dairy sheep supply chains

**C.1.1 – Methodological guidelines for LCA studies in Mediterranean dairy sheep supply chain**

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## Executive summary

The guidelines is exclusively addressed to key methodological issues of LCA studies in agri-food sector, such as seen as the main challenge for enabling the reliable environmental assessment of Mediterranean dairy sheep supply chains. The methodology illustrated is based on and conform to the standards of the main LCA's international guidelines. The guidelines users shall be individuals or organizations with competences in life cycle assessment applied to livestock and dairy sector.

# Summary

## Introduction

This document is a deliverable of the SheepToShip LIFE, a project financed by the EU LIFE Programme Climate Action 2014-2020 and aimed to reduce the GHG emissions from the Sardinian dairy sheep sector.

The purpose of these guidelines is to build and share a harmonized approach for assessing the environmental implications of Mediterranean dairy sheep supply chains in a manner that *i*) takes account of the production systems specificity, and *ii*) highlights effective solutions to improve the environmental performance and quality of Mediterranean dairy sheep products.

This deliverable is not intended to be comprehensive of the whole steps of environmental profile of sheep milk and cheese supply chain but it represents a tool to be used associated with the main international procedures. The methodology illustrated herewith is built on and conform to the standards of the main LCA's international guidelines. In other terms, the intent of this document is to outline a protocol based on the current best knowledge among the main international standards. In addition, it introduces some sector-specific approaches defined by scientific literature and reports on the initiatives on dairy sheep supply chain environmental assessment. Therefore, the specific purpose of this deliverable is to provide a clear definition of methods and data requirements options with the aim to enable consistent LCA application and environmental comparison between Mediterranean dairy sheep production systems. In particular, it is exclusively addressed to the well-debated methodological issues of LCA studies in agri-food sector (functional unit, co-products handling, etc.), such as seen as the main challenge for enabling the reliable environmental assessment of agri-food chains. For all remaining LCA steps and methodological issues, it refers to: PEF - Product Environmental Footprint (PEF, 2013) and Livestock Environmental Assessment and Performance (LEAP) guidelines (FAO, 2016a; 2016b).

The guidelines users should be individuals or organizations with competences in life cycle assessment applied to livestock and dairy sector.

The guidelines will be updated during the SheepToShip LIFE implementation, in order to taking into account specific methodological issues and data provided by the LCA studies carried out within the project and the news LCA's rules developed by international initiative, i.e. PEF sector's protocols promoted by EU.

**Acronyms**

AP: Acidification potential
CAP: Common Agricultural Policy
CF: Carbon Footprint
CFC: Trichlorofluoromethane
$CH_4E$: $CH_4$ Energy Emission
CML: institute of the Faculty of Science of Leiden University
CTUe: Comparative Toxic Unit for ecosystems
DB: Dichlorobenzene
DE: Digestible Energy
DMI: Dry Matter Intake
ECM: Energy-corrected Milk
EC: European Commission
ED: ecosystem diversity
EDIP: Environmental Design of Industrial Products
EF: Environmental Footprint
EP: Eutrophication potential
EU: European Union
FAO: Food and Agriculture Organization
FC: Fat Content
FPCM: Fat and Protein Corrected Milk
FU: Functional Unit
GHG: Greenhouse Gases
HH: human healthIDF: International Dairy Federation
ILCD: International Life Cycle Data
IPCC: Intergovernmental Panel on Climate Change
ISO: International Organization for Standardization
LCA: Life Cycle Assessment
LCI: Life Cycle Inventory
LCIA: Life Cycle Impact Assessment
LEAP: Livestock Environmental Assessment and Performance
LULUC: Land Use and Land Use Change
MEI: Metabolizable Energy Intake
NE: Net Energy
NMVOC: Non-Methane Volatile Organic Compounds
ODP: Ozone Depletion Potential
OEF: Organisation Environmental Footprint
PC: Protein Content
PEF: Product Environmental Footprint
PEFCRs: PEF Category Rules
POCP: Photochemical oxidation potential
RA: resource availability
RM: Raw Milk
SOC: Soil Organic Carbon
SOM: Soil Organic Matter
UFL: Feed Unit for Lactation
USEtox: model for characterizing human and ecotoxicological impacts of chemicals
Ym: methane emission factor
WFP: Water Footprint
WFPnet: Net Water Footprint
WMO: World Meteorological Organization

## 1. The Mediterranean sheep farming systems

Sheep are multi-purpose animals, producing meat, milk, wool and leather. At global level, their primary function is to produce meat, although in some countries sheep milk has become of greater importance. In general, the milk production in the Mediterranean region is mainly confined to the Near East countries (such as Turkey and Iran), and to Southern and Central Europe (Greece, Hungary, France, Italy, Spain and the Czech and Slovak Republics) (Zygoyannis, 2006). Therefore, sheep farmings are multi-functionally systems, which play a relevant role in socio-economic and ecological terms, providing a wide range of goods and services.

As well as for all agricultural and livestock systems, the sheep production sectors developed in the Mediterranean basin strongly depend on quantity and quality feed availability. This is in turn determined by local agro-ecosystem conditions. According to Porqueddu (2007), in the Mediterranean areas the climatic, physiographic, edaphic heterogeneity associated with a large variety of vegetation types and with the effect of socio-cultural traditions have induced a complex mosaic of feed resources and their integration into land use. About half of the total world surface under Mediterranean climate is located in southern Europe and over 50% is represented by grasslands, rangelands and woodlands. For this reason, sheep and goat systems (belonging to local breeds) are relevant livestock productions in Mediterranean Europe. In fact, respect to dairy cows, small ruminants better exploit unfavourable areas and uplands under all year round open-air grazing. Due to physical and climatic constraints, sheep farming systems are quite extensive with a low use of pesticides, fertilizers, concentrates and irrigation and most of them could be considered a sort of low-input farming systems. Moreover, traditional extensive pastoral systems can still be found in southern Europe, especially on public lands, where short vertical transhumance is still present. In these areas it is possible to identify four main representative types of the sheep farming systems existing with a decreasing incidence of natural resources (Porqueddu, 2007):

i. Silvopastoral farming systems. This typology is based on the utilization of native forests for feeding domestic animals by providing foliage (lower branches, basal resprouts, litter and fruits). “Dehesa” in Spain, “Montado” in Portugal and “Phrygana” in Greece represent the main examples of agro-silvopastoral systems. Such systems show the highest level of complexity because of the contemporary presence of pastures, crops, shrubs and/or trees often under mixed “hierarchic” grazing (beef cattle, sheep, goats and pigs) and multiple products. Pastures are the main component of animal feed and annual plants usually dominate with a low forage production and quality.

ii. Agro-pastoral farming systems. These are widespread all over the hilly and mountainous regions. It is mainly based on natural and sown pasture utilization and in some cases a relatively small portion of the animal nutritive requirements are covered by annual forage crops. These are usually based on mixtures of cereals (barley, oats) grasses (Italian ryegrass) and annual legumes (vetch, crimson and berseem clover). One of the main limits of this system is the difficulty of matching the energy requirements of the flock with the available forage from the native pasture. The problem is still often resolved by short distance transhumance and by concentrates, cereal grains or/and hay supplementation. Sometimes mixed livestock systems (goats or/and local races of cattle) are integrated to sheep farms.

iii. Cereal-based farming systems. Since ancient times Mediterranean sheep farming is complementary to arable agriculture and a strong link exists between cultivated areas and pastures. Cereals are grazed or harvested depending on total farm forage availability. Animals consume the by-products of arable crops, stubbles and graze fallow land which is unsuitable for cultivation. The predominant crops in rainfed arable systems are winter cereals (wheat, barley and oats). Permanent grasslands represent a small portion of the total farm area; they are confined to marginal soils and they usually present low forage production and quality. Due to their easy cultivation and multi-purpose exploitation (herbage, hay, grain and stubbles) winter cereals maintain a key-role in animal feeding for the flexibility given to the system. When cereal-based fodder crops are sown early in autumn, they can give high dry matter yield in winter reducing the use of expensive supplements.

iv. Fodder crop-based farming systems. These specialised systems are located in areas suitable for cultivation (sown pastures, short term forage crops and meadows) a part of which is often irrigated. In these systems, high stocking rates and agronomic inputs (hay and silage instead of grazing) are present. Double cropping of Italian ryegrass followed by maize or sorghum for silage in rotation with alfalfa or white clover meadows is common.

## 2. Guiding principles and normative references

These guidelines are based on the attributional LCA approach which refers to process-based modelling they provide a static representation of average conditions. The guidelines cover the key stages of the life cycle of the dairy sheep supply chain, which is subdivided in three main phases: a) milk production at farm, following a 'from cradle-to gate' approach. Milk production includes feed production, animal breeding until to milk cooling; b) cheese and/or other dairy production at dairy plant, following a 'from farm gate-to-retailer' approach. These phases also include milk collection (transport from farms to dairy plant) and final product's packaging; c) cheese or other dairy product distribution (transport from dairy plant to the first customer). The LCA approach of SheepToShip LIFE is consistent with ISO 14040-44 (2006) and ILCD Handbook (2010) rules and it is mainly based on PEF (2013) and LEAP (FAO, 2016a,b) guidelines.

The following standards and guidelines constitute the main international efforts in harmonizing the life cycle assessment approach, and represent the methodological references that these guidelines adopt in total. Hereafter is reported a comprehensive list and a general outline of each one of them, with specific references to original sources.

ISO 14040-44 rules

The LCA method was worldwide standardized by International Organization for Standardization (ISO), starting from 1998 and trough ISO 14040 and 14044 standards. The more recent version of these was published in 2006. Hereafter the topics of both International Standards are reported from ISO web-site (https://www.iso.org/standards.html):

- "ISO 14040:2006 describes the principles and framework for life cycle assessment (LCA) including: *(i)* definition of the goal and scope of the LCA, *(ii)* the life cycle inventory analysis (LCI) phase, *(iii)* the life cycle impact assessment (LCIA) phase, *(iv)* the life cycle interpretation phase, *(v)* reporting and critical review of the LCA, *(vi)* limitations of the LCA, *(vii)* the relationship between the LCA phases, and *(viii)* conditions for use of value choices and optional elements.
  ISO 14040:2006 covers life cycle assessment (LCA) studies and life cycle inventory (LCI) studies. It does not describe the LCA technique in detail, nor does it specify methodologies for the individual phases of the LCA.
  The intended application of LCA or LCI results is considered during definition of the goal and scope, but the application itself is outside the scope of this International Standard."
- "ISO 14044:2006 specifies requirements and provides guidelines for life cycle assessment (LCA) including: *(i)* definition of the goal and scope of the LCA, *(ii)* the life cycle inventory analysis (LCI) phase, *(iii)* the life cycle impact assessment (LCIA) phase, *(iv)* the life cycle interpretation phase, *(v)* reporting and critical review of the LCA, *(vi)* limitations of the LCA, *(vii)* relationship between the LCA phases, and *(viii)* conditions for use of value choices and optional elements.
  ISO 14044:2006 covers life cycle assessment (LCA) studies and life cycle inventory (LCI) studies."

ILCD Handbook

In 2010 the ILCD Handbook was published by the Joint Research Centre of European Commission (EC). The ILCD Handbook represents one of the main efforts required by the EC in the Communication on Integrated Product Policy - EU Communication, COM(2003)302 - for assuring quality and consistency of life cycle data, methods and assessments. Considering that ISO 14040-44 standards “leaves the individual practitioner with a range of choices, which can affect the legitimacy of the results of an LCA study”, the ILCD Handbook introduced further methodological specifications useful to achieve more consistent, comparable and accurate results. The ILCD Handbook consists of a set of technical documents providing guidance for good practice in LCA in business and government. The ILCD Handbook was also designed as a "parent" document for developing sector-specific guidelines, in order to provide the most appropriate solutions for enabling the efficient use of reliable and robust life cycle approaches in Small and Medium Enterprises. In fact, with the ‘COM (2013)196 - Building the Single Market for Green Products’ the EC launched the Product Environmental Footprint (PEF) and Organisation Environmental Footprint (OEF) methods (see below). Citing the Communication, “these two methods introduce several important improvements compared to other existing methods, among others:

- a clear identification of the potential environmental impact categories to be looked at in order to perform a comprehensive LCA;
- the requirement to quantify data quality;
- setting minimum data quality requirements;
- clearer technical instructions for addressing some critical aspects of a LCA study (such as allocation, recycling).”

IDF guide

The International Dairy Federation, in collaboration with the main organizations involved in improving the standardization of the LCA approach (ISO, British Standards Institution, FAO, IPCC, Carbon Trust, World Business Council for Sustainable Development and World Resources Institute) developed the main international LCA guidelines for the dairy sector: “A common carbon footprint approach for dairy. The IDF guide to standard life cycle assessment methodology for dairy sector” (IDF, 2010). The IDF guide is focused on Carbon Footprint of dairy activities, with the specific aim of avoid ambiguities about some critical aspects of this method, such as functional unit, system’s boundaries, impact allocation and land use change. Despite the fact that the IDF guide only covers the milk production from cattle, postponing the work on others milk systems for future initiatives, their standards shall represents a valid reference for GHG emissions assessment of dairy sheep sector too.

LEAP guidelines

The first version of the "Greenhouse gas emissions and fossil energy use from small ruminant supply chains. Guidelines for assessment" by the LEAP Partnership (FAO, 2016b) represents the latest effort in defining a harmonized application of LCA in the small ruminant sector. The main purpose of the guidelines is "to increase understanding of small ruminant supply chains and to help to improve their environmental performance". The LEAP guidelines are explicitly addressed to climate change and fossil energy demand over the key stages of the cradle-to-primary-processing-gate. They are focused on sheep and goat production and "strives a pragmatic balance between flexibility and rigorous consistency across scale, geographic location, and project goals". The LEAP guidelines for small ruminant assessment are strongly connected with the associated LEAP Animal Feed Guidelines (FAO, 2016a), which covers the cradle-to-animal's mouth stage for all feed sources (including raw materials, inputs, production, harvesting, storage and feeding) and other feed-related inputs.

PEF guidelines

In 2013 the European Commission released a guideline, called "Commission Recommendation of 9 April on the use of common methods to measure and communicate the life cycle environmental performance of products and organisations". This document contains the PEF and the OEF methodologies. They have been established in order to get a harmonised and more comprehensive European methodology for evaluating Environmental Footprint. It can have a big role in reaching "Resource-Efficient Europe", that is one of the main targets of the Europe 2020 Strategy.

The PEF is a multicriteria measurement that allows the evaluation of the environmental performance of products, services and organisations from a broadened supply chain perspective. Applying the PEF manner is a perfect tool in assessing the entire supply chain and get very detailed results about certain activity. The PEF method is also based on the "from cradle to grave approach" and includes every production stage from the acquisition of raw material till retail the products, to the end-of-life treatment. The PEF guideline (2013) encourages the organizations to accomplish the environmental performance analysis based on the data quality requirements set up in the PEF method and to optimise their processes along the life cycle. It is a voluntary policy that the member states can choose to apply. One important point of this approach is that the same models and factors are applied to several sectors because they are not specific to one. In fact, in addition to the general LCA guidelines provided by PEF, a more recent initiative known as PEFCRs have been developed for specific sets of products sold within the European area. The PEFCR provides specialized rules for conducting LCA studies according to each product category. Currently the European Joint Research Centre is working on developing 25 sector specific approaches within the PEF, 10 of which were completed and the relative final PEFCRs delivered (http://ec.europa.eu/environment/eussd/smgp/PEFCR_OEFSR_en.htm). 7 of these 10 PEFCRs refer to food, agricultural and livestock sectors such as: dairy, feed for food producing animals, leather, packed water, pasta, pet food, wine.

Since there are some challenges and gaps in the previous LCA methodologies, the PEF (2013) guideline is addressed to give suggestions on how to solve these issues. LCA uncertainty arises from (1) lack in the knowledge and in the data related to the process being studied or from (2) the heterogeneous nature of the observed phenomenon. The first uncertainty can be limited by more reliable and more accurate data acquisition while the second one can be reduced by dividing process data sets and characterized it by better sampling.

In conjunction with uncertainty analysis, the sensitivity analysis can be used to study the robustness of the results and their sensitivity to data, assumptions and models. The aim of the sensitivity analysis is to investigate (1) how a small perturbation around a reference input parameter impacts on the output value, and (2) the effects of uncertain factors when these later may vary over a significant range of uncertainty (Wei et al., 2015). The PEF highly recommends applying sensitivity analysis in order to reduce the choice-related uncertainties and to be sure that the results will meet with the requirements. The sensitivity analysis is needed especially for sectors with more functions (such as sheep farm systems) based on different functional units. The sensitivity analysis in the LCA can be performed as one-at-a-time approach (OAT) "meaning that a subset of the input parameters are changed one at a time to see how much influence it has on the results" (Groen et al., 2014).

The PEF approach is the most appropriate method to evaluate the environmental impacts during the SheepToShip LIFE project, because it covers the comprehensive aspects of the environmental performance of the sheep farm systems with several adopted impact categories and releasing a clearer picture about the processes along the broadened impact categories.

### PEFCR for dairy products

In April 2018, a specific PEFCR has been developed for the dairy sector, which covers the life cycles of various subcategories of dairy products (liquid milk, dried whey products, cheeses, fermented milk products, and butterfat products) for their full life cycle, including not only milk production and processing but also distribution, packaging, consumer use, and disposal. The goal of developing PEFCR for the dairy sector is to enable legitimate and verifiable comparisons between different products within the same subcategory on the EU market. The PEFCR Dairy guidelines, which were finalized by the EU-JRC in 2018, identify default values for LCA components for use in environmental footprinting (Galatola, 2018). The default FU identified by PEFCR Dairy is a mass or volume based FU, with a provided default value to be used for each sub-category in the event of lacking primary data to determine a study specific one. Provisions for the use of other FU are allowed for in certain cases, such as using the serving size or a particular macronutrient as the FU. Guidance regarding the selection of FU is provided in the PEFCR guidelines following a flow diagram based on the B2B or B2C oriented nature of the undertaken LCA study. Pre-defined inputs and outputs for each life cycle stage of the dairy products are suggested to aid in LCA modelling. Additionally, the PEFCR Dairy report classifies the types of data to be used within the LCA study and assigns which data category should be used for each life cycle stage. It distinguishes among primary, semi-specific and secondary data, with semi-specific data defined as that for which default values are proposed by the PEFCR, but for which study specific data should be supplied if available. Secondary data is defined as that coming either from reliable external sources or from PEFCR default values. The PEFCR Dairy guidelines advocate for studies to make every effort to collect primary data for all foreground processes, to the extent possible. Secondary data sources may be used for background processes.

Tab. 14: Data requirements for dairy processors

| Life cycle stage | Foreground/Background | Data requirements |
|---|---|---|
| 1. Raw milk supply | Foreground | Primary or semi-specific if justified |
| 2. Dairy processing | Foreground | Primary |
| 3. Non-dairy ingredients supply | Background | Semi-specific |
| 4. Packaging | Background | Semi-specific |
| 5. Distribution | Background | Semi-specific |
| 6. Use stage | Background | Secondary |
| 7. End-of-life | Background | Secondary |

(PEFCR Dairy (2016), pg. 47)

Furthermore, specific allocation procedures are identified for each possible co-product to be evaluated throughout the dairy supply chain.
While the ILCD 2011 impact assessment method is recommended, the PEFCR Dairy highlights 8 categories within the ILCD 2011 LCIA that are deemed most important in the evaluation of dairy products: climate change, water resource depletion, freshwater eutrophication, marine eutrophication, terrestrial eutrophication, freshwater ecotoxicity, land use and acidification. Additionally, 3 LCIA categories are identified as absolutely necessary, as a bare minimum, for the proper communication of product impacts: climate change, water resource depletion, and land use. In the future, PEFCR Dairy will provide calculated benchmark impact values for each dairy product sub category in order to provide an EU average against which products can be compared (PEFCR Dairy, pg.81).
It is important to note that, to date, the PEFCR Dairy guidelines are only valid for milk and associated dairy products produced from dairy cow supply chains. However, given the comprehensive research undertaken to provide the PEFCR dairy guidelines, it can also be applied with caution to milk and dairy products from other lactating livestock, including sheep. It is also important to note that, while the PEFCR Dairy guidelines advocate for a complete cradle to grave assessment of dairy products, SheepToShip LIFE will be undertaking a study only from cradle (on farm production) to the first retailer.

Tab. 18: Allocation methods to be used for products produced on dairy farms

| Farm products | Description | Allocation method |
|---|---|---|
| Raw milk | Raw milk delivered for consumption. | Biophysical allocation (IDF, 2015) |
| Dairy products produced on farm | Any dairy product directly sold for consumption. | If both raw milk and dairy products are produced on the farm use system subdivision for on farm dairy processing. |
| Sold live dairy cattle | Dairy cattle sold for fattening or replacement. | Biophysical allocation (IDF, 2015) |
| Dead dairy cattle leaving the farm | Dairy cattle that died on the farm. | No allocation. |
| Manure as residual product | Manure is exported form the farm as product with no economic value. | No allocation: burden allocated to other products produced at farm, including pre-treatment of manure. |
| Manure as co-product | Manure is exported from the farm as product with economic value. | Economic allocation of the upstream burden shall be used for manure by using the relative economic value of manure compared to milk and live animals at the farm gate. Biophysical allocation based on IDF rules shall be applied to allocate the remaining emissions between milk and live animals. Environmental burden form manure treatment is allocated to manure as co-product. |
| Manure as waste | Manure is not used to produce products but treated as waste. | Apply end-of-life formula and allocate environmental burden to other products produced on the farm, including treatment of manure. |
| Sold non-dairy products. | Sold feed, arable products and non-dairy animal products, non-dairy animals. | If both raw milk and non-dairy products are produced on the farm use system subdivision for non-dairy farming activities. |
| Energy produced on farm | Any type of energy produced at farm, such as solar energy, biogas, heat-recovery and wind-energy. | If both raw milk and energy are produced on the farm use system subdivision for on farm energy production. Within the assessed system boundary, energy may be produced from renewable sources. If renewable energy is produced in excess of the amount consumed for dairy production and it is provided to third parties, this may only be credited to the dairy products assessed provided that the credit has not already been taken into account in other schemes. |

(PEFCR Dairy (2016), pg. 54)

## 3. Goal and scope definition

As reported in LEAP (FAO, 2016b) and PEF (2013) guidelines, the following aspects shall be addressed and documented during the LCA goal definition:

- Subject of the analysis (milk, cheese or other dairy products);
- Key properties of the assessed system: organization, location(s), dimensions, products, sector, and position in the value chain;
- Purpose for performing the study and decision-context;
- Intended use of the results: will the results be used internally for decision-making or shared externally with third parties?
- Limitations due to the method, assumptions, and choice of impact categories: in particular, limitations to broad study conclusions associated with exclusion of impact categories shall be addressed;
- Target audience of the results: scientific community, producers, policy makers, etc.;
- Comparative studies to be disclosed to the public and need for critical review;
- Commissioner of the study and other relevant stakeholders.

The scope shall identify the product system or process to be studied, the functions of the system, the functional unit, the system boundaries, the allocation principles, and the impact categories.

Functional unit (FU)

Functional unit describes the quantified performance of the function(s) delivered by a final product.

In the case of milk, the functional unit shall be the weight of the milk as it leaves the farm gate corrected for *i*) fat, protein and lactose content (energy-corrected milk, ECM), as suggested by LEAP (2016b), or *ii*) fat and protein (fat and protein corrected milk, FPCM), as reported in several scientific papers (Marino et al., 2016; Vagnoni et al., 2015).

When a comparison with dairy cow milk is foreseen, LEAP recommends the following equation from the IDF (2010) methodology:

$$\text{kg ECM} = \text{kg milk} \times (0.1226 \times \%\ \text{fat} + 0.0776 \times \%\ \text{true-protein} + 0.0621 \times \%\ \text{lactose}) \qquad (1)$$

where % crude-protein is used instead of % true-protein, the relevant multiplier is 0.0722 (instead of 0.0776). This equation standardizes the milk to 4 % fat, 3.3 % protein and 4.8 % lactose. If data on % lactose are unavailable, a default value of 4.8 % lactose shall be used.

When the second FU is preferred, as in the case that the  data of milk lactose content are not available and/or a specific correction's equation are available for the considered sheep breed,  FPCM amounts (expressed in kg) shall be calculated using the specific equation. For instance, for Pecora Sarda breed is available the equation defined by Pulina and Nudda (2002):

$$FPCM = RM\ (0.25 + 0.085FC + 0.035PC) \qquad (2)$$

where RM, FC, and PC indicate raw milk amount (kg), fat content (%), and protein content (%) of the raw milk, respectively.

For cheese, which represents by far the main milk primary processing stage, the FU shall be expressed by the product weight, as well as for other dairy sheep products (yogurt, fermented milk, etc.).

According to the utilized FU, a reference flow chart shall be defined. The later provides orientations to which input and output data are normalized in a mathematical sense. As required by ISO 14044:2006 standard, both functional units and reference flows shall be clearly defined and measurable.

The sensitivity analysis is strongly recommended by the PEF (2013) rules in order to track the influences of applying different inputs data. Therefore, a sensitivity analysis of the results using different FUs is strongly recommended because it may offer useful insights (e.g. comparing FU's based on output mass, land use, price-based, nutritional value).

System boundary

The system boundary shall be defined following the supply chain logic and in close coherence with the scope of the analysis. According to the PEF guidelines (2013), the system boundaries shall contain all the processes related to the product supply chain. The system boundaries have to be divided in foreground processes (the core activities with direct available information) and background processes (the processes without available direct information). PEF guidelines adopt to draw a system boundary diagram in the scope definition.

For practical reasons, the cut-off criteria of the LEAP (FAO, 2016b) will be applied during the SheepToShip LIFE project. These guidelines suggests that processes which contribute less than 1% to the mass or energy flow may be cut off from further evaluation, but they should not be excluded from the inventory. In fact, some of them can have small mass or energy contributions but still significant impact in one of the environmental categories. A minimum of 95% of the environmental significance for each category shall be accounted for. In any case, the application of cut off criteria in a LCA is intended to help the expenditure reviews in reduction of uncertainty associated with those processes which weight the most in the system.

According to the above mentioned “from cradle to retailer” approach, LCA boundary shall include all inputs to the dairy plant, from crop farming to livestock operations, from refrigerated milk to the final disposition of the cheese packaging at the first customer. The LCA system boundaries may be divided into the following main phases (Fig.1): a) milk production at the sheep farm (from cradle to gate), b) milk collection and cheese-making at the dairy plant (from farm gate to dairy plant gate, taking into account cheese packaging and cleaning of equipment), and c) cheese distribution (from dairy plant to retailer).

As foreseen in LEAP guidelines (FAO, 2016b), a minimum period of 12 months should be considered for the data survey, in the way to cover all life stages of the animal through to the specified end-point of the analysis. To achieve this goal, the study must use an “equilibrium population” which shall include all animal classes and ages present over the 12 month period required to produce the given mass of product. The time boundary for data acquisition shall be representative of the period associated with the average environmental impacts for the products. In extensive production systems, some important parameters (such as the reproductive rates and the growth rates) may change based on seasonal conditions and through years. In the cases of considerable inter-annual variability in the inputs, production and emissions, to meet representativeness criteria the one-year time boundary needs to be determined using data averaged over 3 years. An averaging period of 3 to 5 years is commonly used to smooth the impact of seasonal conditions and market variability on agricultural products.

All processes linked with the productive life of livestock shall be accounted when defining the system boundary for a sheep milk cheese, such as: *i*) the land use and all the other inputs and agricultural operations required for feed production (e.g. seeds, fertilizers, pesticides, fuel, etc., and plowing, sowing, harrowing, irrigation, haymaking, threshing, etc.); *ii*) the whole consumption of feed from pastures and concentrates; *iii*) livestock operations such as shearing and milking. Each of these data shall be surveyed for the different categories of sheep, depending on the breeding techniques adopted by the farm under study, having as primary reference points, the quantity and quality of sheep diet. Therefore, the LCA model shall include ewes and rams, each subdivided into lambs, replacement animals and adults. The ewes shall be grouped by physiological and productive phase (maintenance, dry and lactation).

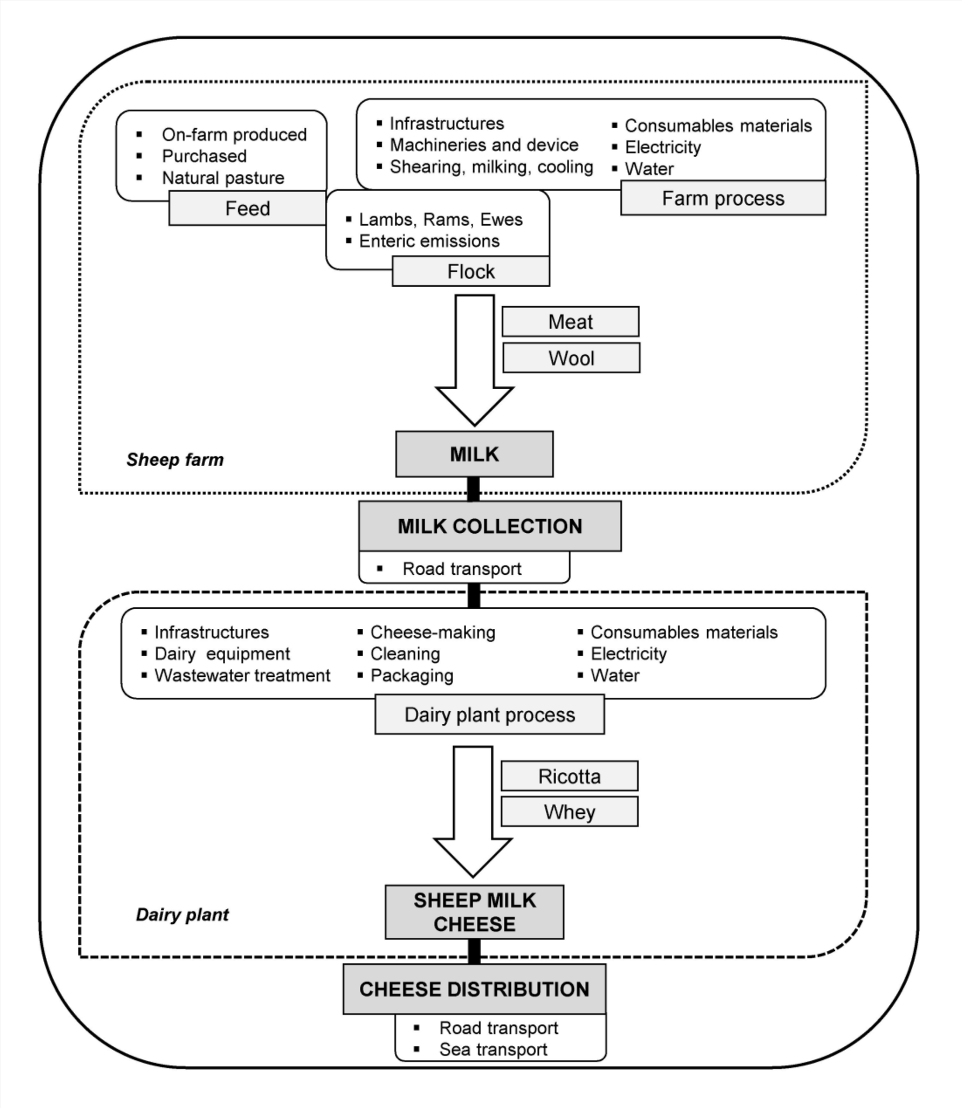



**Figure 1 -** System boundary of a sheep milk cheese LCA.

According to LEAP guidelines (FAO, 2016b), the production of capital goods (buildings and machinery) with a lifetime greater than one year may be excluded in the life-cycle inventory. However, when detailed primary data are available, the processes linked with the farm structure shall also be included. In this case, the impacts related to capital goods have to be allocated according to the equipment/infrastructure lifetime by dividing the related process/input by the lifetime, expressed in year. Within the SheepToShip LIFE LCA's studies capital goods will be included in the life-cycle inventory and accounted for LCIA.

All modes of transportation and distances covered within the system shall also take into account. Moreover, all the emissions into the soil, air and water from the use of fertilizers/pesticides/agrochemicals in general shall be included. From the other hand, the emissions related with the livestock manure can be excluded from the system boundary when the farm recurred to free-range housing and daily grazing of sheep on pastures (as in most of Mediterranean farms).

Impact categories and evaluation methods

Over the past years, the Carbon Footprint has become one of the most important environmental protection indicators. It is widely used in agricultural LCA analysis and represents a reliable tool for comparing results from different research studies. In order to assess in a more comprehensive way the environmental performances of dairy systems, other impact categories rather than global warming potential are relevant, such as acidification, eutrophication, eco-toxicity, water consumption/contamination, minerals depletion, and fossil energy use. LCA is a complex task: many data shall be collected to be able to get mainly single environmental impact categories. Some of them can be already considered as an environmental indicator, with relevant and meaningful content. In addition, most of the evaluation methods combine and aggregate the single impact categories together to obtain mid-point indicators. The PEF guidelines (2013) describe a wide range of impact categories and a complex method for evaluating the Environmental Footprint (EF) of the entire supply chain. Therefore, the environmental impact assessment of the SheepToShip LIFE project will be based on the PEF (2013). According to these guidelines, there are 14 different mid-point levels (Table 1).

The main goal of the EF impact assessment is to collect and list precisely all single impact category in the inventories of the examined processes and then to associate them to a potential damage factors until the 14 mid-point levels are identified. In order to get the end-point categories (potential damage factors), the mid-point indicators shall be grouped and aggregated. The three end-point indicators are the following: i) resource use, ii) pollutant emissions and the ones which may affect the iii) human health.

There are several LCA studies published in international literature in the last years in which different procedures for evaluating the environmental impacts have been implemented. Hereafter a non-exhausting list of the previous and existing methods is reported:

Carbon Footprint (global potential warming or GHG estimates) (IPCC, 2013): using a 100-year time horizon, the different kinds of greenhouse gases that contribute to the global warming are examined from several points of view. Therefore, the global warming potential (GWP) allows to compare the different gases impacts. In fact it measures “how much energy the emissions of 1 ton of gas will absorb over” 100 years, respect to “the emissions of 1 ton of carbon dioxide ($CO_2$)”. When primary data is lacking, the models to calculate changes in soil carbon stocks can be calibrated on the basis of default carbon stocks defined by IPCC in Volume 4, Chapter 2 (2006). Otherwise, GHG emissions from land-use-change shall be analysed separately from other sources.

**Table 1** - Default EF impact categories (with respective EF impact category indicators) and EF impact assessment models for PEF studies (Source: PEF guidelines, 2013).

| EF Impact Category | EF Impact Assessment Model | EF Impact Category indicators | Source |
|---|---|---|---|
| Climate change | Bern model - Global Warming Potentials (GWP) over a 100 year time horizon. | kg $CO_2$ equivalent | Intergovernmental Panel on Climate Change, 2007 |
| Ozone Depletion | EDIP model based on the ODPs of the World Meteorological Organization (WMO) over an infinite time horizon. | kg CFC-11 (Trichlorofluoromethane) equivalent | WMO, 1999 |
| Ecotoxicity for aquatic fresh water | USEtox model | CTUe (Comparative Toxic Unit for ecosystems) | Rosenbaum et al., 2008 |
| Human Toxicity - cancer effects | USEtox model | CTUe (Comparative Toxic Unit for ecosystems) | Rosenbaum et al., 2008 |
| Human Toxicity – non-cancer effects | USEtox model | CTUe (Comparative Toxic Unit for ecosystems) | Rosenbaum et al., 2008 |
| Particulate Matter/Respiratory Inorganics | RiskPoll model | kg PM2.5 (Particulate Matter with a diameter of 2,5 µm or less ) equivalent | Humbert, 2009 |
| Ionising Radiation – human health effects | Human Health effect model | kg $^{235}U$ equivalent (to air) | Dreicer et al., 1995 |
| Photochemical Ozone Formation | LOTOS-EUROS model | kg NMVOC (Non-Methane Volatile Organic Compounds) equivalent | Van Zelm et al., 2008 as applied in ReCiPe |
| Acidification | Accumulated Exceedance model | mol $H^+_{eq}$ | Seppälä et al.,2006; Posch et al., 2008 |
| Eutrophication – terrestrial | Accumulated Exceedance model | mol $N_{eq}$ | Seppälä et al.,2006; Posch et al., 2008 |
| Eutrophication – aquatic | EUTREND model | fresh water: kg P equivalent marine: kg N equivalent | Struijs et al., 2009 as implemented in ReCiPe |
| Resource Depletion – water | Swiss Ecoscarcity model | $m^3$ water use related to local scarcity of water | Frischknecht et al., 2008 |
| Resource Depletion – mineral, fossil | CML2002 model | kg antimony (Sb) equivalent | van Oers et al., 2002 |
| Land Transformation | Soil Organic Matter (SOM) model | Kg (deficit) | Milà i Canals et al., 2007 |

- CML-IA (Guinée et al., 2002): besides the GHG emissions this method considers other 10 categories of environmental impact, i.e.: Stratospheric Ozone Depletion (ODP) measured as kg of Trichlorofluoromethane equivalent, kg CFC-$11_{eq}$), Human toxicity (expressed as kg 1,4-dichlorobenzene equivalent, kg 1,4-$DB_{eq}$), Fresh-water aquatic eco-toxicity (kg 1,4-$DB_{eq}$); Marine ecotoxicity (kg 1,4-$DB_{eq}$); Terrestrial ecotoxicity (kg 1,4-$DB_{eq}$); Photochemical oxidation potential (POCP, expressed in kg of ethylene equivalent, kg $C_2H_{4eq}$); Acidification potential (AP, expressed in kg of sulfur dioxide equivalent, kg $SO_{2eq}$); Eutrophication potential (EP, expressed as kg of phosphate equivalent, kg $PO_4^{3-}{}_{eq}$); Abiotic depletion measured as elements and ultimate reserve (expressed as kg of antimony equivalent, kg $Sb_{eq}$) and fossil fuel (expressed in MJ per $m^3$ of fossil fuel, MJ).

- ReCiPe (Huijbregts et al., 2017) offers another method of evaluating the environmental impacts in a life cycle assessment. It is a harmonised process that considers the principles and the choices. The ReCiPe can provide results at mid-point and end-point level. The ReCiPe comprises a wide assessment of life cycle environmental performances, considering 18 different categories of environmental impact. These categories are addressed at mid-point level. The mid-point impacts can be later converted and aggregated into three of the above-mentioned end-point categories: damage to human health (HH), damage to ecosystem diversity (ED), damage to resource availability (RA).

- Water Footprint (WEF)(Hoekstra et al., 2011) is basically a multidimensional supply chain indicator, showing the consumption of fresh water and its polluted volumes by type of contamination. The Water Footprint method considers the direct and indirect water consumption. According to Hoekstra et al. (2011), three types of water footprints are included:

  *Blue water footprint*: is the measurement of the amount of available surface and ground water used along the supply chain of a product (both evaporated and incorporated into it).

  *Green water footprint*: refers to the quantification of the amount of rainwater stored in the soil moisture and used by plants via transpiration spent for a productive cycle.

  *Grey water footprint*: is defined as the volume of freshwater that is required to assimilate the load of pollutants associated to a product supply chain and released into the environment through pipes, runoff, leaching or indirect ways. This water should meet with the specific water quality standards.

  The approach to calculate the WFP is based on absolute values and the water consumption indicator is expressed as volume of freshwater used to produce a kg of product. However the WFP method is still incomplete and needs to be improved. In fact it accounts for blue water only even if the green water is the main component of a WFP in livestock sector. In order to plan effective mitigation strategies, the WFP methodology should include the green water too. The Net Water Footprint ($WFP_{net}$) (Atzori et al., 2016) is the current alternative to the previous WFP concept. It calculates the green water for WFP taking into account the differential between the water consumed by a cultivated crop or pasture and the amount of water used by a spontaneous natural cover on the same area. Although it considers the consumption of green water in the territory, the method attributes a low weight to it. However, the methodology appears to be very sensitive to blue water, attributing a greater impact to systems that use larger quantities of managed water resource. Furthermore, this index refers to the consumption of natural vegetation covers and local pedoclimatic conditions with respect to managed water resources.

## 4. Allocation rules

Handling co-production in a multi-functional process, as sheep farming, is a crucial step of a LCA, due to the relevant impact that it has on the results of the study. For this reason, the LEAP guidelines recommend a clear documentation and explanation of the adopted options. Moreover a sensitivity analysis to ensure robustness of conclusions is required.

After the ISO 14044 standard (2006), the LEAP (FAO, 2016b) guidelines provide a useful decision tree diagram that helps in choosing the appropriate methodology for dealing with co-products in small ruminant supply chains (Fig. 2).

LEAP guidelines exclude the application of system expansion for sheep production by means of substitution. Anyway, in the case in which system separation or expansion is not used, the allocated inputs and outputs should equal the unallocated ones. Therefore, the main option still open is the possibility to perform a physical allocation (ISO step 2). The condition imposed by LEAP guidelines is the application of this distribution when the products have similar physical properties and serve similar goals or markets. Alternatively, known processing or biophysical relationships can be used to assign inputs and outputs of a single production unit to each product that is made from that production unit. When physical allocation is not possible or allowed, economic allocation should be applied as often reported in international literature on LCA studies of dairy sector. When system expansion is not used, the remaining outputs must be classified as co-products, residual products or wastes.

Outputs of a production process are considered as residual flows when they do not contribute to the revenue of the owner. Residual products will not receive any allocated emissions, nor will contribute emissions to the main co-products of the production unit. However, it is useful to track residual flows with the purpose of understanding the mass balance of the production unit.

An output of a production process shall be considered as waste if the production unit incurs a cost for treatment or removal. Waste has to be treated and/or disposed of and the related emissions shall be included in the inventory and allocated among the co-products (i.e. wastewater treatment at manufacturing facilities). Of course, it is necessary that all activities associated with waste treatment fully comply with any local legal or regulatory requirements.

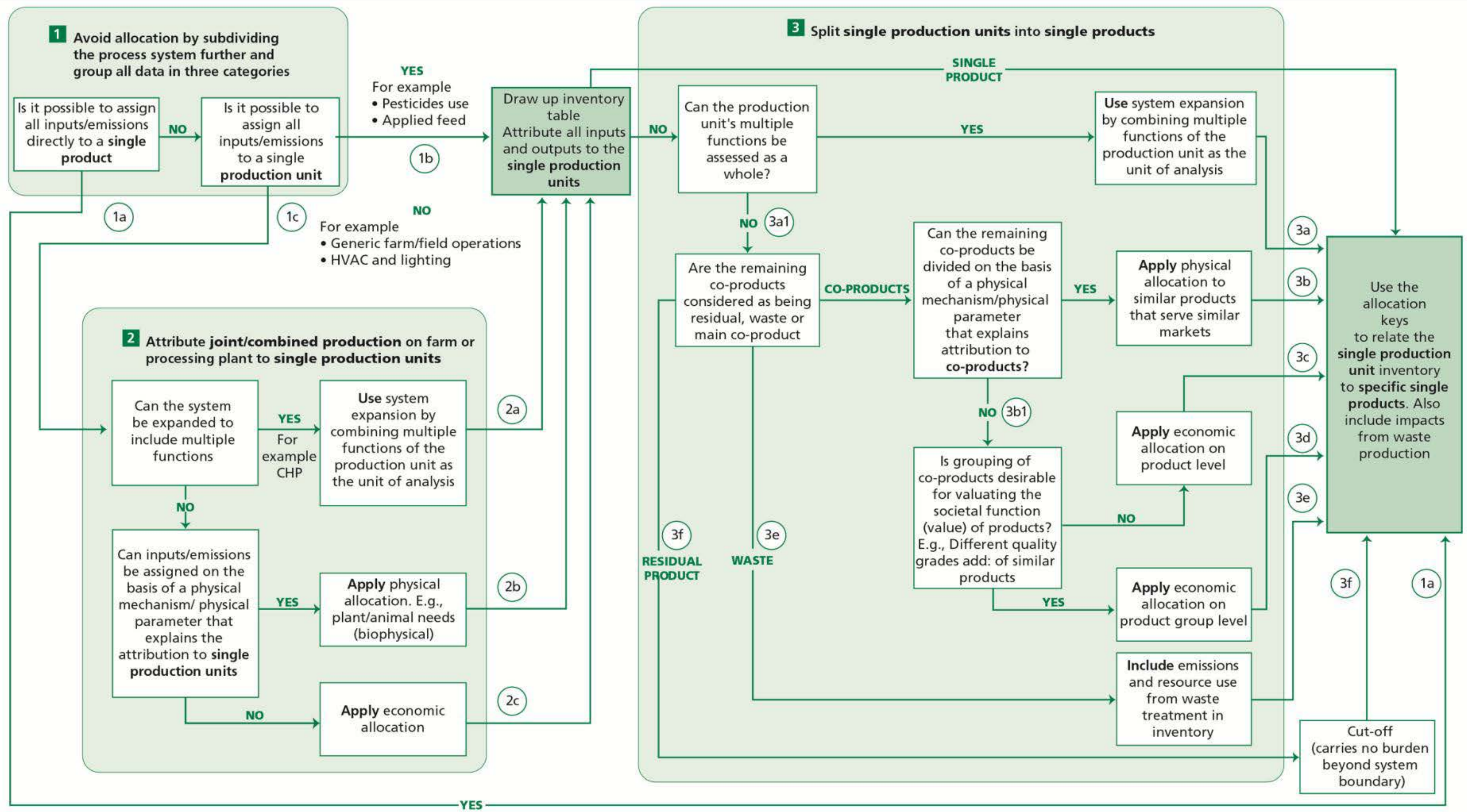



**Figure 2** - Multi-functional output decision tree, from LEAP guidelines (FAO, 2016b).

Following the recommended methods for milk sheep in LEAP guidelines (step 1b in Fig. 2), the allocation among milk, meat and wool shall be based on biophysical distribution according to feed requirements for production of the goods (stage 3a1 and 3b in Fig. 2). This is coherent with IDF methodology for allocation between milk and meat for dairy cattle.

In particular, LEAP guidelines recommend performing the biophysical allocation for milk sheep using a tier-2 approach, by means of primary and secondary data, and calculating the energy requirements for milk and meat production according to an internationally acceptable methodology. The allocation ratio for milk, relative to its sum with meat and wool (in Mediterranean milk sheep breed, wool is a minor co-product), is then calculated from the ratio of the energy requirement for milk production respect to the sum of energy requirement for milk and meat (i.e. animal growth component) production:

$$\text{Milk Allocation \%} = 100 \times [\text{Milk energy req.}/(\text{Milk energy req.} + \text{Meat energy req.})] \qquad (3)$$

The determination of animals metabolizable protein requirements is mandatory for systems in which fibre is an important product, so that biophysical allocation between fibre and co-products (e.g. meat) can be calculated.

Taking into account the milk processing respect to milk products, the allocation method recommended by LEAP guidelines is to separate specific activities to individual products based on dry matter content.

IDF guide gives more details for manufacture of dairy products allocation. The first recommendation is to allocate raw milk intake and transportation on the basis of the "milk solids" of the final products. For all remaining inputs, three scenarios are possible:

a) Detailed process and co-product data are available: energy and material usage as well as emissions can be directly assigned to the specific products;

b) A mixture of detailed process and co-products data as well as whole plant data are available: assign detailed process and co-products data to specific products, subtract assigned detailed process and co-products data from the whole plant total and then allocate the remainder based on milk solids;

c) Only whole plant data are available: apply specific allocation coefficients (in IDF guidelines only available for dairy cow industry).

## 5. Data collection and LCI analysis

As far as possible, inventory of directly measured data representative of processes at a specific facility or for specific processes within the product supply chain (primary data) shall be collected for all used resources and emissions associated with each life cycle stage included within the defined system boundaries. Otherwise, according to the PEF guidelines (2013), secondary data (information obtained from sources other than direct measurement of the inputs/outputs) can be used. When possible, primary data collected directly from suppliers should be used for the most relevant products. If secondary data are more representative or appropriate than primary data for foreground processes (to be justified and reported), secondary data shall also be used (for example the economic value of products over 5 years).

In order to clarify the nature of the inventory data, it is useful to differentiate between "measured" and "modelled" foreground system LCI data.

For projects where significant primary data have to be collected, a data management plan is a valuable tool for the treatment of the data and tracking the process of LCI data set creation, including metadata documentation. The data management plan should include:

– description of data collection procedures;
– data sources;
– calculation methodologies;
– data transmission, storage and backup procedures;
– quality control and review procedures for data collection, input and handling activities, data documentation and emissions calculations.

The recommended hierarchy of criteria for acceptance of data is:

– primary data collected as part of the project which have a documented Quality Assessment;
– data from previous projects that have a documented Quality Assessment;
– data published in peer-reviewed journals or from generally accepted LCA databases;
– data presented at conferences or otherwise publicly available (e.g., internet sources);
– data from industrial studies or reports can be considered.

The following data collection criteria have to be taken into account when a LCA analysis is carried out (adapted from ISO14044:2006 and reported in LEAP guidelines):

- representativeness: qualitative assessment of the degree to which the dataset reflects the true population of interest. Representativeness covers the temporal, geographical and technology dimensions (Table 2);
- precision: measure of the variability of the data values for each reported data (e.g. standard deviation);
- completeness: percentage of flow that is measured or estimated;
- consistency: qualitative assessment of whether the study methodology is applied uniformly to the various components of the analysis;
- reproducibility: qualitative assessment of the extent to which information about the methodology and data values would allow an independent practitioner to reproduce the results reported in the study;
- sources of the data;
- uncertainty of the information (e.g. data, models and assumptions).

**Table 2** - Summary of selected requirements for data quality, from LEAP guidelines (FAO, 2016b).

| Indicator | Requirements/ data quality rules |
|---|---|
| Technological representativeness | • The data gathered shall represent the processes under consideration. |
| Geographical representativeness: | • If multiple units are under consideration for the collection of primary data, the data gathered shall, at a minimum, represent a local region such as EU-27.<br>• Data should be collected respecting geographic relevance to the defined goal and scope of the analysis. |
| Temporal representativeness | • Primary data gathered shall be representative for the past three years and 5-7 years for secondary data sources.<br>• The representative time period on which data is based shall be documented. |

In the sheep dairy supply chains the cradle-to-farm-gate stage normally dominates the whole life cycle emissions (80-90% of total carbon footprint) and methane enteric can represent around 50-70% of cradle-to-farm-gate emissions. For these reasons, flock composition, ewe's productivity and feed quality data are key primary activity data required for LCI analysis. Where manure is collected from animals, methods of storage and use can have a significant effect on emissions, so that primary activity data are also needed.

If primary data are unavailable and the process is not environmentally significant, secondary data should only be used for foreground processes. Moreover, secondary data collection is allowed from national databases or equivalent sources, if the goal and scope permit them. However, proxy data shall be used just in the case that the quality of available specific data is considerably lower and the proxy or average data sufficiently represents the process.

All secondary data should satisfy the following requirements:

- They shall be as current as possible and collected within the past 5-7 years; however, if only older data are available, documentation of their quality is necessary and determination of the sensitivity of the study results to these data must be investigated and reported.
- They should be used only for processes in the background system. When available, sector-specific data shall be used instead of proxy LCI data.
- They shall fulfil the data quality requirements.
- They should, where available, be sourced following the data sources.

An assessment of the quality of these data sets should be made and included in the documentation of the data quality analysis for using in the specific application.

Data collected from primary sources should be checked for validity (1) by ensuring consistency of units, (2) for reporting and conversion, and (3) material balances. These guarantee that, for example, all incoming materials are accounted in products leaving the processing facility.

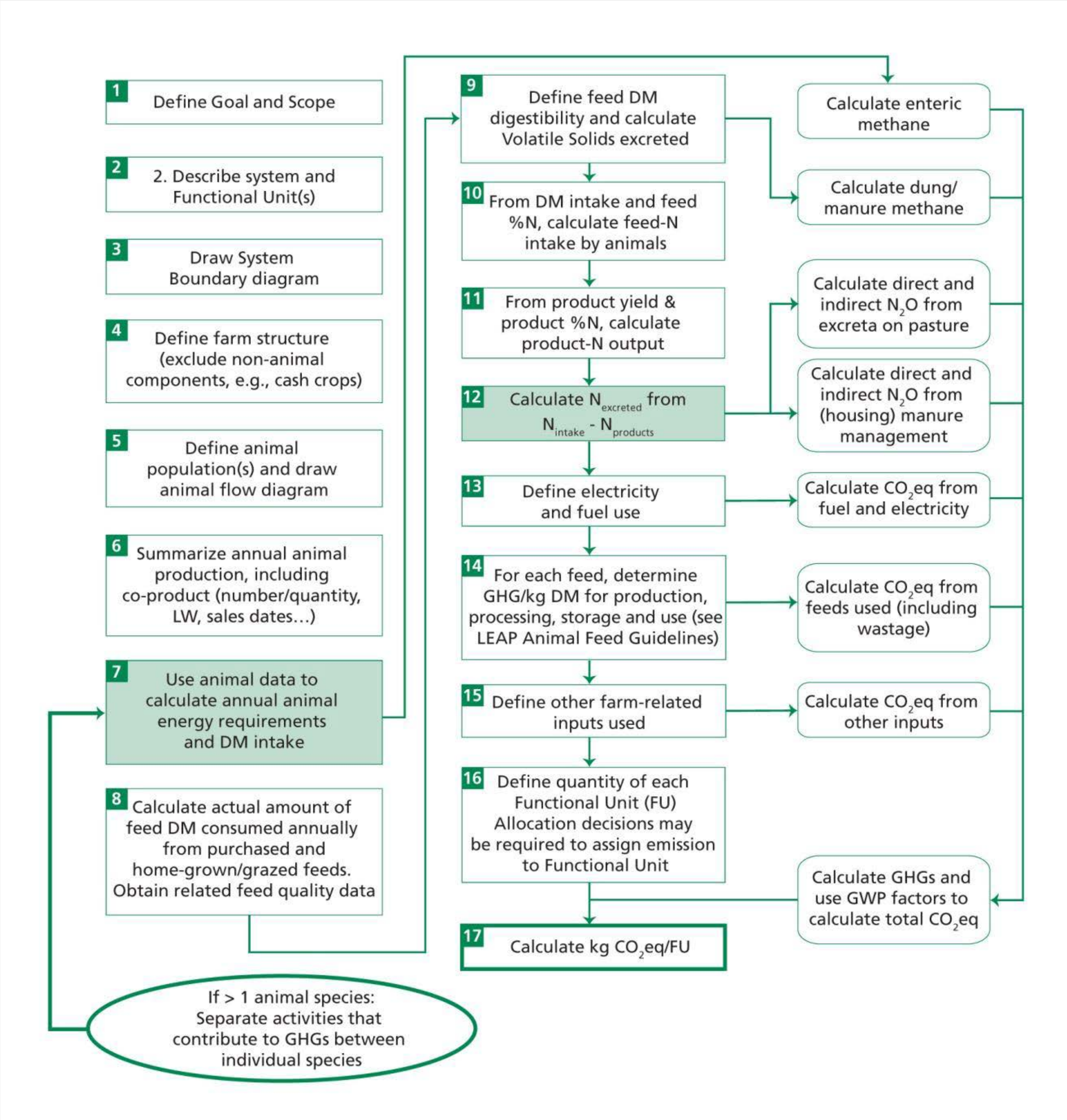



**Figure 3** - Flow diagram as a guide to the procedure for determining the carbon footprint of small ruminant products for the cradle-to-farm-gate stage (from LEAP guidelines: FAO, 2016b).

As reported in LEAP Animal Feed Guidelines (FAO, 2016a), dealing with the production cycles variability for on-farm feed crops implies that the cultivation data shall be collected over a three-years rolling average, which is considered a period of time sufficient to provide an average assessment of the emissions and resource's use associated with the inputs and outputs that will offset fluctuations due to seasonal differences.

The LEAP guidelines (FAO, 2016b) schematize all steps required for data collection utilized in LCI stage (Fig. 3) and describe in detail the key processes (feed production, animal diet, etc.), which should be referred to for further information.

In order to better characterize the environmental profile of the Mediterranean dairy supply chains, the development of a site-specific and harmonized methodological approach is needed for the following key issues:

- Feed intake calculation;
- Enteric methane emissions estimation;
- Carbon sequestration from crops and grasslands estimation;
- Ecosystems services valuation (biodiversity and landscape maintaining, environmental risks reduction, etc.).

Hereafter the methodological references suggested for LCI elaboration in the first two of the above mentioned issues are presented and will be completed and updated as soon the further methodological development is implemented during the SheepToShip-LIFE. The remaining last two issues in this document refers to LEAP Animal Feed Guidelines (FAO, 2016a) and to other international references.

### Feed intake calculation

As reported above in the System Boundary section of this document, the LCA model shall include data on ewes and rams, each subdivided into lambs, replacement animals and adults. Moreover, the ewes shall be grouped by physiological and productive phases (maintenance, dry and lactation) which have specific energy and dry matters requirements according to breed and productivity level.

The amount of fodder crops and pastures consumed by flocks shall be recovery directly in farm (by animal nutrition plan) and then cross-checked respect to i) the estimated and/or measured forage availability (feed produced on-farm, including natural grassland, and purchased), performing a mass balance between the total feed availability and the total feed consumed by flock or destined for other purposes, and ii) the estimated nutritional needs expressed in dry matter mass and gross energy and based on gender, age, weight, physiological stage and production level of animals (theoretical values reported in international scientific literature). Finally, the more representative data criteria shall be utilized in LCI.

Enteric methane emissions estimation

Enteric methane emissions should be quantified using the methane emission factor (Ym). The energy of emitted $CH_4$ should be calculated as function of metabolizable energy intake (MEI) which is based on net energy (NE) requirements and a conversion of MEI in NE (Vermorel et al., 2008).

This method is coherent with the LEAP guidelines rules and allows to estimate emissions with more flexibility increasing the accuracy of the estimation in different farming conditions. The proposed method can be considered a modified TIER2 approach. It considers specific emission values for different animal categories (lactating, dry, pregnant sheep, rams, replacement and fattening lambs) and dietary characteristics.

It consists in the estimation of $CH_4$ emission for each animal category using this formula:

$$\text{kg of emitted } CH_4\text{/day per head} = \text{MEI (MJ/d)} \times \text{Ym}/55.65 \qquad (4)$$

where MEI estimation can be directly calculated by using the Small Ruminant Nutrition System (Tedeschi et al., 2010).

DMI for grazing and confined dairy sheep can be estimated using equations reported by Pulina et al. (2013).

Ym values should change depending on diets and categories based on Vermorel et al. (2008) as follow:

- for confined sheep with diets of 70% forage and 30% concentrate, Ym can be equal to 12.3 MJ;
- for grazing lactating sheep Ym (MJ) = -0.15 x Digestible energy of the diet % + 21.89;

  Ym values obtained with this formula are specific for grazing animals. On average, Ym can be considered equal to 12 for energy digestibility of the grass ranging from 60 to 76%. Digestible energy of the diet can be also calculated considering the proportion of each feed included in the diet and the energy digestibility of each feed. Energy digestibility of each feed is reported in INRA feed tables (INRA, 2007);

- for pregnant sheep from 14 MJ in early gestation to 12 MJ in the last two months of gestation;
- for replacement lambs 3.6 MJ in the weaning phase with diets at 85% of concentrate; 9.3 MJ from 3 to 7 months with diet at 50% of concentrate, 11.3 MJ from 8 to 12 months, then the same values that adult sheep could be used following the physiological stages;
- for rams can be equal to 12.0 MJ.

Carbon sequestration from crops and grasslands estimation

In Mediterranean environment, natural grasslands are an important source of food in livestock diet and they are characteristic both extensive and semi-intensive dairy sheep production systems. The farmers utilize and preserve grasslands through traditional pasture practices, grazing management and reseeding techniques of grass and clovers. Depending on their management, natural grasslands can provide some ecosystem services, as the soil C sequestration. However, a large debate is ongoing regarding the inclusion of soil C sequestration in LCA calculation. It is poorly considered in recent past LCA's studies and the IDF guidelines (2010) do not account of it. On the other hand, soil C sequestration in the CF assessment has been recently taken into account in several papers - one of them on sheep farming systems (Batalla et al., 2015). The LEAP Animal Feed Guidelines (FAO, 2016a) also contain specific methodological references on this issue. In particular, SOC change can be estimated by 4 methods following two different approaches (Batalla et al., 2015) using changes in soil C stocks according to inventories:one based on IPCC Guidelines (IPCC, 2006), as reported by Vleesshouwers and Verhagen (2002) and another one using a balance of net carbon fluxes in agricultural soils, as reported by Soussana et al. (2010) and Petersen et al. (2013). Among these 4 soil C sequestration estimation methods, the model used by Peterson et al. (2013) seems to give more precise and realistic results. In fact, it is based on actual data on C inputs over a 100 years' time perspective as for GWP (Batalla et al., 2015), as opposed to the 20 years' perspective of IPCC guidelines. This estimation methodology is based on the study of two phenomena: i) when C (crop residues or manure) is added to the soil, part of it remains into the soil and part is released to the atmosphere in the form of $CO_2$, depending of the time (Fig. 4); ii) when C-$CO_2$ is released into the atmosphere, it follows a decay pattern (absorption in sinks as oceans or soil) as described by the Bern Carbon Cycle Model (Fig. 5), according to the following equation that serves as a proxy (IPCC, 2007):

$$f(t) = 0.217 + 0.186\exp(-t*1.186^{-1}) + 0.338\exp(-t*18.51^{-1}) + 0.259\exp(-t*172.9^{-1}) \quad (5)$$

where *f(t)* is the fraction of $CO_2$ left into the atmosphere depending on time *t.*

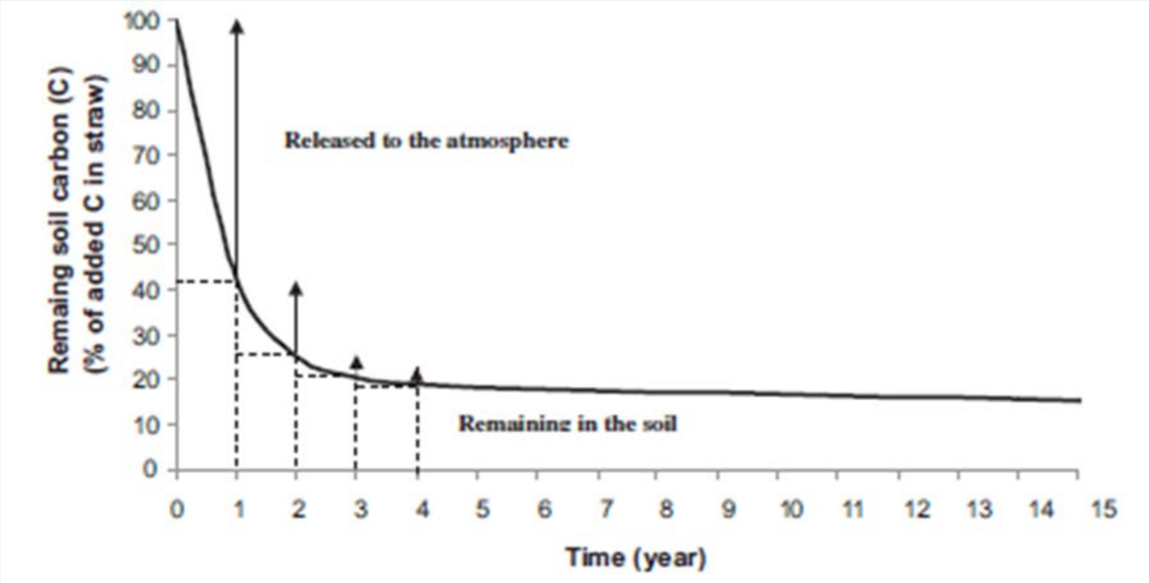



**Figure 4** - Generic illustration of the decay of carbon C (e.g. crop residues or manure) added to soil as a single event in the first year. The area below the graph is C retained in the soil and the arrows above the graph illustrate the C that is released to the atmosphere (modified from Petersen et al., 2013).

Figure 5 shows the temporal dynamics of this $CO_2$ decay from the atmosphere to the other pools (terrestrial ecosystems and oceans) and the area ($A_T$) below the curve is 48% of the hypothetical value without sinks. The area $A_T$, the time-integrated mass load of $CO_2$ in the atmosphere, is calculated by the following formula:

$$A_T = \int_1^T f(t)\mathrm{dt} \qquad (6)$$

where *T* is the time horizon and *f(t)* is derived from Equation (5).

This approach estimates the change of the atmospheric $CO_2$ content as balance between the C added to the soil, the release of $CO_2$ from soil to the atmosphere over time (Fig. 4) and the rate of $CO_2$ decay from atmosphere to the sinks (Fig. 5). The estimation of the SOC changes for LCA calculation is based on two different LCA situations, using a case study approach: removal of crop residues (for bioenergy use or open field burning) or leaving it on the soil (soil C storage). Figure 6 shows the temporal dynamics of the decay rates of C added to the soil in the two different cases: i) the upper dashed line represents the scenario where the entire C in crop residues is removed from the field (for bioenergy use or open field burning), according to the Bern Carbon Cycle Model. The area below this curve corresponding to $A_T$ (Equation 6); ii) the lower dotted line (with spherical elements) represents the scenario where the crop residues are left on the field and the curve (summed emission curve) is a combination of the decay curve of a single event of C added to the soil (Fig. 4) in the first year and the decay curve of $CO_2$ in the atmosphere (Bern Carbon Cycle Model) (Fig. 5) over time.

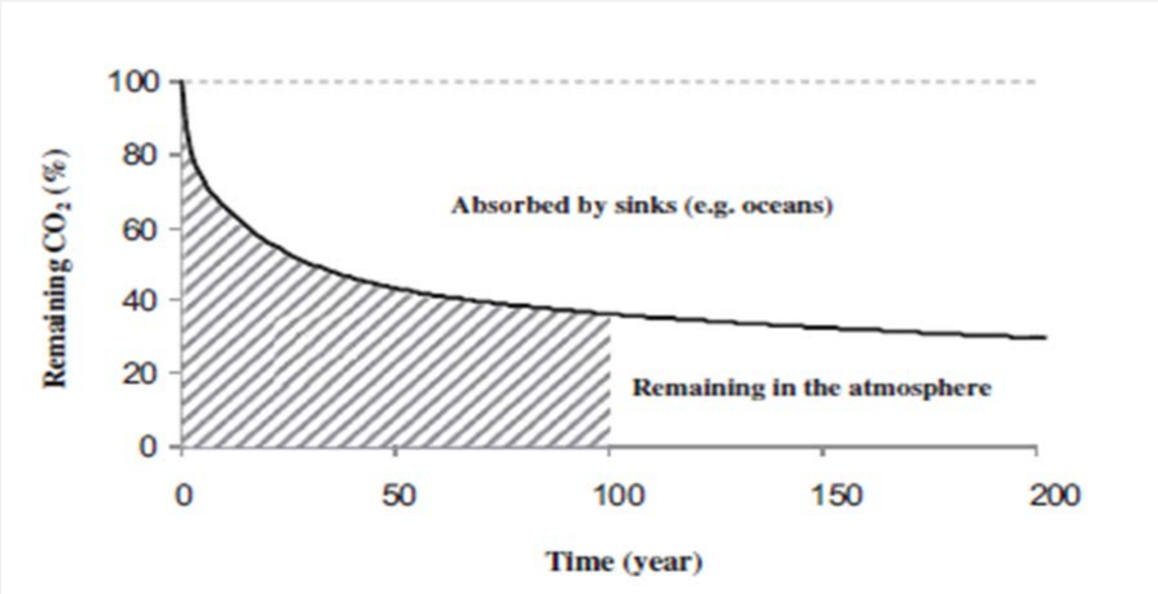



**Figure 5** – Decay of $CO_2$ in the atmosphere, based on the Bern Carbon Cycle Model, f(*t*) (IPCC, 2007). The area under the curve is the time-integrated mass load of $CO_2$ in the atmosphere and is described by $A_T$ (Equation (6)). An example of the time-integrated mass load of $CO_2$ in the atmosphere in 100-year perspective, $A_{100}$, is given (modified from Peterson et al., 2013).

The area ($S_T$) below the summed emission curve represents the atmospheric load of $CO_2$ as influenced by soil storage. The area $S_T$ is calculated by the following formula:

$$S_T = \sum_{i=1}^{T} \left( a(i) \sum_{j=1}^{T-i} f(j) \right) \qquad (7)$$

where *T* is the time frame, *a(i)* is the release of $CO_2$ in year *i* from a single addition of crop residues (as resulting from the decay of organic matter) and *f(j)* is given by Equation (5).

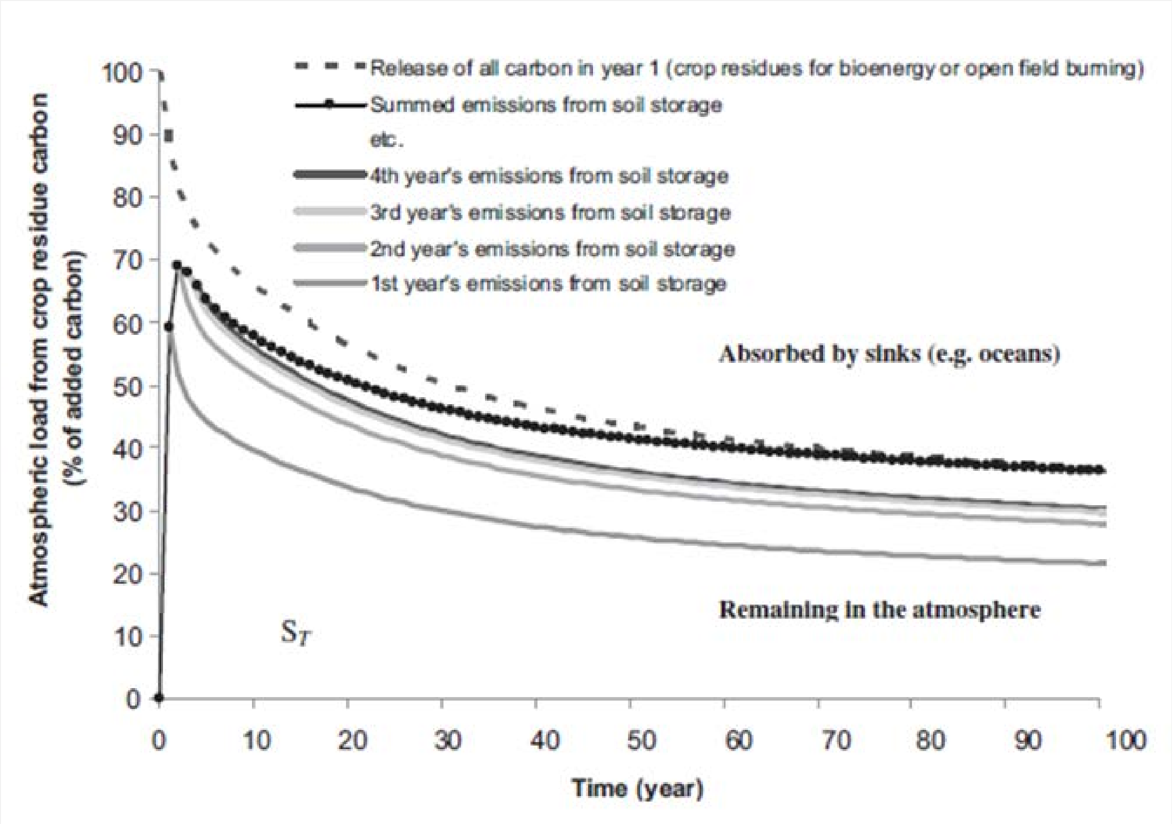



**Figure 6** – Illustration of the atmospheric load from either soil storage or burning of crop residue carbon C. The soil storage curves are a combination of the decay curve of a single event of carbon added to the soil in the first year and the decay curve of $CO_2$ in the atmosphere (Bern Carbon Cycle Model) – shown on a yearly basis for the first four following years only as an illustration. The curve of the summed emissions from soil storage contains all the following years. The upper dotted line represents the scenario where the entire C in crop residues is released in the first year (as for bioenergy use or open field burning) (modified from Petersen et al., 2013)

The area ($R_T$) between the two curves (not indicated in the figure 6) represents the fraction of total C (crop residues) added to the soil in the first year that is not released in the atmosphere because sequestered in the soil over a *T*-years perspective. The area $R_T$ is calculated as follow:

$$R_T = \frac{A_T - S_T}{A_T} \qquad (8)$$

To estimate the soil C sequestration for LCA calculation, the value of $R_T$ (%) is to be applied to the total amount of C left on the soil. Data needed for the calculation are:

- amount of C from crop residues (aboveground, belowground and rhizodepostion residues);
- amount of C from organic fertilizer application (manure, slurry, etc.);
- amount of C from faecal excretions produced during grazing.

Regarding to Equation 7, the yearly organic C decay "*a(i)*" applied to the soil in the first year can be estimate using crop models that simulate the SOC change over time (e.g. EPIC model by Williams and Sharpley, 1989).

Batalla et al. (2015) estimated $R_T$ value applying a coefficient of 10% to the amount of C left in the soil with crop residues, manure and fecal excretions during grazing. This coefficient is the fraction of the total C applied in the first year that is sequestered into soil in a 100-years perspective (Petersen et al., 2013). However, the decay rate of organic matter can vary depending on several factors. Soil temperature and soil water content are the primary environmental factors that regulate the seasonal variation of soil respiration (Davidson et al., 1998). Therefore, it is necessary simulate the *a(i)* values in Equation 7 and to calculate the Equation 6, 7 and 8 for the estimation of an actual $R_T$ value.

Ecosystems services estimation

From an environmental point of view, due to the low production efficiency, extensive dairy systems results often more impacting than intensive one (Berlin, 2002; Gerber et al., 2013; González-García et al., 2013). Besides its primary function of milk and meat (and wool) producing, most Mediterranean sheep farming systems provide other functions to society: maintaining both the vitality and the traditions of rural communities (specially, in marginal areas), as well as preventing environmental issues (i.e., soil erosion and desertification, wildfire, biodiversity depletion, etc.) and conserving cultural landscapes (Plieninger et al., 2006). In general, all these functions, also defined as ecosystems services (Millennium Ecosystem Assessment, 2005), are not considered in LCA calculations of sheep farming. Otherwise, including ecosystem services in LCA shall lead to a more complete comparison among the environmental profile of extensive and intensive sheep farming systems. Probably, the negative incidence of low production efficiency of the extensive systems should be offset by the positive effect of ecosystem services they provide to the society. In order to allocate emissions to ecosystem services, Ripoll-Bosch et al. (2013) proposed for grazing systems an approach that uses agri-environmental payments from CAP (EU Common Agricultural Policy). This method is a viable solution to consider for future LCA application to Mediterranean sheep farming systems.

## 6. Modelling LULUC

Importance of LULUC in LCA of small ruminant supply chains

Another important consideration in LCA studies of small ruminant supply chains is the topic of LULUC. Agricultural systems produce not only products for human consumption, but are also much more intimately linked with the landscape and the environmental benefits it provides than other production systems. Furthermore, given the wide variety of production and management methods present in global agriculture systems, the impact that a land use has in one global region cannot be generalized to have the same impact globally. For this reason, special attention must be paid to how LULUC is measured, calculated and allocated within agricultural LCA studies (Notarnicola, 2017). Land use, also referred to as land occupation, is defined as the "total arrangements, activities, and inputs undertaken in a certain land cover type (a set of human actions)" (UNEP-SETAC 2016). The term land use also refers to the social and economic purposes for which land is managed (UNEP-SETAC 2016). In regards to elementary flows recorded in LCIs, land use/occupation can be modelled as "square meter × years, land use type i, and region k" (Koellner, 2013) or more generally as "changes in quality multiplied by area and duration" (FAO, 2016). Land occupation results in emissions or sequestration according to land management strategies, intensities, and the resulting change in soil organic carbon (SOC)(FAO, 2016a). Land use change, also referred to as land transformation, is a change in the manner in which humans use or manage the land (ISO/TS 14067:2013). This therefore implies the need to model both the initial and subsequent land use state, and can be modelled in LCI elementary flows as "square meter, initial land use type i→final land use type j, and region k" (Koellner, 2013) and more generally as the change in quality multiplied by the area. Emissions from land transformation are a result of the conversion of both aboveground (AGB) and belowground biomass (BGB), most often from burning or clear cutting to create space for agricultural production (FAO, 2016). Both land use mechanisms are important to consider within small ruminant LCA studies for their effect on both GHG emissions and local ecological dynamics.

The effects of LULUC can be separated into those which contribute to climate change through a change in the carbon balance of land and those which contribute to ecological damage (e.g. soil, water, nutrient and biodiversity loss, etc.) via changes to the soil, vegetation, and native habitats. Carbon emissions from land use and land use change (LULUC) accounted for 12.5% of the total anthropogenic carbon emissions between 1990 and 2010 (Houghton, 2012). However, this factor is one of the most uncertain when determining the global carbon budget, as the amount of carbon stored or released by managed land, including agricultural land, is still poorly understood. Management activities such as the use of fertilizers, tillage, cropping and grazing practices can all have an effect on the net carbon flux from LULUC. Other studies have shown damage from land use in other categories, such as: decreased biotic productivity (NPP) in terrestrial ecosystems (Kaenchan, 2018), salinization and erosion of soils, disruption of the water cycle via changing the surface water balance, regional climate variability via changes in surface albedo (Foley, 2005).

Land use impacts can be especially important to consider when comparing the net environmental effects of intensive vs. extensive livestock systems. Extensive livestock systems provide many other environmental goods and services outside of food production.  While several studies have found intensive livestock systems to be more eco-efficient than extensive ones per kg of milk or meat produced, many of these studies failed to include the role of carbon sequestration present in the grasslands and pastures of extensive systems (O'Brien, 2016; Capper, 2009). More recent studies have found that, when accounting for carbon sequestration in the Carbon Footprint calculation, the net impact of extensive systems can actually be less than intensive ones (Ripoll-Bosch, 2013; Batalla, 2015; O'Brien, 2016). However, carbon sequestration within extensive livestock systems is dependent on the management practices of farmers and their contribution to either the preservation or degradation of grassland vegetation and soil carbon. Furthermore, while some intensive systems may provide less GHG emissions per kg of product produced, it has been found that other environmental impacts, such as acidification, eutrophication, and fossil fuel usage are often far greater in intensive systems than extensive ones when compared on the basis of impacts per hectare of land (Salou, 2017). This a result of the multi-functionality of extensive livestock systems in providing environmental public goods (Ripoll-Bosch, 2013). Extensive livestock systems based on pastures and grasslands often use far less concentrate and off-farm feeds than intensive systems, which contributes to less overall resource use in extensive systems by reducing indirect land use and "virtual water" use (Bernuès, 2011).

The potential positive effects for land use from extensive livestock systems based on pastures and grasslands is especially important in Mediterranean small ruminant systems, as the use of marginal land or less favored areas (LFAs) can contribute to conserving biodiversity in the form of High Nature Value (HNV) farmland and prevent land abandonment in rural areas (Bernues, 2011). LFAs are common in the Mediterranean region (Porqueddu, 2017a; EEA, 2004). LFAs are defined by the EU as "mountainous or hilly areas or areas with natural handicaps for cropping (lack of water, harsh climate, short cropping season), or that are remote, with difficulties in rural mobility or that are at risk due to depopulation" (Porqueddu, 2017a; EEA 2004). In the case of Sardinia, approximately 90% of its total area is classified as LFAs (Porqueddu, 2017b). HNV farmland is characterized by low input-farming systems that incorporate low stocking densities, low use of chemical inputs and labour heavy management practices, all of which facilitate a greater range of biodiversity by protecting flora and fauna from the overuse of pesticides and an overabundance of nutrients (EEA, 2004). Farmland biodiversity is declining in many parts of Europe. The main causes behind this phenomenon have been identified as land abandonment and intensification of agricultural production systems via land use intensification (Strohbach, 2015). Land abandonment can bring indirect negative effects in the form of further biodiversity loss due vegetation encroachment, as well as increased fire risk from excess vegetation. By allowing for managed grazing on marginal lands, such as that present in extensive small ruminant systems, the potential fuel load for forest fires can be greatly reduced and vegetation structure maintained in a way that promotes greater species diversity (Bernuès, 2011; Kramer, 2003). For these reasons, the proper characterization of LULUC within extensive small ruminant systems is of special concern.

In regards to the inclusion of LULUC impacts within LCA of livestock systems, several organizations currently give guidelines for their incorporation. To better understand the nuances and applications of these recommendations and to determine the best course of action for the inclusion of LULUC in LCA studies of small ruminant supply chains, a thorough literature review of all current methodologies is undertaken.

## Guidelines for the inclusion of LULUC in LCA of small ruminant supply chains

While the overall LCA methodology and guidelines are published by the ISO in their standards 14040, 14044, and 14067 and outline the general steps that must be present in an LCA study, they lack specific guidelines for the collection of data and allocation of environmental impact within an LCA study. Further complication is present in agricultural LCA, due to the multi-functionality of agricultural systems in providing not only products for human consumption, but also in its effect on the provisioning of environmental public goods such as healthy soils, biodiversity and ecosystem services (Notarnicola, 2017). The topic of including land use and land use change within an agricultural LCA is a matter of yet greater complexity, as no consistent methodology exists for calculating and characterizing the impacts of LULUC over time. For this reason, a comprehensive review was undertaken of the current best standards in agricultural LCA practice to compile recommendations for the inclusion of LULUC in an attributional LCA of a small ruminant supply chain. Guidelines provided by organizations prominent in the overall European LCA community, as well as recommendations from specialized agriculture and livestock organizations, were reviewed. Organizations from which LULUC relevant guidelines were reviewed include the European Union's Joint Research Commission's (JRC) International Life Cycle Data System (ILCD) Handbook and Product Environmental Footprint (PEF) guide, the International Dairy Federation (IDF), and FAO-LEAP guidelines.

### ILCD handbook (2010) & impact assessment methods analysis (2011)

The ILCD Handbook for Life Cycle Assessment advises practitioners to inventory direct land use and land use change in accordance with the best impact assessment method chosen for the specific study, with no further recommendation regarding which impact assessment methods to use. Regarding GHG emissions stemming from LULUC, the most recent IPCC CO2 emissions factors are to be used for calculation, and are included in Annex 13 of the Handbook (ILCD, 2010). These factors are defined according to temperature, precipitation and management intensity, for both arable land and grassland. ILCD further identifies 2 different cases for the distribution of land use related CO2 emissions based on the length of time over which they occur. For emissions related to land occupation, emissions should be assigned equally over each year of the time period of the occupation (ILCD, 2010). The default time period over which emissions related to land transformation should be allocated is 20 years, unless it can be otherwise proven that effects from emissions will take place over a longer or shorter timespan. The assumption behind the distribution of land transformation emissions over a longer time horizon is that "the decision to change the land use is not motivated for the next single crop year, but over a longer period" (ILCD, 2010). Activities from which land use related CO2 emissions should be considered include processes lasting longer than 1 year, such as changes in soil carbon stocks, as well as more immediate processes such as using machines or burning of existing biomass to convert land for use (ILCD, 2010).

Overall, the recommendations for time periods of allocation of LULUC inventory results are similar to those of the PAS 2050 guidelines, which are referenced in other, more recent, organizational guidelines on agricultural LCA, including the PEF guide (2013) issued by the European Commission. Given the more recent publication of the PAS 2050 and 2050-1 guidelines relative to that of the ILCD Handbook, and the high recommendation rate for its use among other published agriculture LCA guidelines, it can be assumed that the PSA guidelines are the more current and relevant guidelines to follow regarding allocating LULUC emissions over time. In terms of impact assessment methods for LULUC, the soil organic matter (SOM) based method of Mila i Canals (2007) is proposed for further review by ILCD (2011), which is later addressed in greater depth in the PEF (2013) guidelines.

PEF

The PEF guidelines, issued by the European Commission in 2013, build upon the LULUC assumptions and calculation scenarios outlined by the BSI PAS 2050 to make recommendations for including direct land use change in agricultural LCA. According to PEF, the scenario method outlined by BSI in PAS 2050 for calculating LULUC change should be followed. PEF guidelines consider mainly the calculation of the GHG emissions from LULUC by measuring CO2 emissions and emissions of all other relevant GHGs (N2O, CH4) in terms of CO2 equivalents and global warming potential (GWP). However, PEF suggests that other emissions from LULUC such as "NO3 losses to water, emissions from biomass burning, soil erosion, etc. should be measured or modelled for the particular case or using authoritative sources" (PEF, 2013). The recommended characterization factor for LULUC impacts is soil organic matter (SOM) in kg deficit/year, as suggested by Milà i Canals (2007). However, this method is suggested "with caution", with a Level 3 rating by the Commission, indicating that SOM as an adequate characterization factor for LULUC is still uncertain (Hauschild, 2012).

PEFCR for dairy products

Land use is among the 3 LCIA categories from the ILCD 2011 method highlighted by PEFCR Dairy as imperative for evaluating EU dairy products. For the characterization of land use, the model of Mila i Canals (2007), quantifying land use effects in terms of changes in SOM, is still maintained, in accordance with previous PEF guidelines. In regards to the contribution of land use to the climate change impact category, changes in carbon stocks from LULUC are not advised to be included under “climate change”, unless the related change in carbon stocks from land use change can be proven to have occurred less than 20 years prior to the year of assessment (PEFCR, 2016).

One additional aspect emphasized in the PEFCR Dairy guidelines is the importance of biodiversity in land use evaluation. Biodiversity is inherently linked to land use due to the effects from agricultural practices and land use change on habitats. PEFCR Dairy therefore advises stakeholders utilizing its guidelines to report on additional biodiversity related measures, which serve as an attempt to evaluate impacts from dairy on biodiversity in a semi-quantitative manner (PEFCR, 2016). The PEFCR recommends that users report on the following indicators (PEFCR, 2016):

- share of grass from pasture in the feed ration (% of total DMI)
- semi-natural habitats in the dairy farm’s area (% of total area)
- share of feed used with possible risk of deforestation in its supply chain (% of total DMI)
- biodiversity conservation schemes in which the dairy farm or upstream suppliers participate (% of total raw milk within the product recipe that participates in each scheme)

Units of measurement for each indicator can be found in PEFCR Dairy Annex VI. Primary, measured values of each indicator should be taken when milk supply is part of the foreground system. In the event that milk supply forms part of the background system, default values for the above indicators are provided in Annex VI of the PEFCR Dairy report (PEFCR, 2016). These reporting measures seek to recognize the role that maintaining pastures, forests, and semi-natural habitats such as hedges and tree strips play in conserving biodiversity and contributing to sustainable land use.

IDF guidelines

The current International Dairy Federation (IDF) guidelines focus mainly on the calculation of GHG emissions and the carbon footprint of livestock supply chains. Within these guidelines, IDF highlights the importance of calculating biogenic carbon emissions from direct land use change as a “key parameter” for calculating the overall GHG emissions of the product or system (IDF, 2015). To do so, the IDF supports the use of PAS 2050 guidelines for calculation, using the suggested time period and selection process for a reference land use type. IDF furthermore recommends that in addition to their inclusion in the carbon footprint of the product, carbon emissions from land use change also be reported separately for greater transparency (IDF, 2015).

In contrast to the EU's PEF guidelines, IDF recommends excluding measurements of changes in SOM from the carbon footprint, due to a lack of scientific data on the level of release and sequestration contributed by changes in SOM from land use (IDF, 2015). It is also important to note that IDF recommendations are based on the assessment of dairy cow supply chains. However, their guidelines can also be considered as a reliable reference for milk production from sheep supply chains.

LEAP guidelines

The comprehensive LEAP guidelines specifically address animal feed, fossil energy uses, and GHG emissions within livestock supply chains. The LEAP Guidelines on GHG emissions and fossil energy use from small ruminant supply chains (2015) give guidance only on the environmental impact categories of climate change and fossil energy use as related to small ruminant supply chains (FAO, 2015). The LEAP Animal Feed Guidelines address emissions from cradle-to-animal's mouth stages of the feed product life cycle for all types of livestock supply chains (FAO, 2016). For LULUC considerations, the LEAP Animal Feed guidelines are of primary importance.

A thorough consideration of land use in the production of animal feed is essential in the LCA of a livestock supply chain, as LULUC accounts for 25% of GHG emissions in animal feed supply chains, or approximately 9% of the livestock sector's emissions related to land-use change (FAO, 2016; Gerber, 2013). According to LEAP Animal Feed guidelines, while still being included in the overall carbon footprint of the product of animal feed, GHG emissions from LULUC should also be recorded and analyzed separately from those originating from other sources in the livestock supply chain (e.g. enteric fermentation) (FAO, 2016). This separation of emissions from LULUC stems from the lack of a coherent methodology for calculating land use change as well as uncertainty regarding the best time horizon over which GHG emissions from LULUC should be allocated.

The LEAP Animal Feed Guidelines recognize that, to date, there is not a universally accepted methodology for calculating LULUC in regards to LCA. Therefore, LEAP proposes a choice between two calculation methods depending on the particular context of the livestock system studied. One method is the BSI PAS methodology method, adapted from the aforementioned PAS 2050-1 guidelines. This method places greater emphasis on local conditions of the system and, as stated previously, differentiates between 3 different calculation scenarios dependent on information availability. The second method, the global average method developed by Vellinga (2013), places greater emphasis on feed products treated as market oriented commodities, and therefore calculates average global GHG emissions from land use as a proportion of total global agricultural land in use.

Additionally, LEAP emphasizes that proper estimation of existing carbon stocks in the reference land use type also play a role in accurately calculating emissions from both land occupation and transformation (FAO, 2016). Specific recommendations are made for inventory data collection in grasslands. As grasslands play an important carbon sequestering role in livestock systems, data on the accumulation of SOM should be collected, including parameters such as the age of the grassland, the level of nutrient inputs¸ the type of management (grazing or cutting), the soil type, soil tillage operations, the current level of soil organic matter and the agro-ecological zone (temperature and precipitation) (FAO, 2016). However, it is acknowledged that when conducting LCA studies on a national or larger territorial level, the collection of such primary data over the entire area will be extremely difficult or impossible. Therefore, LEAP provides default values from literature for different grassland and arable land management regimes as an estimate of the influence of the reference land use type on the land use change calculation of large areas, or in areas where collection of sufficient primary data is not possible (FAO, 2016). These estimated annual change values (kg-ha-yr) for different management regimes are taken from Vellinga and Hoving (2011). However, due to its uncertain nature, it is recommended by LEAP that such carbon offsets not be included in the carbon footprint calculation, but be reported as additional information (FAO, 2016). The LEAP partnership is committed to improving and standardizing the LULUC assessment method, so that climate and ecological effects of LULUC, soil carbon sequestration, as well as synergies and trade-offs from land use may all be better understood and incorporated in future LCA studies of livestock supply chains.

British standards (BSI) PAS 2050 (2011) and PAS 2050-1 (2012)

A common recommendation among many of the reviewed guidelines for LULUC calculations in LCA of small ruminants is the reference to the publicly available specifications (PSA) provided by British Standards (BSI) 2050 and 2050-1. The PAS 2050 (2011) provides guidance for evaluating the GHG emissions from the life cycle of a variety of goods and services, with a special section of recommendations on the general steps to follow for the evaluation of land use in agriculture (BSI, 2011). Calculations according to the PAS 2050 procedure are based on the country of the land use change and the previous land use type. An included table of IPCC emissions factors is used to multiply by the proportion of land area influenced by transformation. The resulting value is then divided by the yield of the land area to allocate land use change emissions (BSI, 2011). Additionally, it sets a guideline for allocating the effects of LULUC over an extended time period. Although the action of land use change occurs in a short, discrete time period, the effects of the change and the subsequent use of the land in its new function occur continuously over time and therefore must be accounted for. PAS 2050 states that the emissions from LUC should be divided over either i) a 20 year period or ii) the length of one crop cycle/harvest period (BSI, 2011). The time period which is the longest of the two should be chosen. In the case of using a 20 year period, for example, the emissions should be linearly divided over the period, resulting in 5% of LULUC emissions assigned to each year over the 20 years after the land use change (IDF, 2015).

The supplemental addition of PAS 2050-1 (2012) provides specific guidance on how to apply aspects of PAS 2050 to agricultural/horticultural products and their special context. In regards to calculating LULUC effects in agricultural LCAs, PAS 2050-1 distinguishes between 3 different scenarios of calculation according to how much information is available regarding the country in which the LUC takes place and its previous land use (BSI, 2012). The three possible calculation scenarios are (BSI, 2012):

1) Where the country of production is known and the previous land use is known
2) Where the country of production is known, but the former land use is not known
3) Where neither the country of production nor the former land use is known

Records of prior land use, such as remote sensing data, satellite images and land use surveys should be used when available to determine previous land uses. In their absence, local knowledge is considered an acceptable alternative to determine prior land use (BSI, 2011). Furthermore, PAS 2050-1 provides a supplemental Excel tool to aid in LULUC calculations according to each scenario above, as well as a table with averaged land use conversions factors for selected countries in Annex C of PAS 2050. For countries that are not included in the Annex C list, it is recommended to refer to the land use factors and calculation methods provided in IPCC (2006). All PAS recommendations are in reference to direct land use change. Indirect land use change is not considered or advised upon, due to the lack of a proper methodology and calculation method. However, it is indicated as a research priority for future publications (BSI, 2011). As previously mentioned, the LEAP Animal Feed Guidelines, PEF guidelines, and IDF guidelines make specific reference to and support the use of the BIS PAS method.

Special topics concerning LULUC in LCA

Treatment of indirect land use change in LULUC calculations

While the previously outlined guidelines provide comprehensive recommendations on accounting for direct land use change (dLUC) in livestock LCAs, a common gap among them is the lack of a calculation methodology for indirect land use change (iLUC). dLUC is defined by ISO as “changes in human use or management of land within the boundaries of the product system being assessed” while iLUC is defined as “changes in the use or management of land which is a consequence of direct land use change, but which occurs outside the product system being assessed” (ISO, 2013) . Major difficulties still exist for methodologies on calculating iLUC in agricultural LCA. For this reason, explicit guidelines on including iLUC calculations into LCA models for livestock supply chains do not currently exist. However, all of the institutions reviewed clearly indicated iLUC calculation for LCA as a future research priority. Styles et al. (2017) found that when intensive bovine dairy production systems use greater amounts of off-farm feeds and concentrates, the iLUC emissions associated with growing these feeds can actually cancel out any reduced on-farm GHG emissions from intensification. Given the important role that livestock and their feed play in changing the demand for certain types of crops on a global scale, future LCA studies on small ruminant supply chains should make an effort to include iLUC calculations into the overall environmental footprint calculation (Styles, 2017).

Accounting for LULUC in LCA inventories

To carry out the LCA study of dairy sheep supply chains in Sardinia, the SheepToShip LIFE project will work with the SimaPro LCA software designed by PRe Consultants. Within the SimaPro software, several public databases are made available. Among these databases, SheepToShip LIFE will use the Ecoinvent database (v 3.4) and Agrifootprint database (v. 4.0) for the majority of its background data.

Ecoinvent

The Ecoinvent 3.4 database contains a multitude of land use classes for both natural (e.g. arable land, pasture, forest) and man-made uses (e.g. construction site, traffic network). These land use classes were developed based on a draft version of the Handbook on LCIA of Global Land Use within the framework of the UNEP/SETAC Life Cycle Initiative (Wiedema, 2013). Specifically for SheepToShip LIFE, the land use classes most relevant for LCA of small ruminant systems are those considering grassland, pastures, and arable land used for feed growth. The complete list of land use classes provided by Ecoinvent v.3 can be found below (Table 1).

**Table 6.1. Land use classes used in the ecoinvent database. Table continues on next page.**

| Land use class | Description |
|---|---|
| Unspecified | |
| Unspecified, natural (non-use) | |
| Forest, unspecified | Areas with tree cover >15%. |
| Forest, primary (non-use) | Forests (tree cover >15%), minimally disturbed by humans, where flora and fauna species abundance is near pristine. |
| Forest, secondary (non-use) | Areas originally covered with forest or woodlands (tree cover >15%), where vegetation has been removed, forest is re-growing and is no longer in use. |
| Forest, extensive | Forests (tree cover >15%), with extractive use and associated disturbance like hunting, and selective logging, where timber extraction is followed by re-growth including at least three naturally occurring tree species, with average stand age >30 years and deadwood > 10 cm diameter exceeds 5 times the annual harvest volume. |
| Forest, intensive | Forests (tree cover >15%), with extractive use, with either even-aged stands or clear-cut patches exceeding 250 m length, or less than three naturally occurring species at planting/seeding, or average stand age <30 years, or deadwood less than 5 times the annual harvest volume. |
| Wetland, coastal (non-use) | Areas tidally, seasonally or permanently waterlogged with brackish or saline water. Includes costal marshland and mangrove. Excludes coastal land with infrastructure or agriculture. |
| Wetland, inland (non-use) | Areas partially, seasonally or permanently waterlogged. The water may be stagnant or circulating. Includes inland marshland, swamp forests and peat bogs. |
| Shrub land, sclerophyllous | Shrub-dominated vegetation. May be used or non-used. Includes also abandoned agricultural areas, not yet under forest cover |
| Grassland, natural (non-use) | Grassland vegetation with scattered shrubs or trees (e.g., steppe, tundra, savanna). |
| Grassland, natural, for livestock grazing | Grasslands where wildlife is replaced by grazing livestock. |
| Arable land, unspecified use | Land suitable for crop production, in unspecified use |
| Pasture, man made | Arable land used for forage production or livestock grazing. |
| Pasture, man made, extensive | + no artificial fertiliser applied, mechanically harvested less than 3 times per year or equivalent livestock grazing |
| Pasture, man made, intensive | + artificial fertiliser applied, or mechanically harvested 3 times or more per year or equivalent livestock grazing |
| Annual crop | Cultivated areas with crops that occupy the land < 1 year, e.g. cereals, fodder crops, root crops, or vegetables. Includes aromatic, medicinal and culinary plant production and flower and tree nurseries. |
| Annual crop, non-irrigated | Annual crop production based on natural precipitation (rainfed agriculture). |
| Annual crop, non-irrigated, extensive | + Use of fertiliser and pesticides is significantly less than economically optimal. |
| Annual crop, non-irrigated, intensive | + Fertiliser and pesticides at or near the economically optimal level. |
| Annual crop, irrigated | Annual crops irrigated permanently or periodically. Most of these crops could not be cultivated without an artificial water supply. Does not include sporadically irrigated land. |
| Annual crop, irrigated, extensive | + Use of fertilizer and pesticides is significantly less than economically optimal. |
| Annual crop, irrigated, intensive | + Fertiliser and pesticides at or near the economically optimal level. |
| Annual crop, flooded crop | Areas for rice cultivation. Flat surfaces with irrigation channels. Surfaces regularly flooded. |
| Annual crop, greenhouse | Crop production under plastic or glass. |
| Field margin/hedgerow | Land between fields with natural vegetation. |
| Heterogeneous, agricultural | Agricultural production intercropped with (native) trees. |
| Permanent crop | Perennial crops not under a rotation system which provide repeated harvests and occupy the land for >1 year before it is ploughed and replanted; mainly plantations of woody crops. |
| Permanent crop, non-irrigated | Perennial crops production based on natural precipitation (rainfed agriculture). |
| Permanent crop, non-irrigated, extensive | + Use of fertilizer and pesticides is less than economically optimal. |
| Permanent crop, non-irrigated, intensive | + Fertiliser and pesticides at economically optimal level. |
| Permanent crop, irrigated | Perennial crops irrigated permanently or periodically. Most of these crops could not be cultivated without an artificial water supply. Does not include sporadically irrigated land. |
| Permanent crop, irrigated, extensive | + Use of fertilizer and pesticides is significantly less than economically optimal. |
| Permanent crop, irrigated, intensive | + Fertiliser and pesticides at or near the economically optimal level. |
| Cropland fallow (non-use) | Cropland, temporarily not in use (<2 years). |
| Urban/industrial fallow (non-use) | Areas with remains of industrial buildings; deposits of rubble, gravel, sand and industrial waste. Can be vegetated. |

**Table 6.1., continued. Land use classes used in the ecoinvent database.**

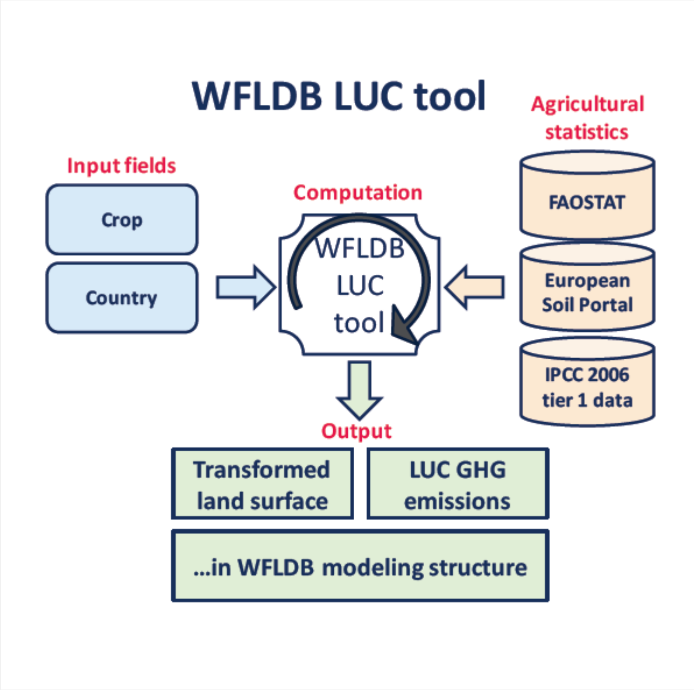
| Land use class | Description |
|---|---|
| Urban, continuously built | Buildings cover most of the area. Roads and artificially surfaced area cover almost all the ground. Non-linear areas of vegetation and bare soil are exceptional. At least 80% of the total area is sealed. |
| Urban, discontinuously built | Most of the area is covered by structures. Buildings, roads and artificially surfaced areas, associated with areas with vegetation and bare soil, which occupy discontinuous but significant surfaces. Less than 80% of the total area is sealed. |
| Urban, green area | Areas with vegetation within urban fabric. Includes parks with vegetation. |
| Industrial area | Artificially surfaced areas (with concrete, asphalt, or stabilized, e.g., beaten earth) devoid of vegetation on most of the area in question, which also contains buildings and/or areas with vegetation. |
| Mineral extraction site | Areas with open-pit extraction of industrial minerals (sandpits, quarries) or other minerals (opencast mines). Includes flooded gravel quarries, except for riverbed extraction. |
| Dump site | Landfill or mine dump sites, industrial or public. |
| Construction site | Areas under construction development, soil or bedrock excavations, earthworks. |
| Traffic area, road network | Motorways, including associated installations (stations). |
| Traffic area, rail network | Railways, including associated installations (stations, platforms). |
| Traffic area, rail/road embankment | Vegetated land along motorways and railways. |
| Bare area (non-use) | Areas permanently without vegetation (e.g., deserts, high alpine areas). |
| Snow and ice (non-use) | Areas permanently covered with snow or ice considered as undisturbed areas. |
| Inland waterbody, unspecified | Freshwater bodies. |
| River, natural (non-use) | Natural watercourses. |
| Lake, natural (non-use) | Natural stretches of water. |
| River, artificial | Artificial watercourses serving as water drainage channels. Includes canals. |
| Lake, artificial | Reservoir in a valley because of damming up river. |
| Seabed, unspecified | Area permanently under seawater. |
| Seabed, natural (non-use) | Natural seabed. |
| Seabed, bottom fishing | Seabed disturbed by bottom trawling or fishing dredge |
| Seabed, sediment displacement | Seabed disturbed by dumping or shellfish- or sediment-dredging |
| Seabed, infrastructure | Seabed disturbed by infrastructure like harbours or platforms |
| Seabed, drilling and mining | Seabed disturbed by drilling and mining, including cuttings and tailings disposal |

(Table 1, Land Use Classes in Ecoinvent v.3; Wiedema, 2013).

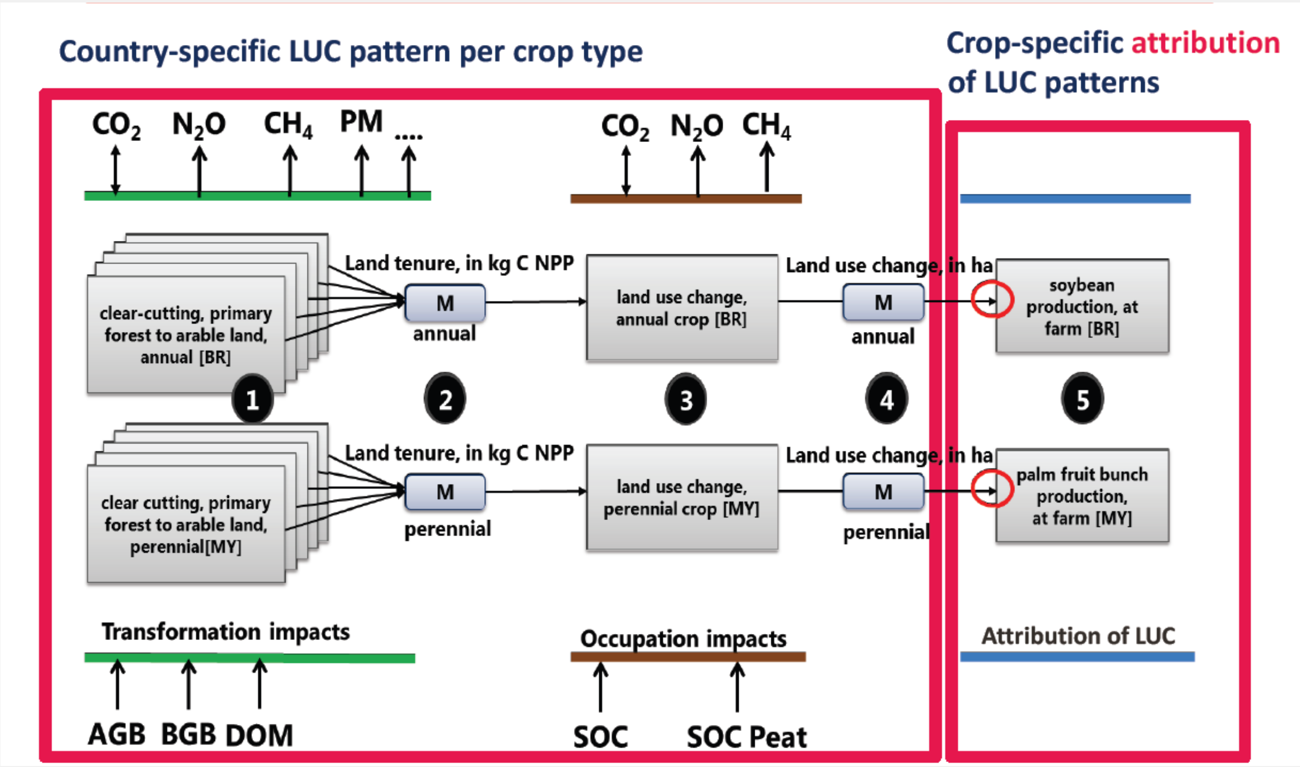
The Ecoinvent database models land use in terms of both land occupation and land transformation. Land occupation is defined as the current land use, and is impactful because the land is prevented from returning to its natural state due to its use (Wiedema, 2013). Land occupation is recorded in terms of both area and time, or $m^2$/year. As land transformation models a change in land uses, it requires 2 entries from the Ecoinvent database in order to be modelled. The first entry lists the land use class the land is being transformed from (land use class X) and the second lists the new land use class that will exist as a result of the transformation (land use class Y). Both X and Y land use class entries are recorded in terms of area in $m^2$.

The current version, Ecoinvent 3.4, models land occupation and transformation using the World Food LCA Database tool provided by Quantis and Blonk consultants (Reinhard, 2017). This calculation tool calculates country specific GHG emissions from LULUC by calculating how much of a certain crop type is attributed to a particular country. The WFLDB tool (Fig. 1) integrates data on crops by country level from FAOSTAT, the European Soil Portal, and IPCC 2006 Tier 1 publications to then calculate the carbon inventory of land occupation and transformation

(Reinhard, 2017). Assumptions made within the WFLDB tool, regarding the time horizon over which LULUC impacts should be allocated, are in line with recommendations issued by PAS 2050-1, and therefore also with EU-PEF and FAO LEAP guidelines (Reinhard, 2017). In Ecoinvent 3.4, impacts on all major carbon pools are considered, including above ground biomass (AGB), below ground biomass (BGB), dead organic matter (DOM), and soil organic matter (SOM). Changes to AGB, BGB, and DOM are accounted for in transformation impacts, while changes to SOM through impacts to soil organic carbon (SOC) are accounted for in occupation impacts (see Fig. 2).




(Fig. 1; Reinhard, 2017, Quantis Consultants)




(Fig. 2; Reinhard, 2017, Quantis Consultants)

The effects of indirect land use change (iLUC) are also modelled in the Ecoinvent database through the inclusion of a market for "land tenure". In Ecoinvent, land tenure is defined as the market for land of a specific use type or class, or the market for land use change (Reinhard, 2017). The market for land tenure of a specific use type is formed by all available types of land, including land already in use, recently transformed land, and land use efficiency improvements which compensate for land (Wiedema, 2013). Land tenure is expressed in terms of potential net primary productivity (NPP), which is measured in kg of carbon-m$^2$-year (Wiedema, 2013). The same market modelling rules are applied here as for all other markets in Ecoinvent (Wiedema, 2013). In this way, all land uses are linked to a country specific market for land use, which allows for the modelling of iLUC within country specific land use markets. However, because the Ecoinvent database models LULUC on a country specific basis (e.g. country specific LULUC patterns and emission rates), the effects of cross-border iLUC (e.g. the substitution of crop A over crop B in country A causing more demand for crop B in country B) are not modelled within the WFLDB tool in Ecoinvent (Reinhard, 2017).

Agrifootprint

Agrifootprint specializes in providing data regarding food, feed, and biomass products for the agricultural sector (agri-footprint.com). Data inventories in Agrifootprint explicitly support the midpoint impact categories and methods of the EU-PEF and PAS 2050 protocols (Durlinger, 2017). Similar to Ecoinvent, both land occupation and land transformation are measured in terms of $m^2$ (Durlinger, 2017). However, climate change from land transformation is modelled separately from land use, as “Carbon dioxide, land transformation” under the category of emissions to air (Durlinger, 2017). It is therefore important to keep in mind when using impact assessment methods with Agrifootprint data to not double count the LULUC impact across multiple categories. Unlike Ecoinvent, the Agrifootprint database does not include a mechanism for accounting for iLUC (Agrifootprint, 2017). Additionally, it should be noted that Agrifootprint only supports system boundaries spanning from cradle to farm or factory gate, and does not contain process data for the life cycle stages of packaging, distribution, retail, consumer storage or waste treatment (Durlinger, 2017).

Measuring and characterizing LULUC: impact assessment methods

Various impact assessment methods exist within LCA practice to evaluate the data collected in the LCI phase. These impact assessment methods identify the environmental impact pathway, quantify its effect on the environment according to a characterization factor, and then assign that effect to a particular environmental damage category. The environmental impact pathway is commonly defined as the cause and effect relationship between an environmental action or intervention (e.g. the emission of a substance and its potential effect) (PRe, 2014). Characterization factors are commonly defined as a means to express or quantify the contribution from a single unit of a particular substance or process to environmental damage (PRe, 2014). After quantifying the emission by its characterization factor, it is then assigned to an impact category according to the effect it brings about in the natural world. Impact categories exist in both midpoint and endpoint forms. A midpoint impact category identifies a link midway along the environmental cause-effect chain. Some examples of midpoint categories include ozone depletion potential or global warming potential. Endpoint categories illustrate the ultimate effect from the environmental cause-effect chain. For example, an increase in ozone depletion or global warming potential may ultimately lead to a decrease in ecosystem health or human health (Bare, 2000). Among the most commonly used European impact assessment methods are the PEF (2013) Midpoint, ReCiPE, and CML-IA impact assessment methods, which include both midpoint and endpoint methods.

ReCiPe

In the latest version of the ReCiPe method, developed by the Netherlands’ National Institute for Public Health, LULUC effects are characterized in two separate categories, land occupation and natural land transformation (Huijbregts, 2017). The land occupation category is further divided between agricultural and urban land occupation. These categories are characterized at the midpoint level in terms of $m^2$/year. ReCiPe evaluates land use further by then integrating midpoint indicators in to endpoint effects using a damage factor. The midpoint category of land occupied or transformed is therefore further characterized in terms of “the relative species loss (Srel) caused by land use type x, proportionate to the relative species loss resulting from annual crop production” (Huijbregts, 2017). The use of this endpoint method therefore emphasizes measuring the effects of land use on biodiversity and ecosystem health.

CML-IA

The CML-IA method, developed by the University of Leiden, is also a midpoint only impact assessment method. Land use is characterized in terms of “land competition”. However, land use is not one of the “baseline” indicators that are considered of principal important in the CML impact assessment method, and is instead recommended as an additional, non-baseline impact category (PRe, 2016). Land competition is assessed in terms of area, and is not assigned to any further impact category using an ecological indicator, such as soil conditions or biodiversity (Acero, 2016). Therefore, it is not determined to be an adequate indicator of LULUC effects in an LCA of livestock supply chains.

PEF

The PEF guidelines are in fact an aggregation of impact categories from various other impact assessment methods, drawing from CML 2002, EDIP, Swiss Ecoscarcity and USEtox impact assessment methods, among others. The PEF (2013) recommended impact categories are a continuation of the original impact assessment published in the ILCD Handbook (2011). In regard to LULUC impacts, the PEF impact assessment method uses the soil organic matter (SOM) model recommended by Milà i Canals et al. (2007) as a midpoint assessment indicator for land transformation (PEF, 2013). This method evaluates the land use impact pathway in terms of soil fertility and biotic production potential by measuring the change in SOM as the carbon kg deficit per year (PEF, 2013; Milà i Canals et al., 2007). PEF impact categories are rated according to three levels, with Level I indicating a full recommendation, Level II indicating a recommendation which is still in need of some improvements, and a Level III rating indicating a recommendation that should be applied with caution (Hauschild, 2012). Due to the uncertainty associated with the use of SOM as a characterization factor for land use, the method by Mila i Canals (2007) is recommended at a Level III rating (Hauschild, 2012).

The PEF LCIA method was chosen for the SheepToShip LIFE impact assessment as it is currently the most relevant method for the European context and is proposed as a standard impact assessment method among European LCA studies to improve the comparability of LCA studies of European products. Using SOM as the LULUC characterization factor was determined as the best choice for SheepToShip LIFE, as it is currently one of the most accepted indicators for overall soil health and therefore agricultural productivity (Hauschild, 2012). Increasing the amount of

SOM in agricultural land has been shown to be imperative for maintaining land fertility, including the water retention capacity and nutrient availability of the soil (Foley, 2005). Additionally, SOM plays a key role in soil carbon sequestration, which is an important consideration when attempting to reduce the GHG emissions of an agricultural supply chain.

Recently, a draft update to the PEF impact assessment method, including possible revisions of the characterization method for land use impacts, was published (Sala, 2016). This acknowledged that the current indicator, SOM, recommended for land use characterization in the PEF LCIA method ignores other fundamental soil functions that are affected by land use, such as soil's ability to resist erosion, compaction, and salinization (Sala, 2016). The new draft recommendations review other models in the literature that include additional measures for both midpoint and endpoint methods of land use evaluation, including factors related to erosion, salinization, albedo change, sealing, and habitat or landscape fragmentation. While such recommendations are important to keep in mind when studying the effects of the land use, the characterization models proposed in the update are still in the process of review and are not yet officially recommended by the EU-JRC PEF initiative (Sala, 2016). Therefore, SheepToShip LIFE will utilize the SOM characterization factor developed by Mila i Canals (2007).

### Methodology for LULUC inclusion within SheepToShip LIFE

The SheepToShip LIFE project has developed its methodology for the inclusion of LULUC effects within its LCA study based on a thorough review of relevant literature as well as the latest recommendations on LULUC calculation within LCA. SheepToShip LIFE will follow the recommendations of the EU-PEF, IDF, and LEAP guidelines, all of which include the information/scenario based calculation methods recommended by PAS 2050-1 for specific time horizons. The second calculation method suggested by LEAP, Vellinga's global averaging method, is poorly suited for use in small ruminant supply chains. SheepToShip LIFE will primarily utilize the Ecoinvent database within SimaPro as a source of secondary data, as the LULUC modelling tool utilized by the Ecoinvent database is based on the PAS 2050 calculation scenarios, and is therefore already compliant with both PEF and FAO LEAP guidelines (Reinhard, 2017). Furthermore, the EU's PEF impact assessment method will be followed in order to better contribute to the standardization of European LCA and Product Environmental Footprints. According to recommendations in the aforementioned guidelines, carbon emissions from land use will be reported separately. This will be done through a sensitivity analysis, which is specifically recommended by the PEF (2013) guidelines.

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