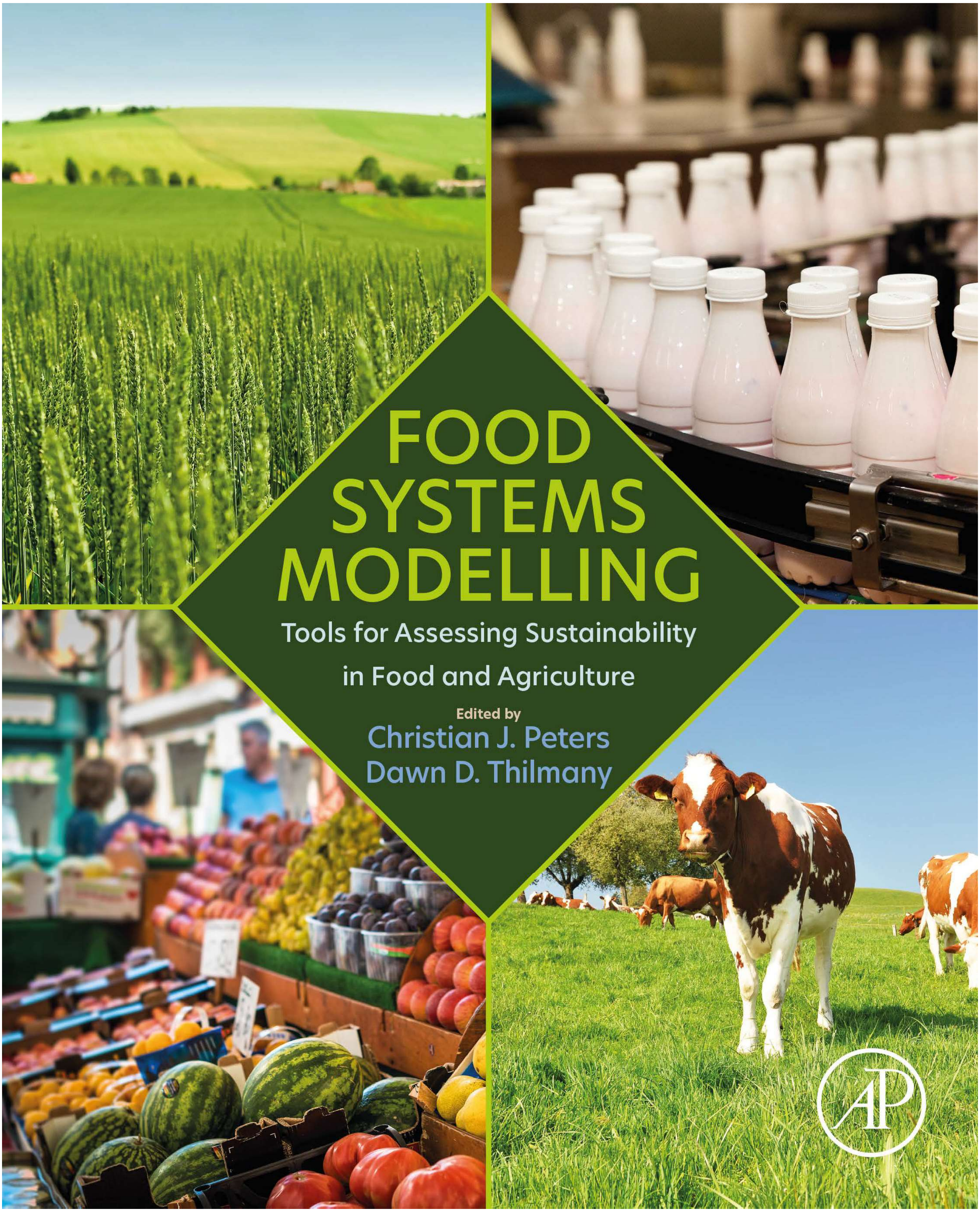

FOOD SYSTEMS MODELLING

Tools for Assessing Sustainability in Food and Agriculture

Edited by
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FOOD SYSTEMS MODELLING

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CHAPTER

3

Life cycle assessment of food systems and diets

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3.1 Introduction

The Anthropocene, the current period in which human activities are significantly affecting conditions on the planet is a time when the adage "you manage what you measure" is increasingly important. Our manipulation of and reliance on the natural environment for the provision of basic human needs like food are increasingly stressed by the growing demands of humanity driven by a combination of factors including population growth and an expanding and increasingly affluent global middle class. Many of the systems we have developed for provision of food are highly complex interconnected global networks. At each stage of the supply network, resources are used (e.g., water, materials, land, energy), substances are emitted to the environment (e.g., greenhouse gas emissions to the air, nutrient runoff to water), and waste is produced (e.g., packaging, uneaten food). We can account for all the resources used, pollution, and waste produced across a supply chain or life cycle of a food product to estimate its potential environmental impacts using life cycle assessment.

Life cycle assessment is a framework for quantifying the impacts of complex systems providing goods and services. As a tool, it enables evaluating system performance in support of better management towards the goal of sustaining food systems into the future.

In this chapter, we will introduce life cycle assessment (LCA), which focuses on the environmental impacts of products; Chapter 9 presents an alternate computational framework known as environmentally extended input output (EEIO) LCA, which focuses on whole economic sectors. We will use strawberry yogurt as a case study to illustrate major steps in an LCA

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and to discuss both the capabilities and limitations of LCA as a framework for evaluating and comparing sustainability characteristics of foods and diets. We will also explore the two major LCA paradigms, attributional and consequential.

LCA has three main characteristics:

It considers the whole life cycle from the extraction of resources to disposal of any waste generated ("cradle-to-grave").

It considers all relevant environmental impact categories, thus highlighting trade-offs and potential burden shifting burdens from one impact category to another. This distinguishes LCA from footprint methodologies, such as carbon footprint, ecological footprint, or water footprint, which only consider one impact category.

The environmental impacts are set in relation to a unit of product, the so-called functional unit (see below).

3.2 A brief history of life cycle assessment

Life cycle assessment dates to the late 1960s when the Coca-Cola Corporation conducted an environmental evaluation of packaging, although the report was not made public. However, it was in the early 1990s that the field began moving towards evaluation of agriculture and food systems and efforts to standardize the practice were also initiated. These efforts were led by the Society for Environmental Toxicology and Chemistry (SETAC) and the United Nations Environment Program, various European research projects as well as the U.S. Environmental Protection Agency (USEPA). These organizations remain active today, with the Life Cycle Initiative hosted by the UN as a leading example (Koellner et al., 2013; Teixeira et al., 2016; UNEP, 2011; Verones et al., 2017). Standardization of the methodology was not formalized till publication of the International Organization for Standardization (ISO) 14,040 standard in 1997 (with subsequent updates) (ISO, 2006a, 2006b). More recently, other guidelines, largely based on the ISO series of standards, have been produced, notably the Product Environmental Footprint (PEF) guidelines (European Commission, 2013a), PAS 2050 (British Standards Institution, 2011) for greenhouse gas emissions, and a series focused on agriculture by the Food and Agriculture Organization of the United Nations (LEAP, 2018;2016;2015).

LCA has become widely regarded as one of the principal frameworks for evaluating the environmental sustainability characteristics of goods and services. It has been adopted by the European Union's PEF program as the basis for communicating sustainability metrics to consumers (European Commission, 2013b). In addition, a wide variety of industries from construction to agriculture have established LCA as the backbone of their environmental sustainability efforts. These efforts are often based in companies' sustainability reporting and serve multiple goals ranging from: internally identifying supply chain hotspots that can be targeted for improvement of environmental and potentially economic performance (e.g., opportunities to reduce energy use), establishing benchmarks to gauge future improvements against, and informing marketing efforts. Some policy analysts are beginning to consider how to incorporate environmental sustainability characteristics into dietary guidelines (Blackstone, El-Abbadi, McCabe, Griffin, and Nelson, 2018; Fischer et al., 2016; van Dooren, Marinussen, Blonk, Aiking, and Vellinga, 2014).

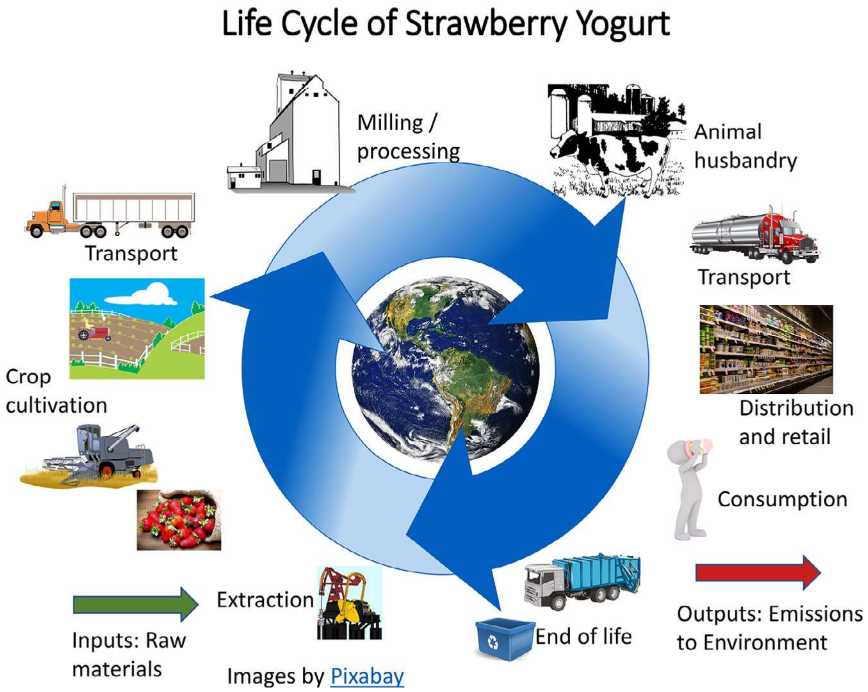

FIGURE 3.1 Schematic of life cycle stages included in an LCA.

3.3 The four phases of LCA

As mentioned, life cycle assessment is guided by a series of international standards, the ISO 14,040 series (ISO, 2006a, 2006b). The standards identify four phases of performing an LCA. These are 1) goal and scope definition, 2) life cycle inventory, 3) life cycle impact assessment, and 4) interpretation.

3.3.1 Phase 1: goal and scope

The goal of an LCA identifies its intended application, rationale, intended audience and whether a comparative assertion of superior performance (e.g., a product marketing claim) will be made. The scope of an LCA defines the system boundaries, functional unit, and impact categories to be considered. System boundaries are a set of criteria defining which activities or unit processes are part of the product system that delivers or provides the functional unit. The most comprehensive boundary is cradle-to-grave. Another common system boundary in LCA is cradle-to-gate, which sets the downstream boundary at either the farm or processing gate and excludes distribution, retail, consumption, and end-of-life activities (Fig. 3.1). A complete system boundary definition should also specify any ancillary activities which are expressly excluded from the system. Activities which are commonly excluded from the system are, for example, employee commuting, executive air travel, or financial services.

The functional unit is a key aspect that sets LCA apart from other methods. The function of a system describes what the system does or is for. This is often difficult to define for food systems research (see box). The functional unit is intended to represent the function of a system in quantitative terms and may be distinct from the reference flows of materials/energy required to produce the function (see box). Study results are scaled by the functional unit, and the functional unit provides the basis establishing a fair comparison across the systems being studied.

Appropriate functional units for food systems studies will vary depending on the goal and scope of the research (Heller, Keoleian, and Willett, 2013). For example, if the goal of the study is to compare dietary patterns, a functional unit of daily or standardized intake (2000 kcal per capita per day) may be appropriate. If the goal of the study is to compare disparate food items, the basis for a fair comparison across foods could be an index of nutrient quality (see nutrition and LCA section). If the goal of the study is to compare versions of a food made with different agricultural production or processing methods, such as our strawberry yogurt case, a mass or volume based functional unit is sufficient.

Functional unit

As an example, the function of exterior paint is protecting the surface from the elements (with an added characteristic of aesthetics). Different quality paints may protect for different lengths of time; thus, the requirement of functional equivalence necessitates specification of the length of time of the protection and may require different amounts (reference flows) of different paints. Suppose two coats of paint requires one liter to cover the surface. If the low-quality paint's lifetime is five years and the high-quality paint's lifetime is 10 years, the reference flows necessary to provide the function of 10 years of protection would be one liter and for the high-and low-quality paints, respectively.

Food is more complex to characterize – is its function satiety? Nutrition? Enjoyment? Since no two foods are entirely equivalent, the challenge of comparative evaluation is significant.

Defining the life cycle impact categories relevant to the system under study is another aspect of the goal and scope definition phase of an LCA. Here, the practitioner should identify the classes of environmental impact which are most relevant in the context of both the system under study and the target audience's intended use of the results. It is important to note that the ISO standards do not support "cherry picking" of impact categories to avoid reporting on aspects that may not be favorable for the system under study. There are several impact assessment methods which have been critically evaluated by the LCA community and are generally considered to be suitable for use in life cycle assessment studies (European Commission and Joint Research Centre, 2010).

3.3.2 Phase 2: life cycle inventory (LCI)

3.3.2.1 Unit process and databases

The life cycle inventory (LCI) phase consists of data collection for the major contributing activities or stages of the supply chain. For a typical LCA study, we need hundreds or thousands of datasets. Our case study, for example, uses more than 13,000 datasets to calculate the resources used and emissions released over the whole life cycle. Why do we need so many? This is due to the manifold interrelationships in supply chains. To grow sugar beets, we need a tractor, machinery, fertilizers, fuels, pesticides, seed, and more. To produce mineral fertilizer, we need raw materials, such as phosphate rock or potassium chloride, fossil fuels, a factory, and electricity. To produce electricity, we need a power plant, built with cement, steel and other materials. Furthermore, all inputs need to be transported. This results in a complex network of interrelationships. To sum up all the natural resources consumed, and emissions released to the environment for a product's supply chain, we need comprehensive databases to provide datasets for the required inputs and processes across the full supply chain.

Yogurt case study: goal and scope

The goal of our case study is to compare the potential environmental impacts of consuming one serving of strawberry yogurt, produced under five different scenarios. The intended audience for this case study is readers of this textbook. The results will not be used to support a comparative assertion to the public regarding which strawberry yogurt option has superior environmental performance.

The five strawberry yogurt production systems are as follows: Yogurt A includes milk sourced from dairies where the cows are primarily grain fed, the strawberries are produced in an open field farming system, and beet sugar is used as a sweetener. We have chosen a recipe with a relatively high fruit content of 13 percent and sugar content of 9 percent to accentuate the impacts of these ingredients for illustrative purposes. Yogurt B simply replaces the beet sugar in Yogurt A with cane sugar as the sweetener. Our third alternative (Yogurt C) replaces the grain-fed milk in Yogurt A with milk produced from a pasture-based dairy. Yogurt D replaces the open field strawberries in Yogurt A with strawberries grown in a heated greenhouse. This production method is included primarily for illustrative purposes, as greenhouse strawberries would not be commonly processed into a yogurt ingredient. Finally, we consider an additional scenario which uses a smaller quantity of strawberry (3.5 percent) and less sugar (6.1 percent) for the purpose of demonstrating the effect of composition on human health outcomes (Yogurt E).

We define our system boundary as cradle-to-grave. This includes all the necessary extractions of resources from nature, production of all inputs such as fertilizer, fuel, and electricity, necessary for agricultural production of yogurt ingredients, followed by processing and packaging for retail distribution, consumption, and disposal of packaging. The functional unit is the consumption of one serving (170 g) of strawberry yogurt.

We adopt the ReCiPe methodology which includes both midpoint and endpoint impact categories (described in more detail in a subsequent section).

For each input and process, the natural resources used, and emissions generated are calculated. These exchanges between the economic system (technosphere) and the environment (ecosphere) are called flows and can be goods, services, or natural resources. Goods and services (output of economic activities) consumed as inputs to an activity are often termed technosphere flows, while direct exchanges with the environment are termed elementary flows. Resources are the elementary flow inputs from the environment and emissions are the elementary flow outputs to the environment. Several hundreds or thousands of elementary flows can be recorded in an LCI at this stage. Examples of resources (elementary flow inputs) are mining activities, land- and water-use. Examples of emissions (elementary flow outputs) are the greenhouse gases (GHGs) such as CO_2, CH_4 and N_2O, and other emissions like ammonia (NH_3), nitrate (NO_3^-), phosphorus containing substances, toxic pollutants, and more. We distinguish emissions to the environmental compartments air, soil, and water, with sub-compartments such as surface freshwater (rivers and lakes), groundwater, and ocean.

Each activity that uses inputs and produces outputs in the supply chain is known as a unit process. Unit processes are linked together as a model of the supply chain by the flows of products that connect them. The final process produces the functional unit for the study. In the strawberry yogurt case, an example of these connections would be where the product of the dairy farm, milk, is an input into the yogurt manufacturing process. This set of linked unit processes is known as a life cycle inventory model and is constructed with the use of databases for the numerous inputs and processes (e.g., transportation, electricity production, waste treatment, etc.).

After more than two decades of development, we now have several comprehensive LCI databases. There are generic databases like ecoinvent, which cover the major economic sectors and provide some data for the agri-food sector. Examples of databases specific to the food sector are the World Food Life Cycle database (WFLDB), Agri-Footprint and the French Agri-Balyse database. Construction and maintenance of these databases is time consuming and expensive. Despite the existence of these databases, due to the multitude of food products and the various geographical regions and production systems, many gaps still exist, and techniques are needed to fill these gaps, as introduced in the following section.

3.2.2 *Emission modeling*

Estimating emissions in agricultural systems is challenging because of the strong dependence on natural resources, the high variability of soil, climate, topography and production systems, and the large number of often small production units (farms). We need data, models, and efficient tools for the calculation of emissions. An emission can be calculated by a simple emission factor. An example are the emissions of nitrous oxides (N_2O) from N fertilizers: the amount of N applied is multiplied by a default emission factor of 1 percent (Ogle et al., 2019), and subsequently converted from N to N_2O by stoichiometric calculation. Such emission factors can also be differentiated by soil, climate, or production system. As an example, IPCC (Ogle et al., 2019) gives the values of 1.6 percent, 0.6 percent and 0.5 percent for synthetic fertilizer in wet climates, other N inputs in wet climates, and N inputs in dry climates, respectively. However, there are frequently situations where these simple factors are not sufficient to adequately describe the environmental mechanisms. Therefore, LCA practitioners often use complex, process-based models to calculate emissions. For example, the Integrated Farm System Model simulates dairy and beef production systems and includes simulation of all crop production activities (field preparation through harvest), biogeochemical cycling in the soil, ration formulation and animal performance (milk production and growth). It provides a detailed accounting of energy consumption, greenhouse gas emissions (from crop cultivation, animals, and manure), water consumption and reactive nitrogen losses (Kim et al., 2019; Veltman et al., 2018). The choice of model complexity depends on the goal and scope. Mechanistic models can simulate environmental processes; however, they often require a large number of input variables, which might not be available in many situations, or require adoption of default values that may not be fully representative of the situation under study. In LCA practice, we often use models of medium complexity (such as Tier 2 IPCC models), which are a good compromise between simple emission factors and complex process models.

3.3.2.3 *Data quality*

Even with the comprehensive databases, it is frequently not possible to find the specific dataset for some ingredient(s) from the country or region of origin and the given production system. Therefore, we need to simplify and approximate our data identification efforts to a certain extent. We need to consider three main data quality criteria:

- Temporal: do we have recent or outdated inventories?
- Spatial: do we have datasets from the country or region under consideration?
- Technological: do we have data for the technology under consideration? (e.g., organic vs. conventional, irrigated vs. rainfed, intensive vs. extensive, open field vs. greenhouse)

The data quality must be sufficient to satisfy the goal and scope of the study and answer our research question. For an ingredient, which is used only in very small quantities, rough approximations might be adequate, while we need high-quality data to model impacts of the main ingredients, which contribute most significantly to the environmental impacts. Database developers necessarily make decisions regarding the structure of the database, including decisions regarding multi-functionality and selection of inventory data. It is very important to note that when datasets from different databases are used, care must be taken to ensure their consistency; a harmonization effort is very likely to be needed to avoid unintended data quality effects due to different inventory modeling assumptions between databases. If, for example, we chose unit processes from different databases that each consume electricity in the same region, a harmonization check would require that the background electricity grid is the same for both selected processes – which could be different due to, for example, something as simple as the age of the databases. Using different background electricity introduces artificial differences between the processes. The practitioner should harmonize the datasets to remove this bias from the analysis.

3.3.3 The problem of multi-functionality

Unit processes frequently produce more than one product, yet it is desirable to distribute the impacts to the individual products. This is the problem of multi-functionality. Broadly speaking, two paradigms for solving multi-functionality exist: consequential and attributional. Consequential modeling intends to account for both direct and indirect environmental burdens from the activity. The indirect burdens are accounted through market-mediated effects in the broader economy, typically using system expansion, described below (UNEP, 2011). Attributional modeling allocates the burdens arising from multi-functional processes to individual products based on some attribute of the activity, such as revenue generated by each product or its energy content. The ISO standards provide an accounting hierarchy for managing multi-functionality. First is system separation followed by system expansion, then allocation based on physical causality, and finally allocation based on product characteristics (ISO, 2006a).

System separation relies on the ability to independently identify inputs and emissions from each individual product in a multifunctional unit process. This is not always possible (distiller's grains cannot be produced without also producing ethanol) and often not feasible (data are frequently only available for a full facility).

System expansion solves multi-functionality by substituting (mathematically taking a credit) for displacing the primary production of a product based on the amount of co-product made by the unit process; that is, the system under study is "expanded" to include separate processes that produce the co-products as their main product. This approach is sometimes also called "avoided impacts". Dairy farming, a multi-functional system that produces milk and meat, can be used as an example. Assuming the product of interest is milk, system expansion would give the dairy farming system a credit for the avoided production of meat. A fundamental consideration in selection of the credit is that the external market response will be through the marginal, not average production activity (Weidema, 2000; Weidema and Schmidt, 2010).

Allocation divides the total impact of a multi-functional unit process among the products based on physical causality or product attributes. This is an attributional approach and can take several forms. To illustrate, let us consider how we could allocate the environmental burdens of dairy farming between milk and meat. Thoma, Jolliet, and Wang (2013) and Nemecek and Thoma (2020) have proposed an approach based on the physiological requirements of cows to produce milk and body mass (meat) as an example of physical causality-based allocation. Other approaches to allocation between milk and meat on a dairy farm include simple product mass, protein or other nutrient contents, or revenue-based approaches.

The overarching goal of multifunctional accounting is to ensure that a mathematical solution to the system of Eqs. representing the supply chain exists. Although both consequential and attributional modeling solve the mathematical problem, and therefore, mathematically, can be applied simultaneously to different multi-functional processes in a product system, the conceptual basis for the two solutions is fundamentally different. The two approaches should not be combined in a single LCA to avoid complications in interpretation of the results. Nonetheless the literature is replete with examples of this kind of mixed modeling.

3.3.4 Phase 3: life cycle impact assessment (LCIA)

The impact assessment (LCIA) phase of LCA is typically performed with software tools designed to calculate the cumulative resource use and emissions across all the activities in the life cycle inventory model and characterize these emissions in terms of a smaller number of impact categories, such as climate change or eutrophication. The ISO standards require that life cycle impact assessment methods be based on a causal chain. For example, greenhouse gas emissions trap heat in the atmosphere, contributing to global warming, which can decrease

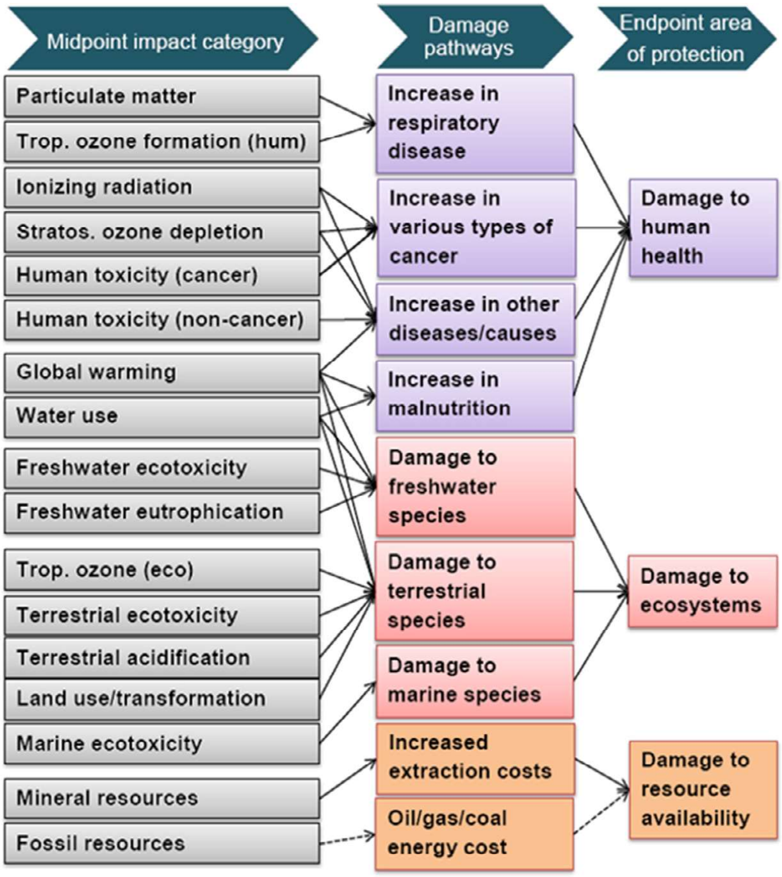

FIGURE 3.2 Midpoint and endpoint categories in the ReCiPe impact assessment framework. Arrows represent causal pathways; inputs to midpoint categories are the life cycle inventory (Huijbregts et al., 2017).

agricultural productivity and increase malnutrition (Fig. 3.2). In LCA, the impact categories we can analyze correspond to three areas of protection (AoP): human health, ecosystem quality, and resource conservation. Along the causal chain, there are different impact indicators, which are known as midpoint and endpoint impacts (Fig. 3.2). Midpoint impacts are assessed at some point in the causal chain between the emission or resource use and the final damage(s) they cause. Endpoint impacts correspond to the final damages for the three AoP.

The impact assessment phase consists of up to five steps - two required and three optional. First, in the *classification* step, the resources and emissions in the inventory are sorted into their corresponding impact categories. This stage is essentially assigning the flows of emissions and resources into the impact buckets to which they belong. For example, carbon dioxide (CO_2), nitrous oxide (N_2O) and methane (CH_4) all trap heat in the atmosphere and are therefore sorted into the climate change/global warming potential category.

TABLE 3.1 Ingredient list for yogurt varieties evaluated in the chapter case study. Quantities required to product 100 g of the final product, accounting for processing losses.

Composition	A) Yogurt, standard high fruit content	B) Yogurt, with cane sugar	C) Yogurt, milk from grass-fed cows	D) Yogurt, with greenhouse strawberries	E) Yogurt, standard low fruit content
Milk, maize-fed	80.7	80.7		80.7	93.1
Milk, grass-fed			80.7		
Beet sugar	9.0			9.0	6.1
Cane sugar		9.0			
Strawberries, open field, macrotunnels	13.0	13.0	13.0		3.6
Strawberries, heated greenhouse				13.0	
Total	102.7	102.7	102.7	102.7	102.7

Yogurt case study: life cycle inventory

For our case study of strawberry yogurt, the life cycle inventory encompasses all the inputs and outputs of the production of feed for cows, the dairy operation including animal husbandry, milking and manure management followed by processing of raw milk into yogurt, strawberry cultivation, and introduction to the yogurt, along with additional ingredients of packaging and then distribution to consumers. Food loss in the supply chain is also quantified and included. The processing stage inventory (yogurt recipe) for each of the five varieties of yogurt is presented in Table 3.1. The upstream production stage data, such as the rations consumed by dairy cows, milk and strawberry yields, and all other inputs are also included in the inventory (supplementary material). The multi-functionality of the milk production stage was adopted directly from the Agri-Balyse data sets for milk production which was based on a physical causality model. Other allocation in the model is based on the background datasets from Ecoinvent, which is based on revenue generation as the key.

Second, midpoint *characterization* quantifies the magnitude of impact. In the example of global warming potential, 1 kg of CH_4 is equivalent to 28 kg of CO_2 and 1 kg of N_2O is equivalent to 265 kg CO_2 (Myhre et al., 2013). For each impact category, characterization converts the classified emissions or resource use flows to a common unit (e.g., CO_2-equivalent for global warming potential), and sums them up. The indicator units are different for most midpoint impact categories; therefore, we can compare only within an environmental category, but not between. An analogy is that if we had different currencies, but we did not know the exchange rates, we could not make price comparisons of commodities in different countries. Recent LCIA methods also include endpoint characterization factors, which aggregate all midpoint impact categories that contribute damage to a given area of protection, such as damage to human health shown in Fig. 3.2 (Huijbregts et al., 2017). Damages to the same AoP can be summed up or directly compared, but not across AoPs (as noted by the color coding in Fig. 3.2). Finally, it is important to note that classification and characterization occur within LCA software tools; LCA practitioners do not commonly compute these steps by hand.

The next three steps in impact assessment are optional due to the additional uncertainty and subjectivity that is introduced. *Grouping* is not commonly applied and means that similar impact categories are grouped according to certain criteria.

Normalization typically compares the environmental impact of the food product to the environmental impact of an average person from a given area during a specified time period. This allows expressing the different impact categories with a common unit typically as a fraction of the per capita impact for that impact category, which makes them comparable. However, these results still do not tell us which impact category is the most important when it comes to decision-making, but they can indicate which impact categories are relative hotspots.

The final step is *weighting*, which can be applied to indicate the relative importance of impact categories at the midpoint or endpoint levels. In the impact assessment method used in our case study (ReCiPe (H) 2016), there are three endpoint impacts, which have different weights that can be applied in the default method: 40 percent for ecosystem quality, 40 percent for human health, and 20 percent for resource availability. Weight sets can be generated using different approaches, such as surveying a panel of experts or using distance to science-based targets (Pizzol et al., 2017). Weighting is based on value choices and is the most subjective LCIA step. Normalized and weighted results can be combined to produce a single score, which can be helpful for decision-making and applications like eco-labeling. It is important to note, however, that an LCA that includes these optional LCIA steps should also provide raw results (i.e., unnormalized, unweighted) and/or normalized or weighted results still differentiated by impact category (as discussed below) for transparency, according to ISO standards.

In addition to the method adopted for this case study (ReCiPe 2016), there are numerous other LCIA methods commonly used by practitioners (Bulle et al., 2019; European Commission et al., 2011; Frischnecht and Jolliet, 2016; Jolliet et al., 2003; Verones et al., 2020). Additional information for impact assessment of water and land use is provided chapters 4 and 5 of this book.

3.3.5 Phase 4: interpretation of the assessment

The interpretation of the impact assessment includes identification of hotspots in the supply chain, that is, activities which are particularly impactful. Interpretation can be used to recommend improvements, identify trade-offs, establish a baseline benchmark for a service or product and support policy recommendations. It should also include an uncertainty analysis (see below). In short, LCA provides a quantitative view of the system providing our food and can identify resource use, pollution and waste considering the full production and consumption life cycle.

Providing quantitative estimates of systems' performance also reduces reliance on intuition. As an example, many consumers believe that packaging is a significant driver of the sustainability of food products. In fact, for a large majority of foods, packaging plays a relatively minor role in terms of direct contribution to environmental impacts (Williams and Wikström, 2011) (Fig. 3.3), but plays an important beneficial role in terms of preservation (reducing food loss) and safety. However, for some food categories like beverages, packaging can be quite relevant. Many consumers also believe that transportation has a major contribution to foods'

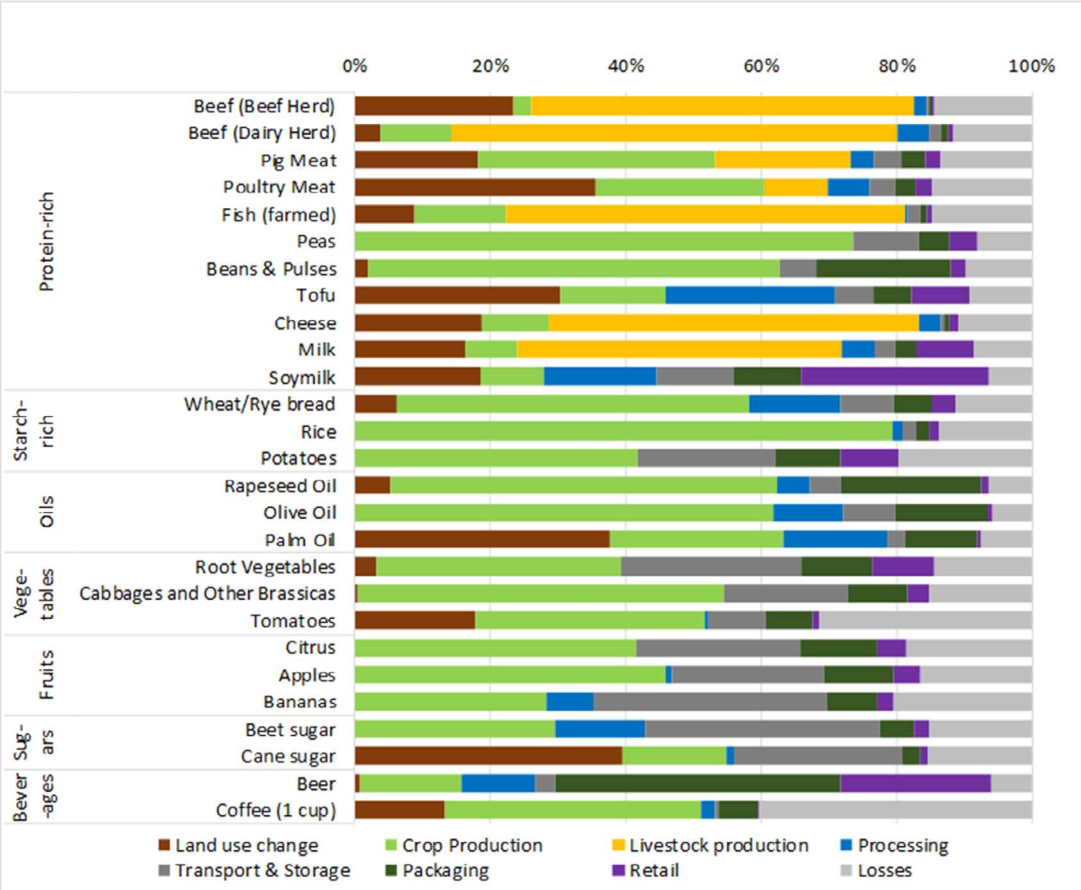

FIGURE 3.3 Contribution of different life cycle stages to the greenhouse gas emissions of selected food groups (Meyer et al., 2020). Reproduced with permission.

environmental impacts. While this is true for air freight and fruits and vegetables transported over longer distances, transport is of low importance for food groups like meat. The impacts of transportation are furthermore dependent on the mode of transport and decrease in the order of air freight, lorry, railway, inland water transport, and transoceanic freight ship. Therefore, domestic products are not necessarily more environmentally friendly than imported food; frequently the impacts are more dependent on the production system.

3.4 Yogurt case study: LCIA result and interpretation example at midpoint

Returning to our strawberry yogurt case study, we will provide some examples of impact assessment results and their interpretation. Fig. 3.4 shows how the production system con-

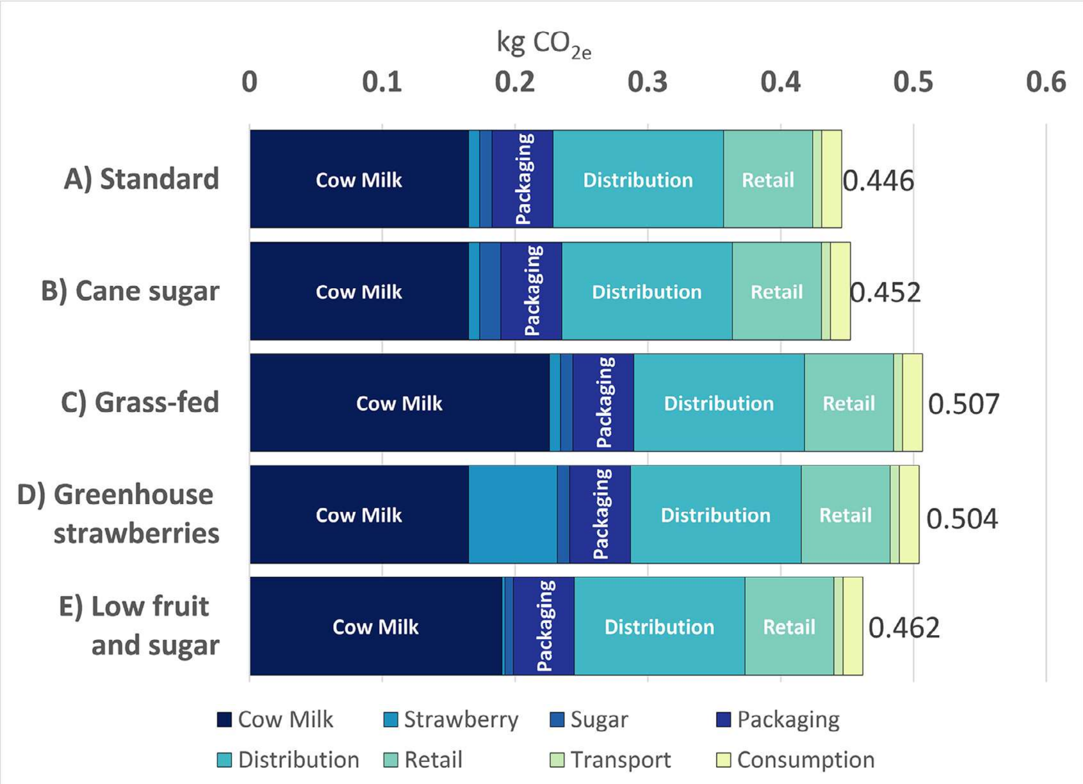

FIGURE 3.4 Global warming potential for 100 years (IPCC 2013 methodology) for alternative strawberry yogurt products.

tributes to global warming potential impact. There are several interesting comparisons to note. First, we can explore the influence of sugar sourcing. Although sugar is not a major contributor to the overall impact, in our example, the climate change impacts of cane sugar are almost twice as high as of beet sugar (in Yogurt B versus A). Why might that be? We know from our LCI research that sugar cane is primarily produced in tropical regions. While the crop is very productive, in some cases sugar cane plantations have been established on land previously covered by tropical rain forest and cleared to grow crops (see also "Land use change" in Fig. 3.3). In such situations, the emissions from land clearing and the subsequent decomposition of organic matter cause greenhouse gas emissions (CO_2 and N_2O) that are much higher than the emissions from the sugar production itself. This is a major driver of the differences in climate impact between beet and cane sugar sourcing.

Let us next consider the alternate production of milk from pasture-based systems (Yogurt C versus A). Again, from our LCI research, we know that pasture-based cows have typically lower milk yields. In addition, feeding roughage tends to produce more enteric methane emissions compared to feeding grains. These effects typically lead to higher GHG emissions per kg milk for pasture-based production.

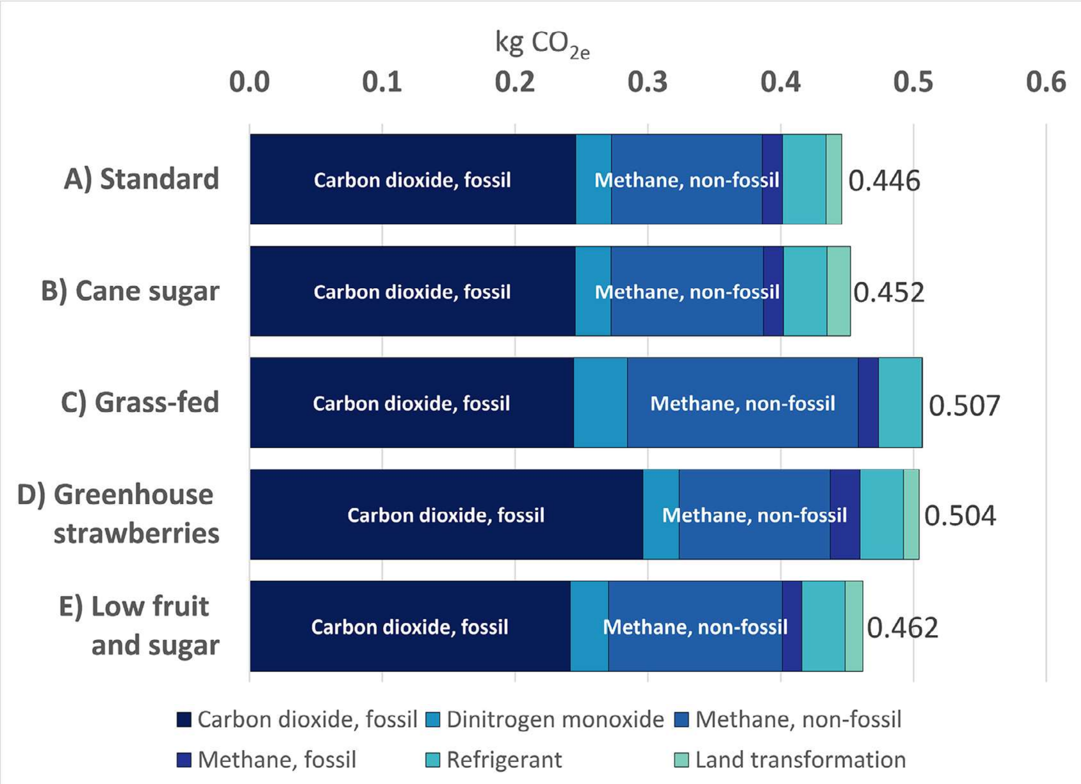

FIGURE 3.5 Contribution of various greenhouse gases across the full supply chain.

Across all yogurt systems studied, processing adds some emissions, but the distribution phase is a quite significant driver of impact, due to refrigerated transport and storage. Consumer transport is included in the consumption phase but is less important in terms of impact in this example than in-home refrigeration.

Now, let us take a different view of contributions to global warming potential impact for the five yogurt systems. We can explore which greenhouse gasses are the major contributors to global warming impact across the yogurt supply chains (Fig. 3.5). We can see that carbon dioxide is the dominating GHG contributing 55 percent in Yogurt A, followed by CH_4 (29 percent), refrigerants (7 percent) and N_2O (6 percent). In Yogurt B the share of CO_2 from land transformation is slightly increased, due to deforestation for sugar cane production, while it is decreased in system C because the grass-fed milk does not include soy products from South America. Non-fossil methane increases in Yogurt C, due to higher enteric emissions in the pasture-based system, while CO_2 becomes even more important in system D, due to heating of the strawberry greenhouse with fossil fuels.

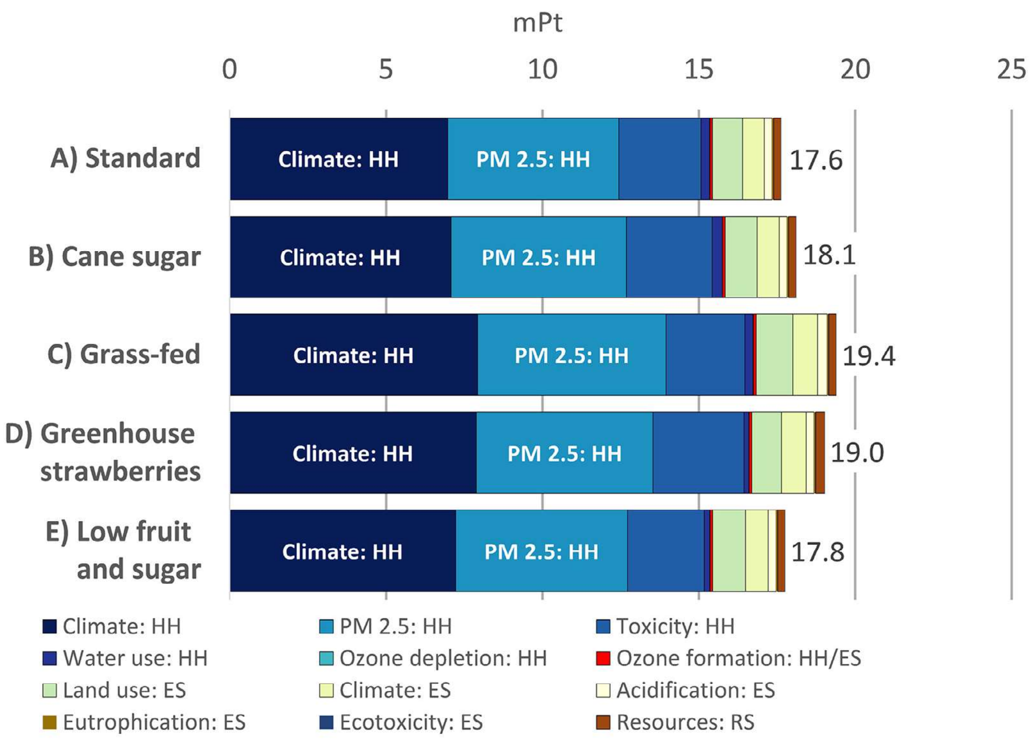

FIGURE 3.6 Weighted endpoint impact per serving of strawberry yogurt.

3.5 Yogurt case study: LCIA results and interpretation at endpoint

We have explored in Fig. 3.4 and 3.5 the global warming scores as an example of midpoint impact results for our yogurt case study. We would also be able to analyze multiple impact categories side by side (e.g., global warming potential, eutrophication potential, and land use) at the midpoint level to identify tradeoffs and support decision-making. Our analysis could - and in many cases in food LCAs, does - stop there. Here, we take the results a few steps further. We also present LCIA results at the endpoint level, which have been normalized, weighted, and combined into a single score (Fig. 3.6). Remember, normalization and weighting are optional LCIA steps that can be helpful for decision-making.

Fig. 3.6 presents a normalized and weighted single score for each yogurt system. The score is reported in milli-points. One point represents the fractional contribution of one EU citizen in one year to the combined endpoint categories. The contribution of each weighted impact category to the single score is shown in the legend. As a reminder, these endpoint impacts correspond to damages to one or more Areas of Protection (AoP). Climate change, for example, corresponds to the AoP of human health (Climate: HH, in Fig. 3.6) and ecosystem quality (Climate: ES, in Fig. 3.6). The correspondence of the impact categories to each AoP is also shown in the Y axis of Fig. 3.7.

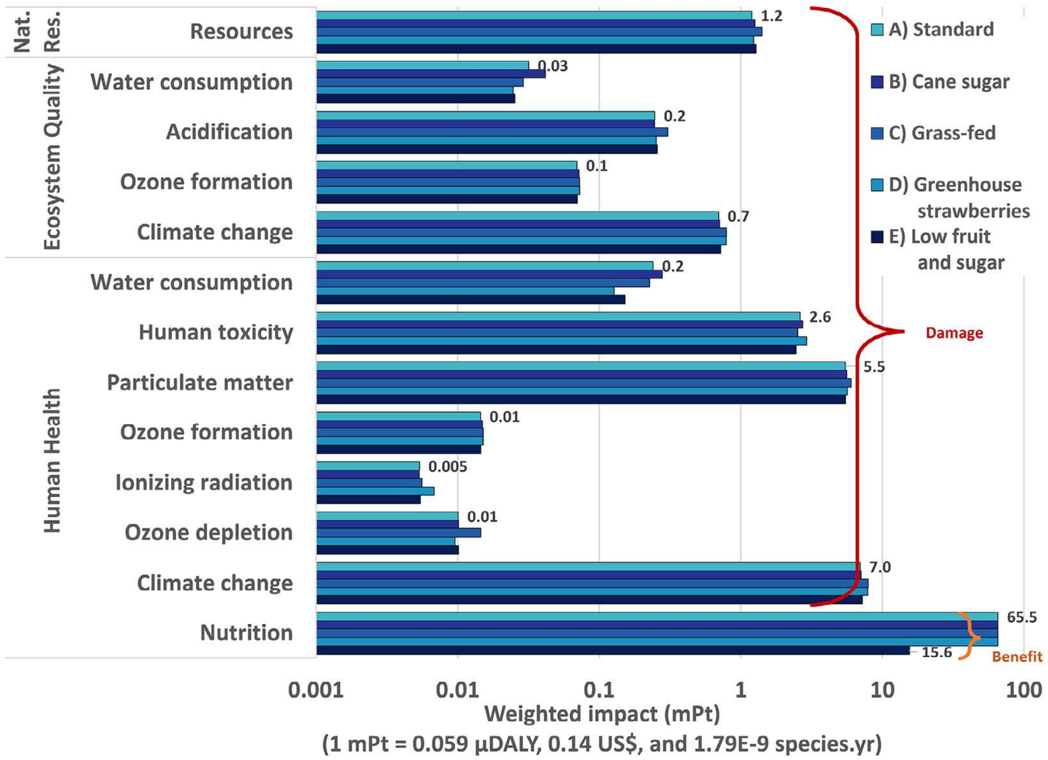

FIGURE 3.7 Endpoint contribution to natural resource, ecosystem quality, and human health impacts. Comparison with nutritional benefits (bottom bars) per serving of yogurt with high and low fruit content. The dietary health benefits are notably larger than the adverse impacts shown for all the other categories (remaining bars). Note the axis is logarithmic.

In the legend, HH = human health; ES = ecosystems; RS = resource availability.

Comparing the overall results for our five yogurt systems, Yogurt C has the highest overall environmental impact, while Yogurt A has the lowest (Fig. 3.6). At the same time, the differences between all systems are relatively small; they may not be significantly different once we consider the uncertainty of our results (see uncertainty in LCA section). The major factors contributing to the larger impact of Yogurt C are the climate change and particulate matter effects on human health followed by land use impact on ecosystems. This follows directly from the lower milk yield from pasture-based milk production.

For each yogurt system, the weighted impact of climate change (CC) and particulate matter on human health (Fig. 3.6) are the greatest contributors to overall system impacts. The red bar (ozone formation) separates the human health related impacts from ecosystem and resource depletion impacts in the single score. Concerning the impacts to ecosystems, land use is the largest, followed by climate change and terrestrial acidification. The standard yogurt with high fruit content (A) has the lowest impact on human health (excluding nutrition which is discussed below) while the grass-fed and greenhouse strawberry scenarios (C/D) are the highest, due to enteric methane and more fossil fuel consumption contributing to climate change and particulate matter formation. Yogurt (A) also has marginally lower impacts on ecosystems compared to the grass-fed milk-based yogurt (C) which has higher land use impacts. There is relatively little difference for the resource use categories. Yogurt (A) and the cane sugar yogurt (B) have the lowest impacts, while yogurt (D) as the highest resource consumption, from fossil fuel consumption to heat the greenhouse.

Since the uncertainty of the endpoint categories shown in Fig. 3.7 is high, it is in general preferable to report the weighted results differentiated by impact category. Comparing endpoint impacts across the five yogurt scenarios shows that the overall impact profiles are quite similar across all categories. Fig. 3.7 shows us the differences between scenarios for each impact category. We observe patterns of impact that are more similar across scenarios than are the differences between impact categories. For example, climate change and particulate matter impacts to human health are the top two contributing categories for all scenarios.

3.6 Including nutritional benefits and impacts in LCA

While human health is one of the three AoP of focus in LCA, paradoxically, the human health impacts and benefits of consuming foods (part of the use or consumer phase of an LCA) have not historically been included in food LCAs. Recent research has changed this, allowing us to incorporate these nutritional impacts into LCA. Building on the Global Burden of Disease (GBD) studies in nutrition epidemiology that have identified 15 risk factors contributing to detrimental or beneficial effects of foods on health, Stylianou et al. (2016), 2021) proposed an approach to translate the GBDs population-based impacts to the level of individual, complex foods. Based on the composition of individual foods coupled with the 15 GBD dietary risk factors (Fulgoni, Wallace, Stylianou, and Jolliet, 2018), nutrition impacts have been calculated with units of micro-Disability Adjusted Life Years (DALYs) per serving for 5000+ items found in the US and the Swiss diet (Ernstoff et al., 2020).

1 DALY is approximately equivalent to half a minute, and benefits and impacts can thus be expressed as minutes of life gained or lost per serving size via the Health Nutritional Index (HENI).

Fig. 3.8 illustrates the HENI index scores for Yogurt A (high strawberry content of 13 percent) versus Yogurt E (low strawberry content of 3.5 percent). Three risk factors contribute to most of the nutritional impacts and benefits. On the detrimental side, the sodium content of 0.10 g sodium/yogurt serving leads to 0.75 min of healthy life lost. This is largely compensated by the calcium (+0.7 min. gained per serving) and the fruit (+2.1 min. gained per serving for high strawberry yogurt A), yielding a net HENI score of 2.05 min of healthy life gained per serving for Yogurt A. Reducing the fruit content to 3.5 percent reduces the net benefit per serving down to only 0.5 min gained.

Since these scores can also be expressed in DALY, they can be combined as weighted, normalized endpoint damages and benefits (note that the nutritional benefit in Fig. 3.7 is presented as the absolute). In Fig. 3.7, the bottommost two bars represent the net nutritional benefit for the standard and low fruit/sugar alternates. The details of the specific components of the dietary contribution leading to a net health benefit is presented in Fig. 3.8. This shows that the direct nutritional impacts are substantial, exceeding environmental impacts by over a factor of 3 for the high fruit content options (65.5 mPt benefit vs. an average of 18.3 mPt damage from environmental impact), while the dietary benefit from the low-fruit yogurt (E)

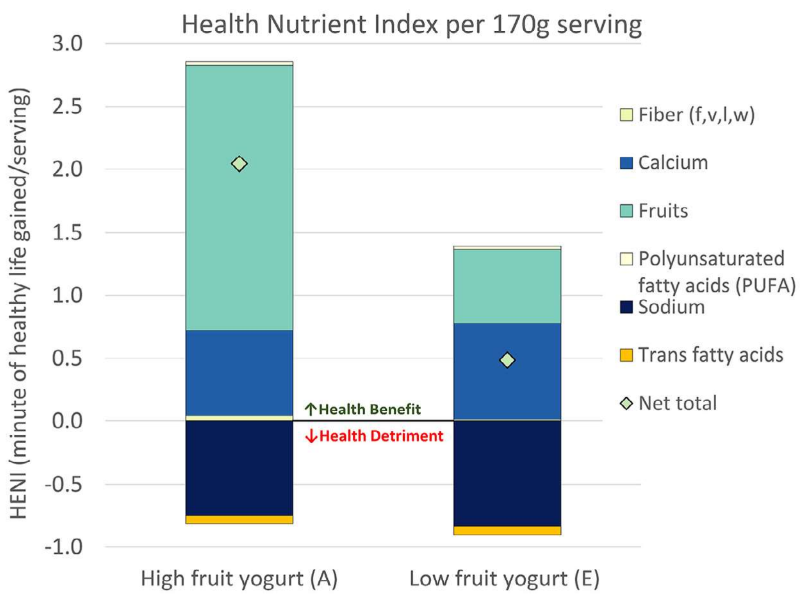

FIGURE 3.8 Human health burden by dietary risk in minutes of healthy life per serving of strawberry yogurt. Purple diamonds represent the net Health Nutritional Index (HENI) per serving.

nearly offsets the adverse environmental impacts. It is therefore crucial to consider nutrition in LCA when analyzing trade-offs between impact categories and scenarios over the entire life cycle.

3.6.1 Which yogurt is better?

Among these five options, which yogurt is the preferred choice from a life cycle perspective? It is not sufficient to base our analysis only on climate change (Fig. 3.4). As we stated, one of the primary strengths of LCA is that it provides a multidimensional picture of systems' performance. With LCA, we can (and should!) estimate multiple environmental impacts of systems (see Fig. 3.6). By including multiple impact categories and a life cycle perspective, the LCA framework enables an understanding of trade-offs between relevant impacts and across supply chain stages. Although, in this case study, there are not significant tradeoffs, by quantifying trade-offs we can identify and avoid burden shifting and other unintended consequences.

3.7 Uncertainty in LCA

The challenge of constructing a representative life cycle inventory model from multiple sources (measured, estimated or modeled) is generally the most time consuming and difficult stage of performing an LCA. There are several considerations regarding the accuracy of the data quality and model construction which are directly relevant for evaluating the robustness of conclusions from any LCA study. Uncertainties in LCA modeling arise from the following sources:

- Inherent variability of activities (e.g., inter-annual differences in milk or strawberry yields)
- Epistemic uncertainty, or the absence of knowledge or data for an activity known to contribute (an unknown amount of a pesticide used in strawberry cultivation) or missing a contributing activity altogether (exclusion of a pesticide which is used).
- Uncertainty in the causal chain defining the midpoint and endpoint impacts, that is uncertainty in the impact assessment method's characterization factors.

LCA is frequently used for benchmarking, product comparison, and setting policy. The uncertainty inherent in LCA modeling requires that practitioners consider the potential for reaching an incorrect conclusion. The most common approaches used in the field are a combination of uncertainty and sensitivity analyses, which together can provide insight regarding which activities require higher quality data and whether the conclusions are sufficiently robust to support the goal and scope of the study.

3.8 Sensitivity analysis

From a practical perspective, it is not feasible to conduct a sensitivity evaluation of all the parameters contributing to all the activities in a complete supply chain. Thus, one approach is to perform a one at a time evaluation of the contributing activities in the foreground system based on the fractional change in an impact category resulting from a specified fractional change in the input parameter value. Some authors choose a standard plus or minus 10 percent variation in the input value; however, a better approach is to base this on the expected range of variation in the input parameter. In the strawberry yogurt case, because milk represents a significant contribution to system impacts, it is logical that an error in the inventory (i.e., the quantity used) of milk used in the yogurt will lead to a significant error in the result, thus milk quantity is a sensitive parameter for which uncertainty must be reduced. In this instance, simple inspection is sufficient to identify milk as highly sensitive input parameter; in other cases, formal testing, as described above is needed.

3.8.1 Monte carlo analysis

Many life cycle inventory databases have included estimates of inventory uncertainties which can be used to support Monte Carlo Simulations (MCS) - a diagnostic tool to assess robustness of conclusions from an LCA study. More specifically, MCS is a method estimating the uncertainty of the results of a complex model based on known or estimated variability of input data. For example, the quantity of electricity consumed in many of the unit processes contributing to a supply chain will not be known with high precision (for example, the electricity usage of in-home refrigeration may have a mean value of 5 kWh and coefficient of variation of 20 percent). MCS randomly selects an input from the distribution (for the electricity and potentially thousands of other inventory flows), and in successive calculations for the functional unit, will provide the range of calculated impacts (for example, climate change) which can then be used for statistical inference tests.

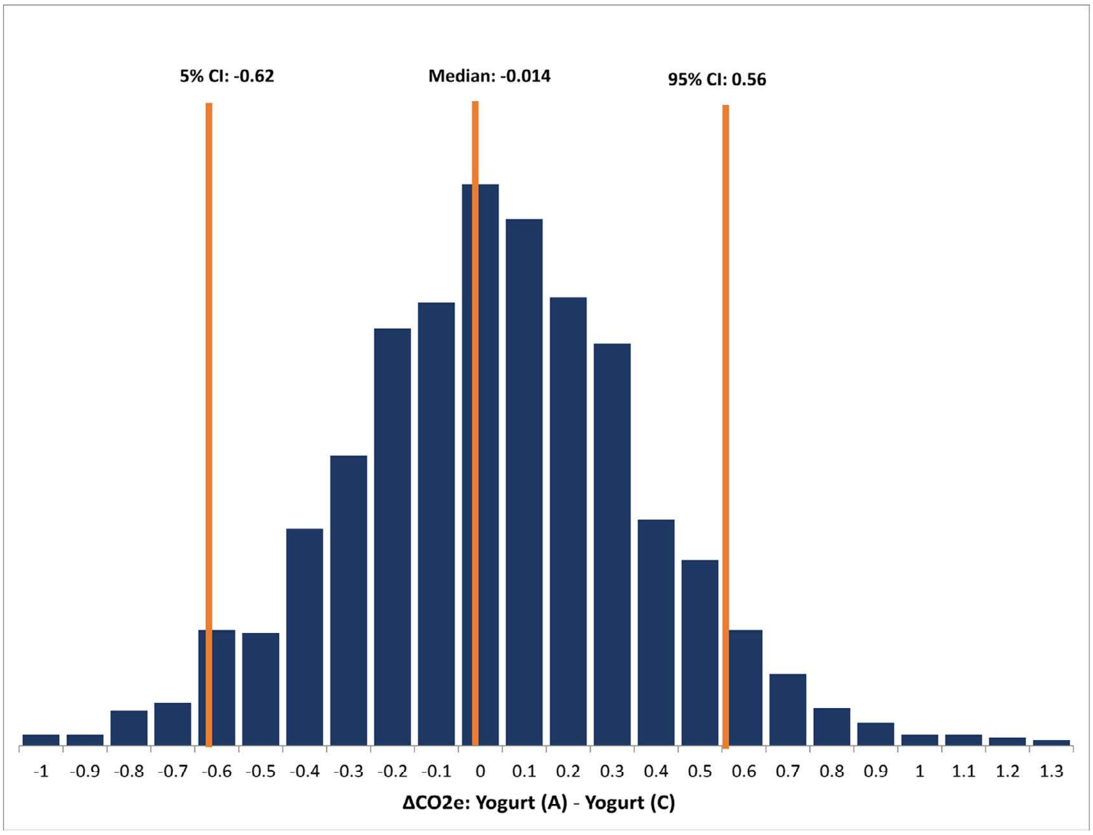

FIGURE 3.9 Pairwise comparative climate change impact of yogurt A minus yogurt C. The negative median indicates that C has slightly larger climate change impact, however it is not a statistically significant difference given the confidence intervals (CI).

Most standard LCA software provide a mechanism for Monte Carlo simulation. Each of the activities for which uncertainty information is known, or can be estimated, is assigned a mean value and a probability distribution. The software will then perform the specified number of complete simulations for the product or products to produce a distribution of impact values from which the statistical likelihood of a difference between systems can be inferred. In making product comparisons or longitudinal comparisons against a benchmark, it is imperative that shared background processes are matched in each of Monte Carlo simulations. This helps to prevent the inflation of variance between systems and provides for a more robust comparison.

Fig. 3.9 presents the results of 1500 Monte Carlo simulations comparing Yogurt A and Yogurt Cs climate change results. Each simulation selects the same background LCI data so that the difference between the two systems' impacts is not artificially inflated because of the different choices of, for example, electricity emissions in the upstream supply chain. In this case, although the median is slightly negative, the wide confidence interval indicates that the difference is not statistically significant at the 5 percent confidence level, meaning that these alternative yogurt systems yield very similar carbon footprint results.

The combination of sensitivity and Monte Carlo analysis is used to test the robustness of conclusions in comparative studies. If the uncertainty in the input data do not obscure the differences in the output results, the conclusions are considered robust.

3.9 Gaps and further research needs

LCA is a widely adopted framework for evaluation of food system sustainability characteristics, but there are limitations to the methodology that should be understood. One important point to understand is that most impact assessment frameworks do not have geospatially or temporally explicit characterization factors. This means, for example, that phosphorous emissions from fertilizer or manure application to crops from two different regions will be assigned the same potential eutrophication (water quality) impact – even if one emission source is near a sensitive waterbody and the other is not; the "true" impact will not be the same at the local level. This is a consequence of the geospatial scale (continental to global) for most characterization factors commonly used in life cycle assessment. There are two notable exceptions. The first is the Aware method for water scarcity which provides both geospatially (watershed level) and temporally explicit (seasonal) characterization that accounts for the local relative availability of water. The second is a biodiversity impact methodology proposed by Chaudhary, Pfister, and Hellweg (2016) and Chaudhary and Brooks (2018). The Aware LCIA method (Boulay et al., 2015 Boulay, Hoekstra, and Vionnet, 2013) is an alternative approach to the water footprint method presented in Chapter 4. The biodiversity method is linked to land use and land use change which is the topic of Chapter 5.

Additional impact categories are currently the subject of significant research in the field. These include ecosystem services, biodiversity, antibiotic resistance, and soil quality (Bakshi and Small, 2011; Chaplin-Kramer et al., 2017; Chaudhary and Brooks, 2018; Chaudhary et al., 2016; Cowell and Clift, 2000; De Laurentiis et al., 2019; He et al., 2016). While there are some initial and directionally correct estimates for several of these categories, more work is needed.

There are also erroneous extensions of life cycle assessment results, for example, if results obtained for a product or service are applied at a scale beyond that chosen for the study. This is because of a foundational assumption of life cycle assessment that the systems modeled are marginal in a macro-economic sense; specifically, the effects modeled are not large enough to affect the background economy. Thus, one cannot extrapolate the large-scale consequences of, for example, eliminating dairy products from the US diet based on a study comparing a serving of a plant-based beverage versus fluid milk. Elimination of the dairy sector would have far reaching effects that are not captured by a simple product LCA. In such cases, LCA should be coupled with general equilibrium modeling where such large shocks to the economy can be simulated providing a completely new background economy in which to contextualize the conclusions.

3.10 Conclusions

LCA provides a systems framework for evaluating and comparing food systems. It is designed to quantify potential impacts and identify tradeoffs between actors in the supply chain as well as among different facets of environmental concern. We have shown that even for simple foods there can be notable differences arising from different production systems. In addition, determining an appropriate function for food remains a challenge. Some researchers propose inclusion of nutritional quality in the functional unit (Saarinen, Fogelholm, Tahvonen, and Kurppa, 2017), while others argue it should be considered in impact assessment, as we have done in this chapter (Weidema, 2018). Further there are shifts in sources of emissions which may seem to be intuitively beneficial but may not provide the expected result after careful quantification using the LCA framework. As a simple example, it is possible that environmentally friendly reduction in food packaging material quantity may in fact result in larger food loss since a primary function of packaging is food preservation leading to larger negative impacts from the loss of the food.

LCA can also provide the basis for product or system comparison and benchmarks for longitudinal studies demonstrating continual improvement. However, in these applications caution in interpretation is needed because there are pitfalls in performing LCA which can lead to the results from different studies/authors not being directly comparable – for example, mixed system boundaries or background databases can cause incomparability issues.

LCA is rapidly becoming a prominent tool in the assessment of sustainable food systems and holds great potential, particularly when used with other modeling tools described in this text. While the capability of LCA is not limited in principle, as discussed in the uncertainty section, the robustness of conclusions, especially comparative assertions of superior performance must be evaluated in the context of the available data.

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