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Primer

Life Cycle Assessment of Food Systems

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The production and consumption of food are responsible for serious environmental degradation. Given the nature of the global economy, the impacts of food are dispersed over the full extent of the planet because food commodities may travel long distances from production to consumption. In this Primer, we introduce the principles of life cycle assessment (LCA), which allows for the assessment of the global extent of the inputs, outputs, and potential environmental impacts throughout the life cycle of a product system. We describe how LCA works following the standard phases of (1) goal and scope, (2) life cycle inventory, (3) life cycle impact assessment, and (4) interpretation. We show that LCA studies can capture the environmental impacts of foods, diets, and food production systems. While LCA has been expanding in scope and breadth, collaboration across disciplines is needed to further capture the diversity of food systems and to better deal with underassessed foods.

Introduction

The production and consumption of food is one of the major determinants of environmental degradation at the global scale. Likewise, individual dietary choices determine serious impacts on human health, due to an ever-growing demand for highly processed foods, refined sugars, refined fats, oils, and meats.

Unless radical changes are implemented on the production and consumption sides, global trends of population growth, increased affluence, and dietary choices are likely to worsen the impacts of food systems. The resource requirements and emissions vary widely among foods, food production systems, and regions, thus requiring assessment methods that take into account such diversity.

Life cycle assessment (LCA) is the method typically recommended by international institutions, such as the European Commission and the United Nations Environment Programme, to support policy making for sustainability by quantitatively assessing the environmental impacts during the entire life cycle of a product. Practitioners regularly use LCA studies in corporations, as well as to support eco-labeling schemes and environmental product declarations. LCA allows minimizing trade-offs between comparable alternatives, while avoiding the shifting of environmental burdens spatially from one stage or process of the life cycle to another, and physically from one environmental impact to another.

In this Primer, we first discuss the broad set of principles of LCA. Second, we describe the application of LCA to assess individual foods and food production systems, respectively. Finally, we discuss emerging topics in LCA of food systems.

Principles of Life Cycle Assessment

LCA is the "compilation and evaluation of the inputs, outputs, and potential environmental impacts of a product system throughout its life cycle." Standard practice for LCA is recorded in the 14040 series of standards issued by the International Organization for Standardization (ISO). LCA comprises four iterative phases: goal and scope definition, inventory analysis, impact assessment, and interpretation.

Goal and Scope

At the start of an LCA study, the practitioner establishes the goal and scope. This phase focuses on formulating the question and stating the context of answering this question. The plan of the LCA study is defined as clearly and unambiguously as possible. The goal of the LCA should deal with the intended application (e.g., product improvement, strategic planning, and policy making for sustainability), the reasons for carrying out the study, the intended audience, and whether or not the results are to be used in comparative assertions disclosed to the public. In practice, the practitioner determines the conditions and assumptions under which the study results are valid, as these conditions and assumptions will have an impact on the later phases.

An important aspect of the scope definition is the functional unit. In LCA, all environmental impacts are related to the function that is delivered by the system under assessment. The so-called "functional unit" is a quantitative description of that function, and represents the basis for comparison between systems. For example, the primary function of food is to satisfy the need of the human body to be nourished. Therefore, typical examples of functional units include formulations based on a quantity of food, such as "the delivery of 1,000 L of drinking milk brought to the consumers." Alternatively, functional units can also express the quality or nutrient content of a food commodity, e.g., expressing the function of system as "the supply of the recommended dietary intake for vitamin C." The functional unit can reflect one or several of these aspects.

Life Cycle Inventory

Once the practitioner has sketched the scope of the study and continues on to the life cycle inventory (LCI) phase, she or he collects data, identifies relationships, and quantifies the inputs and outputs for the system under assessment. Starting from the functional unit under consideration, the practitioner backtracks and draws a flowchart that maps all individual subunits

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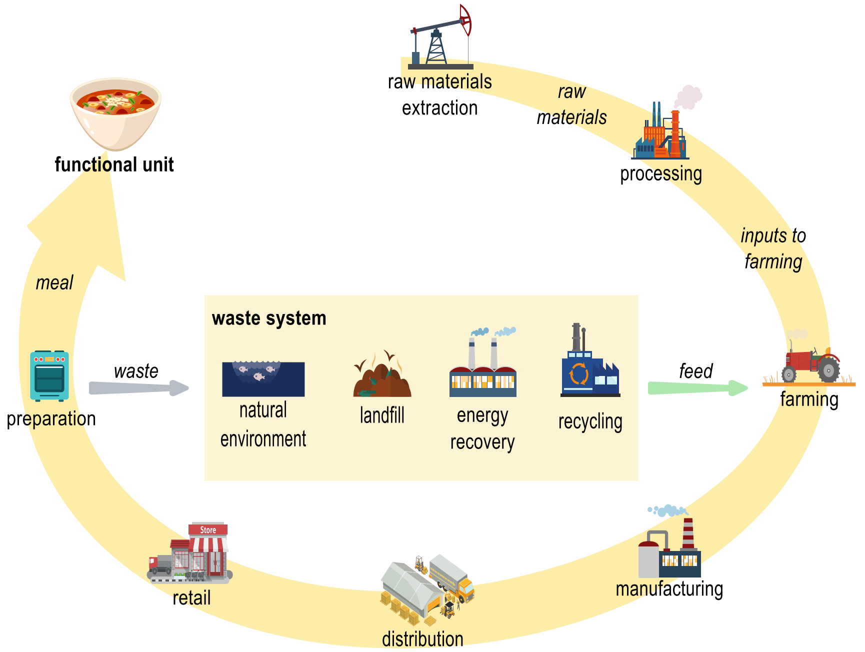

Figure 1. The Life Cycle of a Meal
The life cycle of a meal is depicted as a series of processes contributing to delivery to the functional unit, to which all processes are scaled. A study could assess, for instance, the LCA impacts of a meal providing the recommended dietary intake of fibers for an adult. LCA studies can be conducted up to the farm gate of the life cycle. In this case, all inputs to farming and raw materials are assessed with the related emissions. Examples include water for irrigation, pesticides applied for pest control, or fertilizers applied to the soil. The farm may produce more than one output, and determine the production of waste. The life cycle of food systems may additionally include the phases of processing produce, manufacturing products containing the farmed produce, and distributing and selling the products. Processing steps can be included at any stage of the life cycle. The use phase of the life cycle of food includes all activities that take place on the consumer side. This phase includes, for instance, the resources needed to prepare a meal and the refrigeration of ingredients. Waste and losses can be accounted for at any stage of a life cycle. The waste outputs of processes can be further recycled and reprocessed to be turned into inputs to production, such as feed, or, for instance, end up in a landfill facility.

(i.e., unit processes) that together make up the system. Typical examples of unit processes include “fodder production” and “electricity production from natural gas.”

The inventory records “elementary flows,” i.e., the natural resources extracted from the natural environment and the chemicals emitted to the natural environment. Economic flows between unit processes are also recorded. These occur within the technosphere, and are subject to human transformations. In the case of the analysis of food systems, the technosphere is tightly interlinked with biological processes, such as pollination.

LCA studies a product (e.g., milk), technology (e.g., pasteurization machine), or function system (e.g., dairy farming) (Figure 1). The product is studied across its full life cycle, and all the related processes are together called the “product system.” The practitioner defines the “system boundaries,” specifying what is assessed and what is omitted from the study. The system boundaries should ideally cover the full life cycle, upstream and downstream. In practice, simplifications are necessary to restrict the model scope, due to the rapid increase in complexity once farther ramifications upstream and downstream are added to the analysis.

Depending on the boundaries, a study of milk, for example, may include inputs to the farm, such as the production of fertilizers, the extraction and refining of oil to fuel the tractors, and the production of crops to feed cows and heifers (i.e., the cradle). The study may further include processing activities at the farm, such as the production and the storage of milk (i.e., processes up to the farm gate), or also include processes that take place once the product has left the farm gate, such as transportation to the consumer, the consumption phase, and waste management of the discarded milk (i.e., cradle to grave).

Processes are seldom producing just one single economic output. Consider, for instance, a system producing both milk and beef. A number of methodological procedures are considered in the standard LCA practice to deal with such multi-functional processes. These include the use of allocation rules based on the physical or economic relationships among the connected subsystems.

Given the complexity of the systems typically under assessment, the LCA practitioner collects primary data to model all the processes immediately upstream from the delivery of the functional unit (i.e., the so-called “foreground system”). In contrast, the practitioner would typically rely on existing standard LCI databases to model the “background” system, which includes, for example, data on the water demand for irrigation or the electricity grid mix at a specific geographical location. The result of the LCI phase is an inventory table of the exchanges (resources and emissions) between the system under assessment and the natural environment.

Life Cycle Impact Assessment

In the following phase of life cycle impact assessment (LCIA), the practitioner generally uses predefined methods implemented in dedicated LCA software to group and aggregate inventory data, i.e., resources and emissions, to environmental impact categories. For example, all greenhouse gas emissions (GHGs; e.g., CO_2 and CH_4) recorded across the life cycle of, for example, 1 L of skimmed milk, are translated into impacts on climate change expressed in the same unit (i.e., kg CO_2 equivalents). For this, the LCI results are multiplied with their respective global warming potentials (GWPs), as provided by the Intergovernmental Panel on Climate Change. The result is an impact score for climate change, which is often referred to as a carbon footprint. However, the scope of an LCA is broader than just an assessment of climate impacts, and GWPs are just one example of a wider range of characterization factors. Characterization models and factors have been developed, among others, to characterize the use of water, land, and resources, and also to characterize human- and eco-toxicity impacts as a result of, for example, the application of agrochemicals to soil (Figure 2). Impact scores across diverse impact categories can be normalized internally

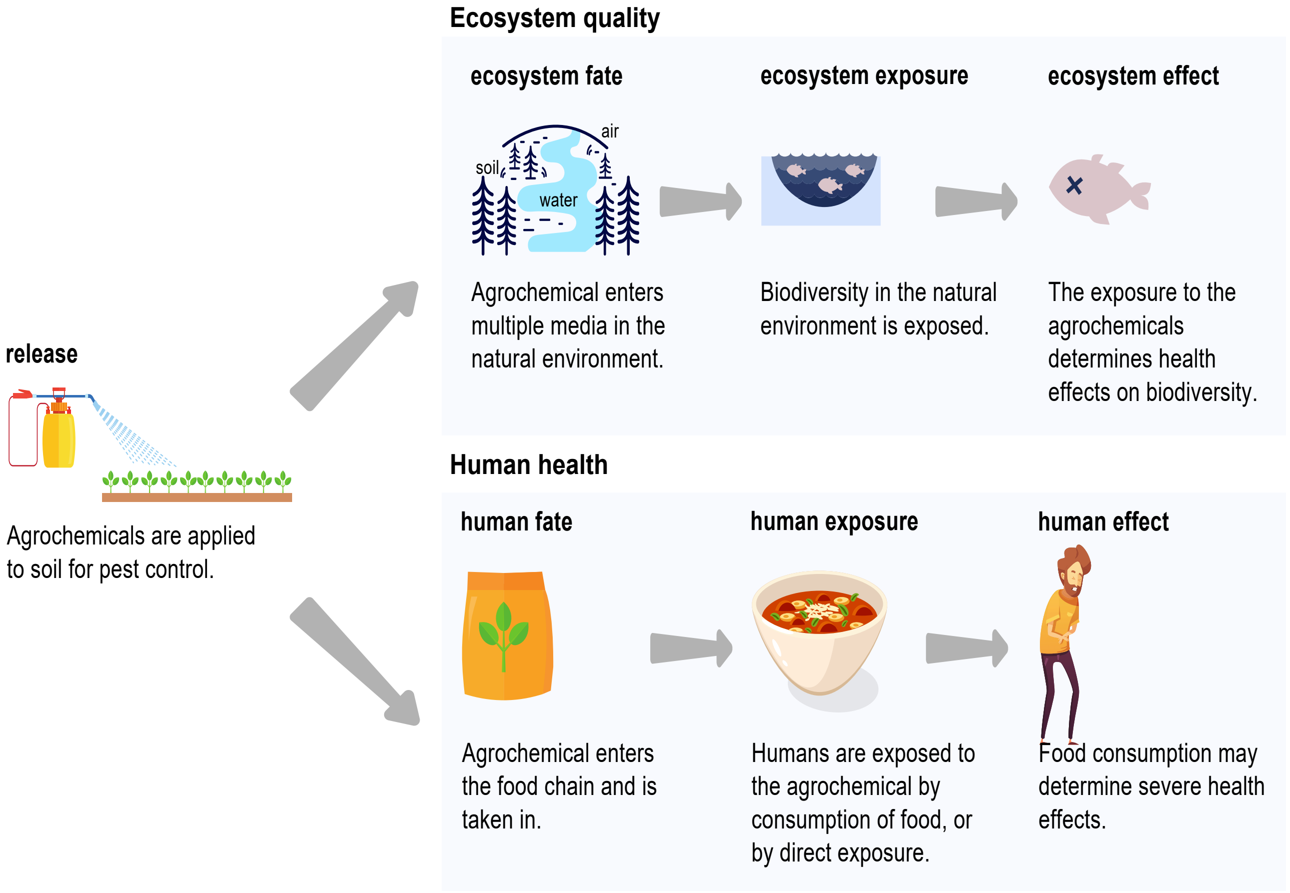

Figure 2. Characterization and Impact Pathway

As a result of the inventory analysis, resource use and emissions are recorded for all processes considered in the life cycle. The practitioner, for instance, records the quantity of agrochemicals applied to the soil. This quantity and the related emissions are characterized during the LCIA phase. Alternative pathways can be considered, depending on the impact assessment model used. In the case of an agrochemical applied to the soil, impacts on both ecosystem quality and human health could be considered. In both cases, the typical impact pathway considers the fate, exposure, and effect of the emitted substance. In the case of the agrochemical depicted, this may enter the natural environment and propagate through media until determining an effect on biodiversity, or enter the food chain and cause an effect on human targets.

(e.g., comparing alternatives with the best performer) or externally (e.g., comparing impact scores with reference impacts for Europe or the world). Finally, weighting methods mirroring normative values of the decision-maker or of society can be adopted to further aggregate (normalized) impact scores across different impact categories.

Interpretation

In the last phase of LCA, the practitioner interprets the inventory and impact results. At this stage, the practitioner may highlight potential areas for improvements related to hotspots in the life cycle and decide upon a preferable option in a comparative assessment. The relationship between results and methodological issues, assumptions, and limitations of the study are assessed here with their influences on the decision at stake and goal of the study. These increasingly include aspects related to the uncertainty in the results of the study, and the potential sources affecting the uncertainty of the results (e.g., lack of data, unrepresentative process data, or difference in geographical or temporal scopes of the data collected).

Foods and Diets

LCA studies have been applied to assess a number of food products, for instance to identify potential mitigation opportunities by changing production practices, to assess novel zoo-technical practices, and to suggest preferable options in comparative assessments. Thousands of small and big farms, processors, and retailers contribute to the environmental impacts of food commodities, which vary largely across production systems. Farmers cultivating the same crop in different countries can determine impacts that can span orders of magnitude. Climate conditions, technological differences, and nutritional differences, among others, can contribute to such variations.

Variations aside, LCA studies suggest that animal-based foods have typically higher environmental impacts across a wide spectrum of impact categories as compared with plant-based alternatives. For instance, a meta-analysis of LCA studies suggests that 100 g of protein of beef from a beef herd (not a dairy herd) determine an average impact score for climate change of 50 kg CO_2-equivalents, while determining a land use of 164 m^2 per year. The climate-change and land-use impacts of the protein-equivalent for peas, in turn, are over 100-fold and almost 50-fold lower than those of beef. Similar trends can be highlighted for other impact categories. Within major crops, global LCA studies suggest that the cultivation of irrigated wheat, rice, maize, and sugar cane are global drivers of water scarcity and land stress. In terms of GHG emissions, wheat has one-fifth of the carbon footprint per gram of protein in rice.

LCA studies have also targeted aspects related to food losses and food waste, i.e., food that is not consumed for reasons related to human action or inaction, or due to other spoilage factors. Such losses typically relate to the retail and consumption phase in high-income countries, while higher fractions of food losses relate predominantly to the production stages in low-income countries. According to estimates, for instance, the production of food lost in the United States in 2010 contributed to 160 million tons of CO_2 equivalents of GHG emissions (equivalent to the CO_2 emissions of 33 million average passenger vehicles annually). At the consumption stage, food losses can also be connected to the use of protective packaging, which will affect the specific functioning of the system in terms of lifetime and nutritional properties.

Global trends of socioeconomic change will also likely affect the environmental impacts of food. If we project status quo trends into the future, rising incomes and urbanization will foster a global dietary transition toward unhealthier dietary options higher in refined sugars, fats, oils, and animal products. However, interventions to stimulate more conscious dietary changes can potentially reduce environmental impacts more than technological solutions implemented at the production stages of the life cycle of foods. Compilations of LCA studies have attempted to describe typical diets and regional variations. Results suggest that reducing the consumption of animal-based products directly translates to reduced environmental impacts. In particular, compared with the projected 2050 income-dependent diet, significant and increasing reductions in impacts across impact categories can be achieved by switching to a Mediterranean, pescatarian, and vegetarian diet, respectively. Transformative benefits, also in relation to health, are associated with diets that completely exclude animal products, which would reduce food's environmental impacts of various impact categories from 19% (scarcity-weighted freshwater withdrawals) to 76% (land use; reference year 2010).

Food Production Systems

Over time, traditional food production systems have given way to more intensive systems characterized by increased yields, monocultures, and a high level of pest control. Inputs to production have also changed. Inputs such as manure, fertilizers, feed, and agrochemicals are imported and transported to the farm site. Also, the by-products and waste of the modern conventional farming system are used only to a limited extent on the farm. This is an important aspect to consider when trying to reduce the environmental impacts of food production systems. It has been recognized that, in order to become more sustainable, such systems should minimize externalities by optimizing the use of internal production inputs (e.g., applying manure on site and implementing crop rotation). Similarly, the global economy has modified the way food production systems operate. The products of most farms enter a global marketplace and travel large distances before reaching a processing facility or the final consumer.

LCA studies can describe the environmental impacts of conventional and alternative food production systems, and identify opportunities to develop sustainable high-yield production systems with minimal environmental impacts. Organic systems, for instance, are often proposed as a solution to reduce environmental impacts. Compared with conventional options, organics have typically lower crop yields and thus require more land to produce the same amount of food. Focusing on the production efficiency may often favor products from intensive production systems. As a result, LCA studies typically find higher impacts per product unit of organic versus conventional systems. In contrast, organic systems have typically lower environmental impacts across a wide spectrum of impact categories when assessed on a per-area basis. Further variations are found in individual LCA studies, and are due to modeling choices, such as the representation of individual management choices of farmers.

Recent advances in technology have increased the viability and productivity of urban food production systems. Such systems aim to maximize yield while minimizing land use and inputs to production. Innovative urban food systems make use of technologies for indoor agriculture and innovations, such as vertical farming, hydroponics, aeroponics, aquaponics, and soil-less systems. The LCA perspective has yet to be applied to assess these systems and the related environmental impacts across geographical boundaries.

A growing body of scholarship has also been focusing on the assessment of seafood supply chains and seafood production systems. LCA studies have been used to quantify the life cycle impacts of conventional fisheries, certified and responsible fisheries, and aquaculture systems. Seafood LCA studies typically conclude that the initial production phases, such as fishing, dominate total results across multiple impact categories. Variations across studies are determined by factors such as management regulations, processing and transportation options, choice of fishing methods and gear, and post-landing aspects (i.e., yield, use of by-products, and losses). With regard to fisheries, such aspects are also strictly related to management practices and decisions on when, where, and how to fish. Compared with land-based food systems, fisheries do also present environmental benefits, which are related to a reduced need for inputs. Aside from fuel to power fishing vessels, fisheries do not require irrigation, feed, agrochemicals, fertilizers, and land use. However, because fisheries rely on rapidly depleting wild stocks, their sustainability needs to be assessed by taking a broader perspective encompassing the impact of fisheries on the ecosystems in which they operate. Such aspects are challenging to model in LCA. Rapidly depleting stocks and changes in consumption patterns have also increased the consumption of farmed seafood. While the environmental challenges of aquaculture are different from those of wild fisheries, fishery products (e.g., Atlantic cod) are often compared with aquaculture products (e.g., Atlantic farmed salmon) and agricultural products (e.g., chicken). Looking at the life cycle of farmed seafood, the production of feed ingredients in agriculture and fisheries often dominates LCA results.

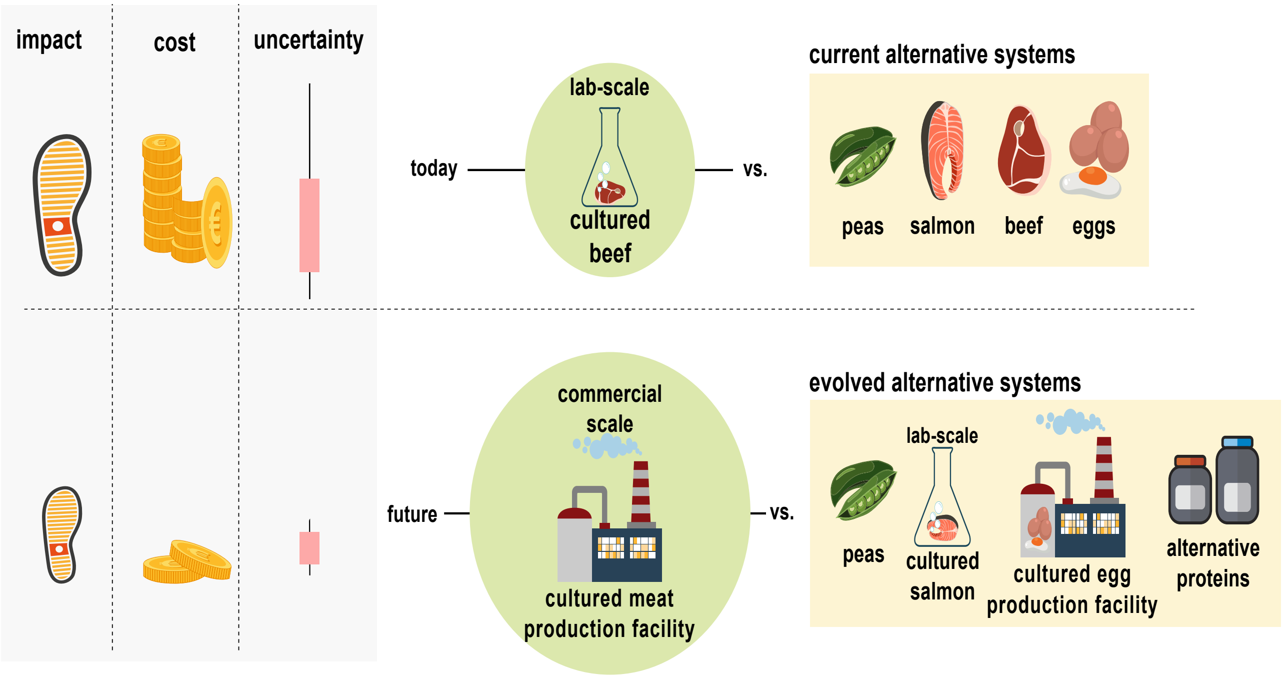

Figure 3. ***Ex Ante*** **LCA of Emerging Food Technologies**
LCA can be used to assess the environmental impacts of lab-scale cultured meat, e.g., beef, and to obtain an environmental score comparable with alternatives, such as peas, beef, salmon, or eggs. The impacts of cultured beef at this stage of technological development are likely to be higher. Similarly, production costs will be high due to small volumes. The low level of maturity of the technology will also determine higher uncertainty in the results. Looking at the future, trends could be assessed combining LCA with scenario analysis. Increased production and market penetration will likely lower costs. Using scenarios will allow uncertainty in the results to be reduced. The evolution of the technology is modeled, taking into account the future food-technology landscape in which other evolved alternative systems will likely operate.

Emerging Topics and Future Directions in LCA

Starting from the basic standard principles, we have seen how LCA functions and how the method is applied to study individual products, diets, and production systems. We focus in this closing section on some of the emerging aspects of LCA that are of relevance for assessing food systems. Recent proposals also look into using LCA to respond to an increased public concern toward the social repercussion of the food system. For instance, the standard set of LCA impact categories has expanded to integrate animal welfare. Preliminary results show that, besides less consumption of animal-based products, a shift to other animal products can significantly improve animal welfare.

LCA studies are currently being conducted at the earlier stages of research and development, also for food systems and technologies. While LCA studies have traditionally been *ex post* assessments of well-established product systems, recent advances in the literature propose the use of LCA in an *ex ante* fashion to maximize the potential for sustainability by design. *Ex ante* LCA empowers guidance of technology developers when a system is still under development, i.e., when it is still possible to operate changes to, for example, the quantity and choice of inputs or the manufacturing routes. LCA could, for instance, be used to assess the environmental impacts of cellular agriculture, i.e., the ensemble of technologies based on tissue engineering and cell culturing with the aim of growing cellular and acellular animal products *in vitro*. In the case of cultured meat (Figure 3), LCA could guide the developers toward preferred sustainability pathways by quantifying the impacts of the current state-of-the-art lab or pilot food technologies, project their potential evolution over time as the technology progresses, and compare their sustainability profile with existing alternatives, now and in the future. Other novel food technologies, such as plant-based protein alternatives for human and animal consumption, or novel practices, such as plant-based meal replacements, can be assessed in similar fashion.

As already noted, LCA studies of food systems have methodological issues that require further developments. As described, a number of studies exist that broadly sketch the environmental impacts of individual products and diets. However, most past research has focused on a limited set of key foods (e.g., beef or staple crops). Similarly, most studies have focused on a limited set of impact categories, in particular on climate change. Studies also suffer from a geographical bias, due to limited inventory data from certain countries. Therefore, LCA studies of food are typically representative of few countries, leaving a large section of the world food system out of the picture. This hampers assessment of impacts of entire diets across different countries, each composed of a multitude of different food products. Scholars describe the issue of underassessment as an acute problem that hinders our ability to truly understand the food system and support effective decision-making for sustainability for a substantial part of the world. Similarly, another critical issue concerns the complexity of interactions, but also the negative and positive linkages among food systems, which may compete for resources or share inputs and outputs. LCA studies notoriously struggle to model potentially positive impacts of a system on, for example, soil quality, landscape provision, and ecosystem services.

The strategy to improve on such important limitations is twofold. First, LCA should not be used in isolation but complemented with other methods that together are better suited to capture the diversity of the food system. Taking into account global trends, this concerted effort should also be directed at the understanding the trade-offs between the production of food for human consumption and the farming of land for animal feed, fuel, and fiber production, among others. Assessing such systems requires enlarging the LCA toolbox to better model how demand and impacts change as a consequence of systemic shifts. In the case of diets, environmental extended input-output (EEIO) methods have allowed broadening of the assessment of the global food system. EEIO, however, typically distinguishes a dozen categories of agricultural products, and hence lacks the detail of LCA. Second, additional efforts should be made in collecting data for underassessed foods and impact pathways. The complexity of mechanisms calls for an interdisciplinary platform of scientists to collaborate beyond the LCA community to describe mechanisms, and more accurately quantify the environmental impacts related to the interactions between food systems.

RECOMMENDED READING

Cucurachi, S., Yang, Y., Bergesen, J.D., Qin, Y., and Suh, S. (2016). Challenges in assessing the environmental consequences of dietary changes. Environ. Syst. Decis. *36*, 217–219.

Guinée, J.B. (2002). Handbook on life cycle assessment operational guide to the ISO standards. Int. J. Life Cycle Assess. *7*, 311–313.

Halpern, B.S., Cottrell, R.S., Blanchard, J.L., Bouwman, L., Froehlich, H.E., Gephart, J.A., Jacobsen, N.S., Kuempel, C.D., McIntyre, P.B., Metian, M., and Moran, D.D. (2019). Opinion: putting all foods on the same table: achieving sustainable food systems requires full accounting. Proc. Natl. Acad. Sci. U S A *116*, 18152–18156.

Heller, M.C., and Keoleian, G.A. (2015). Greenhouse gas emission estimates of US dietary choices and food loss. J. Ind. Ecol. *19*, 391–401.

Hellweg, S., and i Canals, L.M. (2014). Emerging approaches, challenges and opportunities in life cycle assessment. Science *344*, 1109–1113.

Meier, M.S., Stoessel, F., Jungbluth, N., Juraske, R., Schader, C., and Stolze, M. (2015). Environmental impacts of organic and conventional agricultural products–Are the differences captured by life cycle assessment? J. Environ. Manage. *149*, 193–208.

Nemecek, T., Jungbluth, N., i Canals, L.M., and Schenck, R. (2016). Environmental impacts of food consumption and nutrition: where are we and what is next? Int. J. Life Cycle Assess. *21*, 607–620.

Pfister, S., Bayer, P., Koehler, A., and Hellweg, S. (2011). Environmental impacts of water use in global crop production: hotspots and trade-offs with land use. Environ. Sci. Technol. *45*, 5761–5768.

Poore, J., and Nemecek, T. (2018). Reducing food's environmental impacts through producers and consumers. Science *360*, 987–992.

Ridoutt, B., Motoshita, M., and Pfister, S. (2019). An LCA impact assessment model linking land occupation and malnutrition-related DALYs. Int. J. Life Cycle Assess. 1–11.

Schau, E.M., and Fet, A.M. (2008). LCA studies of food products as background for environmental product declarations. Int. J. Life Cycle Assess. *13*, 255–264.

Scherer, L., Tomasik, B., Rueda, O., and Pfister, S. (2018). Framework for integrating animal welfare into life cycle sustainability assessment. Int. J. Life Cycle Assess. *23*, 1476–1490.

Tilman, D., and Clark, M. (2014). Global diets link environmental sustainability and human health. Nature *515*, 518.

Tuomisto, H.L. (2019). The eco-friendly burger: could cultured meat improve the environmental sustainability of meat products? EMBO Rep. *20*, e47395.

Ziegler, F., Hornborg, S., Green, B.S., Eigaard, O.R., Farmery, A.K., Hammar, L., and Vázquez-Rowe, I. (2016). Expanding the concept of sustainable seafood using Life Cycle Assessment. Fish Fish. *17*, 1073–1093.