

WASTE NOT, WANT NOT



REDUCING FOOD LOSS AND WASTE
IN NORTH AMERICA THROUGH
LIFE CYCLE-BASED APPROACHES

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LIFE CYCLE-BASED APPROACHES

Acknowledgements

The idea for this report emerged from a consultative process between the US Environmental Protection Agency (US EPA)'s Office of Global Affairs and Policy and UN Environment's North America Office. UN Environment is grateful to the US EPA for its collaboration on this effort, including for its financial support.

The author of the report is Dr. Martin Heller of the Center for Sustainable Systems at the University of Michigan. Project supervision and oversight was provided by Hilary French from UN Environment's North America Office and by Ted MacDonald from the US EPA's Office of Global Affairs and Policy.

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Foreword

Globally, an estimated one-third of all food produced is wasted rather than eaten. In North America, an estimated 30 to 40 per cent of the food available for human consumption is lost. This food loss and waste occurs throughout the food supply chain: on farms, in processing and manufacturing facilities, during transport and distribution, in retail and foodservice outlets, and in households.

Fortunately, there is growing national, regional and international impetus to address food loss and waste, and food waste-related policies and programmes across North America are gaining momentum. The 2030 Development Agenda underscored the importance of the issue by including the target of reducing per capita global food waste production by one-half by 2030. The United States government has a national goal for food loss and waste reduction and also runs the Food Recovery Challenge with businesses and organizations that have been taking steps to reduce their food waste since 2011. The Canadian government is also paying growing attention to the food waste challenge. And many states, provinces, cities and private actors are increasingly focused on the issue as well.

This report is the product of a collaboration between UN Environment North America and the United States Environmental Protection Agency. The study examines ways in which life cycle thinking and related tools such as life cycle assessment can be used to inform effective policymaking, aimed at reducing food loss and waste. It describes how these methodologies can help decision makers prioritize policies and interventions through better estimates of the environmental impact of food loss and waste, comparisons of food waste disposal options, and evaluations of alternative intervention or abatement strategies. Case studies presented in the report highlight examples of how life cycle thinking is already being used successfully to reduce food loss and waste in North America.

We hope that the report will be useful for policymakers and other stakeholders, as we all confront the critical challenge of reducing food waste and loss around the world.

Dr. Barbara Hendrie
Director, North America
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List of Acronyms

CEC	Commission for Environmental Cooperation of North America
CO₂	Carbon dioxide
CO₂ eq.	Carbon dioxide equivalent
FAO	Food and Agriculture Organization of the United Nations
FLW	Food loss and waste
GWP	Global warming potential
HFW-ICS	High wood waste content industrial, commercial and institutional waste generators
ISO	International Organization for Standardization
LCA	Life cycle assessment
LCC	Life cycle costing
LCSA	Life cycle sustainability assessment
MFA	Material flow analysis
NRDC	Natural Resources Defense Council
OR DEQ	Oregon Department of Environmental Quality
SDG	Sustainable Development Goal
SETAC	Society of Environmental Toxicology and Chemistry
UNEP	United Nations Environment Programme
US	United States
USDA	United States Department of Agriculture
US EPA	United States Environmental Protection Agency

Executive Summary

Food loss and waste is a major challenge globally, and in North America an estimated 30 to 40 per cent of the food available for human consumption is lost. Achieving both global and national food loss and waste reduction goals will require a broad-based effort across the supply chain, from farm to fork and beyond. It also will require the involvement of a broad range of stakeholders, including national and sub-national policymakers, farmers, businesses such as grocery stores and restaurants, and consumers. Fortunately, there is growing national, regional and international impetus to address food loss and waste, and food waste-related policies and programmes across North America are gaining momentum.

The causes of food waste are often deeply embedded in the complexities of food systems and engrained in the perspectives and behaviours of stakeholders throughout the food supply chain. Often what is needed to effect change is a fresh framing and perspective and a new set of tools for evaluating success. The goal of this report is to highlight one such framing – life cycle thinking and associated analytical methodologies – and to explore its usefulness for reducing food loss and waste.

Life cycle thinking is a holistic way of approaching the environmental, social and economic effects of our actions when we design, purchase and use products and services. These impacts occur at all stages of a product's life cycle: raw material extraction, processing and manufacturing, distribution, consumption and waste management. Consideration of this full life cycle perspective can be helpful in avoiding unintended consequences, re-evaluating "conventional wisdom", choosing between products and prioritizing competing programmes.

Life cycle assessment (LCA) focuses on quantifying the environmental impacts associated with a product's life cycle. It is perhaps the most

developed and applied of the quantitative methods based on life cycle thinking. While LCA has become more standardized through decades of development, methodological choices made for specific studies can influence results. It is therefore important for those who interact with and interpret LCA results to have a foundational understanding of the method itself. This report provides the starting point for that foundation.

Evidence from LCA has shown that for most food products, the bulk of the environmental impacts occur earlier rather than later in the life cycle. By the time food waste is ready to be discarded, most of the environmental impacts have already occurred. Thus, preventing food waste and therefore reducing excess food production is a far more effective strategy for minimizing environmental impact than optimizing end-of-life management.

This notion – a focus on food waste prevention, and solutions that address it directly – applies across the food value chain: from household behaviours and attitudes to entrenched practices and attitudes in food service, retail, processing and on farms. While often acknowledged, the simple fact that preventing waste is more environmentally beneficial than managing waste is not always reflected in policies, programming and investments related to food loss and waste.

Life cycle assessment and related assessment methods can help inform a number of important questions in the food loss and waste arena, thereby supporting decision-making and directing programming. Such inquiries include estimation of the environmental impact of food loss and waste, evaluation and comparison of food waste management options, and evaluation of intervention or abatement strategies.

Life cycle thinking helps us recognize that minimizing the generation of food loss and waste will lead to the greatest environmental benefit, but

that eliminating this waste altogether is not fully possible, and the existing waste must be dealt with somehow. LCA is an effective tool in comparing the environmental impacts connected with various food waste destinations (management methods). While results are dependent on local conditions and system specifics, most studies that compare management options find that anaerobic digestion – treatment that generates and collects methane for use as biogas and produces a soil amendment – has lower environmental burdens than composting, and all of these outperform landfilling.

A collection of case studies presented in this report show how life cycle thinking is being used to address food loss and waste in North America¹:

- Oregon's Department of Environmental Quality has deeply engrained life cycle thinking and LCA in its long-term vision and strategic planning. This has led to, among other things, a concerted effort to change the conversation about food waste in order to prioritize prevention over recovery efforts and to make investments in non-traditional (for an environmental quality department) information-gathering on how Oregonians buy, use and dispose of food in search of drivers of preventable food waste. This is informing messaging and outreach activities and leading to programming from a materials management entity directed at prevention of household food waste.
- In Canada, Provision Coalition, an alliance of 16 member associations representing the food and beverage manufacturing industry across the country, is helping food manufacturers think differently about food loss and waste in their plants. Cost-shared facility assessments are identifying potential interventions and

encouraging businesses to evaluate these food loss and waste prevention strategies not in terms of the costs of waste disposal (as is typical) but in terms of the value of the food right before it is lost. This leads to short pay-off periods and to significant economic, environmental and social savings through reductions in food waste.

- The US Environmental Protection Agency's Waste Reduction Model (WARM) provides a valuable life cycle-based tool for evaluating the environmental benefits associated with changes in materials management, including food. It can estimate the reductions in greenhouse gas emissions due to food waste reduction, as well as shifts in disposal, and is being used by municipalities to support decision-making as well as by private enterprises to communicate the value of their services.
- North American entrepreneurs are demonstrating the power of food upcycling: turning what may be otherwise considered food waste into valuable products, thereby blazing the way towards a circular economy.

Efforts to tackle food loss and waste are accelerating throughout North America and around the globe. Life cycle thinking and associated analytical methods offer a framework to support these efforts, helping to assure that they move towards the ultimate sustainable development goals of improved human livelihood, reduced environmental impact and prosperous economies. A central lesson from this perspective is to “get real” about emphasizing food waste prevention over recovery efforts. Still, recovery and disposal will be necessary, and a life cycle approach helps to minimize the impacts of these actions. Ultimately, life cycle thinking is a philosophy, a world view, and one that can be adopted by individuals as well as be institutionalized by governments and corporations at all scales.

¹ For the purposes of this report, the North American region is generally understood to include Canada and the United States but not Mexico. This is in order to be broadly consistent with United Nations regional groupings.



1.

Introduction

*Global food loss and waste has
a carbon footprint of
4.4 gigatons of carbon dioxide
equivalent per year,
and if it were a country it would
rank as the third top emitter
after the United States
and China.*

Food loss and waste has arisen as a key issue of our time. Food loss has been a challenge in some manner for civilizations since the dawn of agriculture. Yet recent recognition of the biophysical limitations of our planet, combined with ongoing food insecurity, population growth and pressing environmental challenges such as climate change and deforestation, have brought food loss and waste to the forefront of global attention.

Food loss refers to food leakages at upstream stages of the food supply chain such as in food production and processing, while food waste refers to discarded food at the downstream stages of the supply chain – in distribution, retail, food service and households. Food loss and waste refers to the aggregate of food loss and food waste throughout the food supply chain (see appendix A for complete definitions).

Ongoing understanding of the sheer extent of the food loss and waste problem amplifies concern and underlies calls to action. The Food and Agriculture Organization of the United Nations (FAO) estimates that globally, one-third of the food produced for human consumption is wasted – approximately 1.3 billion metric tons per year (Gustavsson *et al.* 2011). A 2017 report from the Commission for Environmental Cooperation (CEC) found that in the United States and Canada combined, an estimated 139 million tons of food is lost and wasted each year across all stages of the food supply chain (CEC 2017).

The environmental and socioeconomic impacts of this food loss and waste are staggering. FAO estimates that global food loss and waste has a carbon footprint of 4.4 gigatons of carbon dioxide equivalent (CO₂ eq.) per year (FAO 2015), and if it were a country it would rank as the third top emitter after the United States and China. The water footprint of global food loss and waste is three times the volume of Lake Geneva, and production of uneaten food occupies close to

30 per cent of the world's agricultural land area (FAO 2013). The impacts of food loss and waste in the United States and Canada alone are estimated at 144 million tons of CO₂ eq. per year, 14.9 billion cubic metres of water used, and 17.7 million hectares of cropland used (CEC 2017).

FAO also conducted a full-cost accounting of the global food wastage footprint and found that in addition to the \$1 trillion of direct economic costs per year, environmental costs reach around \$700 billion, and social costs reach around \$900 billion. The cost of the food wastage carbon footprint in particular, based on the social cost of carbon, is estimated to total \$394 billion in damages per year (FAO 2014). All of the above approximations are rough estimates, as major data gaps exist, and they must be interpreted with a high degree of uncertainty. Still, they point to the sheer magnitude of the problem.

**The cost of the food
wastage carbon footprint,
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Calls to action, targets and programmes to address food loss and waste are now widespread. For example, the Think.Eat.Save campaign was launched in 2013 as a partnership between United Nations Environment, FAO and Messe Dusseldorf, a German events planning firm. The programme's goal is to galvanize widespread actions, raise awareness and exchange ideas and projects about food loss and waste. The following year, Sustainable Development Goal (SDG) 12.3² established the following target at the international level:

2 See www.un.org/sustainabledevelopment/sustainable-consumption-production.

By 2030 halve per capita global food waste at the retail and consumer level, and reduce food losses along production and supply chains including post-harvest losses.

Executives from governments, businesses and international organizations, as well as research institutions and civil society, are aligning under the banner of Champions 12.3³, mobilizing action and accelerating progress towards the food waste reduction goal. The United States Department of Agriculture (USDA) and the United States Environmental Protection Agency (US EPA) announced the first US national food waste reduction goal in 2015, aligning with SDG 12.3 in calling for a 50 per cent reduction by 2030 (USDA 2015). In October 2018, the Trump administration restated the US commitment to addressing food waste by launching the Winning on Reducing Food Waste initiative, a joint agreement among the USDA, the US EPA and the United States Food and Drug Administration to improve collaboration and coordination across agencies in areas relating to food loss and waste reduction (USDA 2018).

These international and national calls to action have united and energized existing waste reduction programmes and catalysed many others. A growing number of businesses and organizations have publicly committed to reducing food loss and waste in their own operations under the US Food Loss and Waste 2030 Champions group. Organic waste bans that keep food out of landfills and organic waste recycling laws have been enacted in the states of California, Connecticut, Massachusetts, Rhode Island and Vermont and in the cities of Austin, Boulder, Minneapolis, San Francisco and Seattle. In Canada, the National Zero Waste Council has galvanized diverse stakeholder support for, among other things, a national target aligned with SDG 12.3.

Food loss and waste is clearly an urgent problem, and there is significant national and international impetus to address it. But the causes of food loss and waste are often deeply embedded in the complexities of food systems and engrained in the perspectives and behaviours of stakeholders throughout the food supply chain. Often what is needed to effect change is a fresh framing and perspective and a new set of tools for evaluating success. The goal of this report is to highlight one such framing – life cycle thinking – and to explore its usefulness for addressing food loss and waste in the North American context.

A. Objective and scope of report

The objective of this report is to describe life cycle thinking and the suite of quantitative tools such as life cycle assessment (LCA) that are rooted in that perspective, and to detail where and how these tools can be beneficially applied in the food waste space. As LCA and related tools have begun to enter common parlance, occasionally their strengths and limitations are misunderstood. Establishing realistic expectations and detailing what these tools can and cannot do is equally important.

Numerous previous reports have characterized food loss and waste in North America and beyond, providing best estimates of the magnitude and sources of this waste, best practices for measurement and reporting, detailed analyses of causes, and considerations of policy responses and opportunities for management. This report draws on insights from these works as needed, but does not attempt to update or exhaustively report on these topics.

3 See www.champions123.org.

B. Organization of report and navigational guidance

This report is organized to first give the reader an appreciation of life cycle thinking and its analytical applications (sections 2 and 3) and then to consider how – and why – those approaches have been utilized in understanding and acting on food loss and waste (sections 4 and 5). Terms used throughout the report are defined in appendix A. The reader should feel empowered to enter the report where he/she is drawn, perhaps returning to earlier sections to answer questions that arise. Here is a brief walk-through for orientation purposes:

Section 1 sets the stage for the report by providing an overview of the food loss and waste challenge in North America.

Section 2 introduces the concept of life cycle thinking, providing the framing and perspective for the remainder of the report.

Section 3 provides an overview of the more common quantitative methods for evaluating life cycle impacts. It offers a high-level appreciation of the differences between methods and their various applications to considering food loss and waste. This section is supplemented by a deeper exploration of life cycle assessment methods in appendix B, of potential interest to programme implementers and practitioners looking to better understand encountered research studies or for those interested in designing a study based on life cycle approaches to support decision-making.

Section 4 demonstrates the types of questions or decision-making within the food loss and waste space that life cycle-based approaches may be helpful in understanding. Examples from the academic literature are provided to give a flavour of the research that has been conducted and to inspire life cycle approaches to addressing food loss and waste in North America.

Section 5 provides a collection of case studies of life cycle thinking being successfully applied to the challenge of addressing food loss and waste in North America.

Section 6 summarizes the report by offering overarching conclusions and suggesting paths forward.

C. Overview of food loss and waste in North America

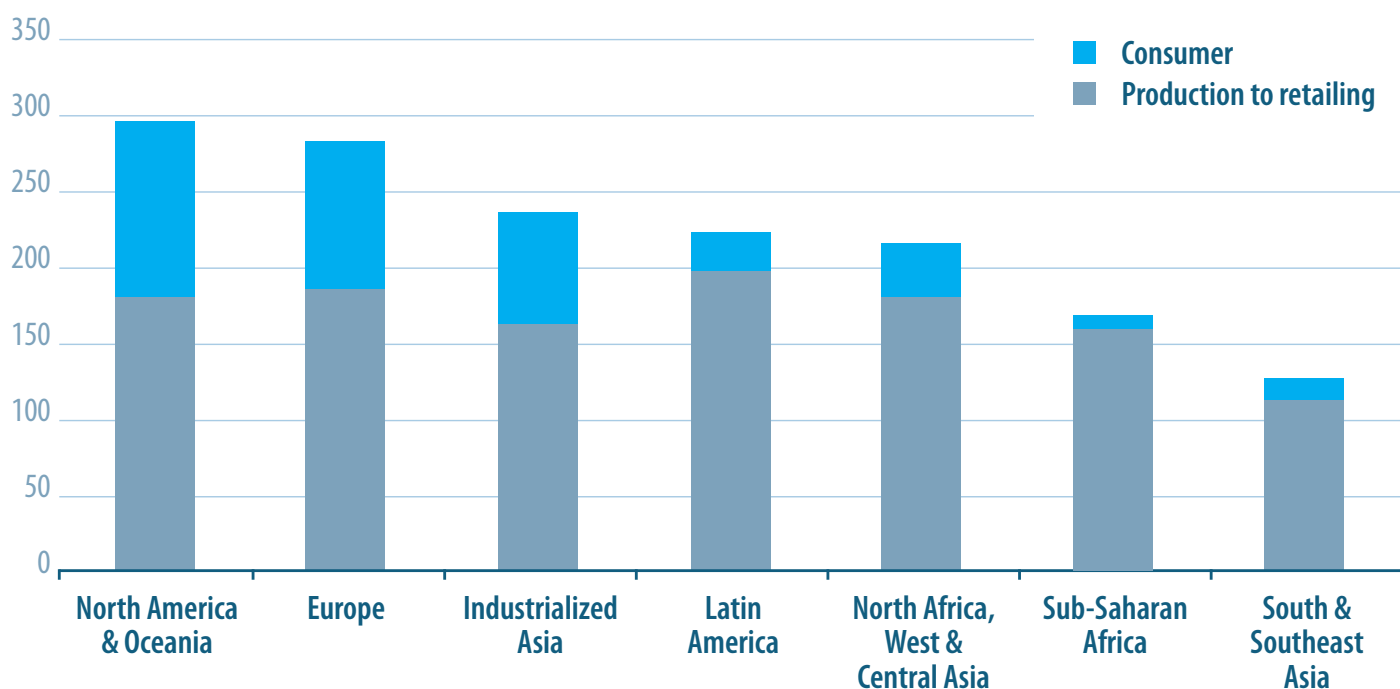
A number of approaches have been taken in quantifying food loss and waste in North America and throughout the world, and they differ in both methodology and scope. At first glance, these differences may seem confusing or daunting, but it may help to recognize that food loss and waste is a historically elusive topic that has been largely overlooked for much of the past century. Notable data gaps exist, and assumptions and estimations are thus necessary. Fortunately, interest in and concern about food loss and waste has accelerated of late, meaning that measurements are improving and we are continuously learning more about its

characteristics. This growing knowledge is leading to new opportunities and innovative solutions for minimizing food loss and waste.

Still, the availability and quality of data on food loss and waste in many regions remains problematic. Figure 1 shows differences between medium-/high-income countries and low-income countries, with more food being wasted per capita in medium-/high-income countries, and food loss and waste generally occurring from the production to retailing stages in low-income countries and at the consumer stage in medium-/high-income countries. However, these conclusions cannot be solidly substantiated due to a lack of household data in Africa and Asia (Gustavsson *et al.* 2013).

Figure 1

Per capita food loss and waste by region (Kilograms per year)



Source: Food and Agriculture Organization of the United Nations, 2011, Jenny Gustavsson *et al.*, *Global Food Losses and Food Waste: Extent, Causes and Prevention*, www.fao.org/3/a-i2697e.pdf. Reproduced with permission.

The recent CEC report on characterization of food waste in North America (CEC 2017) summarizes food loss and waste quantification efforts in North America, including three methodologies specific to Canada and four specific to the United States. These methods vary in the stages of the food supply chain and in the food types that are included, as well as in the approaches used to estimate food waste.

As a result, estimates of food loss and waste range widely: from 6 million to 13 million metric tons per year in Canada and from 35 million to 60 million metric tons per year in the United States. The CEC report details some of these differences; a critique of their relative merits is unwarranted as there is no truly “right” answer. Here, we rely on the food loss and waste characterization used in the CEC report, which is based on the methodology adopted by FAO (Gustavsson *et al.* 2013).

Figure 2 shows both the total and the per capita food loss and waste generated in the United States and Canada. While food loss and waste in the United States is much greater than in Canada in absolute terms, on a per capita basis the countries are similar. Note that the estimates in figure 2 are based on the FAO methodology, which relies on food loss factors estimated for geographic regions, not country-specific conditions. Thus, the same loss factors at each stage of the food supply chain were applied to both the United States and Canada, meaning that the differences in food loss and waste estimates for the two countries are due completely to differences in the amount and types

of food produced, manufactured and distributed. In addition, there is no distinction between distribution, retail and foodservice⁴ food loss and waste; all of these are aggregated as “distribution”.

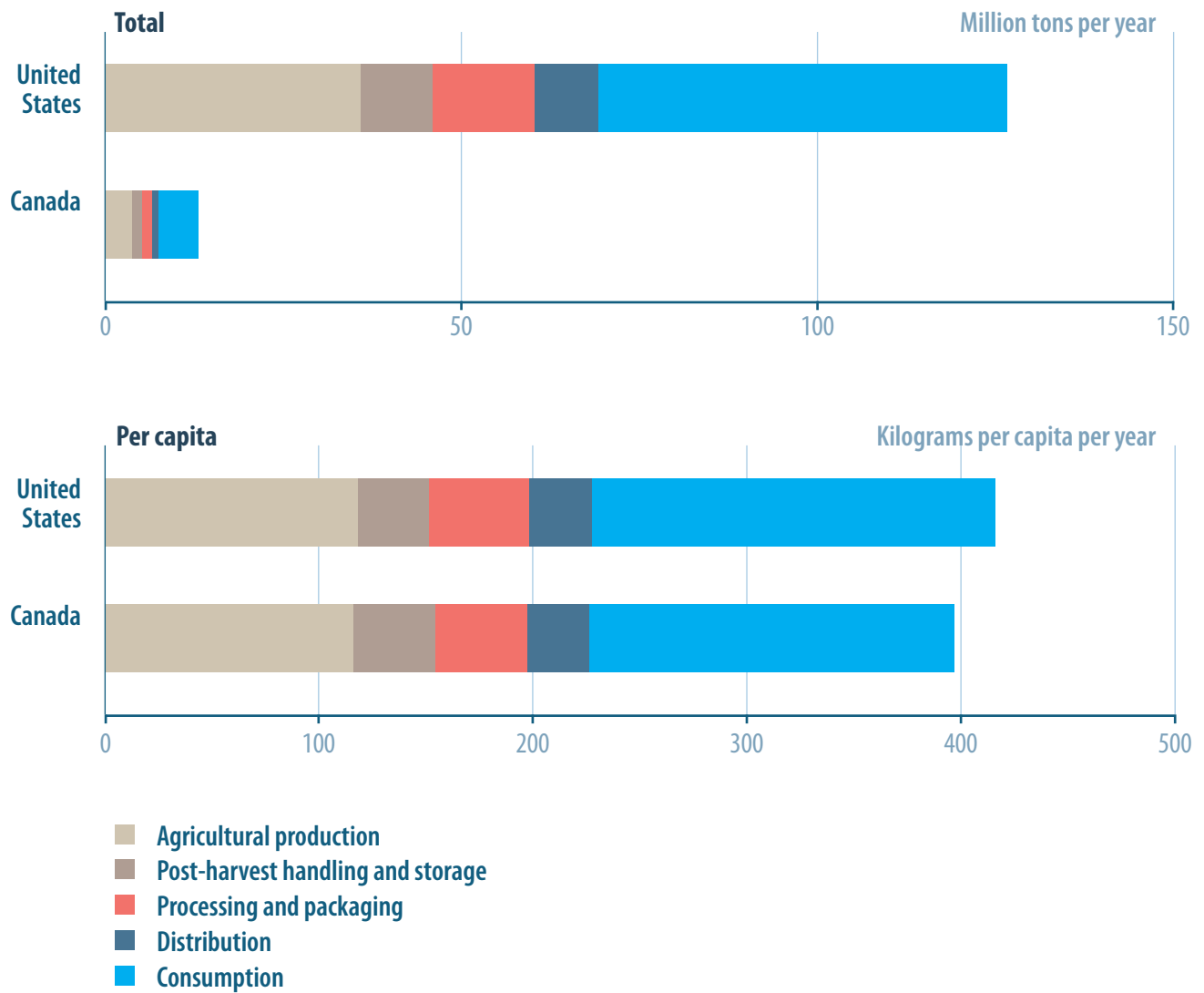
Finally, the estimates in figure 2 include losses of both food and its inedible parts (such as orange rinds and banana peels). An estimated 12 to 14 per cent of total food waste in the United States and Canada is considered inedible (CEC 2017). Such inedible parts likely cannot be avoided, nor can they be recovered through donation to food rescue programmes. On the other hand, reducing edible food waste by avoiding overproduction or over-purchasing also avoids inedible parts. Furthermore, “inedible” does not mean without value, and the division between edible and inedible is culturally determined and can change over time (including as a result of policy/awareness-raising). Efforts and innovations are under way that seek to valorize inedible parts both as feedstock for non-food items, such as biochemicals from citrus rinds, but also as novel food and feed products, such as flours from wine grape seeds.

Estimates of food loss and waste range widely: from 6 million to 13 million metric tons per year in Canada and from 35 million to 60 million metric tons per year in the United States.

4 “Foodservice” includes restaurants, cafeterias, catering operations, and other businesses, institutions and companies responsible for any meal prepared outside the home.

Figure 2

Estimates of food loss and waste across the food supply chain in the United States and Canada



Source: Adapted from CEC 2017. Supply chain definitions are provided in appendix A.

Food loss and waste is significant in North America, on the order of 30 to 40 per cent of the food available for human consumption, and the majority of food loss and waste occurs in the beginning (agricultural production) and end (consumer) stages of the supply chain.

The important take-home messages here are: 1) food loss and waste is significant in North America, on the order of 30 to 40 per cent of the food available for human consumption (CEC 2017), and 2) the majority of food loss and waste occurs in the beginning (agricultural production) and end (consumer) stages of the supply chain. Specific definitions of the supply chain stages are given in appendix A. Agricultural production includes losses during harvest as well as losses due to animal sickness and death, and accounts for about 30 per cent of the food loss and waste in figure 2. Food waste at the household level accounts for 43 to 45 per cent of the total food loss and waste estimates in figure 2.





2.

Life Cycle Thinking

"Life cycle thinking" involves broad consideration of a product's entire life cycle rather than a focus on just one stage, such as end-of-life management. Ideally, life cycle thinking also involves consideration of multiple environmental, social and economic concerns.

The “stuff” around us that supports and enhances our modern lifestyle – including the food we eat – typically goes through multiple stages in its journey to serve our needs: raw materials and resources must be extracted from the environment, converted and manufactured into a product, which is then distributed to an end user and used or consumed (often requiring additional resources), and then finally the product is discarded. These stages of a product’s life can be viewed as its life cycle, and each stage carries social and environmental ramifications.

A. Background and definition

Put simply, “life cycle thinking” involves broad consideration of a product’s entire life cycle rather than a focus on just one stage, such as end-of-life management. Ideally, life cycle thinking also involves consideration of multiple environmental, social and economic concerns. Such a perspective can be helpful in avoiding unintended consequences, re-evaluating “conventional wisdom”, choosing between products and prioritizing competing programmes. In short, life cycle thinking is a holistic way of thinking about the environmental and other effects of our actions when we design, purchase and use products and services.

As stated in the report *Greening the Economy Through Life Cycle Thinking* published by the UN Environment Programme (UNEP) and the Society of Environmental Toxicology and Chemistry (SETAC):

By considering a life cycle perspective, governments, businesses and civil society can create products, deliver services, implement strategies, policy instruments, and/or incentives that can purposefully lead society down the path towards a green economy. A life cycle perspective broadens our understanding of where along a product’s life cycle lie the greatest opportunities for environmental, social, or economic impact reductions. This allows decision makers to make choices that anticipate and optimally avoid any potential shifts of the environmental burden to other phases in the life cycle, to other impact categories, to other social groups, or in our globalized economy, to other regions of the world. In some cases, this can also help safeguard the security and livelihoods of future generations. (UNEP 2012)

Of course, life cycle thinking is not new. It has become an explicit part of the philosophy of numerous organizations including the US EPA (e.g., US EPA 2009) and UN Environment, whose Life Cycle Initiative⁵, launched in partnership with SETAC and industry partners, is over 15 years old. The USDA supports access and preservation of life cycle assessment data, tools and resources through the USDA Life Cycle Assessment Commons⁶. Multinational corporations such as Unilever, 3M and Nokia have adopted life cycle thinking as a critical component of sound business decisions. And it permeates much of the food loss and waste agenda. The US EPA’s commonly referenced Food Recovery Hierarchy, based on a broader materials management hierarchy, is grounded in a life cycle perspective (see figure 3 on page 20).

5 See www.lifecycleinitiative.org.

6 See www.lcacommons.gov.

Reducing the demand for food production by reducing food waste (top of the hierarchy) is a far more effective strategy for minimizing environmental impact than optimizing end-of-life management (bottom tiers of the hierarchy).

Evidence has shown that for most food products, the bulk of the environmental impacts occur earlier rather than later in the life cycle. By the time a material is ready to be discarded, it has already incurred most of its environmental burden. Thus, reducing the demand for food production by reducing food waste (top of the hierarchy) is a far more effective strategy for minimizing environmental impact than optimizing end-of-life management (bottom tiers of the hierarchy).

The intent to reduce excess or surplus food supply can be applied across the food value chain: to production (over-production), retail (overstocking) or food service (over-preparing). While often acknowledged, the simple fact that preventing waste is more environmentally beneficial than proper disposal is not always reflected in food loss and waste policy, programming and investments. To do so would be to truly embrace life cycle thinking.

Life cycle thinking is also an important gateway to developing circular economy approaches – moving away from the linear “make-use-dispose”

model of meeting our needs. A circular economy is an industrial system that is restorative or regenerative by intention and design. Closing the loop on wastes of all types is central to the idea of a circular economy, by rethinking and redesigning products and processes to minimize the use of virgin materials and to efficiently reuse, recover or regenerate materials at the end of service life.

Food production and waste is an area of particular concern in this new economic model. International efforts such as the Platform for Accelerating the Circular Economy, a cooperative effort between UN Environment and the Ellen MacArthur Foundation⁷, and national efforts such as the US EPA’s Sustainable Materials Management framework⁸ use life cycle thinking to better inform transitions towards a circular economy.

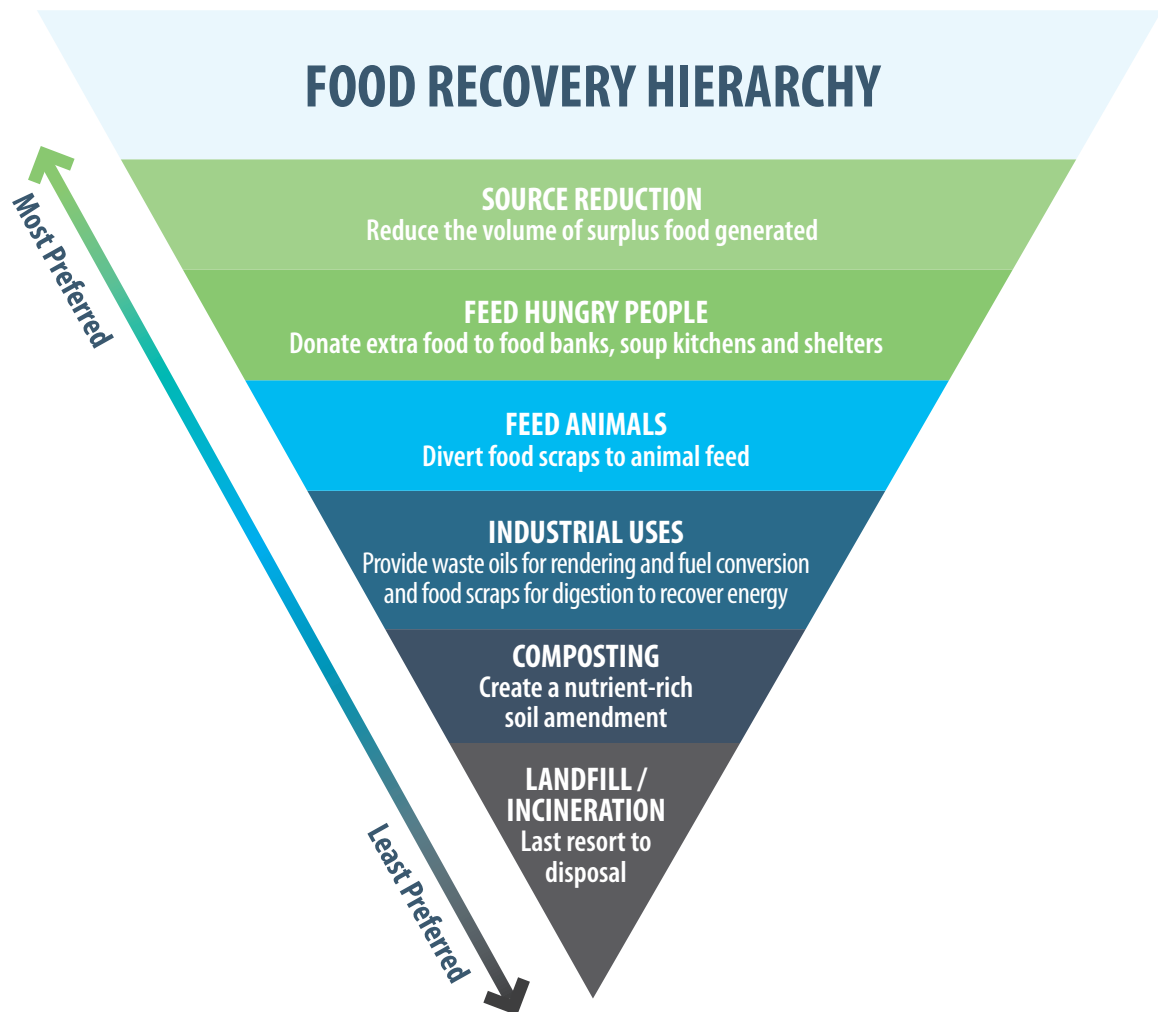
The simple fact that preventing waste is more environmentally beneficial than proper disposal is not always reflected in food loss and waste policy, programming and investments. To do so would be to truly embrace life cycle thinking.

⁷ See www.globalbusinesscoalition.org/global-governance-news/unep-irp-platform-accelerating-circular-economy-pace.

⁸ See www.epa.gov/smm.

Figure 3

The Food Recovery Hierarchy shows the preferred ordering of food loss and waste responses



Source: US EPA 2017.

B. The life cycle of food

Life cycle thinking in the food loss and waste area starts with an appreciation of the life cycle of food. Most of us understand that the majority of our food originates on a farm somewhere and often undergoes numerous processing and manufacturing steps before it is distributed to the grocery store or restaurant where we first encounter it. Wild-caught seafood and other wild-harvested foods may have a different origin story, but the basic life cycle of these foods is similar. Despite the large aggregation of farms and reduction in farm numbers in the United States and Canada over the past 50–60 years, these farms are still extremely diverse in size, outputs and management styles, and they exist in a wide range of biophysical and socioeconomic contexts, making generalizations difficult.

Yet the farm is only the starting point of the food life cycle. Figure 4 on page 22 offers a schematic representation of the food life cycle. Processing and manufacturing involves all of the necessary conversions from foods as they leave farms to the foods that we eat. Regardless of the level of processing, foods must be distributed from their place of origin to their place of consumption. For many modern foods, a cold chain (continuous refrigeration) must be maintained throughout this distribution and into retail. The “use” phase of food is where we actually eat it – whether in our homes or in cafeterias, restaurants or other food service establishments – but this also requires additional resources in the form of refrigeration and cooking.

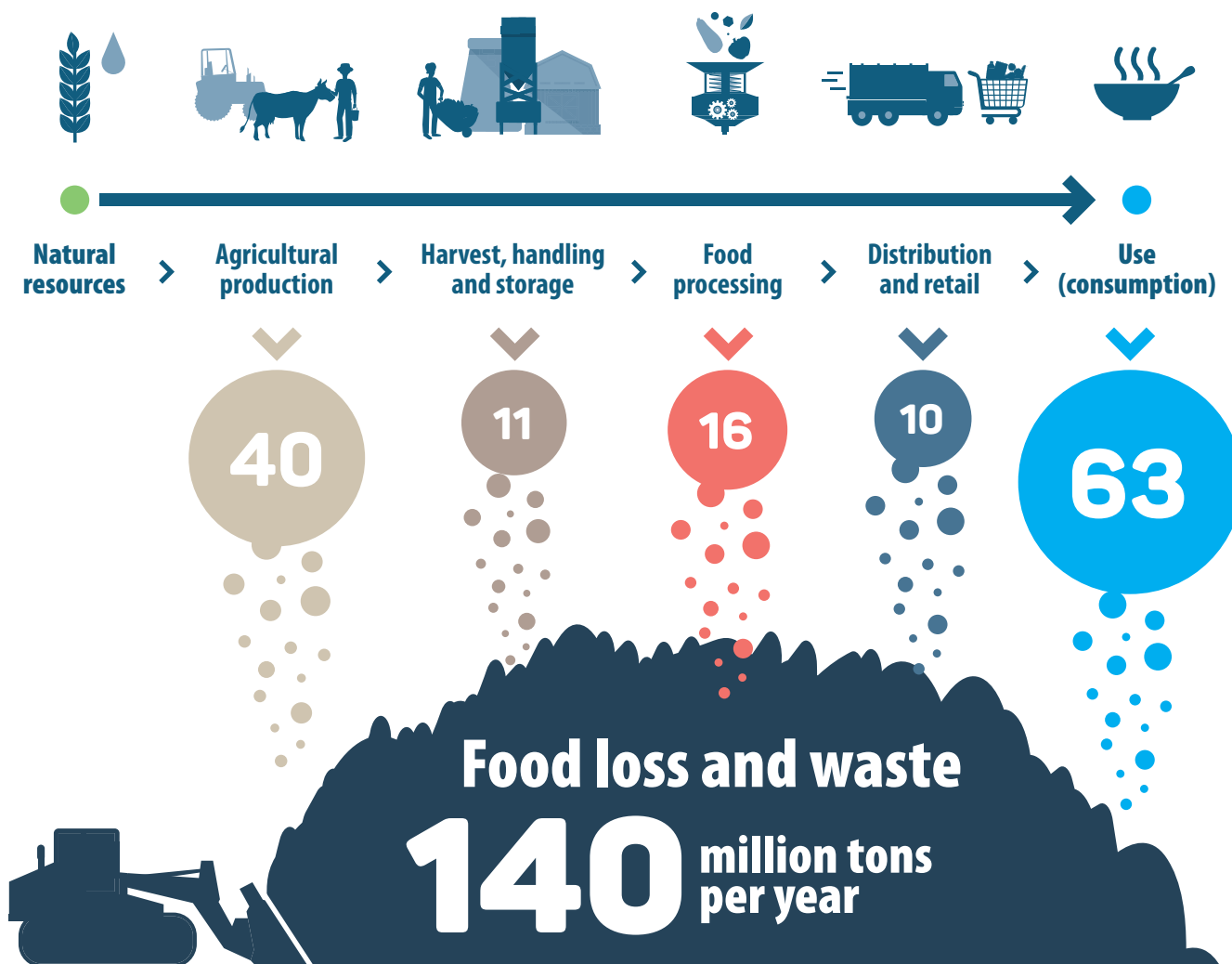
Finally, food that is not consumed, i.e., food waste, must be disposed of or otherwise managed, but different options have varying environmental and social implications. Consideration of this full life cycle of a product – from raw materials and resources to final waste management – is often referred to as a “cradle-to-grave” approach.



Source : Adobe Stock by © Irina

Figure 4

Graphical representation of a generic food life cycle with total North American food loss and waste shown at different stages



Note: Due to rounding of numbers, the total food loss and waste expressed in this figure is slightly higher than that expressed in figure 2 on page 15.
Source: Food loss and waste data from CEC 2017.

Take a moment to consider one impact – energy consumption – throughout this food life cycle. Sketch out, in your head or on paper, your best guesses of how the fossil energy consumed in the food life cycle is distributed across the stages in figure 4. Which stages do you think are the biggest energy consumers?

Now take a look at figure 5 on page 24: how does this estimate of the distribution of energy use in the US food system differ from your initial impressions? How does this influence your thinking about food loss and waste? Often, farm production or transport for distribution are thought of as the dominant energy consumers in our food system, but the data point elsewhere. Keep in mind that energy use is only one of many indicators of environmental, social and economic sustainability that might be considered in a holistic, systems perspective, and other indicators may offer complementary or contradictory conclusions. What additional information would you like to know in order to make an informed policy or programming choice? This is life cycle thinking!

Of course, food systems and food life cycles exist at multiple embedded scales – local, regional, national, international – and are deeply interconnected with other complex systems. Countless actors with a diversity of goals make decisions that shape the food system every day, and often these decisions have unexpected consequences far beyond the original intent. A recent report from the Institute of Medicine and the National Research Council of the National Academies explores the characteristics and structure of the US food system as a complex, adaptive system. The report offers an analytical framework that can be used to examine policies or changes in the food system (Institute of Medicine and National Research Council 2015). Deeply rooted in life cycle thinking, it serves as a valuable companion resource for considering the breadth of food system implications.

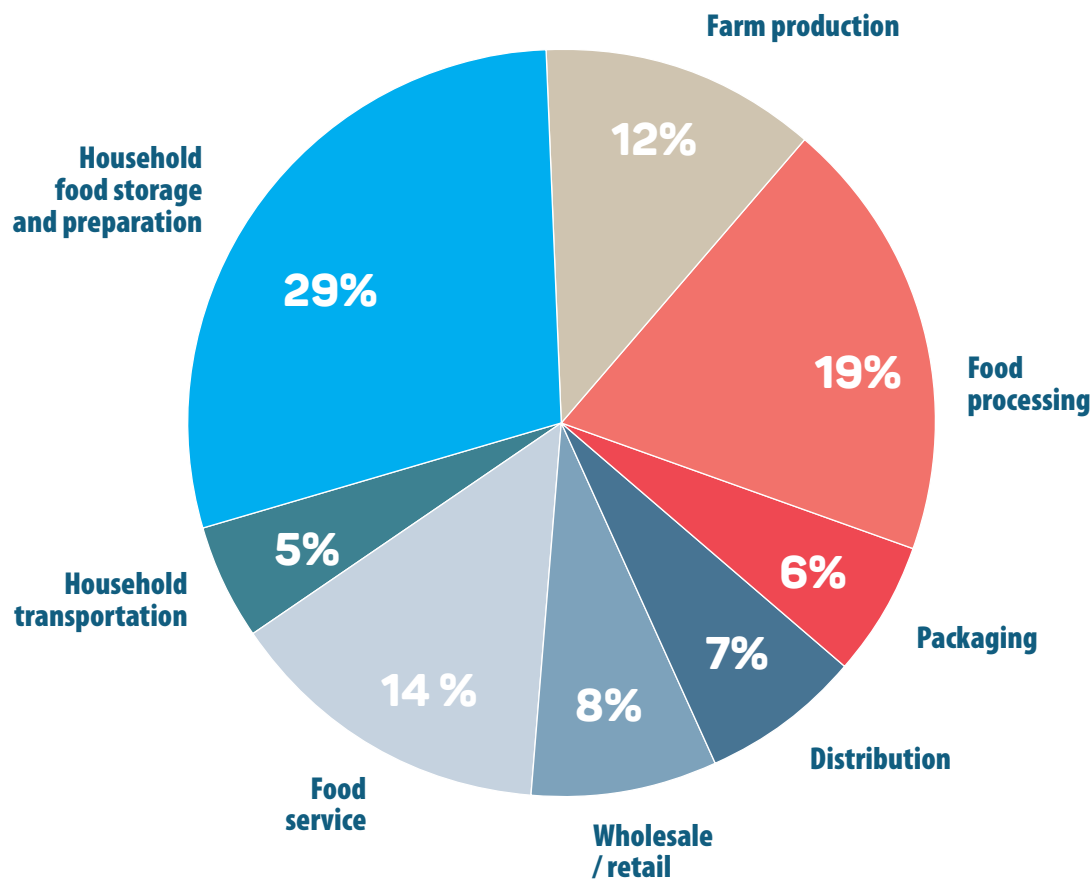


Source : Adobe Stock by © somegirl

When considering wasted food, it is critical to keep in mind that it has all of the embedded costs of food production without the direct social benefit of nourishing people. Wasted food utilizes land that can detrimentally affect biodiversity. Resources such as water, nutrients and fossil fuels are used in its production, and regional and global shortages of such resources are of increasing concern. Associated combustion of fossil fuels, along with emissions of other potent greenhouse

gases such as nitrous oxide and methane, contribute to climate change. Further, wasted food has the embedded costs of pesticides and other agricultural inputs that may impact ecosystems, including biodiversity loss and eutrophication from nutrient run-off (resulting in marine dead zones). A single act of scraping a plate of food into the trash bin can seem insignificant, but a life cycle perspective helps us remember the cumulative impacts of such actions.

Figure 5
Distribution of the annual energy used by the US food system



Note: Total energy used by the US food system is 11.9×10^{18} joules, or 12.5 per cent of the total national energy budget. Based on data from 2012.
Source: Adapted from Canning *et al.* 2017.



3.

Quantitative Evaluations Based on Life Cycle Thinking

Life cycle methodologies can be appropriate tools for the identification of win-win solutions, maximizing environmental impact reduction and economic resource efficiency.

Life cycle thinking becomes operational through life cycle management, an approach that puts into practice the tools and methodologies in the life cycle thinking basket. True to the old adage, “you manage what you measure”, many of the tools and methodologies that have evolved out of life cycle thinking are aimed at quantifying the impacts – whether they are environmental, social or economic – of a product or service in ways that can help inform decision-making.

This section summarizes some of those methodologies and their strengths and weaknesses in addressing food loss and waste topics. Table 1 offers an overview of the methods, with subsequent sections providing more detail. Consistent approaches are needed for the assessment of current impacts and future scenarios of food

loss and waste prevention, valorization and management. Life cycle methodologies can be appropriate tools for the identification of win-win solutions, maximizing environmental impact reduction and economic resource efficiency. The goal in this section is not to make the reader an expert in these methodologies, but to provide sufficient background to support informed review and discussion.

A. Life cycle assessment

Life cycle assessment (LCA) refers to the process of compiling and evaluating the inputs, outputs and potential environmental impacts of a product system throughout its life cycle (International Organization for Standardization [ISO] 2006a). In other words, it is a systematic accounting method based on a standardized framework and

Table 1

Summary of quantitative methodologies based in life cycle thinking

	Defining characteristics	Strengths	Weaknesses	Example applications in food loss and waste
Life cycle assessment (LCA)	Considers environmental impacts across life cycle from a product or process perspective	<ul style="list-style-type: none"> Evaluating environmental consequences associated with a given product or process Highlighting “hotspots” that warrant focused attention. Where are the largest burdens? Analysing trade-offs between stages of a product life cycle, environmental impact categories, societies/ geographic regions or generations Identifying unexpected consequences of a product or innovation Identifying “burden shifts” between environmental impact categories or across life cycle stages Comparing potential impacts between two or more products or processes 	<ul style="list-style-type: none"> Informs decisions, but other considerations must be made Requires additional tools/protocols to support action Indicates <i>potential</i> environmental impact Relative assessment method: cannot tell if a product is “sustainable” or “environmentally friendly” Data-intensive, time-consuming and costly Often only proxy data may be available Assumes linear scaling of technologies Often does not include important factors such as soil health Boundary-setting and methodological choices make comparisons across studies difficult 	<ul style="list-style-type: none"> Estimating environmental impact of wasted food via LCAs of food production Estimating environmental impact of wasted food via LCAs of food production Evaluating environmental implications of interventions and abatement strategies

Table 1 (continued)

Input-output life cycle assessment	Subset of LCA utilizing economic input-output models for a top-down assessment of sector-level environmental impacts	<ul style="list-style-type: none"> • Avoids the need to define boundary for analysis: includes full life cycle as represented by the economy • Based on economic activity, easily allowing inclusion of socioeconomic indicators • Typically requires less effort (time, cost) than process-based LCA • Generally provides consistency among studies 	<ul style="list-style-type: none"> • Data based on highly aggregated industry sectors; difficult to consider particular products • Tied to cost data, subject to market fluctuations • Notable time lags in data; i.e., representative year is usually “old” 	<ul style="list-style-type: none"> • Evaluation of the resources and environmental impacts embodied in food waste at the aggregated economy (i.e., that of a country) level • Investigation of the consequences (economic, environmental) of reducing food waste at different food supply chain stages
Material flow analysis	Quantifies the bio-physical flows and stocks of given materials or substances for a defined system	<ul style="list-style-type: none"> • Identifying opportunities for improved resource use efficiencies • Identifying potential problems due to undesirable stocks or flows • Identifying how material flows have changed with time or with interventions • Can be applied at different spatial and temporal scales 	<ul style="list-style-type: none"> • Does not evaluate environmental impact 	<ul style="list-style-type: none"> • Estimations of the quantity of food waste (in a city, country, region, globally)
Life cycle costing	Compilation and assessment of all costs related to a product over its life cycle	<ul style="list-style-type: none"> • Allows comparison of production costs with operation, maintenance and disposal costs • Promotes decision-making that accounts for costs • Can be integrated with environmental LCA to consider trade-offs between environmental and economic impacts 	<ul style="list-style-type: none"> • Standardization of methods currently lacking • Multiple “costing” perspectives possible (e.g., individuals, companies, society), adding difficulty to interpretation 	<ul style="list-style-type: none"> • Evaluation of economic costs of food waste management • Assessments of the costs (over the full food life cycle) of wasted food prevention • Identification of “win-win” solutions that maximize economic resource efficiency and minimize environmental impact
Social life cycle assessment	Applies concepts and principles of environmental LCA to consideration of the social and socioeconomic aspects of a product supply chain	<ul style="list-style-type: none"> • Identifying hotspots, trade-offs, burden shifts • Can aid in making the social impacts of long or distant product chains visible 	<ul style="list-style-type: none"> • Methods still in early stages of development • Limited by data availability 	<ul style="list-style-type: none"> • Consideration of the social value of an intervention (e.g., food rescue) relative to social impacts at other stages (e.g., farmworkers)
Life cycle sustainability assessment	Transdisciplinary integration framework evaluating environmental, social and economic aspects throughout the life cycle of a product or service	<ul style="list-style-type: none"> • Aids in understanding hotspots and trade-offs among and between economic, social and environmental metrics 	<ul style="list-style-type: none"> • Many critical methodological development issues remain 	<ul style="list-style-type: none"> • Evaluation of the “triple bottom line” (economic, environmental, social) of food waste and/or food waste prevention activities

terminology that is used to quantify the effects on the environment from the systems and stuff that meet our human needs. The focus in LCA is on a given product, process or service, and typically many different environmental impact indicators are considered (common indicators are described in appendix A).

This approach offers a means of benchmarking the environmental impact of a given product and promotes comparisons of impacts between products or processes that may differ significantly in form but provide the same function. LCA also allows identification of the largest burdens across a product's life cycle, pointing to areas deserving focused attention. It also can aid in tracking potential unexpected consequences or burden shifts – between environmental impact categories or across life cycle stages – when designs or scenarios change.

A more nuanced account of the environmental LCA methodologies is provided in appendix B, as these methods often provide the foundation for the other approaches described below. This detail may be useful to practitioners looking to better understand and interpret studies of interest or directing the design of their own studies.

While LCA can potentially encompass multiple environmental factors, often resource and data availability dictate a focus on a few key indicators such as greenhouse gas emissions or water use.

Life cycle assessment and the related methods described here are complex: they often require modelling of complicated systems and biophysical processes. They demand large amounts of data, often data that simply are not available. While LCA can potentially encompass multiple environmental factors, often resource and data availability dictate a focus on a few key indicators such as greenhouse gas emissions or water use. Assumptions are required to overcome limitations in data and other uncertainties. The LCA method is intentionally flexible to accommodate a wide range of applications, scopes and inquiries. Sometimes assessments are conducted at more of a “scan level”, as not all questions require a completely thorough accounting of every detail.

Because of all of these limitations, the depth, breadth and quality of studies called “life cycle assessment” vary widely. A good LCA is a difficult and wonderful thing; but it is important to recognize that not all LCAs are created equally.

B. Material flow analysis

Material flow analysis (MFA) is an analytical method to quantify flows and stocks of materials or substances in a well-defined system. A central tenet of MFA is the mass balance principle: the mass of all inputs equals the mass of all outputs plus changes in stock (either accumulation or depletion) within the system. While MFA shares some of the same approaches and principles as LCA, the primary difference is that MFA studies typically focus on a single (or a limited) collection of substances used in many different products, whereas in LCA, the focus is on the product or process and inventorying the multitude of associated materials and substances.

For example, MFA may consider the flow of nitrogen compounds through a city to better

understand pollution problems; inputs would include food, fuels like coal, etc., and outputs would include wastewater effluent, smokestack emissions, etc. Understanding the relative magnitudes of these flows could help focus attention on a problem area and suggest solutions. On the other hand, LCA would likely focus on a particular process such as the wastewater treatment plant, considering many different impacts (climate change, eutrophication, energy use) and look for ways to improve the process or compare it with an alternative.

Another primary difference is that MFA is concerned with the biophysical flows of substances – which can be specific chemicals, energy or water, materials like steel or timber, or products like cars or food – between and across systems, whereas LCA is also interested in assigning environmental impact to these flows. In MFA, system boundaries are fixed in space and time, considering material flows through a specific geographic entity for a certain period of time. In LCA, all relevant flows associated with a particular product are included, regardless of when or where they occur.

A strength of MFA is the ease at which it can consider different spatial and temporal scales. MFA could be used to track the flow of nitrogen compounds through a wastewater treatment plant, particular plastics through a company's various product lines, or fossil energy carriers through the US economy. Such analyses could be considered for a given day, or over a year; they could consider changes in flows over time. MFA can lead to improvements in resource use efficiencies, identify potential problems due to undesirable stocks or flows, or demonstrate how material flows have changed with time or with a particular intervention. Many approaches to estimating food waste are, in essence, applications of MFA. Consideration of the environmental

impacts associated with food waste is an example of MFA and LCA being used in complement.

C. Life cycle costing

Life cycle costing (LCC) is a compilation and assessment of all costs related to a product over its life cycle. It is a decision-making support tool that acknowledges that choices made in a design phase can greatly affect costs throughout the life cycle (operation, maintenance, disposal), not just the initial purchase or manufacturing cost. For example, typical architectural design may focus on upfront manufacturing costs, with consideration of material quality and longevity. But much of the cost associated with the life of a building occurs in its operation – heating, cooling, system energy needs, etc. LCC also may account for things like occupancy productivity, or loss of productivity due to maintenance shut-downs. In addition, many upfront design choices, such as the thermal envelope, passive solar features or building automation (think: occupancy detection lighting), have a strong influence on operating costs.

LCC accounts for all of these, typically discounted and adjusted to a net present value basis, supporting more informed economic decision-making. LCC can be used in complement with environmental LCA, and, in some instances, it is referred to as societal LCC and also may include the indirect costs due to environmental and other impacts. A recent systematic literature review of LCC methods applied specifically to food and food waste highlights the opportunities for using LCC to tackle food loss and waste issues, but also identifies a distinct need for standardization of modelling frameworks and methodologies (De Menna *et al.* 2018).

D. Social life cycle assessment

Social life cycle assessment applies the concepts and principles of environmental LCA to consideration of the social and socioeconomic aspects of a product supply chain (UNEP and SETAC 2009). Social LCA addresses issues of human rights, health and safety, economic livelihood and governance, among others, while also taking into account the utility of the product. It aims to assess both positive and negative social and socioeconomic impacts directly affecting stakeholders across the entire life cycle of a product or service. Social LCA has the same goal and scope requirements as environmental LCA. Many of the applications or outcomes are also similar: identifying hotspots and trade-offs, evaluating different scenarios, etc.

Social LCA may utilize quantitative (e.g., accidents per unit process), semi-quantitative (e.g., categorizing qualitative indicators into a yes/no or scoring system form) or qualitative (e.g., descriptions of measures taken to manage stress) data; those data may be site-specific or generic for a country, region or industry. Such data collection is a central challenge, as databases are currently limited; one notable effort is the Social Hotspots Database⁹. Social LCA should be considered a method still in its infancy. Still, social LCA frameworks, indicators, assessment methods and databases continue to develop and evolve (Petti, Serreli and Di Cesare 2018; Wu, Yang and Chen 2014), and it is broadly understood that the social pillar of sustainability also must be recognized and evaluated in the quest for sustainable development.

E. Life cycle sustainability assessment

Life cycle sustainability assessment (LCSA) is a transdisciplinary integration framework for evaluating all three pillars of sustainability – environmental, social and economic – throughout the life cycle of a product or service (Ciroth *et al.* 2011). It is in essence an integration of environmental LCA, LCC and social LCA and follows the same basic implementation framework represented in figure 10 (appendix B), albeit with a general broadening and deepening of mechanisms.

In theory, LCSA would help in understanding hotspots and trade-offs among and between economic, social and environmental metrics, but in practice, many unaddressed challenges and critical issues remain. These include methods development for: understanding the complex dependencies, interconnections and causal relationships between sustainability indicators; dealing with uncertainties during multi-criteria decision-making; and broadening the scope to include social, environmental and economic impacts at the regional and global level (Onat *et al.* 2017).

⁹ See www.socialhotspot.org.

4.

Applications of Life Cycle Assessment and Related Methods to Food Loss and Waste

Food losses contribute 1.4 kilograms of CO₂ eq. per capita per day (28 per cent) to the overall carbon footprint of the average US diet. Across the entire US population, this is equivalent to the annual emissions of 33 million average passenger vehicles.

From a sustainability perspective, waste represents an inefficient use of natural resources. Understanding current food loss and waste behaviours – where and why they occur – is the first step in addressing this inefficiency. Further, understanding the contribution of wasted food to natural resource use and environmental impacts can aid in motivating stakeholders and aligning interests for taking action. Adopting a life cycle perspective encourages policymakers and programme developers to consider the environmental aspects of the entire system, including activities that occur outside of the traditional waste management framework, as well as outside of cities and regions where wastes are generated.

Preventing food loss and waste is often the most beneficial outcome, but as reduction or recovery strategies become more sophisticated, they may present their own notable impacts. Evaluating such potential trade-offs will be critical for aligning intervention strategies with the ultimate intended outcomes of sustainable development. Once generated, the management of wasted food can present additional adverse impacts to the environment. Careful comparative assessment of alternative management destinations is important for minimizing these impacts.

This section provides a more directed view of how LCA and related assessment methods can help in answering these questions. The goal is to illuminate potential applications of life cycle approaches in the food loss and waste space and inspire such applications in a North American context. Research examples are provided not necessarily to supply answers but to provide a sense of what such studies can offer when applied to *your* context. In most instances where environmental LCA is applied, social LCA or life cycle costing could also be considered, if necessary data are available.

A. Estimating food loss and waste through material flow analysis

Many estimates of the quantity of food loss and waste in a given country or region are essentially examples of material flow analysis (MFA), whether acknowledged as such or not. For example, the FAO approach to estimating food loss (Gustavsson *et al.* 2013), which was used subsequently in the CEC report, begins with a “food balance” of food commodities in a given country. This food balance accounts for production within country, imports, exports, changes in stocks and utilization other than for human consumption. This is a mass balance for each food commodity for a given year in a given country. Loss factors at various stages in the food supply chain, which are informed by measurements or approximations based on waste composition analysis, records, surveys and the like, are then applied to estimate food loss and waste.

The core principles of MFA – well-defined scope and system boundaries and mass balance – are valuable in measurement of food loss and waste at any scale. The scope of food loss and waste measurements – the time frame, material types, destinations and geographic boundaries – can vary greatly depending on the goal of the quantification. However, for measurements to be effective, these aspects need to be determined as explicitly as possible. Mass balance principles can be an important approach to inferring food loss and waste in instances where direct measurement is not possible.

Importantly, with the exception of MFA, the other life cycle-based methods discussed in this report cannot provide additional information on the quantity of food wasted. However, many of the assessment approaches discussed below *are* dependent on the quality of the food waste data used. The principles of relevance, completeness, consistency, transparency and accuracy, as laid out in the Food Loss and Waste Accounting and Reporting Standard (Food Loss & Waste Protocol [FLW Protocol] 2016), are useful both in guiding food loss and waste measurement and evaluating the quality of existing data for a given application.

B. Environmental impact of food loss and waste

Often it is desirable to express the impact of food loss and waste (and the subsequent benefits of food loss and waste abatement) in terms of environmental indicators such as greenhouse gas emissions, water use, land use, etc. This can be useful in communicating the impacts of food loss and waste, aligning interests and stakeholders in addressing this waste and possibly prioritizing particular approaches to reduce it. Appendix D in the Food Loss & Waste Protocol offers an overview guide on expressing food loss and waste in terms other than weight (FLW Protocol 2016).

Measurement of the environmental and socioeconomic impacts associated with food loss and waste in North America is a focus of ongoing efforts by the CEC as well. Applying a life cycle thinking perspective to this task requires the consideration of the natural resources and environmental impacts associated with producing, processing and distributing wasted food, not just the impacts linked to waste management. Wasted food carries the same environmental burden through these upstream stages as food that is eaten, without providing any of the social “function” of supplying nutrition to people.

There has been a sizable increase in LCA studies of food product chains in the past decade, and one generalizable lesson to come from this scholarship is that, in most cases, the bulk of the environmental impact across the food life cycle occurs in the upstream stages. Based on the mean of all foods in a survey of LCA literature, presented in figure 6 on page 34, upstream stages (agricultural production through distribution) represent 82 per cent of the greenhouse gas emissions of the food life cycle. Thus, most of the greenhouse gas emissions connected with wasted food are actually due to the production of that food, not its disposal. This is the primary reason why source reduction – prevention of wasted food – has the greatest savings potential of the food recovery options in the hierarchy in figure 3.

A number of examples exist of using LCA data on the production of food to estimate the environmental impacts of food waste. FAO’s *Food Wastage Footprint* (FAO 2013; FAO 2014) estimates the global impact of food waste and concluded that annual food produced and not eaten has a carbon footprint of 3.3 gigatons of CO₂ eq., making food waste the third top emitter after the two countries the United States and China. The blue water footprint (consumption of surface and groundwater) of food wastage is 250 cubic kilometres (three times the volume of Lake Geneva), and food produced and not eaten occupies 1.4 billion hectares of land (30 per cent of the world’s agricultural land area) (FAO 2013).

FAO also conducted a full-cost accounting of the food wastage footprint and found that in addition to the \$1 trillion of economic costs per year, environmental costs reach around \$700 billion, and social costs reach around \$900 billion. The cost of the food wastage carbon footprint in particular, based on the social cost of carbon, is estimated to reach \$394 billion in damages per year (FAO 2014).

Figure 6

Greenhouse gas emissions associated with the life cycle stages of a variety of foods



Note: The figure demonstrates that emissions predominantly occur in upstream (production) stages. Red horizontal lines are the mean value of all data in the life cycle stage. Many of the LCA studies included here do not consider the full cradle-to-grave life cycle; hence, the decreasing number of data points in successive life cycle stages.

Source: LCA literature review described in Heller *et al.* 2018.

Another study connecting global food loss and waste to the greenhouse gas emissions associated with producing that wasted food also considered the historical trends in both food loss and waste and associated emissions (Porter *et al.* 2016). This study found that not only has the quantity of food waste increased, but emissions also have increased disproportionately due to shifts in diet.

Table 2 shows this trend over the 50-year period analysed in the paper. Economic development in China, which is the primary driver of change for the Industrialized Asian countries in table 2, has led to shifts to higher-calorie diets as well as shifts to more emission-intensive foods, such as beef. This study also confirmed earlier observations that food waste occurs more readily in downstream (consumer) stages in developed countries, whereas food losses on-farm and in handling are more prevalent in developing countries.

Not only has the quantity of food waste increased, but emissions also have increased disproportionately due to shifts in diet.

Heller and Keoleian (2015) estimated the greenhouse gas emissions associated with food loss in the United States based on data from the USDA's loss-adjusted food availability dataset. They found that food losses contribute 1.4 kilograms of CO₂ eq. per capita per day (28 per cent) to the overall carbon footprint of the average US diet. Across the entire US population, this is equivalent to the annual emissions of 33 million average passenger vehicles. The distribution of this food loss carbon footprint across food types is included in figure 7, shown in comparison to the distribution on the basis of total quantity, total dollar value and food energy (calories).

Table 2

Changes in per capita food loss and waste and associated greenhouse gas emissions, 1961 to 2011 (Percent increase)

Region	Per capita food loss and waste (mass basis)	Associated production-phase greenhouse gas emissions
Europe	5%	17%
Industrialized Asia ^a	123%	241%
North America and Oceania ^b	26%	10%
Latin America	53%	50%
North Africa, West and Central Africa	46%	53%
Sub-Saharan Africa	25%	30%
South and South-East Asia	62%	58%
World	36%	44%

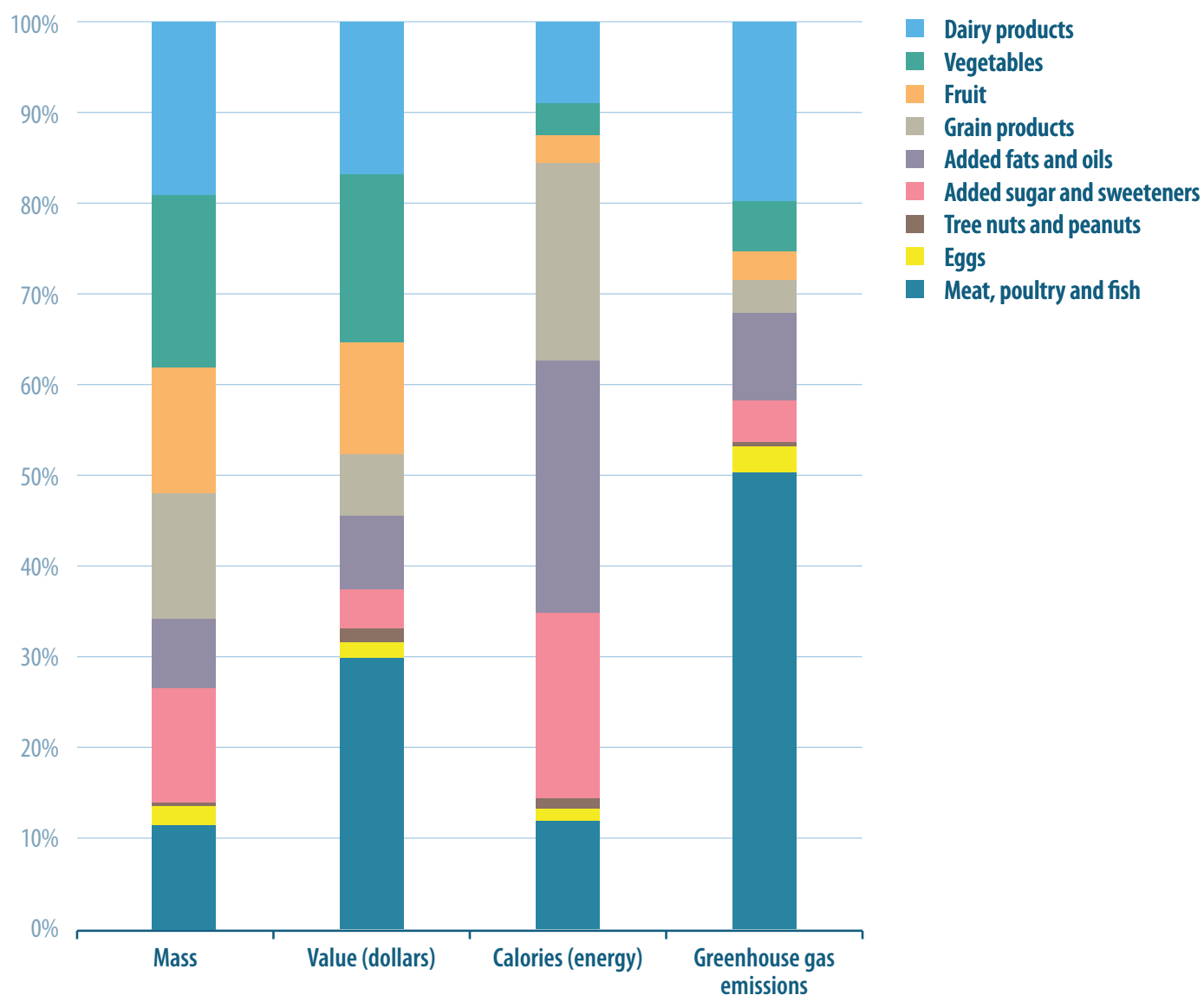
Source: Based on data included in Porter *et al.* 2016.

a Industrialized Asia includes China, Japan and the Republic of Korea.

b North America and Oceania includes Canada, the United States, Australia and New Zealand.

Figure 7

Distribution of US food loss by food group



Source: Adapted from Buzby, Farah-Wells and Hyman 2014, with greenhouse gas emissions added from Heller and Keoleian 2015.

A notable challenge in quantifying the environmental impacts of food loss and waste is determining which data and methodological approaches are most appropriate for a given application. The literature is rich in specific studies, but methodological expertise and caution are needed in making generalizations. To this end, a number of calculation tools, summarized in table 3, have been introduced or are in development to assist with providing screening-level estimates.

C. Comparing food waste management methods

Life cycle thinking helps us recognize that minimizing the generation of food loss and waste will lead to the greatest environmental benefit. Eliminating all food loss and waste is impossible, however, and the existing waste must be dealt with somehow. LCA is also an effective tool in comparing the environmental impacts connected with various food waste destinations (management methods). Such assessments must account for energy and resource use attributable to management processes (waste handling, compost processing, etc.) and emissions occurring in disposal methods (e.g., methane from landfills).

Table 3

Emerging quantification tools for measuring the environmental impacts of food loss and waste

Tool	Application area	Geographic relevance	Indicators	Developer	URL
Food Loss and Waste Value Calculator	Across food types, destinations and value chain stages	Global (with regional data when possible)	Greenhouse gas emissions, land use, water use, nitrogen and phosphorus equivalents, nutritional value	World Business Council for Sustainable Development, Quantis, World Resources Institute	www.flwprotocol.org/why-measure/food-loss-and-waste-value-calculator
Food Loss + Waste Toolkit	Food processing/manufacturing	Canada and beyond	Greenhouse gas emissions, electricity and water use	Provision Coalition	www.provisioncoalition.com/whatwedo/foodlosswaste
WARM	Waste reduction and management	United States	Greenhouse gas emissions, energy use	US EPA	www.epa.gov/warm
IMFO	Solid waste and solid waste management	Oregon, United States		Oregon Department of Environmental Quality	(in development)

In addition, some management methods generate products that have value elsewhere (e.g., electricity generation from anaerobic digestion, or compost as a soil amendment). An LCA also must account for these products, typically by “crediting” the system with the impacts associated with the product being displaced (e.g., electricity from a natural gas plant, or synthetic fertilizer). Because management methods can consist of dramatically different processes, proper definition of a functional unit that permits a fair comparison is crucial. Often this is a defined quantity (say one ton) of food waste disposed.

It also is important to note that the composition of food waste can greatly affect results. Because of this, systems preferable for management of traditional household food waste – which tends to be fairly wet because it is primarily perishable items – may be quite different from the management methods that would perform best with waste from an individual processing business such as a cereal manufacturer with predominantly dry matter.

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Food waste management has been studied extensively via LCA, including a number of comparative reviews of management systems (Bernstad and la Cour Jansen 2012; Laurent *et al.* 2014; Morris *et al.* 2014; Schott, Wenzel and la Cour Jansen 2016) and assessments that make direct comparisons between management options (Cristóbal *et al.* 2016; Edwards *et al.* 2018; Eriksson and Spångberg 2017; Eriksson, Strid and

Hansson 2015; Gao *et al.* 2017; Hodge *et al.* 2016; Opatokun *et al.* 2017; Salemdeeb *et al.* 2017a; Thyberg and Tonjes 2017; Vandermeersch *et al.* 2014). Here we summarize results from those studies in a North American context (Hodge *et al.* 2016; Morris *et al.* 2014; Thyberg and Tonjes 2017) as well as one very comprehensive study from Australia (Edwards *et al.* 2018).

The Oregon Department of Environmental Quality (OR DEQ) commissioned a study to systematically review and harmonize the LCA literature examining food waste management options (Morris *et al.* 2014). The study focused on greenhouse gas emissions, energy use and potential soil productivity benefits for four management methods: aerobic composting; anaerobic digestion; in-sink grinding (flushing to sewer and management with other sewerage at a wastewater treatment plant); and landfill. The resulting rankings of the four management strategies are summarized in table 4.

While this comparison is based on existing LCA literature, the researchers astutely addressed two important limitations. First, they “harmonized” results from various LCA studies by assuring consistent boundary conditions (what is included and what is not) and by applying consistent values for key parameters (aligned with conditions in Oregon), and then adjusting results accordingly. This is a primary challenge in comparing existing LCA studies, as often systems are modelled using local conditions such as electricity grid mix or landfill gas capture efficiency and utilization rates, and while these can influence results, they are by no means universal.

Second, the researchers recognized that LCA methods currently do not sufficiently address effects to soil quality or agricultural productivity of material outputs such as compost, anaerobic digestate or wastewater treatment biosolids. To overcome this, they developed a qualitative

Table 4**Ranking of food waste management options across multiple indicators, as reported**

Ranking from harmonized LCA studies			Qualitatively ranked soil productivity benefits ^a			
	Greenhouse gas emissions	Cumulative energy demand ^b	Soil carbon	Fertilizer replacement	Water conservation	Yield increase
Aerobic composting	2	4	1	2	1	1
Anaerobic digestion	1	2	2	1	2	1
In-sink grinding	3	1	3	3	3	3
Landfill	4	3	4	4	4	4

Note: The rankings use 1 for best and 4 for worst.

Source: Morris *et al.* 2014.

^a These metrics were included to evaluate the benefits associated with land application of composts and digestates: soil carbon (sequestration of carbon in soils promotes soil health and reduces net carbon emissions); fertilizer replacement (mineral nutrients in applied composts/digestates can substitute the use of synthetic fertilizers, reducing system resource intensity); water conservation (organic amendments can increase soil infiltration rates, reduce evaporation losses and increase soil water holding capacity); and yield increase (organic amendments have been shown to increase plant yields through multiple factors in addition to the previous three).

^b Cumulative energy demand considers the net energy use – both energy consumption and energy production or generation – across the life cycle. This also includes the embodied energy in materials such as plastics.

ranking based on the scientific literature on plant and soil productivity benefits of organic amendments. Introducing these additional indicators permits valuation of food waste treatment material outputs that might otherwise be undervalued in LCA comparisons.

The study by Hodge *et al.* (2016) focuses on “high food waste content industrial, commercial and institutional waste generators” (HFW-ICI), such as restaurants, hotels, supermarkets and conference centres. These HFW-ICI have become the target of laws to limit landfill disposal of food waste, as their discards commonly range from 36 to 75 per cent food waste. This study acknowledges that ignoring the non-food materials in evaluating management options is a notable omission because removing food from the conventional waste stream can affect the performance of management systems

(i.e., landfills and waste-to-energy perform differently without food waste because there is less organic material to convert to methane or energy). Therefore, they consider alternative waste management of the total HFW-ICI waste, which (in their study) includes 58 per cent food waste, in order to capture the interactions of food waste management alternatives with the larger solid waste management system.

The study considered food waste-to-landfill, waste-to-energy (or incineration), composting and anaerobic digestion, with the non-food fractions going to either landfill or waste-to-energy. Global warming potential (greenhouse gas emissions), fossil energy demand, eutrophication, acidification and photochemical oxidation impacts were all considered, and a range of typical US facility configurations and parameter sensitivities were

examined. The complexity of this study makes a complete summary challenging here, but the authors do offer a number of relevant policy implications:

- Results show that, in most cases, it is beneficial in terms of greenhouse gas emissions to divert food waste from landfill to anaerobic digestion, composting or waste-to-energy, but often not beneficial to divert food waste from waste-to-energy. The higher emissions when diverting food waste from waste-to-energy challenges the assumption that food waste diversion to composting or anaerobic digestion is always beneficial.
- The benefits of energy recovery are dependent on the greenhouse gas intensity of the regional grid that is being displaced. Therefore, regions with more carbon-intensive regional grids have more incentive to switch to anaerobic digestion or waste-to-energy, but these benefits decrease as electrical grids get cleaner.
- Sensitivity analysis on food waste material properties (moisture content, nutrient content, methane yield) suggests that these properties have a notable impact on the relative ranking of scenarios, and it could be beneficial to consider these characteristics when developing diversion policies.
- The choice of global warming potential time horizon was also found to significantly alter the rank of the scenarios. Global warming potentials (i.e., CO₂ equivalents) have been calculated based on the effects of a particular greenhouse gas over a set period of time; the relative magnitudes of these effects change depending on that time horizon. A 100-year time horizon is standard, but increasing interest in mitigation of short-term climate impacts may elevate the relevance of 20-year global warming potentials as a standard. The shorter time horizon emphasizes the impact of methane

and would make minimizing fugitive methane emissions at landfills a primary concern in waste management systems. Under the 20-year global warming potential, waste-to-energy performs best (considering only greenhouse gas emissions), making diversion of food waste from waste-to-energy even more counterproductive from the standpoint of greenhouse gas emissions reduction.

- Rankings were dependent on facility configurations, meaning that actual site-specific facility performance should be evaluated in decision-making.
- The above conclusions were based primarily on greenhouse gas emissions impacts. Fossil energy use, acidification and eutrophication generally followed trends in greenhouse gas emissions, but photochemical oxidation did not. Increasing waste-to-energy and anaerobic digestion could potentially increase photochemical oxidation impacts, meaning that trade-offs must be considered in setting food waste diversion policies.

Another study based in the United States analysed the environmental impacts of alternative food waste treatment scenarios for the town of Brookhaven, Long Island, a suburban New York municipality (Thyberg and Tonjes 2017). Brookhaven currently uses waste-to-energy incineration to dispose of all collected wastes; therefore, the goal of the study was to determine if food separation and diversion to composting or anaerobic digestion was beneficial to the baseline case. As in the previous example, this study also evaluated disposal of all residual waste – rather than just food waste in isolation – in order to capture system-wide impacts from alternative food waste treatments.

Differences between scenarios were small, as it was only the food waste portion of the municipal solid waste stream that varied (food was

13.4 per cent of municipal solid waste, with 70 per cent source-separation efficiency assumed). Rankings of the scenarios across impact categories are shown in table 5. In general, results indicate that source-separating food waste and treating it by anaerobic digestion offers the greatest reduction in overall environmental burden, but in some impact categories, the business-as-usual waste-to-energy scenario performs best. The authors acknowledge that LCA can support decision-making, but because it does not account for important factors such as local environmental impacts (e.g., odours, noise), working conditions, investment and maintenance costs, specific stakeholder concerns and full valuation of some outputs (such as compost), it must be used in conjunction with other tools.

The recent study by Edwards *et al.* (2018) used life cycle assessment to compare seven contemporary food waste management systems across eight environmental impact categories. This study has

many unique features: the baseline and many of the scenario operating parameters were informed by measured data at two Australian jurisdiction case studies. In addition to the commonly assessed food waste management alternatives of separate anaerobic digestion and centralized composting, this study also considers anaerobic co-digestion with sewage sludge both via food waste separation (and subsequent curbside pick-up) and in-sink grinding (and sewer delivery to wastewater treatment), home composting and mechanical biological treatment.

Ultimately, the study found that no scenario performed best across all impact categories and that trade-offs would need to be evaluated.

Table 5

Ranking of environmental impacts for alternative food waste management scenarios in Brookhaven, Long Island

Scenario	Climate change (greenhouse gas emissions)	Stratospheric ozone depletion	Terrestrial acidification	Terrestrial eutrophication	Freshwater eutrophication	Marine eutrophication	Depletion of fossil resources	Average ranking
All going to waste-to-energy	1.5	2.5	3.5	4	4	1	2	6
Tunnel composting and waste-to-energy	3	2.5	2	2.5	2.5	3	3	2.6
Windrow composting and waste-to-energy	4	2.5	3.5	2.5	2.5	4	4	3.3
Anaerobic digestion and waste-to-energy	1.5	2.5	1	1	1	2	1	1.4

Note: Score of 1 indicates best environmental performance. Ties were ranked as average of otherwise occupied rankings.

Source: Reprinted from *Journal of Cleaner Production* 158, K.L. Thyberg and D.J. Tonjes, The environmental impacts of alternative food waste treatment technologies in the U.S., Pages 101–108, Copyright 2017, with permission from Elsevier.

As some of these scenarios interacted with sewage sludge treatment and garden waste management, the boundary conditions for the study were expanded to avoid allocation and include these systems in all scenarios. The study did include credit for biogenic carbon sequestration for carbon pools remaining in landfill or the soil after 100 years. In addition, an uncommon level of sensitivity and uncertainty assessment was conducted, allowing a richer understanding of system behaviours and the reliability of the ranking.

Ultimately, the study found that no scenario performed best across all impact categories and that trade-offs would need to be evaluated. Anaerobic digestion-based systems did significantly outperform composting-based systems for global warming potential, even when accounting for carbon sequestration of compost, due largely to energy generation offsetting coal-derived electricity. As the authors indicate, “this study provides an important demonstration of how a municipality can incorporate LCA into their decision-making process, not only through baseline results but also by including market and technological uncertainties, to enable a more robust and justified selection.”

D. Evaluating interventions and abatement strategies

Another valuable application of LCA in the food loss and waste space is in evaluating potential trade-offs across the supply chain introduced by remediation or abatement strategies. Food systems are clearly complex; it is extremely difficult to anticipate all possible outcomes of even the most well thought out policy or programme aimed at reducing food waste or minimizing the environmental impact of food loss and waste management. LCA applied early in policy or programme design can aid in achieving environmental goals by identifying sensitivities

and offering a means of comparing alternative scenarios. In some instances, it may identify well-meaning programmes that simply do not provide environmental savings; even this may be a necessary trade-off as other goals may ultimately prevail, but acknowledging such trade-offs in decision-making should lead to better informed and executed programmes.

LCA applied early in policy or programme design can aid in achieving environmental goals by identifying sensitivities and offering a means of comparing alternative scenarios.

The following sections offer a few examples of LCA being applied to identify and evaluate potential interventions for reducing the environmental impact associated with food waste.

a. Collection and handling

Many of the studies comparing food waste management options include the collection and handling of source-separated food waste within the system boundary (Hodge *et al.* 2016; Thyberg and Tonjes 2017), although in general these transport impacts rarely have a large influence on overall system environmental impacts (Laurent *et al.* 2014). Sensitivity assessment performed by Thyberg and Tonjes (2017) suggests an increase of about 3 kilograms of CO₂ eq. per ton of waste managed (roughly 1.5 per cent of total system impacts) when transport distance between waste generators and treatment facilities increases from 11 kilometres to 400 kilometres (a 3,500 per cent increase in distance). While these relative effects are small, the cumulative impact over millions of tons managed can be notable. Such transport

impacts become more relevant in less population-dense areas and could become an important consideration for implementing food waste source separation and curbside pick-up.

b. Food rescue strategies

Incorporating food rescue – donations to assist the food insecure – into quantitative environmental impact accounting presents an interesting challenge. On the one hand, such food recovery may be seen as having the same environmental “benefit” as other food waste reduction measures: recovered and donated food has the same embodied resources as other food, and diverting it from becoming waste is certainly beneficial. On the other hand, it may be argued that such donations may not affect food production and therefore do not have the same reductions in life cycle environmental impacts as food waste prevention.

In addition, food recovery mechanisms – collecting, storing and distributing rescued food – introduce additional impacts that should be considered. In the examples summarized below, food rescue is treated as an alternative surplus food management option and is “credited” with source reduction benefits of the embodied resources and emissions from the production of food, with slightly different approaches taken in each study.

Reynolds, Piantadosi and Boland (2015) introduced an approach to compare food rescue to food waste management methods (composting and landfill) by treating charity food donations in Australia as a waste product within an economic input-output framework. The study found that every ton of food donated carries a “price” of US\$222, with the comparative price for landfill and composting being \$2.53 and \$47.37, respectively. This cost of donation is offset by the fact that each ton of edible food was worth on average approximately \$6,000, meaning that food with a

value of \$5.71 was rescued for every dollar spent on food rescue activities. An environmentally extended input-output analysis determined that every dollar spent on food rescue (in Australia) saved food that represented 6.6 cubic metres of embodied water, 40 megajoules of embodied energy and 7.5 kilograms of CO₂ eq. of embodied greenhouse gases.

Another study compared food waste management scenarios available to supermarket retailers in Sweden by considering five specific food products (bananas, tomatoes, apples, oranges and sweet peppers) and four management scenarios: incineration, anaerobic digestion, conversion and donation (Eriksson and Spångberg 2017). Here, “conversion” involved collecting unsellable but not inedible fruit/vegetables and making it into a salable chutney product in a central kitchen. Donation involved collection every weekday by a charity organization, with redistribution to a mixed group of people with various economic means.

This study adopted a “system expansion” approach, meaning that the systems were credited for the “products” created (energy from incineration, biogas and digestate from anaerobic digestion, chutney from conversion and edible food from donation) by considering the alternative production of the products being displaced. “Conversion” displaced other chutney sold at the supermarkets, whereas because of the diversity of customers served, the donated food was assumed to replace different foods depending on target groups.

Figure 8 compares the greenhouse gas emission results across scenarios, showing re-use approaches (conversion and donation) outperforming the approaches with energy recovery (incineration and digestion). Note that the moisture content in specific foods greatly impacts energy recovery (only bananas and

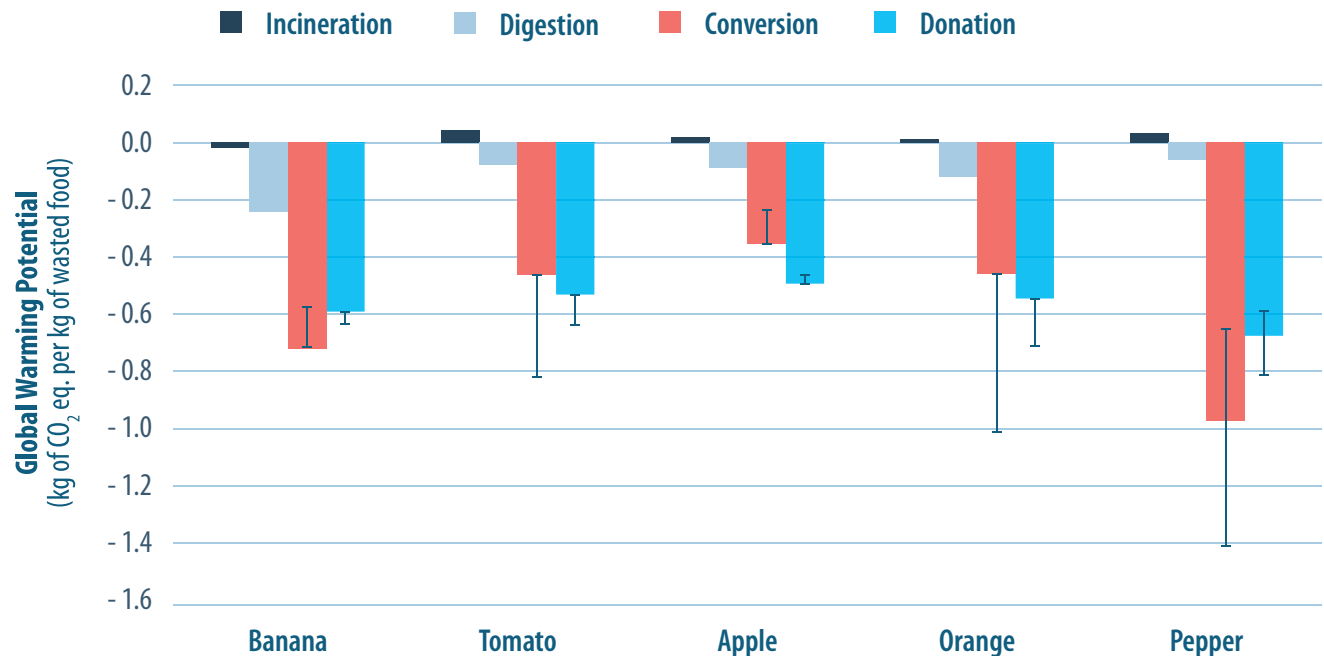
oranges were dry enough to have net energy recovery benefits), and the results also were highly dependent on the product(s) being replaced via the system expansion method. Further, results were influenced by the relatively low greenhouse gas emissions associated with the Swedish electricity grid.

In identified literature examples, transport of donated food has minimal influence on system performance, even in seemingly extreme cases of daily pick-up via passenger vehicle (Eriksson and Spångberg 2017). There may be further extreme examples, however, where such transport

effects become noticeable. In addition, storage impacts such as refrigeration were not taken into account. A further concern may involve the nutritional quality of donated foods: food rescue organizations are often inundated with sugary carbohydrate foods such as donuts and pastries or other foods that may not supply the nutritional needs of their clients. Including a measure of nutritional quality, which in itself is challenging (see Heller, Keoleian and Willett 2013), as part of the functional unit in LCA studies of food rescue programmes may offer a different insight into potential trade-offs.

Figure 8

Comparing greenhouse gas emission impacts of donation versus waste management of specific produce items



Note: For these fruits and vegetables, re-use approaches (conversion and donation) outperform approaches with energy recovery (incineration and digestion).

Source: Reprinted from *Waste Management* 60, M. Eriksson and J. Spångberg, Carbon footprint and energy use of food waste management options for fresh fruit and vegetables from supermarkets, Pages 786–799, Copyright 2017, with permission from Elsevier.

c. Food packaging and food waste trade-offs

The primary function of packaging is to protect and distribute the right product to the right end user in a safe, cost-efficient and user-friendly way (Grönman *et al.* 2013). It should be of no surprise, then, that food packaging plays a major role in the control of food waste. A statistical examination of municipal solid waste composition found that, in the United States from 1960 to 2000, as the use of packaging materials increased, the fraction of food waste in municipal solid waste decreased, and this correlation held over many countries (Alter 1989).

Yet, there is a commonly held belief that food packaging constitutes unnecessary solid waste and that packaging should be reduced whenever possible. Between 75 per cent and 90 per cent of consumers in the United Kingdom believe that discarded packaging is a greater environmental issue than food that is wasted (Cox and Downing 2007). Among organized efforts to reduce food waste in the supply chain, limited attention (exceptions include organizations such as WRAP (WRAP 2013)) has been given to the potential contribution of packaging.

The food packaging industry has embraced sustainability efforts, yet businesses usually only highlight environmental performance improvements due to packaging material reductions or increased use of renewable materials. Opportunities abound for packaging and its functions to significantly influence the amount of food wasted in households. In one Swedish survey sampling, 20 to 25 per cent of food waste was related to the packaging design attributes (Williams *et al.* 2012). Food packaging holds potential for reducing waste in the food supply chain, but packaging optimization approaches do not always take into account the environmental impact of food waste (Wikström *et al.* 2018). In other words, packaging systems are not always optimized to minimize environmental impact.

In some cases, food losses can be reduced while also reducing the environmental impact of the package, but often it will be necessary to increase the impact of packaging in order to reduce food loss and waste.

While packaging materials have environmental impacts just as any other consumer product, they often are relatively small compared to the impacts of the food within the package. In some cases, food losses can be reduced while also reducing the environmental impact of the package, but often it will be necessary to increase the impact of packaging in order to reduce food loss and waste (Wikström and Williams 2010). This presents a potential balancing act between the environmental impacts of the food that is wasted (and thus the environmental benefits from reducing food waste) and the environmental costs of producing and disposing of the package itself. A systems-based approach can assist in identifying situations where this trade-off results in a net environmental benefit for the food production/distribution system.

The hypothetical basis for this packaging / food waste environmental trade-off has been well demonstrated in the literature (see introduction in Heller, Selke and Keoleian 2018), and a number of case studies also have been published, although these studies are often limited by the use of generic or hypothetical data. In fact, identifying and obtaining specific data regarding packaging functions that influence food waste is a primary research gap in realizing packaging strategies that save food *and* reduce system environmental impact (Wikström *et al.* 2018).

A recent study attempts to map the influence of food waste in food packaging environmental performance by considering the life cycle of a range of foods and typical packaging configurations (Heller, Selke and Keoleian 2018). The study used commodity-specific retail- and consumer-level food waste rate estimates and included impacts of food production, packaging production, distribution (including refrigeration), retail, transport to home and home refrigeration, and packaging waste management.

Figure 9 shows how greenhouse gas emissions are distributed across life cycle stages for the different food/packaging combinations. Examples in figure 9 are ordered (from left to right) by the contribution from food production (light blue). On the left side of the figure, the contribution from packaging (yellow and grey) tends to be a larger percentage of the total.

The ratio of the food production environmental impact to the packaging production environmental impact is an important parameter in considering food waste / packaging trade-offs. In situations where this ratio is large (i.e., the impact of producing the food is much greater than producing the packaging, such as with beef or pork), there is greater opportunity for changes in packaging configurations aimed at food waste reduction to result in net system decreases in environmental impact, even when packaging impacts increase. This ratio offers a scan-level indication of the opportunities for packaging-mitigated food waste reduction to result in net reductions in greenhouse gas emissions. Of course, emissions are not the only environmental consideration, and taking into account other issues such as water use, toxicity or resource depletion may paint a different picture.

In general, research conducted to date suggests that there is notable opportunity for optimized packaging systems to reduce food waste;

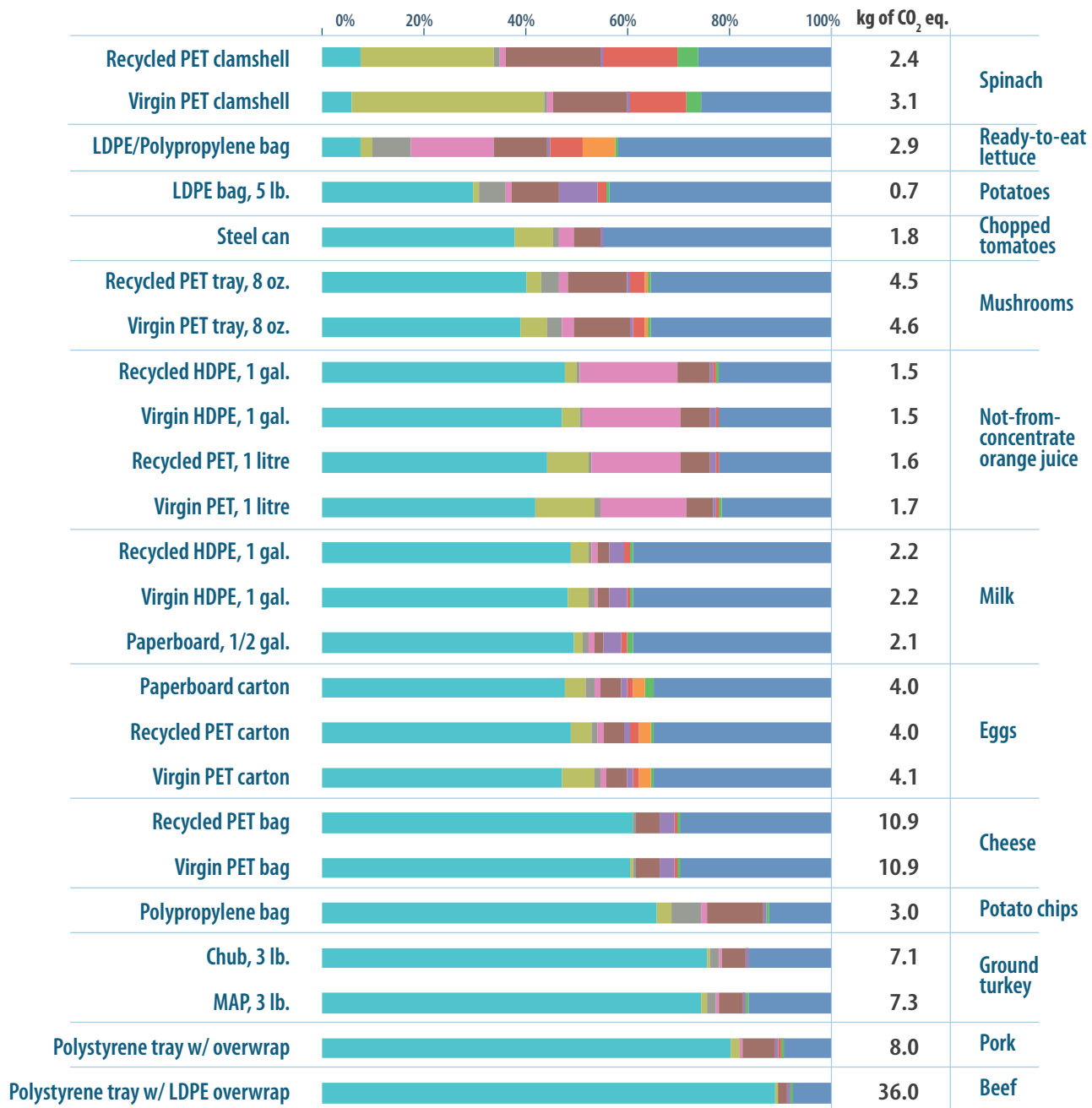
maintaining a life cycle perspective through such efforts will help to assure net system benefit, but a number of concerns remain. A road map report to reducing food waste in the United States estimates that packaging adjustments alone have the potential to divert 189,000 metric tons of food waste annually, with an economic value of \$715 million, and active or intelligent packaging aimed at slowing spoilage offers an additional potential 65,000 metric tons diverted (ReFED 2016). Yet, a number of challenges must be addressed in realizing these benefits, as outlined in Wikström *et al.* (2018), including improving packaging design processes to also consider reducing food waste and considering stakeholder incentives to reducing food waste.

There are environmental concerns such as marine debris that are not adequately captured in current assessments. Many, if not most, food packaging innovations involve plastics; the significant impact of plastics in our oceans and waterways continues to become more apparent.

In addition, there are environmental concerns such as marine debris that are not adequately captured in current assessments. Many, if not most, food packaging innovations involve plastics; the significant impact of plastics in our oceans and waterways continues to become more apparent (UNEP 2016). Yet, to date, LCA and related methods do not have an effective way to account for these impacts, as the flows of plastics from consumer product and service systems to the environment, as well as the specific impacts to the environment,

Figure 9

Contributions to greenhouse gas emissions for a variety of food and packaging configurations



Note: "Edible food waste contribution" includes emissions associated with edible retail- and consumer-level food waste accumulated throughout the life cycle.

Abbreviations: PET, polyethylene terephthalate; LDPE, low-density polyethylene; HDPE, high-density polyethylene; MAP, modified atmosphere package

Source: Heller, Selke and Keoleian 2018.

are problematic to identify and quantify (Quantis 2018). Without quantifiable metrics, it is difficult to assess and value such trade-offs. Experts in LCA are teaming with other key stakeholders to address these gaps in current understanding.

d. Rebound effects

Food waste prevention has been repeatedly demonstrated as the preferred management solution. Most studies, however, do not include indirect considerations such as the rebound effect. The rebound (or income) effect recognizes that the household economic savings from preventing food waste, i.e., avoiding extra food purchase, may be spent on purchasing other goods or services associated with environmental impacts (Martinez-Sanchez *et al.* 2016). The modelling details of these rebound effects are beyond the scope of this report, but the studies that have incorporated these effects into estimates of the environmental benefits of food waste prevention demonstrate that the effects can be substantial.

One such study considers household food waste in the United Kingdom and finds that the rebound effect may lessen greenhouse gas emission savings from food waste prevention efforts by up to 60 per cent (Salemdeeb *et al.* 2017b). Another study analyses the life cycle costing of food waste management in Denmark and concludes that if monetary savings from food waste prevention are spent on low-impact services such as health care, education or insurance, then food waste prevention still results in reduced environmental impacts relative to waste management scenarios including incineration, anaerobic digestion or use as animal fodder (Martinez-Sanchez *et al.* 2016).

On the other hand, if savings are spent on high-impact goods and services such as “housing”, “communication” and “leisure” (as defined in the study), food waste prevention can have significantly greater environmental impacts than the waste management scenarios (Martinez-Sanchez *et al.* 2016). Both studies conclude that food waste prevention measures should be accompanied by efforts to allocate savings towards lower-impact goods and services in order to assure net environmental savings. Some evidence from the United Kingdom suggests that around half of the household financial savings from reduced food waste was spent in “trading up” to higher-value foods (Britton *et al.* 2014).

The rebound (or income) effect recognizes that the household economic savings from preventing food waste, i.e., avoiding extra food purchase, may be spent on purchasing other goods or services associated with environmental impacts

Rebound effects have been largely overlooked or neglected in research conducted to-date, and they have the potential to significantly change the outcome of current understandings of food waste reduction. Additional work is needed to better understand these effects as well as to design policy approaches that help avoid their negative consequences.



5.

Life Cycle Thinking Applied to Food Loss and Waste: Success Stories

*A collection of case studies representing
North American institutions of various types and
scales...serve as examples of life cycle thinking
being applied effectively in addressing
food loss and waste.*

As should be apparent from the previous sections, life cycle thinking and the various life cycle-based analysis approaches offer a valuable decision-informing framework when applied to efforts to minimize impacts of food loss and waste. This section identifies a collection of case studies representing North American institutions of various types and scales that serve as examples of life cycle thinking being applied effectively in addressing food loss and waste.

A. Oregon Department of Environmental Quality

Life cycle thinking and LCA have been embedded in the approaches of the Oregon Department of Environmental Quality for more than a decade and have been central to its concerted effort to shift from waste management to sustainable materials management. The *2050 Vision for Materials Management in Oregon* (OR DEQ 2012) lays out both a desired future and a framework for action, acknowledging that actions taken upstream – in design, production and consumer demand – often offer the best opportunities to reduce natural resource use and environmental impact. This Vision and the materials management approaches that it demands have led to a number of concerted efforts to apply life cycle methods to food loss and waste in Oregon.

a. Food waste management

OR DEQ commissioned a study (summarized in section 4 of this report) to systematically review and harmonize the LCA literature examining the four most common food waste processing technologies (Morris *et al.* 2014) in order to inform waste recovery efforts across the state with the best available science. The high-level results from this project, presented in table 4 on page 39, allowed OR DEQ to embrace anaerobic digestion as an environmentally sound, and perhaps preferred, food waste management option. The

study also clearly demonstrated the inferiority of food waste landfilling in comparison to other management options.

b. Changing the conversation: Prevention over recovery

In 2017, OR DEQ published *Oregon DEQ Strategic Plan for Preventing the Wasting of Food*, a manifesto with a key objective of explicitly shifting the conversation from “food waste” to “wasted food” – i.e., moving from “acceptable disposal” to “concern with wasted resources and nutrients”. The impetus for this strategic plan is based soundly in life cycle thinking and an understanding of the environmental impacts associated with our food system, as demonstrated by LCA. The following quote from the *Strategic Plan* captures this motivation:

What is largely missing from the traditional response to wasted food is a full consideration of the upstream environmental impacts embedded in that lost food and attention to a hierarchy that gives clear preference to source reduction over other options. In other words, what is missing is consideration of food as a valued material, and therefore the wasting of food, from a materials management viewpoint. (OR DEQ 2017, p. 4)

The *Strategic Plan* celebrates the growing public discourse around food waste, but laments the fact that much of the conversation has focused on waste management solutions and efforts to recover energy and nutrients in food loss and waste. OR DEQ’s *Plan* emphasizes the need to step out of a solid waste legacy that defines success as diversion of materials from landfills, a legacy established before much was known about the life cycle impacts of food:

If governments, academic institutions, and entrepreneurs achieved more balance between solid waste recovery (recycling) AND efforts to drive more sustainable patterns of production and consumption through source reduction, communities could waste less and feed more people without the need to convert new lands into cultivation for the production of food. There is significant opportunity to rethink existing systems and approaches. However, because some choices depend, in part, on the way in which problems are stated, these sustainable production and consumption opportunities are overlooked when reducing wasted food is framed simply as conserving landfill space or reducing landfill methane generation. Therefore, while “source reduction” is an expressed priority in the wasted food hierarchy, it is rarely acted on. (OR DEQ 2017, pp. 5–6)

The *Strategic Plan* goes on to identify goals for preventing the wasting of food, including a 15 per cent reduction in Oregon by 2025 and 40 per cent by 2050, and identifies priority activities necessary to achieve those goals. This has led OR DEQ to invest significant resources into prioritizing prevention over recovery. Supported efforts completed to-date include qualitative interviews of Oregon residents (Moreno, McDermott and Billings 2017) and statewide phone surveys of Oregon households (Elliott, Johnson and Conklin 2017) to better understand how food is purchased, used and disposed of, as well as the drivers that contribute to the generation of preventable wasted food. That research informed a more involved study of 72 Oregon households that paired surveys, food waste diaries and waste sorts to explore the quantities, types and causes of wasted food. It was accompanied by a parallel study that explored a variety of food waste prevention interventions through 15 non-residential case studies.

Understanding gained through this research is informing messaging and outreach activities and leading to directed programming. OR DEQ has already developed a “shelf-ready” campaign (“Wasted Food Wasted Money”) that local governments can use for outreach to area businesses. An upcoming residential-facing messaging research project will lead to a similar campaign aimed at households. Partnerships with the Oregon Restaurant and Lodging Association and local governments are establishing a separate educational campaign (“Food Waste Stops With Me”) for restaurant and lodging businesses.

OR DEQ has recently refocused its solid waste grants programme to fund a number of food waste prevention efforts. A screening-level LCA of school milk distribution options conducted by OR DEQ found that bulk milk dispensers significantly reduce milk waste and environmental impacts when compared against individual cartons. OR DEQ also championed a regional collaboration that resulted in the states of California, Oregon and Washington; the province of British Columbia; and the cities of Oakland, Portland, San Francisco, Seattle and Vancouver (BC) committing publicly at the 2018 Global Climate Action Summit to a regional goal of halving food waste by 2030.

These efforts may seem antithetical or inappropriate for a Department of Environmental Quality under a traditional, single-issue lens of “landfill diversion”. However, with a clearly established materials management mandate and a strategic plan to prevent wasted food, they are necessary and logical steps in achieving a goal that is informed by life cycle thinking.

c. Food rescue

Also stemming from the *Strategic Plan* aim of changing the conversation around wasted food, OR DEQ is addressing the need to better understand the relative value and impact of

diverting food from various sources (farms, groceries, restaurants) directly to organizations that serve food-insecure populations. OR DEQ historically has provided significant support to food rescue activities primarily through grants to local governments and non-profit organizations.

Within a materials management framework, however, it is necessary to recognize that not all edible food rescue programmes are the same: the economic, social (nutritional) and environmental implications of food rescue efforts likely vary depending on the source and on the infrastructure necessary to get the rescued food to the people in need. Further, limited research is available that explicitly addresses potential trade-offs. To this end, OR DEQ is conducting an LCA on edible food rescue that will compare foods rescued directly from farms with rescue efforts such as from retailers and restaurants. The study also will consider a range of transport scenarios as well as the financial costs of different food rescue strategies, and qualitatively explore the nutritional content of rescued food and the degree to which it fills the nutritional needs of target populations.

B. Food loss and waste cost-share programme for Canadian food and beverage manufacturers

Provision Coalition¹⁰ is a coalition of 16 industry associations representing the Canadian food and beverage manufacturing industry. It is a public policy collaboration group directed at making food sustainably and facilitating economic growth and resiliency within the food and beverage sector. The Coalition has acknowledged that many of the key sustainability issues facing their industry must be addressed in collaboration across the entire food value chain. Food loss and waste is one such issue, and goals have been set to help the Canadian food and beverage manufacturing industry move towards Sustainable Development Goal 12.3.

10 See www.provisioncoalition.com.

In a recently launched programme, Provision Coalition has partnered with the Canadian Centre for Food Integrity¹¹ to offer an innovative cost-share programme aimed at tackling food loss and waste in Canadian manufacturing facilities and to raise awareness of the issue. Available to 50 Canadian food and beverage manufacturers, the programme identifies and implements measurable solutions for the prevention and reduction of food loss and waste, with cost reimbursement scaled based on the number of employees. In addition to having access and training with Provision Coalition's Food Loss + Waste Toolkit and Key Performance Indicator Dashboard, participating companies will work directly with the environmental engineering firm Enviro-Stewards¹² to identify (at least) three distinct and actionable prevention and reduction opportunities within a facility.

The life cycle thinking wrapped up in this programme is apparent in the way its key facilitators talk about the process. An important challenge and opportunity identified by Provision Coalition was simply the awareness of a food loss and waste problem. As Cher Mereweather, executive director of Provision Coalition, noted, manufacturers were saying, "I don't have any food waste in my facility, I divert it all!" This echoes the need for a change in the conversation identified by OR DEQ.

Food and beverage manufacturers are commonly basing the economic impacts of food loss and waste on the cost of disposal rather than on the cost of production.

11 See www.foodintegrity.ca.

12 See www.enviro-stewards.com.

Bruce Taylor, president of Enviro-Stewards, shares that much of their work is about catalysing a mindset shift. Food and beverage manufacturers are commonly basing the economic impacts of food loss and waste on the cost of disposal rather than on the cost of production. His team helps manufacturers consider how much their product is worth right before it is lost. This shift in economic accounting can help give food loss and waste reduction projects much shorter returns on investment and, in most cases, also results in notable environmental as well as social (in terms of food calories) savings.

A number of valuable case studies have already been amassed and are documented on the Provision Coalition website¹³. For example, a food waste prevention assessment at Campbell's Company of Canada found that food waste reduction measures could increase the yield of the Toronto facility by 938 tons per year, valued at \$706,000. The net payback period for the interventions was less than six months. One intervention involved an optical vegetable sorter: sliced-and-diced carrots and potatoes were processed with an optical sorter to remove blemished vegetables, resulting in collateral losses of good-quality vegetables of 799 tons per year. Reprocessing or reducing the speed of the optical sorter reduced these losses by two-thirds, avoiding 537 tons of food waste and saving \$227,000 in raw ingredient costs annually.

The Food Loss + Waste Toolkit¹⁴, developed by Provision Coalition and based on Enviro-Stewards' food waste prevention approach, is worth detailing specifically here, as it quantifies the impacts of food loss and waste from a life cycle perspective. Food Loss + Waste Toolkit 2.0 is a user-friendly platform for quantifying food waste, assisting

in identifying root causes and solutions, and quantifying net savings and payback periods. The tool also provides an output in terms of environmental and social impact, quantifying greenhouse gas emissions, electricity, natural gas and water reductions as well as calories and meals saved through food loss and waste reductions.

C. US Environmental Protection Agency's Waste Reduction Model (WARM)

The impetus for the development of the Waste Reduction Model (WARM) by the US EPA comes out of a life cycle materials management paradigm. This paradigm acknowledges that since traditional environmental policies focus on controlling "end-of-pipe" emissions, they do not provide a means for systematically addressing environmental impacts associated with the movement of materials through the economy. While end-of-pipe policies are often effective in controlling direct pollution, they may result in some environmental impacts being overlooked or shifted from one area of the life cycle to another (US EPA 2009).

WARM is a tool designed to help managers and policymakers understand and compare the life cycle greenhouse gas and energy implications of materials management options (recycling, source reduction, landfilling, combustion with energy recovery, anaerobic digestion, composting) for materials commonly found in the waste stream. Since the first documentation report of the WARM tool was published in 1998, it has been regularly updated and improved, with version 14 released in March 2016 (US EPA 2016). Version 14 of WARM includes 54 materials, products and mixed categories, 9 of which are food waste.

WARM is designed to compare the emissions and offsets resulting from a material in a baseline

¹³ See www.provisioncoalition.com/Resources/FoodWaste/foodlosswastelibrary.

¹⁴ See www.provisioncoalition.com/whatwedo/foodlosswaste.

scenario with an alternative management pathway. The current model contains emission factors for beef, poultry, grains, bread, fruits and vegetables, and dairy – along with weighted average categories of “food waste”, “food waste (meat only)” and “food waste (non-meat)”. Alternative management pathways include source reduction (the avoidance of wasted food), composting, combustion with energy recovery, anaerobic digestion and landfilling.

The WARM model is a freely available public tool. While municipalities across the United States (and beyond) may be using the tool to support decision-making, this usage is difficult to track.

a. Application: Grow Compost of Vermont LLC

Grow Compost of Vermont is a food scrap hauling and composting business. To better communicate with its customers the benefits of participating in its hauling service, Grow Compost began using the WARM model to estimate environmental savings. Grow Compost records the quantity of food scraps collected from each customer: hospital cafeterias, schools, ski resorts, food cooperatives, restaurants and other food service establishments. Grow Compost then uses the WARM model to calculate the greenhouse gas emissions reductions and energy savings from diverting those food scraps from landfill.

These benefits are communicated back to the customer in the form of a certificate and talking points for use in social media, outreach and business promotion. While early compliance with Vermont’s Act 148, which bans the landfilling of all food scraps by 2020, may be a motivator for some, other customers simply believe that keeping food scraps out of landfill is the right thing to do. But as Carolyn Grodinsky, accounts manager of Grow Compost, pointed out, often the very act of separating food scraps (for pick-up) raises awareness of food waste and leads to exploring options for reduction.¹⁵

b. Application: NRDC and Trillium Asset Management

In a 2017 issue brief, the Natural Resources Defense Council (NRDC), an international non-profit environmental organization, and Trillium Asset Management, an independent investment adviser devoted to sustainable and responsible investing, lay out the case for investors as to why it is important for businesses to address food waste and to be accountable and transparent around food waste issues (Pearce and Berkenkamp 2017). The brief summarizes the consequences of wasting food, the associated business risks that could impact financial performance, guidance on prioritizing corporate action, and best-in-class examples of corporate leadership.

When it comes to demonstrating the environmental rationale for prioritizing action according to the Food Recovery Hierarchy (see figure 3 on page 20), these organizations used reliable data from the WARM model. The WARM model allows quantification of the life cycle greenhouse gas emissions avoided by shifting wasted food management methods. The clear take-home from these data is that prevention offers an order-of-magnitude benefit over any waste management option, making prevention the top priority.

D. Innovations in food waste upcycling: An entrepreneurial medley

Innovators across the continent are proving that energy generation and composting are not the only way to extract value out of discarded food. “Upcycling” refers to the process of transforming by-products, waste materials or otherwise unwanted products into new materials of better quality and higher value. Upcycling food entrepreneurs see food waste – typically pre-consumer food waste – and creatively transform it

¹⁵ See www.growcompost.com.

into a product with market value. In recent years, there has been an explosion of start-up companies doing just that: according to ReFED's Food Waste Innovator database¹⁶, only 11 such companies existed in 2011, and as of late 2018 there were 69.

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While these start-ups may be just scratching the surface of the food waste problem, they are helping to change the marketplace landscape and the business model for food upcycling, according to professor Jonathan Deutsch, founder of the Food Lab at Drexel University's Center for Food and Hospitality Management and Department of Nutrition Sciences. The Food Lab has become the go-to research and development resource for food upcycling entrepreneurs trying to navigate regulation and policy in a food system that has not really been designed to "re-use" surplus food (Beurteaux 2018). But Deutsch and his Food Lab team also work with large, multinational food companies, which have been paying close attention to the business models of upcycling start-ups, and many are now reconsidering the nutrition that is put in the garbage or compost bin in big factories and attempting to turn this into consumer products (Dewey 2017).

Food upcycling strikes a harmonic chord from a life cycle thinking perspective. The USDA and Agri-Food Canada support research and development of innovative new products made from otherwise wasted food or food production by-products. Here, we highlight a few examples of food upcycling.

16 See www.refed.com/tools/innovator-database.

San Francisco's ReGrained turns spent brewer's grain into nutritious and delicious snack bars. But not all food upcycling needs to produce food for humans: BioLogiQ in Idaho Falls, Idaho makes bioplastics out of waste potato starch, and Enterra in Langley, British Columbia converts pre-consumer food waste into highly nutritious feed for livestock and pets using fly larvae.

a. ReGrained

ReGrained was born out of a beer homebrewing habit in college. The beer brewing process extracts sugars from grains but leaves behind proteins, fibre and micronutrients. Founders Dan Kurzrock and Jordan Schwartz discovered that the spent grains that they had been hauling to the dumpster could be used to bake bread, which they began selling to cover brewing costs – free beer! They quickly realized that converting spent grains into nutritious food had much more potential than free beer, and in 2013 they piloted the first ReGrained granola bar. The bars caught on, their business grew, and their techniques and recipes improved.

Today, ReGrained uses a special technique, developed with assistance from the USDA's Albany, California lab, to produce what it calls "SuperGrain+" flour from the spent brewer's grains. Because the brewing process removes the starchy sugars, what is left is highly concentrated fibre and protein, making it an ideal ingredient for specialty foods. ReGrained puts the SuperGrain+ into its nutrition bars, but sees endless possibilities for its use in a variety of functional foods. Plus, the company is creating a positive solution for the brewing industry to handle what is often considered waste.¹⁷

b. BioLogiQ

The US state of Idaho grows a lot of potatoes, many of which are processed into chips and French fries.

17 See www.regrained.com.

Inevitably, not all of the potato becomes chips or fries, leaving waste starch. BioLogiQ founder Brad LaPray grew up among those Idaho potato fields, and after 20 years as an engineer and manager in various manufacturing companies, he returned to Idaho with a vision of using that waste potato starch to make a better plastic.

Potato starch has many industrial uses, and bioplastics made from starch are nothing new, but BioLogiQ's version, called NuPlastiQ®, introduces a number of key innovations. NuPlastiQ BioPolymers overcome many of the quality limitations of previous thermoplastic starches that prevented them from being used in some applications. They are designed to be blended with conventional petroleum-based plastics, and when blended with traditional polyethylene, the resulting thin films are significantly stronger than polyethylene-only films. This means that it is possible to reduce the thickness of films (by up to 30 per cent), using less plastic to do the same job.

Pure NuPlastiQ biodegrades very quickly in industrial composting conditions, but a surprising finding is that monolayer films of NuPlastiQ blended with non-degradable plastic will biodegrade completely in about a year (both the NuPlastiQ and conventional plastic portion) in an environment that is rich in microorganisms. The first commercial product containing NuPlastiQ was introduced in 2015: "Tater Made®" plastic bags for marketing fresh potatoes. Many of the applications for NuPlastiQ displace some of the petroleum-based plastics in a product rather than replace them completely. In addition, biodegradability under industrial composting conditions does not assure that the plastics will not persist in a natural environment if unintentionally released. Still, such innovations towards better plastics are a step in the right direction towards solving multiple critical issues.¹⁸

18 See www.biologiq.com.

c. Enterra Feed Corporation

Located near Vancouver, Canada, Enterra is, in essence, an insect farm. The company's "livestock" of choice is the black soldier fly, an indigenous beneficial insect found throughout North America and the world. The adult black soldier fly is an innocuous critter: it does not eat, sting or bite. The larvae, on the other hand, make up for their parents' fasting by voraciously devouring decaying organic matter. Enterra feeds these hungry larvae pre-consumer food waste from grocery stores, markets, food distributors and food processors in a controlled environment. After a few weeks, the larvae are "harvested" (heated and dried) and turned into feed for poultry, aquaculture or pets. Black soldier fly larvae are superb at converting food waste into high-quality protein and fat, and the resulting products are a natural, sustainable and often cheaper alternative to resource-intensive feed ingredients like fishmeal, fish oil, soybean meal and palm oil.

Approval of Enterra's novel products on federal listings of acceptable animal feeds has been a slow process, but as of February 2018, the company's larvae meal became the first insect meal product to be approved in North America for the aquaculture industry (Fletcher 2018). Previously, Enterra's whole dried larvae product had been approved in both the United States and Canada for poultry and fish feed, and applications for additional markets are under way. The manure from the black soldier fly larvae is also marketed as an excellent organic fertilizer. Demand for these novel products is high: the production facility in Langley, British Columbia is at maximum capacity, and a second, larger facility is under way near Calgary (Leung and Vickerson 2018). But Enterra has lofty goals: "Our mission is to secure the world's food supply," said marketing manager Victoria Leung (Tamminga 2015).¹⁹

19 See www.enterrafeed.com.



6.

Conclusions, Recommendations and Next Steps

In an era of divisive politics, food loss and waste remains largely non-partisan.

Stakeholders at all scales – local, state/provincial, national, regional and international – and across the food value chain from farms and food processors to distributors, retailers and consumers are aligning to tackle what all can see as an inefficiency worth addressing.

Food loss and waste is a societal challenge that urgently needs addressing both in North America and around the world. In an era of divisive politics, food loss and waste remains largely non-partisan. Stakeholders at all scales – local, state/provincial, national, regional and international – and across the food value chain from farms and food processors to distributors, retailers and consumers are aligning to tackle what all can see as an inefficiency worth addressing. Appropriately, such efforts begin with the “low-hanging fruits”: for example, education campaigns to raise awareness and (hopefully) change the behaviours that contribute to food waste, or policy and legislation to keep food waste out of the landfill.

As with nearly all issues embedded in complex systems, however, often “good” solutions for food loss and waste are elusive, thorny and have competing aspects. For example, while most existing LCA studies point to nearly any alternative food waste management having better environmental performance than landfill, it is expected that landfills with methane capture will perform differently in the absence of food waste.

Further, there can be big differences between environmental performance of landfill diversion scenarios, such as anaerobic digestion versus composting, suggesting that landfill bans also should consider promoting preferred options. Composting and anaerobic digestion systems are far from uniform, and environmental performance can vary widely depending on the particulars of system design, feedstock and even climate. An alternative framework for viewing the problem can aid in sorting through these options, identifying novel solutions and informing decision-making. Life cycle thinking and related approaches offer one such framework.

Creating actionable opportunities for source reduction of food loss and waste...may require allowing (or encouraging) stakeholders to step out of their conventional roles and perspectives, to seek non-traditional partners and to be open to solutions that do not comfortably fit within disciplinary or jurisdictional boundaries.

Life cycle thinking encourages us to consider the problem of food loss and waste across the full food value chain – through the full life cycle of food. It reminds us that while concern for food waste disposal is warranted, the majority of the impacts or “costs” of food loss and waste, whether environmental, social or economic, occur much earlier during food production, processing and distribution. This encourages focus on the top tier of the food recovery hierarchy: source reduction.

While widely acknowledged as a priority, creating actionable opportunities for source reduction of food loss and waste may require reframing the problem and redefining success in a way that acknowledges food as a valuable material resource. It may require allowing (or encouraging) stakeholders to step out of their conventional roles and perspectives, to seek non-traditional partners and to be open to solutions that do not comfortably fit within disciplinary or jurisdictional boundaries. For example, surveying consumers on their food purchase, preparation and disposal behaviours may seem out of place for a waste management division of an environmental

agency. Yet, under a strong materials management directive and in support of food waste reduction goals, these activities cohere well with the mission of Oregon's Department of Environmental Quality.

A life cycle perspective also helps demonstrate how reducing food loss and waste can contribute to other conservation or emission reduction goals. Talking about "tons" of food waste reduced tends to limit appreciation of the impacts of food waste: we can imagine not having to haul that waste, or the landfill space potentially saved. Using life cycle assessment to translate food loss and waste reductions into the natural resource use and environmental impacts avoided throughout the life cycle of that food – the land, water, energy, greenhouse gases, etc. associated with food production, processing and distribution – helps to align goals. Such a perspective brings clarity to the fact that achieving food loss and waste reduction goals also supports other critical societal goals such as resource conservation and emission reductions.

Life cycle assessment can be a valuable tool for informing choices among...alternative disposal solutions. But the first question needs to be, "is there a feasible way to reduce the source of this food loss or waste?"

An additional emerging conclusion from this analysis is that, often, solutions start with acknowledgement of a problem, or at least acknowledgement that things could be better than the status quo. Sometimes, this simply requires seeing "wasted food" as any food that is not eaten, rather than only food that ends up in the landfill. Surely, eliminating all food loss and waste is an impossible goal, and there are excellent solutions for extracting value such as energy and nutrients from food waste.

Life cycle assessment can be a valuable tool for informing choices among these alternative disposal solutions. But the first question needs to be, "is there a feasible way to reduce the source of this food loss or waste?" The work of Provision Coalition is an excellent example of this change in perspective within the Canadian food and beverage manufacturing industry. Life cycle-based analytical tools can help demonstrate whether these source reduction opportunities lead to the ultimate goal of net reductions in costs and impacts, thereby contributing to the improved human livelihoods, reduced environmental impacts and prosperous economies envisioned by the United Nations' Sustainable Development Goals.

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Appendix A: Terms and Definitions

Definitions of terms in the food loss and waste space are not always consistent. Attempts have been made to be inclusive in the definitions presented here, but in places where discrepancies exist, definitions as provided in the Food Loss and Waste Accounting and Reporting Standard (FLW Protocol 2016) are used.

Food (edible): Any substance – whether processed, semi-processed or raw – that is intended for human consumption. “Food” includes drink, and any substance that has been used in the manufacture, preparation or treatment of “food”. “Food” also includes the above material when it has spoiled and is therefore no longer fit for human consumption. It does not include cosmetics, tobacco or substances used only as drugs. It does not include processing agents used along the food supply chain – for example, water to clean or cook raw materials in factories or at home (FLW Protocol 2016).

Inedible parts: Components associated with food that are not intended for human consumption in a particular food supply chain. Examples of inedible parts of food could include bones, rinds and pits/stones. “Inedible parts” does not include packaging. What is considered inedible varies among users (e.g., chicken feet are consumed in some food supply chains but not others). It also changes over time and is influenced by a range of variables, including culture, socioeconomic factors, availability, price, technological advances, international trade and geography (FLW Protocol 2016).

Food loss: Food that is intended for human consumption but, because of inefficiencies or poor functioning of the production and supply system, is removed from the food supply chain. Examples include food that rots in the field or in storage because of inadequate management, technology or refrigeration, or food that cannot make it to market because of poor infrastructure and thus goes unconsumed. Food loss tends to focus on the upstream stages of the supply chain (food production and processing).

Food waste: Food that is intended for human consumption but is discarded due to human behaviours. Food waste tend to focus on downstream stages of the food supply chain (distribution, retail, foodservice, consumers) and often occurs through poor stock management or neglect, or due to food that has spoiled, expired, or has been left uneaten after preparation.

Food loss and waste: Food and/or associated inedible parts removed from the food supply chain. As the specific definitions of food loss and food waste vary and because there can be significant overlap between the terms, they are commonly referred to together as food loss and waste, or FLW. The FLW Protocol does not differentiate between “food loss” and “food waste”.

Food supply chain: The connected series of activities to produce, process, distribute and consume food.

Life cycle: Consecutive and interlinked stages of a product system, from raw material acquisition or generation from natural resources to final disposal (ISO 2006a).

Food life cycle: Similar to “food supply chain”, the food life cycle refers to the connected activities of food production, processing, distribution and consumption. In addition, the food life cycle would include food loss and waste disposal/management as well as production of upstream ancillary inputs such as electricity generation or fertilizer production.

Life cycle thinking: A holistic framing or worldview that recognizes the importance of potential environmental, social and economic effects at each life cycle stage of a product or service.

Life cycle assessment (LCA): The most widely used quantitative tool based on life cycle thinking. It involves the compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle.

A. Definitions of food supply chain stages that correspond with food loss and waste estimates in figure 2

Below are the definitions provided by Gustavsson *et al.* (2013) that correspond with food loss and waste at various stages as shown in figure 2 on page 15. Note that the CEC report to which this figure is credited (CEC 2017) uses different language to refer to the initial stage. In the CEC report, the “agricultural production” stage is referred to as “pre-harvest”. To avoid confusion with the meaning of “pre-harvest”, we have reverted to the initial definitions here.

Vegetal products:

Agricultural production

Losses due to mechanical damage and/or spillage during harvest operation (e.g., threshing or fruit picking) and waste due to crops sorted out post-harvest, etc.

Post-harvest handling and storage

Losses include spillage and degradation during handling, storage and transport between farm and distribution.

Processing and packaging

Include spillage and degradation during industrial or domestic processing, e.g., juice production, canning and bread baking. Losses and waste may occur when crops are sorted out if not suitable to process or during washing, peeling, slicing and boiling or during process interruptions or accidental spillage.

Distribution

Include losses and waste in the market system, at e.g., wholesale, supermarkets, retailers and wet markets.

Consumption

Include losses and waste during consumption at the household level.

Animal commodities:

Agricultural production

For bovine, pork and poultry meat, losses refer to animal death during breeding. For fish, losses refer to discards during fishing. For milk, losses refer to sickness (mastitis) for dairy cows.

Post-harvest handling and storage

For bovine, pork and poultry meat, losses refer to death during transport to slaughter and condemnation at slaughterhouse. For fish, losses refer to spillage and degradation during icing, packaging, storage and transport after landing. For milk, losses refer to spillage and degradation during transport between farm and distribution.

Processing and packaging

For bovine, pork and poultry meat, losses refer to trimming spillage during slaughtering and additional industrial processing, e.g., sausage production. For fish, losses refer to industrial processing such as canning or smoking. For milk, losses refer to spillage during industrial milk treatment (e.g., pasteurization) and milk processing to, e.g., cheese and yoghurt.

Distribution

Include losses and waste in the market system, at, e.g., wholesale, supermarkets, retailers and wet markets.

Consumption

Include losses and waste at the household level.

B. Environmental impact indicators

Below are brief descriptions of some of the more common environmental impacts assessed in life cycle assessment.

Climate change / global warming / greenhouse gas emissions: This indicator is concerned with the release of gases that directly or indirectly change the radiative balance in the atmosphere, contributing to the greenhouse effect, warming of the planet's lower atmosphere and changes in weather patterns. According to the Intergovernmental Panel on Climate Change (2013), "It is extremely likely that human influence has been the dominant cause of the observed warming since the mid-20th century."

Carbon dioxide equivalent (CO₂ eq.): The universal unit of measurement to indicate the global warming potential (GWP) of each greenhouse gas, expressed in terms of the GWP of one unit of carbon dioxide. It is used to evaluate releasing (or avoiding releasing) different greenhouse gases against a common base. Greenhouse gases of particular relevance to the food system include CO₂, methane, nitrous oxide and fluorinated hydrocarbons used as refrigerants. These gases differ in their warming effect and are characterized relative to the warming effect of CO₂. Thus, over the 100-year period following release to the atmosphere, methane has a GWP of 30 kilograms of CO₂ eq. (28 for biogenic methane), and nitrous oxide has a GWP of 265 kilograms of CO₂ eq. (IPCC 2013).

Cumulative energy demand considers the net energy use – both energy consumption and energy production or generation – across the life cycle. This also includes the embodied energy in materials such as plastics. In instances when only fossil energy sources are considered, the indicator may be called "depletion of fossil resources".

Eutrophication originates mainly from nitrogen and phosphorus in sewage outlets, manures and fertilizers that find their way to water bodies. Nutrients that run off, leach or otherwise enter waterways accelerate the growth of algae and other vegetation in water. Degradation of this excess organic material consumes oxygen, resulting in oxygen deficiency and fish kills (dead zones). Eutrophication potential quantifies nutrient enrichment by the release of substances in water or into the soil, and is commonly expressed in PO₄ equivalents.

Acidification originates from the emissions of sulfur dioxide and oxides of nitrogen, which react with water vapour in the atmosphere and form acids that precipitate to the Earth's surface (acid rain). Acidification potential measures the contribution of an emission substance to acidification, typically expressed in sulfur dioxide (SO₂) equivalents.

Photochemical oxidation: Certain air pollutants, including nitrogen oxides and volatile organic compounds, can chemically react in the presence of sunlight to produce photochemical smog: airborne particles and ground-level ozone that can cause serious human health problems. Thus, emissions of these compounds, often from fossil fuel-combusting motor vehicles, into the atmosphere contribute to the potential formation of photochemical smog

Water use: Water resources are essential for agricultural production, and irrigation with surface and groundwater (termed "blue water" in water-use jargon) makes agriculture possible in more arid regions. Geographical location influences the amount of blue water required to produce a given crop. The impact of that water use on the local environment and other potential users, however, also varies with location: using water in water-stressed regions is more impactful than using water in regions with ample supply. Generalization of water use from one production region to another is difficult and unadvisable. Water use in LCA is often reported simply as an inventory (litres), but consensus is building as to how best to incorporate the impact of water use in an LCA framework.

Land use: Land-use indicators account for the occupied land required over a given period of time (typically one year) to produce a product. Different types of land use (agricultural cultivation, pastureland, industrial, residential, forest) can carry different impacts on, for example, biodiversity, and occasionally such differences are accounted for in impact assessment methods. Such land-use impacts are the primary motivations for the engagement of groups like WWF²⁰ in food loss and waste issues.

Human toxicity potential, eco-toxicity potential: A toxicological effect is an adverse change in the structure or function of a species as a result of exposure to a chemical. Characterization factors for various chemicals are developed based on multimedia chemical fate models, exposure correlations and chemical risk screenings. Toxicity potentials are characterized by high uncertainties due to the complex fate, exposure and toxicological modelling required.

C. Food waste management options

Various destinations for the treatment of food waste are referred to in this report. The following offers a brief description of each.

Aerobic composting: The intentional decomposition of organic material in the presence of oxygen into a humus-like material, known as compost, that provides a number of benefits to soil health including plant nutrients. In industrial composting, temperature, moisture and nutrient content (the carbon to nitrogen ratio of processed organic materials), along with mixing and blending, are carefully controlled to promote proper decomposition. Under aerobic conditions, the production of methane is avoided, and the resulting compost recycles nutrients in stable forms that can be used for plant growth.

²⁰ See www.worldwildlife.org/initiatives/food-waste.

Anaerobic digestion: A biological waste treatment process whereby the waste (food, animal manure, wastewater treatment sludge) is subjected to conditions that promote digestion by methane-producing microorganisms. Typically, this takes place in enclosed vessels where oxygen can be deprived and the resultant methane can be collected as a biofuel and used to, e.g., generate “green” electricity. Anaerobic digestion also produces liquid and/or solid “digestate” that can be treated for use as a fertilizer and soil amendment.

In-sink grinding / sewage treatment: Food waste that is treated with an in-sink grinder and washed down the drain is ultimately treated with all other water/sewage treatment. Wastewater treatment varies greatly from municipality to municipality, and so the impacts of this treatment option will depend on the local system. Adding food waste to the wastewater stream adds additional organics and nutrients requiring digestion and treatment. Food waste disposed of this way is commonly not accounted for in efforts to quantify food loss and waste destinations, making this treatment and its impacts somewhat hidden.

Waste-to-energy / incineration: Simply put, this involves the combustion of waste materials, either food loss and waste combusted independently or mixed with other solid waste. Such combustion should be highly controlled to minimize detrimental air emissions, and in the “waste-to-energy” scenario, energy from the combustion is captured to generate (typically) electricity.

Landfill: Considered the least preferred food waste treatment option (see figure 3 on page 20), landfill involves the dumping of food waste, typically mixed with other organic and non-organic solid wastes, into a dedicated area that is ultimately enclosed. In the United States, food waste is the largest single component of landfilled municipal solid waste, comprising 22 per cent of such disposals (US EPA 2018). Under typical anaerobic landfill conditions, decomposition of organic materials such as food waste produces methane, a powerful greenhouse gas. This landfill gas is sometimes collected and used to generate electricity, sometimes flared to avoid the atmospheric release of methane, and some share leaks to the atmosphere.

Appendix B: Detailed Account of Life Cycle Assessment Methodologies

Life cycle assessment (LCA) refers to the process of compiling and evaluating the inputs, outputs and potential environmental impacts of a product system throughout its life cycle (ISO 2006b). In other words, it is a systematic accounting method based on a standardized framework and terminology that is used to quantify the effects on the environment from the systems and “stuff” that meet our human needs.

The very first studies recognized as LCAs were conducted in the early 1970s and examined beverage containers, but inconsistencies in approaches, terminologies and results over the following two decades limited acceptance of the approach. In the 1990s, the emergence of international platforms for scientific discussion and exchange on LCA led to coordinated activities and rapid growth in harmonized methods and standardized approaches. The International Organization for Standardization (ISO)²¹ issued a standardized framework and terminology in 1996, while still supporting freedom in LCA methodological detail (“...there is no single method for conducting LCA.”) (ISO 2006a).

²¹ The International Organization for Standardization is an independent, non-governmental organization composed of the standards organizations of the 162 member countries. It is the largest developer of voluntary international standards, facilitating world trade by providing common standards between nations, and safeguarding consumers and the end users of products and services.

The years since have seen an explosion in LCA applied to a wide variety of products and used to inform increasingly diverse questions. Methods continue to evolve, and innovative approaches have emerged. LCA now finds application in defining policy, informing product development and advising consumer decisions, among other applications.

A. Methodological framework

The general methodological framework for LCA is commonly illustrated as in figure 10. Typically, the workflow is from top to bottom, with interpretation occurring throughout. However, the back-and-forth arrows demonstrate the iterative nature of LCA: often, information about a system is gained in a later phase that requires the practitioner to revisit and reconsider choices made previously. Numerous texts, including the ISO standards themselves, detail the approach and stages of LCA (Curran 2012; ISO 2006a; ISO 2006b). Here we offer only a brief orientation.

Despite standardization, LCA remains a rather fluid methodology, capable of examining a wide variety of system types. This also means, however, that fully understanding and interpreting the results of an LCA requires an appreciation of the specific methodological choices employed. Much of the LCA procedure is defined and influenced by the specific question to be examined and the context around answering that question. It is in the goal and scope definition phase where that question is defined as clearly and explicitly as possible, along with the intended application, the reasons for conducting the study, and the intended audience.

Central to this phase is defining the function of the system, as this becomes the basis for comparisons and reporting. LCA is a relative accounting method, such that results are given relative to a quantified definition of the system function, called the functional unit. For example, comparing a natural gas-fired electricity generation plant directly with a solar panel makes very little sense. However, a well-defined function, say “supplying a megawatt of electricity over one month”, allows a meaningful comparison of otherwise disparate systems. The functional unit also permits meaningful comparisons between different stages of the life cycle: for example, LCA could describe how environmental emissions associated with the manufacturing of an electricity power plant compare with those from operation.

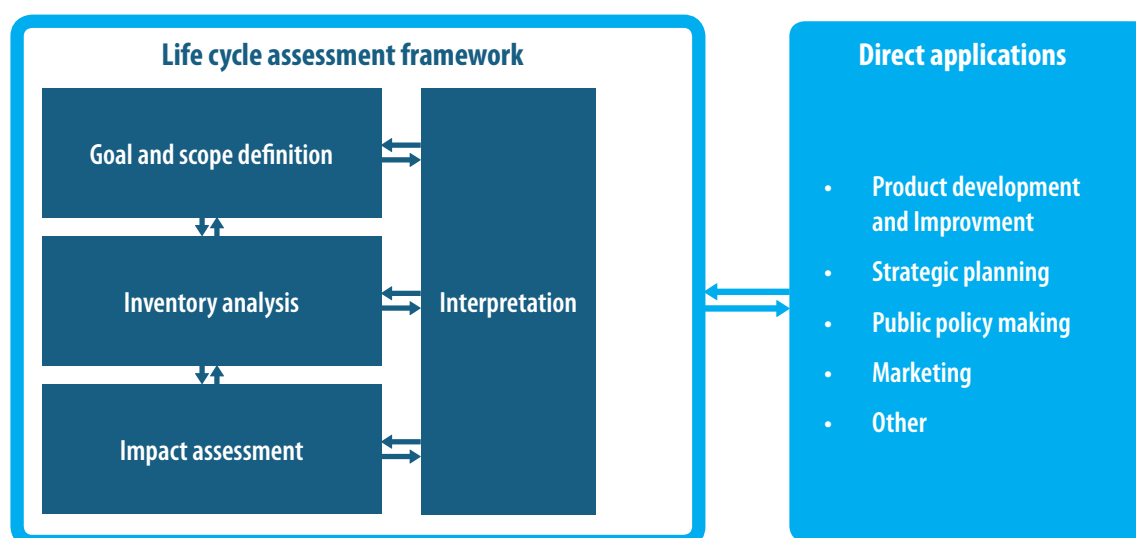
Defining unambiguous functional units in food systems often can be challenging, as foods offer a

variety of functions including supplying nutrition, pleasure, cultural identity and social interaction. Even when this is restricted to the primary function of supplying nutrition, it is still challenging to comprehensively quantify the nutrition supplied, as different foods serve different nutritional roles in our diets (Heller, Keoleian and Willett 2013). As a result, LCA studies of food often default to the far more straightforward reference flow of mass or volume (e.g., LCA results expressed as kilograms of CO₂ eq. per kilogram of food).

This mass or volume basis is usually sufficient for comparing life cycle stages (e.g., how do the environmental impacts from the landfilling of one kilogram of wasted apples compare with those from on-farm production), and it is a convenient basis for formulating comparisons of dietary patterns and other aggregations. However, caution must be exercised when making comparisons of

Figure 10

General methodological framework for life cycle assessment



Source: ©ISO Excerpted from ISO 14040:2006 with permission of the American National Standards Institute (ANSI) on behalf of the International Organization for Standardization. All rights reserved.

the environmental impacts of different foods on a mass basis, as, for example, beef and broccoli have very different nutritional profiles per kilogram.

Inventory analysis, the second phase of LCA, involves “the compilation and quantification of inputs and outputs for a product throughout its life cycle” (ISO 2006a). Inventory analysis is often very data and calculation intensive. In the standard LCA approach, known as process-based LCA, the life cycle under study is divided into unit processes. These include things like coal mining, steel production, assembling and producing an LED lightbulb, operating an electric teakettle, transporting by semi-truck or recycling waste PET (polyethylene terephthalate) plastic.

In LCA, a unit process is typically treated as a black box that converts a collection of inputs into a collection of outputs. Inputs include products (from other processes), natural resources (minerals and ores, energy carriers, biotic resources, land) or waste to be treated. Outputs also include products, waste for treatment, and residuals to the environment such as air, water and soil pollutants, and waste heat. Inventory analysis involves quantifying the inputs and outputs of interest across each unit process and the interconnections between each that form the product’s life cycle. Digital databases and dedicated LCA software can greatly aid in harmonizing this complex and exhaustive accounting.

Life cycles, in theory, can be infinitely large: there is almost always an additional upstream input that also requires materials and resources. This is addressed in process-based LCA by assigning a cut-off criteria, a point where additional contributions are negligible to the results of the study. Another perennial challenge encountered in the inventory analysis phase occurs when a process that cannot be further divided produces several co-products. Take, for example, the production of soy oil. Soy oil cannot be produced without also producing

soymeal, which also has economic value. The upstream impacts leading to oil refining, including the agricultural production of soybeans, must somehow be allocated to the co-products.

Debates on the relative merits of these approaches can be left to LCA practitioners and experts, but all who interact with LCA should appreciate that such choices can influence the results of an LCA.

There are a number of approaches to doing this, and ISO standards offer a suggested prioritization of those approaches, but rarely is there a “right” answer and it becomes a methodological choice within the study. Debates on the relative merits of these approaches can be left to LCA practitioners and experts, but all who interact with LCA should appreciate that such choices can influence the results of an LCA.

The outcome of an inventory analysis can be dozens, hundreds or even thousands of resource and emissions flows. What do these mean? What are the impacts on the environment? This is the purpose of the impact assessment phase. Environmental impacts are divided into categories, such as climate change, eutrophication, toxicity, water use impacts and fossil energy depletion. The impact categories of interest and relevance to a particular study are defined in the Goal and Scope phase. Environmental impacts typically involve a cascading series of causal mechanisms. For example, an emission of greenhouse gases leads to changes in the composition of the atmosphere, which leads to a change in the radiation balance, which contributes to a change in the temperature distribution, which leads to changes in climate, which can affect ecosystems and human activities, etc.

Scientists in chemistry, meteorology, ecology and beyond have developed models to represent such causal relationships, but, in general, the further along the causal chain, the more uncertain and contentious these predictive models become. Choosing to characterize an environmental impact earlier in the causal chain as a midpoint impact indicator, such as global warming potential reported in carbon dioxide equivalents, introduces less uncertainty. In some applications, however, the communicative benefit of a more intuitive endpoint impact indicator, such as loss of human life years, may outweigh the added uncertainty (see figure 11). In addition, the causal chains of various environmental impacts typically converge on a few “areas of protection” at the endpoint, allowing more direct comparisons (albeit with greater uncertainty) and aggregations of disparate indicators.

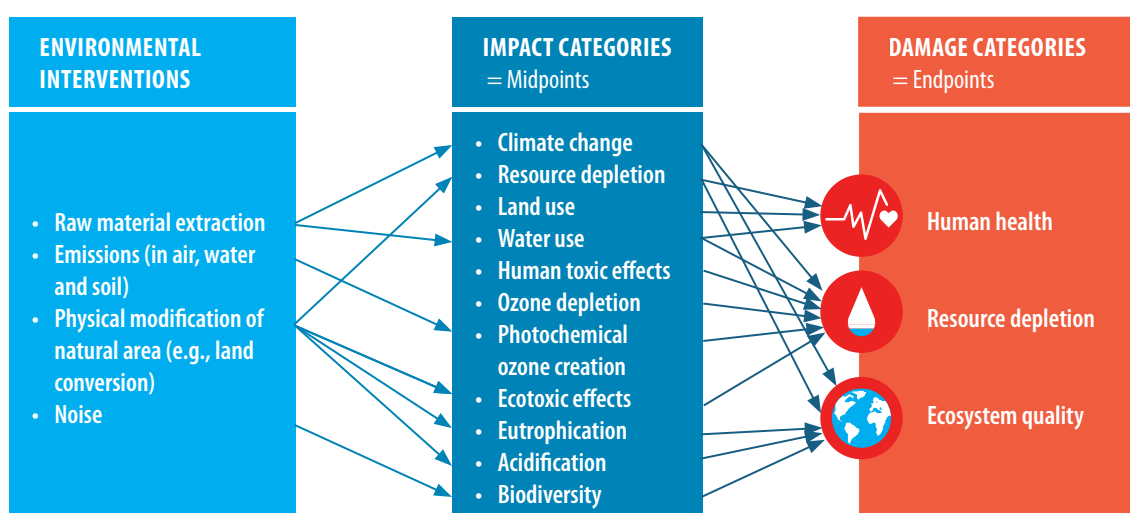
A variety of impact assessment methods have been developed for use in LCA, and these are typically implemented in LCA software, making their application fairly straightforward. Interpretation of impact assessment results,

however, can be challenging and often requires an understanding of and experience with the methods employed. Further, there is little specification or guidance in choosing impact assessment methods, and differing methods can and do offer different results for the same impact category. Again, discussion of the relative merits of various assessment methods is beyond the scope of this text, but it is important to recognize that such choices can matter. Thoroughly conducted LCAs will demonstrate and discuss variability introduced by assessment method choice.

The interpretation phase involves evaluating the findings of inventory analysis or impact assessment (or both) in relation to the defined goal and scope in order to reach conclusions and recommendations. It generally involves an acknowledgement of limitations and assumptions, assessments of data quality and completeness, as well as sensitivity analysis aimed at characterizing the reliability and robustness of conclusions. This occasionally requires returning to decisions, analysis or data collection addressed earlier in the LCA in order to refine and improve the study.

Figure 11

Conceptual framework for the causal linkages in life cycle impact assessment



Source: UNEP 2012.

Conclusions are drawn and recommendations made by putting results in the context of decision-making and limitations.

B. Strengths

LCA was initially developed to evaluate and improve products, particularly in product development, and the method excels in this role of identifying unexpected opportunities to reduce impacts, or unexpected consequences of a particular design choice. A classic example of this is Procter & Gamble's LCA of household laundry detergents in the early 2000s. After determining that the overwhelmingly dominant impacts associated with laundry detergents arise not from resource extraction or packaging manufacture, but from the energy required to heat water in the use phase, Procter & Gamble developed a new detergent that could clean just as effectively in cold water (Saouter and Van Hoof 2002).

As implied earlier, LCA also can be a valuable way of comparing different systems or products that offer the same service or function but involve dramatically different processes. Classic examples include comparisons of glass and plastic beverage containers or paper and plastic shopping bags. Examples relative to food loss and waste may include comparisons of food waste management methods: how do the impacts (and benefits) of a particular composting system compare with a particular anaerobic digestion system?

The strengths of LCA include:

- Evaluating the environmental consequences associated with a given product or process
- Highlighting "hotspots" in a product or process life cycle that warrant focused attention. Where are the largest burdens?

- Analysing the environmental trade-offs associated with one or more products or processes. Trade-offs can occur between stages of a product life cycle, between environmental impact categories, between societies/geographic regions or between generations.
- Identifying unexpected consequences of a product or innovation.
- Identifying "burden shifts" between environmental impact categories or across life cycle stages. In other words, does addressing an environmental problem at one stage simply move the impact somewhere else?
- Comparing the potential impacts between two or more products or processes.

LCA has found application in:

- Product development and improvement

LCA could be used to determine whether a packaging innovation for fresh fish aimed at reducing food waste does indeed result in a net environmental benefit when all life cycle stages are considered. Section 4 explores this concept further.

- Strategic planning

The town of Brookhaven, New York supported an LCA study to determine whether adopting a system of separated food waste recovery and treatment would lead to environmental benefits. Such a study can support discussion and decision-making on sustainable waste management. Results from the study are discussed in section 4.

- Public policymaking

Legislation banning the disposal of food waste in landfill could be further informed by LCA to prioritize alternative destinations and support the businesses and infrastructure necessary to minimize the environmental impact of food waste disposal.

- Marketing

As presented in section 5, Grow Compost of Vermont uses the US EPA's WARM model, an LCA-based tool, to quantify and communicate back to customers of the food scrap hauling service the greenhouse gas emission reductions and energy savings benefits associated with diverting food scraps from landfill.

C. Weaknesses

LCA is a powerful tool. But it cannot do everything. Understanding the limitations of LCA is critical to identifying proper applications. LCA offers a relative look at potential environmental impact that can help inform decisions, but it must be balanced with other considerations and cannot answer absolutely whether a product is sustainable or not. It can be data-intensive and costly, and only proxy data may be available.

- Process-based LCA is typically data intensive, which often means that it is time-consuming and costly. It can offer extremely valuable insights that, when implemented, in many cases translate into direct environmental and financial savings, and, as such, LCA can be a very sound investment. Still, these intensities can make it inaccessible for some stakeholders and applications. That said, there often is value in simplified approximations – “back-of-the-envelope” or scan-level LCAs based on a limited scope and data – but interpretation must carefully account for these limitations.

- LCA can help inform decision-making. Ultimately, however, it must be taken into account with a suite of other considerations including costs and social implications. LCA can help identify an opportunity, but additional tools and protocols are likely needed to help inform and support action.

- LCA offers an indication of potential environmental impact. It is not a measure of impact that has occurred in the absolute sense. This is perhaps only a weakness if it is misinterpreted.
- LCA is a relative assessment method. As a consequence, and perhaps contrary to popular belief, LCA cannot tell if a product is “sustainable” or “environmentally friendly”. LCA can only indicate if product X is “more sustainable” or “more environmentally friendly” than product Y, or that the use phase is the “least sustainable” or “least environmentally friendly” part of the life cycle for product Z.
- Most LCA datasets are based on industry averages, or sometimes even specific examples. As such, they often do not represent the specifics of a particular product chain or fully capture the variability inherent across industries and economies. See the discussion on attributional versus consequential LCA below for more on this.

Table 6

Examples of available input-output life cycle assessment models

Name	Geographic relevance	Availability	URL
United States Environmentally-Extended Input-Output (USEEIO)	United States	Open/Free	www.github.com/USEPA/USEEIO
Economic Input-Output LCA (EIO-LCA)	United States	Free	www.eiolca.net/cgi-bin/dft/use.pl
CEDA	United States	Licensed	www.vitalmetricsgroup.com/data-ceda
Open IO-Canada	Canada	Free	www.ciraig.org/en/open_io_canada/
E3IOT	Europe	Licensed	www.universiteitleid.nl/en/research/research-output/science/cml-e3iot
EORA	Global	Licensed, free for academic use	www.worldmrio.com/
Global Multi Regional Input Output Database (EXIOBASE)	Global	Free with licence	www.exiobase.eu

- The analytical structure of LCA assumes linear scaling of technologies. This assumption means, for example, that producing 1 kilogram of steel has the same impact per kilogram as producing 5 million kilograms of steel. In some applications, consequential LCA is an attempt to address this limitation.

D. Input-output life cycle assessment

Input-output LCA, also known as environmentally extended input-output LCA, is an alternative approach to the traditional process-based LCA. Instead of focusing on particular processes within a product value chain, input-output LCA takes a more top-down view that is rooted in macroeconomics, estimating the resources and emissions associated with the production of broad classes of goods and services (e.g., light trucks, cheese, computers). These analyses are based on traditional economic input-output models, which estimate the amount of economic activity, across multiple industries via supply chains, required to produce a unit of economic output.

By linking an input-output model with information on the environmental emissions or resource use (such as energy) associated with each economic sector, it is possible to do an LCA-style accounting of the environmental impacts associated with a given economic output (e.g., dollars spent in the cheese manufacturing sector). Input-output LCA models have been developed for many economies, and some are openly available. Some examples are provided in table 6.

Reutter *et al.* (2017) identify six major strengths of input-output LCA in comparison to process-based LCA for the purpose of analysing the consequences of food waste:

- **System boundaries:** Environmentally extended input-output tables evaluate the environmental exchanges associated with the full life cycle of any product. This includes all supply chain effects, avoiding the need for defining a boundary for analysis.
- **Whole supply chain inclusion:** Because food waste can occur at any stage of the food supply chain, and the food supply chain has various actors, the fact that input-output LCA is inclusive of all formal economic activity is a benefit.
- **Socioeconomic indicators:** Because it is based upon economic data, the technique allows research on socioeconomic indicators without significant extra effort.
- **Final demand data:** The technique implicitly includes data on final demand of food purchased, thus allowing differentiation between domestic consumption and exports and contrasting food waste impacts with total food purchases within the same data framework.
- **Effort to obtain results:** Input-output LCA provides results for all products in a certain region. In contrast, the effort to obtain the same information for process analysis would be very time-consuming.
- **Consistency:** Policymakers need to be able to evaluate the effect of different actions under a consistent framework. Because input-output LCA is an established technique, and system boundaries and inclusions are well defined, it provides a consistent framework for policymakers.

Input-output LCA also has weaknesses. The most challenging limitations include:

- Data are based on highly aggregated industry sectors, making consideration of a particular product less precise, and possibly misleading if the production processes and/or supply chains for that product are atypical for the sector.
- Input-output LCA is tied to cost data, which are subject to geographic differences and market fluctuations, and typically there are notable time lags in the representative year.

However, if sector-wide or sector-average information is of interest, input-output LCA can provide a much quicker estimate of the complete supply chain environmental impacts. In addition, hybrid models, combining process LCA and input-output LCA, have been proposed to provide differentiation within aggregated economic sectors. See Crawford *et al.* (2018); Hendrickson, Lave and Matthews (2006); and Suh and Huppes (2005) for further reading on hybrid approaches.

E. Attributional versus consequential life cycle assessment

The traditional LCA approach typically uses data that represent the average status quo operation of a process. For example, electricity use in a product life cycle would be modelled using the average electricity generation grid mix for a particular region. This approach is known as attributional LCA because it attributes the environmental impacts as a characteristic of the process or product.

Sometimes, however, we may want to know the consequences of a change in response to decisions. What are the environmental impacts of increasing demand for steel by 30 per cent? What is the impact of a change in market demand from gasoline to ethanol? An alternative approach, known as consequential LCA, seeks to answer these types of questions.

Consequential LCA incorporates economic concepts such as marginal production costs and elasticity of supply and demand into the LCA framework. It uses marginal data rather than average status quo data: in the electricity example above, we would be interested in the electricity generating method most likely to cover a marginal increase in electricity demand. Incorporating economic relationships adds to the complexity of the modelling and increases uncertainty. The linear and static nature of attributional LCA no longer apply. Results can be very sensitive to built-in assumptions.

Still, in some instances, consequential LCA offers a better approach to answering the right question and addressing the goal of a study. As might be expected, results and conclusions from attributional or consequential studies of the same product or system can vary considerably. For the casual LCA consumer, this emphasizes the importance of understanding and appreciating the goal and scope of a particular study when interpreting and drawing conclusions.



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