Report No. CSS16-02
February 25, 2016

Category-Level Product Environmental Footprints of Foods

Food Life Cycle Assessment Literature Review

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STATEMENT OF WORK:
Task 1. **Initial literature scan; first draft of results**: Contractor will identify and review in summary fashion existing literature evaluating the life cycle environmental impacts of foods. Contractor will provide to DEQ an annotated summary of all relevant documents, noting for each document, at a minimum: the authors and their affiliations, year of publication, types of foods, geographic representation, types of environmental impact categories included, and life cycle stages (e.g., cradle-to-farm gate, cradle-to-factory gate, or cradle-to-grave).

1. Introduction to Life Cycle Assessment and Relevant Environmental Impact Categories

Life Cycle Assessment (LCA) is an accounting, evaluation and interpretation methodological tool used to assess the potential environmental impacts of product systems and services, accounting for the emissions and resource use throughout a product's life cycle. "Product life cycle" refers to the stages from raw material acquisition through production, distribution, use, and disposal (see Figure 1). LCA is defined and standardized through international guidelines (ISO-14040-2006, ISO-14044-2006) but remains a flexible methodological framework permitting application to a wide range of questions and product systems. The basic LCA framework is an iterative procedure involving four main steps: 1) definition of the goal and scope of the study – what are we studying, how are we studying it, why, and for whom?; 2) life cycle inventory analysis – data collection and calculation procedures to quantify relevant inputs and outputs (energy, raw materials, co-products, waste, emissions to air, water ,and soil) across each unit process within the system boundary; 3) life cycle impact assessment – associating inventory data with specific environmental impact categories and modeling the relevance of those impacts; and 4) interpretation of outcomes.

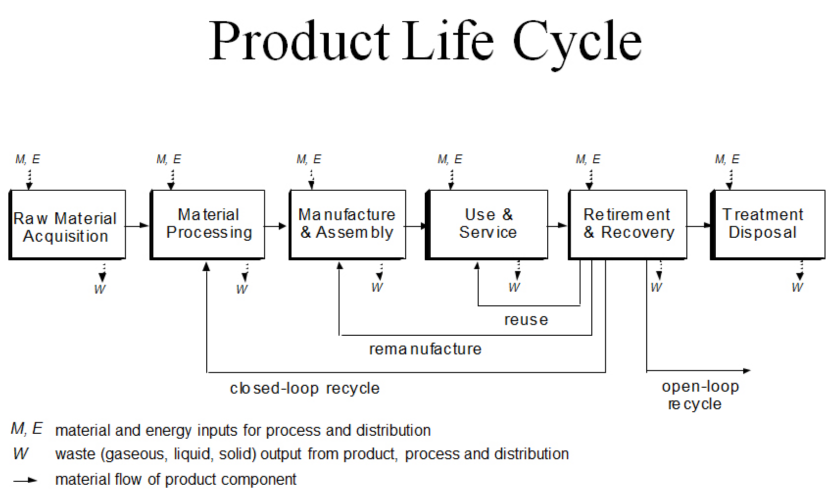

Figure 1. Generic product life cycle diagram showing "cradle to grave" life cycle stages.

LCA can be very useful in providing a broad systems perspective in identifying opportunities for improved environmental efficiency. Its applications include identifying environmental hotspots, evaluating alternative scenarios, and identifying and avoiding burden shifting – between life cycle stages or between environmental impact categories.

While the LCA ideal is certainly to include full "cradle to grave" life cycle stages and evaluate a diverse set of environmental impact categories, often a particular research goal or limited availability of data warrants a reduced scope (e.g., cradle to farm gate, or a focus only on greenhouse gas emissions). Much can be gained from such studies, but interpretation requires caveats.

Environmental impact categories that may be evaluated in food and agricultural LCAs include: cumulative energy demand, global warming potential, eutrophication potential, acidification potential, ozone depletion potential, land use, water use, and human and eco-toxicity potentials. Brief descriptions of these are provided below.

Cumulative energy demand (E):
Virtually all products require energy as part of their life cycle, either directly – as in the use phase of an automobile – or indirectly – as in the embodied energy contained in plastics. What's more, different energy carriers – coal, oil, electricity – require different amounts of primary energy for their production (extraction, processing, generation) and delivery (transport, transmission and distribution). Cumulative energy demand, also called primary energy consumption, is a measure of the energy needs throughout a product's life cycle, and is commonly expressed in megajoules (MJ).

Global warming potential (GHGE):
Incoming solar radiation is absorbed and reemitted back from the Earth's surface as infrared energy. Greenhouse gases (GHGs) in the atmosphere prevent some of this heat from escaping into space and instead reflect the energy back to further warm the surface. Human activities that produce GHGs amplify this greenhouse effect by modifying the Earth's energy balance between incoming solar radiation and the heat released back into space, resulting in climate change. Anthropogenic emissions that contribute significantly to climate change include carbon dioxide, methane and nitrous oxide.
The relative contributions of different chemical emissions to the greenhouse effect are commonly calculated relative to 1 mass unit of carbon dioxide (e.g., kg CO_2 equivalents). The Intergovernmental Panel for Climate Change (IPCC) provides these relative factors, typically based on effects over a time horizon of 100 years. For example, 1 kg of methane has the equivalent global warming potential as 25 kg of CO_2. Nitrous oxide is 298 times as powerful as CO_2.

Eutrophication potential (EP):
Eutrophication originates mainly from nitrogen and phosphorus in sewage outlets, manures and fertilizers. 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 PO_4 equivalents.

Acidification potential (AP):
Acidification originates from the emissions of sulfur dioxide and oxides of nitrogen, which react with water vapor 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 SO_2 equivalents.

Ozone depletion potential (ODP):
The ozone layer in the atmosphere protects plants and animals from harmful UV-radiation from the sun. Some substances in the atmosphere make the ozone layer decline, resulting in increased UV-radiation at ground level. The ozone depletion potential is the contribution of a substance to the depletion of the ozone layer, and is typically expressed in CFC-11 equivalents.

Land Use (LU):
Land resources are obviously very important for agricultural production, but impact assessment methods capable of differentiating land use practices in terms of ecosystem services provided are at early stages of development and not yet routinely applied in LCA studies. If land use is reported in a food LCA, it often is merely an inventory of land use (e.g., hectares per kg of product), which can be a useful indicator, especially for animal based foods where land use of feed crops is amplified. Land use is also highly dependent on location, as yields vary with soils and climate, so generalizations across regions are difficult.

Water use (WU):
Water resources are also essential for agricultural production, and irrigation with surface and ground water (termed "blue water" in water use jargon) makes agriculture possible in more arid regions. Again, geographical location influences not only the amount of blue water required to produce a given crop, but the *impact* of that water use on the local environment and other potential users 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 (liters), but consensus is building as to how best to incorporate the *impact* of water use in an LCA framework.

Human toxicity potential (HTP), eco-toxicity potential (ETP)
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. HTP can be expressed in terms of disability adjusted life years (DALYs) to allow comparisons with other human health effects. ETP are often disaggregated into terrestrial eco-toxicity potential (TETP) and aquatic or marine eco-toxicity potential (AETP) and can be expressed in terms of potentially affected fraction of species or potentially disappeared fraction of species. Toxicity potentials are characterized by high uncertainties due to the complex fate, exposure and toxicological modeling required.

2. Literature review of food LCAs

Agricultural and food product systems have offered both an ideal and challenging application of LCA methods due to their complexity and their close interlink between nature and the technical sphere. Growing interest in the environmental impact of food production systems has resulted in an accumulating number of LCAs conducted on a wide variety of foods produced in diverse regions across the globe. Here, we offer a broad overview of available food LCA research.

Literature review approach

As a complement to literature gathered in previous research efforts, we conducted a systematic search in Web of Science and Google Scholar databases. Search terms included combinations of "LCA" and "life cycle" with "food" as well as specific food types important to the Pacific Northwest. Articles and reports published in the past ten years (after 2005) that applied LCA methods to one or more food products were reviewed and inventoried. Peer reviewed journal articles as well as thoroughly documented reports from governmental and non-governmental organizations were considered. Agricultural crops not expressly grown as human food (e.g., biofuels, timber, fibers) were excluded. Articles that did not present midpoint category results or only presented normalized results were not included.

Summary of literature review results

The literature review resulted in 184 unique publications and 771 entries, where an "entry" represents a food type – production scenario combination (e.g., an article comparing organic and conventional production of apples would result in two or more entries). The full list of entries is cataloged in the spreadsheet, "Food LCA Lit Review DB 020216.xlsx"; fields contained within this catalog are described in Appendix A. The following figures summarize and characterize this collection of food LCAs.

Figure 2 shows the distribution of entries by food type. A relatively even distribution across meat, vegetables, fruit and dairy was found. Table 1 further describes the frequency of occurrence of specific foods within the literature review catalog.

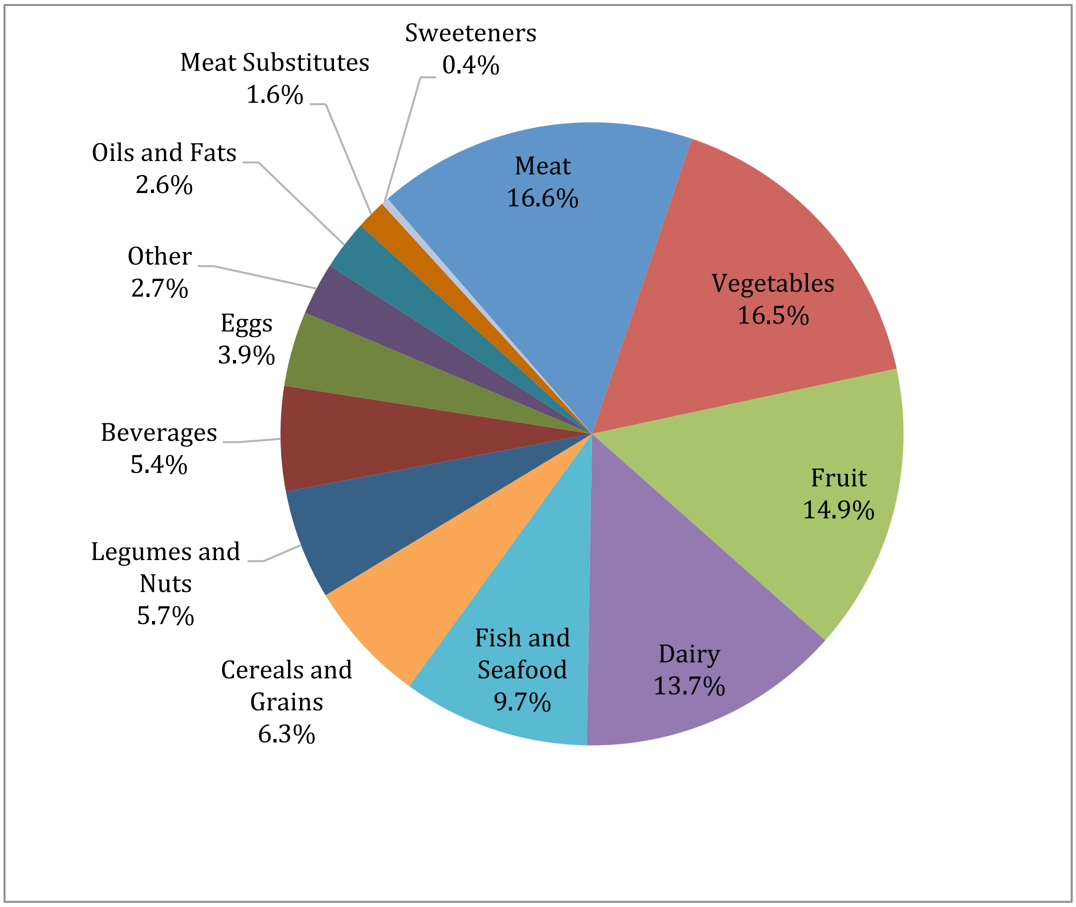

Figure 2. Breakdown of entries contained in Food LCA Literature Review database by food type.

Table 1. Listing of the number of entries contained in Food LCA Literature Review database for specific foods in major food categories.

Meat	127
Beef	48
Pork	39
Chicken	18
Sheep	10
Rabbit, Hare	3
Turkey	3
Veal	3
Duck	1
Goat	1
Snail	1
Dairy	100
Fluid Milk	46
Cheese, Assorted	25
Yogurt	11
Butter	5
Buttermilk	4
Cream	2
Sheep Milk	2
Buffalo milk	1
Dairy Powders	1
Frozen Dairy Products	1
Sour cream	1
Concentrated Milk	1
Nuts & Legumes	42
Cashews	14
Hazelnuts	9
Almonds	7
Peanuts	7
Soybeans	2
Walnuts	2
Pistachio	1

Vegetables	126
Tomatoes	48
Lettuce	20
Potatoes	16
Broccoli	6
Mushrooms	5
Carrots	4
Escarole	4
Green Beans	4
Cucumber	3
Garlic	3
Peas	3
Asparagus	2
Bell Peppers	1
Cauliflower	1
Eggplant	1
Fennel	1
Leek	1
Onions	1
Spinach	1
Zucchini	1
Cereals and Grains	45
Wheat	15
Bread	11
Rice	9
Corn	4
Breakfast Cereal	2
Wheat flour	2
Barley	1
Oatmeal	1

Fruit	111
Apples	27
Strawberries	11
Bananas	9
Pears	8
Peaches	7
Oranges & other citrus	7
Pineapple	6
Avocado	5
Kiwi	5
Raspberries	5
other tropical fruits	5
Blueberries	4
Olives	4
Cherries	3
Grapes	3
Mango	1
Melon	1
Wild caught fish & seafood	39
Atlantic Cod	13
Mackerel	5
Lobster	4
Herring	3
Sardines	3
Haddock	2
Hake	2
Alaskan Pollock	2
Alaskan Salmon	2
Octopus	1
Saithe	1
Tuna	1
Farmed fish & seafood	36
Salmon	17
Trout	6
Mussels	4
Sea Bass	3
Shrimp	2
Tilapia	2
Artic Char	1
Turbot	1

LCA studies can vary in their scope, including the life cycle stages included, depending on the particular goal of the study. Our literature review catalogs specifically which life cycle stages are considered in a given entry. Figure 3 summarizes this information: while all entries considered some form of agricultural production in order to be included in the catalog, only 60% of the entries accounted for processing of farm gate commodities, 27% followed those products through to retail stages, and 7% included use (consumption) stages of household storage and/or preparation & cooking. Typically, if a successive stage is included, transportation to that stage is accounted for in the LCA.

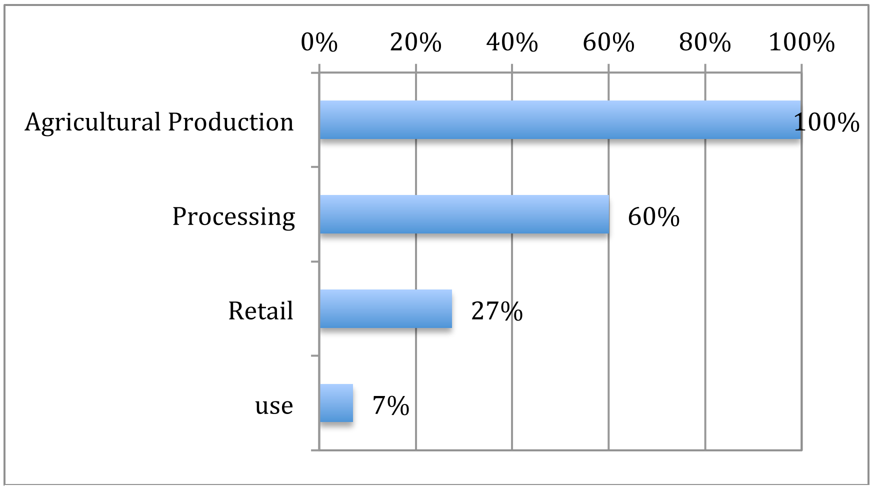

Figure 3. Demonstration of the life cycle stages considered in entries contained in Food LCA Literature Review database.

LCA studies also vary in the environmental impact categories evaluated, depending on the goal of the study, but also often on the availability of data. As can be seen in Table 2, global warming potential (greenhouse gas emissions) is the most common environmental indicator evaluated in food LCA studies. In LCA studies of typical industrial processes, combustion of fossil fuels drives not only cumulative energy demand, but also global warming potential and acidification potential; these indicators therefore tend to track one another. Since agricultural production can involve significant greenhouse gas emissions from non-fossil fuel sources, such as methane from enteric fermentation and manure handling or nitrous oxide emissions from fertilized soils, performance in one impact category is not always a good predictor of other categories.

Table 2. Popularity of environmental impact categories among entries contained in the Food LCA Literature Review database.

Cumulative Energy Demand	37%
Global Warming Potential	97%
Eutrophication Potential	34%
Acidification Potential	31%
Water Use	18%
Land Use	29%

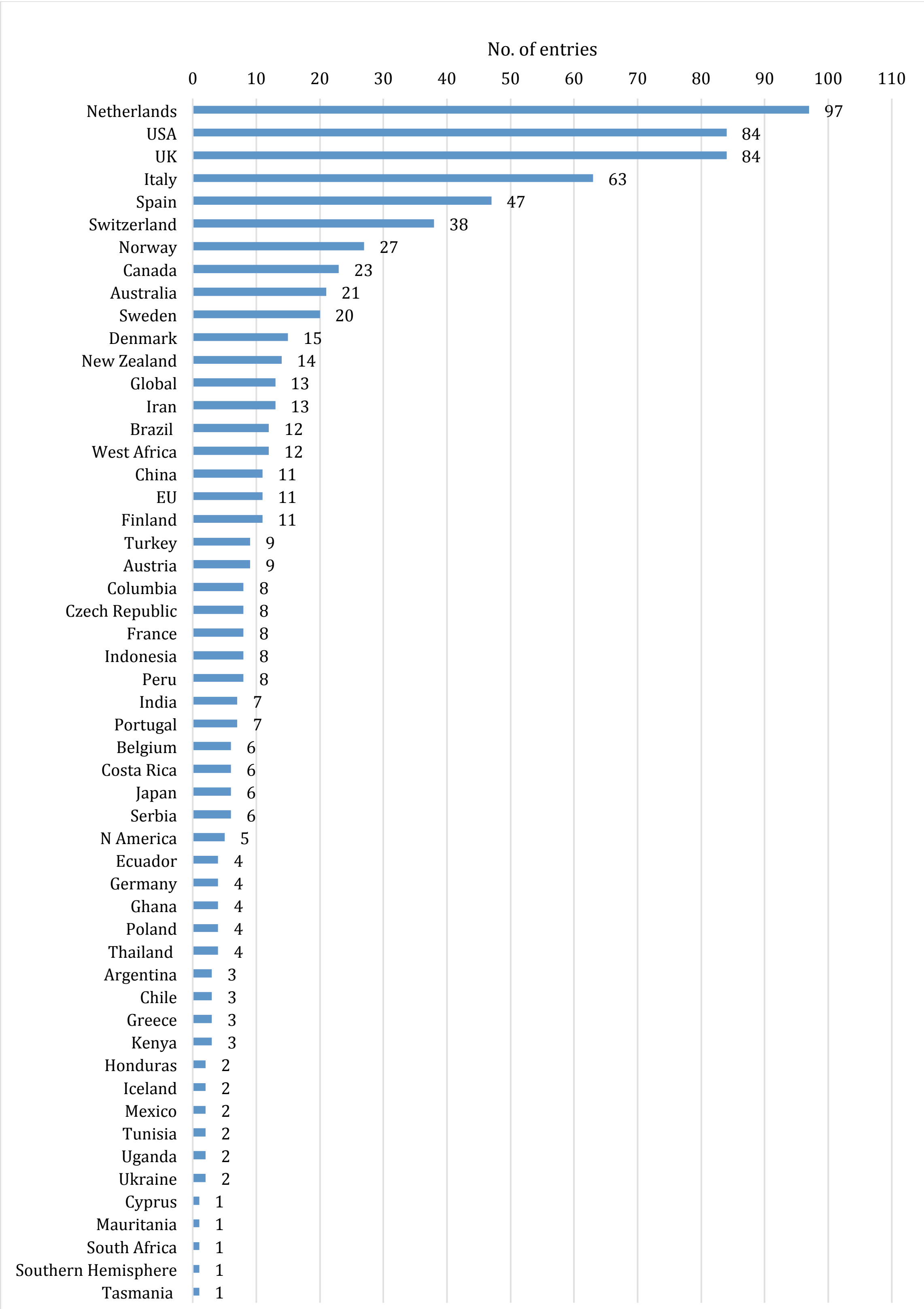

Figure 4. Country of agricultural production for entries contained in the Food LCA Literature Review database.

Figure 4 demonstrates the diversity of countries for which food production has been evaluated via LCA. Northern Europe has dominated much of the food LCA research over the past two decades, but a surprising number of U.S. based studies have arisen in recent years. The extent to which these U.S. studies focus on particular regions in the U.S. is shown in **Error! Reference source not found.**Figure 5. We were unable to identify LCA studies focused on food production within the Pacific Northwest.

Further characterization of the *documents* cataloged reveals an increasing number of food LCA studies over the past decade (Figure 6) and a dominance of peer reviewed journal articles (Figure 7). While other important report types from governmental entities, industry, and NGOs were included, the large majority of peer reviewed journal articles adds a certain level of quality assurance.

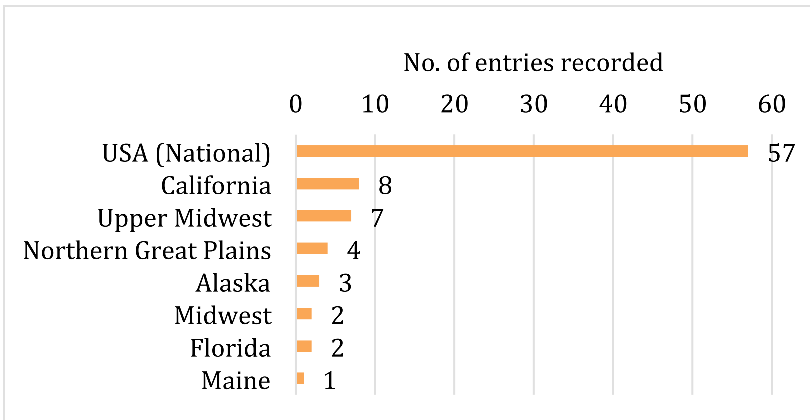

Figure 5. Regional distribution of U.S. based food LCA entries identified in the Food LCA Literature Review database.

We found that 43% of the *documents* cataloged make comparisons between production (or other life cycle) strategies or methods. These comparisons, for example, may be between conventional and organic production methods, between flow-through and recirculation aquaculture systems, or may consider local production relative to import from a distant production region.

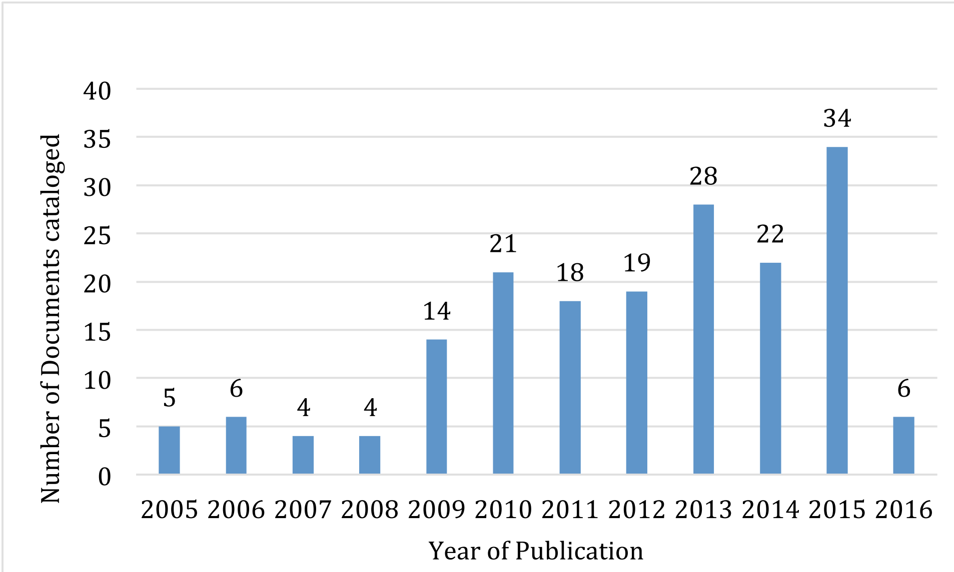

Figure 6. Distribution of the year of publication for documents cataloged in the Food LCA Literature Review database.

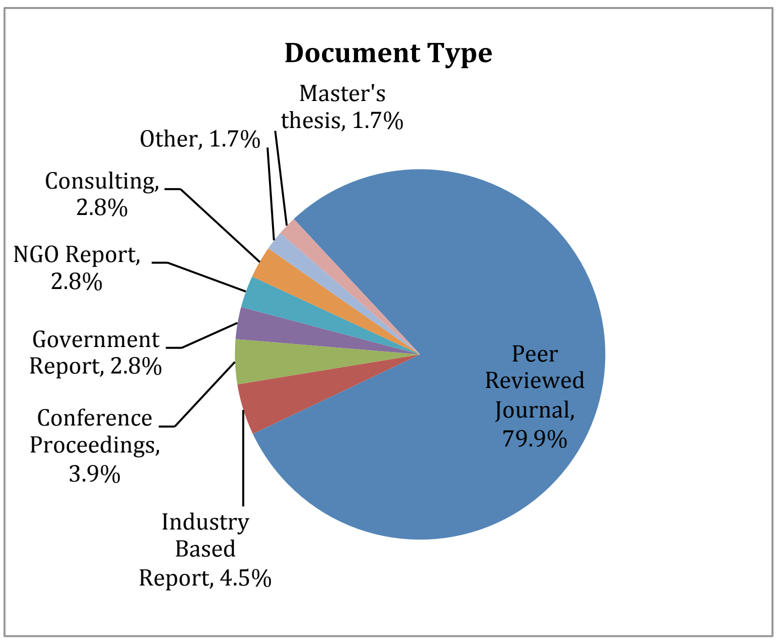

Figure 7. Distribution of the *type* of documents cataloged in the Food LCA Literature Review database.

3. Conclusions

The past decade has seen a great upsurge in the environmental footprinting of foods using life cycle assessment methods. When we began work in this area in the early 2000s, examples of LCA studies of food were extremely limited. Today, the quantity and quality of completed assessments are such that they are being used in a wide range of applications from improving production practices to on-package Product Environmental Footprint

declarations (predominantly in Europe). Still, as this literature review demonstrates, there are limitations.
First, much of the work to date has focused on a limited number of crops and/or food types. For example, the great variety of fruits and vegetables grown around the world are not well represented in the current literature. Even some very common foods, such as onions, for example, have limited LCA data available. Second, much of the research to date has been conducted in a European context. While the number of U.S. studies is increasing, representation is still limited to a handful of foods, and the diverse geographies of the North American continent are poorly represented. Third, many of the studies identified in this literature review are "cradle to farm gate" assessments, meaning they only account for agricultural production. While this may be anecdotally justified as agricultural production often dominates the impacts of full life cycle studies, it nonetheless represents a limitation in considering the impacts of the food system as a whole. Fourth, many studies focus solely on greenhouse gas emissions, with other important environmental impact indicators such as eutrophication, water use, and land use being far less common. This is likely due to the fact that eutrophication, water use and land use impacts in particular are felt locally and require more specific data to be meaningful, whereas greenhouse gas emissions are a global impact that can be more easily generalized. Despite lesser popularity in LCA studies, these other impact categories are very important for food and agricultural sustainability, and there is real potential to shift impacts to other categories by focusing on a single impact.

Despite these caveats, there are many conclusions from the current literature in LCA that can inform food system stakeholders, including producers, consumers and policymakers, in implementing improvement strategies. Application of these findings in future tasks of this project will require careful and balanced consideration of a study's results alongside its research goal and scope.

Appendix A. Description of Fields in Food LCA Catalog

The accompanied Excel spreadsheet ("Food LCA Lit Review DB 020216.xlsx") contains summary information of the Food LCA studies cataloged as part of this literature review. Rows within the spreadsheet represent individual "entries" which may be different foods or the same food in differing life cycle scenarios (e.g., different production practices, countries of origin, or distribution methods). The following descriptions of column categories are intended to aid in interpretation of information logged in the catalog.

Column name	description
Food entry	
Food type	Grouping foods into the following: beverages, cereals and grains, dairy, eggs, fish and seafood, fruit, legumes and nuts, meat, meat substitutes, mixed dishes, oils and fats, sweeteners, vegetables, other.
Specific food	Food studied
Food form	Where appropriate, offers a description of the final food form: fresh, canned, frozen, dried, cured or pickled, and other
Product or production specifics	Text field offering additional descriptive information about the specific entry
Compares production strategies/methods?	Yes/no field identifying whether the entry was compared against other production/distribution scenarios within the given LCA study
Country of origin	Indicates the country of production of the FOOD in question, NOT the document
Citation	
year	Indicates year of document publication
authors	Full listing of author names, typically with symbolic reference to affiliation column
Author affiliations	Listing of author affiliations as indicated in document
Source type	Peer reviewed journal, conference proceedings, government report, industry based report, NGO report, database, other.
Bibliographic citation	Complete citation for document retrieval
DOI or URL	DOI="digital object identifier", and is a unique serial code to identify a specific journal article online. The DOI can simply be copied into Google Scholar or other literature database to link with the article online. For other document types, a URL is included.
Life cycle stages included (all yes/no fields)	
Agricultural production	Does the LCA boundary include agricultural production? Note that different aspects of agricultural production that could or could not be includes are not further specified here. In the case of wild caught seafood, this refers to the fishing stage.
LU/LUC	Does the study include land use and/or land use change as part of its GHGE inventory? While technically not a life cycle stage, this controversial topic is important to note in LCA studies of food/agriculture. Some studies consider the GHGE impact of changes in land use (e.g., deforestation for agricultural purposes), especially when food/feed crops are sourced from South America where market forces are turning rainforest into cropland. While certainly relevant, this can have a significant influence on results and should be considered when making broader generalizations.
Transport: farm to processing	Does the study account for transport from farm gate to processing facility?
Processing	Is some aspect of processing beyond farm gate commodity accounted for in LCA?
Packaging	Does the LCA study account for packaging materials?
Transport: processing to retailer or	Is a transport stage from the processor to retail or distribution hub included?

distribution hub	
retail	Are energy use and emissions associated with retailing the food product included?
Transport: retail to consumer	Does the study account for transport by the consumer from the point of purchase to the home or point of consumption?
Household storage	Is refrigeration or other storage in the home accounted for?
Prep and cooking	Does the study include impacts due to preparation or cooking of the food for consumption purposes?
dishwashing	Does the study include the impacts of dishwashing associated with consuming the food in question?
Capital goods	Often, the production of capital goods (e.g., tractors, barns, processing machinery or facilities) are excluded from food LCA studies because they have proven to be negligible contributors. Some studies, however, choose to include the manufacture of these capital goods. This field is checked "yes" if *production* of major capital goods have been included at some life cycle stage
other	A catch-all field for other relevant life cycle stages not captured in previous fields
Life cycle stages: notes	A text field offering additional relevant information about the life cycle stages covered or caveats of the study in question.
Food waste included?	Food LCAs that cover cradle to grave impacts may account for wastage of the food product in question along the product chain (e.g., at retail or consumer stages). Such wastage increases the impact per unit of food consumed. This is a yes/no field indicating whether such food waste is accounted.
Results at intermediary stages?	Some studies present results such that the impacts of intermediary life cycle stages can be ascertained, whereas others may present only overall results. This yes/no field indicates whether results at intermediary stages are available.
Reported functional unit	The functional unit of an LCA study is the relative basis on which the results are presented. Choice of functional unit is particularly important when comparing impacts of different systems. Ideally, the choice of functional unit reflects the ultimate "function" of the system in question. Given the complexity of food "function", a mass or volume based functional unit is often used.
Environmental impact categories	
Cumulative energy demand	Yes/no whether study reports on this impact category.
Greenhouse gas emissions	Yes/no whether study reports on this impact category.
Water use	Yes/no whether study reports on this impact category.
Land use	Yes/no whether study reports on this impact category.
Freshwater eutrophication potential	Yes/no whether study reports on this impact category.
Marine eutrophication potential	Yes/no whether study reports on this impact category.
Acidification potential	Yes/no whether study reports on this impact category.
Ozone depletion potential	Yes/no whether study reports on this impact category.
Abiotic depletion potential	Yes/no whether study reports on this impact category.
Human toxicity	Yes/no whether study reports on this impact category.
Freshwater eco-toxicity	Yes/no whether study reports on this impact category.
Photochemical oxidation potential	Yes/no whether study reports on this impact category.
Marine eco-toxicity	Yes/no whether study reports on this impact category.

Terrestrial eco-toxicity	Yes/no whether study reports on this impact category.

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