Beyond Meat’s Beyond Burger Life Cycle Assessment:
A detailed comparison between a plant-based and an animal-based protein source

Martin C. Heller and Gregory A. Keoleian
Client: Beyond Meat (Savage River)

Title: Beyond Meat's Beyond Burger Life Cycle Assessment: A detailed comparison between a plant-based and an animal-based protein source

Report version: v.3.1

Report date: September 14, 2018

© Regents of the University of Michigan

On behalf of the Regents of the University of Michigan

Document prepared by

Martin C. Heller  mcheller@umich.edu
Senior Research Specialist  +1 734-474-7166
Center for Sustainable Systems
University of Michigan

Under the supervision of

Gregory A. Keoleian
Peter M. Wege Endowed Professor of Sustainable Systems
Director, Center for Sustainable Systems
University of Michigan

This study has been conducted according to the requirements of ISO 14040-2006, ISO 14044-2006, and reviewed according to ISO 14071-2014.
# Table of Contents

Table of Contents .......................................................... 2  
List of Figures ....................................................................... 4  
List of Tables ......................................................................... 5  
List of Acronyms ................................................................... 6  
Executive Summary ............................................................. 7  
1. Introduction and Goal of the study ........................................ 9  
2. LCA Methodology ............................................................ 9  
    2.1. Scope of the Study ..................................................... 9  
    2.1.1. Product Systems .................................................. 9  
    2.1.2. Product Functions and Functional Unit ................. 9  
    2.1.3. System Boundaries .............................................. 10  
    2.1.3.1. Time Coverage ............................................... 11  
    2.1.3.2. Technology Coverage ..................................... 11  
    2.1.3.3. Geographical Coverage .................................... 11  
    2.1.4. Allocation principles .......................................... 11  
    2.1.5. Cut-off Criteria .................................................. 12  
2.2. Life Cycle Impact Assessment Methodology and Impact Categories ................................................................. 12  
2.3. Data Quality Requirements .......................................... 13  
2.4. Type and Format of the Report ....................................... 13  
2.5. Software and Database ................................................. 13  
2.6. Critical Review .......................................................... 13  
3. Life Cycle Inventory Analysis ............................................ 14  
    3.1. Data Collection Procedure ....................................... 14  
    3.2. Beyond Burger Product System .................................. 14  
    3.2.1. Electricity grid ...................................................... 14  
    3.2.2. Beyond Burger ingredients ................................... 14  
    3.2.3. Beyond Burger processing & packaging ................. 16  
    3.2.4. Cold storage modeling ......................................... 18  
    3.2.5. Processing facility lighting .................................... 19  
    3.2.6. Beyond Burger distribution ................................... 19  
    3.2.7. Packaging disposal modeling ................................ 20  
    3.3. U.S. beef production: baseline for comparison ............. 20  
4. Life Cycle Impact Assessment Results ................................ 23  
    4.1. Beyond Burger LCA results ....................................... 23  
    4.1.1. Greenhouse gas emissions .................................... 26  
    4.1.2. Cumulative energy demand (energy use) ............... 26  
    4.1.3. Land use (occupation) ......................................... 26  
    4.1.4. Consumptive water use ....................................... 27  
4.2. Comparison with beef .................................................. 27  
5. Interpretation .................................................................... 28  
    5.1. Identification of Relevant Findings .............................. 28  
    5.2. Assumptions and Limitations ..................................... 28  
    5.2.1. Boundary condition limitations ......................... 28  
    5.2.2. Spatial and temporal assumptions ......................... 29  
    5.2.3. Beef comparison assumptions: considering beef from dairy and grass-fed beef ......................... 29  
    5.2.3.1. Beef from dairy .............................................. 30  
    5.2.3.2. Grass-fed beef ............................................... 31  
5.3. Results of Sensitivity Analysis ....................................... 31
5.3.1. Modeling parameter sensitivity ......................................................... 31
5.3.2. Sensitivity to measured electricity use .................................................. 32
5.3.3. Final product distribution sensitivity ..................................................... 32
5.3.4. Post-consumer recycled content of tray ............................................... 32
5.3.5. Allocation sensitivity ......................................................................... 33
5.4. Data Quality Assessment .................................................................... 34
5.4.1. Additional inventory data quality assessment ...................................... 34
5.5. Model Completeness and Consistency .................................................... 36
5.6. Conclusions, Limitations, and Recommendations ................................... 36
6. References ................................................................................................. 37
Annex A: Critical Review Statement .............................................................. 40
List of Figures

Figure 1. Life cycle stages included in cradle to distribution system boundary of the Beyond Burger product.................................................................11
Figure 2. Photograph of Beyond Burger retail packaging.................................................................17
Figure 3. BB tray modeling details. Processes informed by personal communication with representatives at tray manufacturer and represent industry averages for this type of production..................................................................................18
Figure 4. System boundary for U.S. beef LCA, as presented by Battagliese et al., 2015. The red border represents the portion of the modeled system used for comparison against the Beyond Burger. Distribution to retail (orange box) is included in the comparison, but are modeled identically to the Beyond Burger case..................................................................................21
Figure 5. Distribution of four impacts across life cycle stages for the Beyond Burger......................24
Figure 6. Relative comparison of impacts between beef (blue bars, set at 100% for each indicator) and Beyond Burger (red bars)..................................................................................................................28
List of Tables

Table 1. Nutritional comparison of Beyond Burger and 80/20 beef................................................................. 10
Table 2. Description of items included and excluded from Beyond Burger system boundary........ 10
Table 3. Summary of Beyond Burger ingredients and data used in modeling ingredient production*.......................................................... 15
Table 4. Beyond Burger packaging materials and modeling approaches .................................................. 17
Table 5. Modeled fractions of disposal pathways for various materials............................................... 20
Table 6. Comparison of system boundaries and data sources between the Beyond Burger LCA and beef LCA........................................................................................................ 22
Table 7. Summary of LCA results for U.S. beef production, per quarter pound boneless, edible beef (modified from Thoma et al., 2017) to remove the effect of food loss)........................................... 23
Table 8. Cradle to distribution LCA results for a one quarter pound Beyond Burger....................... 25
Table 9. Percent contributions to GHGE from different stages and processes in the BB life cycle... 26
Table 10. Comparison of total cradle-to-distribution impacts of quarter pound Beyond Burger and quarter pound U.S. beef. ..................................................................................................................... 27
Table 11. Cradle-to-farm gate LCA results for dairy beef production in the Northeastern U.S........... 30
Table 12. Sensitivity of BB LCA model to a variety of assumed parameters. All values are shown relative to the totals in Table 8.................................................................................................................. 31
Table 13. Sensitivity of total BB results to changes in measured electricity............................................. 32
Table 14. Influence of distribution distance on total BB LCA results. All values are shown relative to the totals in Table 8.................................................................................................................. 32
Table 15. Influence of postconsumer recycled content of PP tray on overall BB LCA results............. 33
Table 16. Percent differences from values in Table 8 for the “ingredient” stage and total impacts, when changing all Agrifootprint processes from economic-based allocation to either energy allocation or mass allocation.................................................................................. 33
Table 17. Pedigree matrix used for data quality assessment derived from (Weidema and Wesnaes, 1996)................................................................................................................................. 34
Table 18. Data quality evaluation and importance of data contribution to life cycle impacts.......... 35
List of Acronyms

BB – Beyond Burger
DS – dry solids
EPA – U.S. Environmental Protection Agency
GHGE – greenhouse gas emissions
GWP – Global Warming Potential
IPCC – Intergovernmental Panel on Climate Change
ISO – International Organization for Standardization
L.A. – Los Angeles
LCA – Life Cycle Assessment
LDPE – low density polyethylene
LLPE – linear low-density polyethylene
Mph – miles per hour
NCBA – National Cattlemen’s Beef Association
NERC – North American Electric Reliability Corporation
PE – polyethylene
PP – polypropylene
SEC – Specific Energy Consumption
SERC – SERC Reliability Corporation (formerly Southeast Electric Reliability Council)
US – United States of America
USMARC – USDA’s Roman L Hruska Meat Animal Research Center
WARM – Waste Reduction Model
WECC – Western Electricity Coordinating Council
Executive Summary

Beyond Meat commissioned the Center for Sustainable Systems at University of Michigan to conduct a “cradle-to-distribution” life cycle assessment of the Beyond Burger, a plant-based patty designed to look, cook and taste like fresh ground beef. The purpose of the study is to compare environmental impacts – chosen here as greenhouse gas emissions, cumulative energy demand (energy use), water use, and land use – with those from typical beef production in the U.S. A secondary purpose is to highlight opportunities for improvement in the environmental performance of the Beyond Burger product chain and provide Beyond Meat with a benchmark against which improvement efforts can be measured. The primary audiences are both internal stakeholders at Beyond Meat as well as external customers, consumers, and interested stakeholders.

The Beyond Burger is considered functionally and nutritionally similar to beef; therefore the chosen functional unit for comparison was defined as 4 oz. (quarter pound, 0.113 kg) uncooked burger patty delivered to retail outlets. This is the marketed patty size of the Beyond Burger and a standard consumer product size for beef patties. System boundaries included upstream ingredient and raw material supply (including farm production of agricultural crops), processing and packaging operations, cold storage, distribution to point of sale, and disposal of packaging materials. Retail and consumer stages, including potential losses at those stages, were excluded, as they were considered equivalent in both product systems. Beyond Meat provided specific information on production of the Beyond Burger, including directly measured processing electricity consumption. This was complemented with information from primary ingredient suppliers. Environmental impact of U.S. beef production was drawn from an existing LCA study commissioned by the National Cattleman’s Beef Association (Thoma et al., 2017). The Beyond Burger LCA was evaluated using the same impact assessment methods used in the U.S. beef study.

Table ES1 provides a comparison of the total impacts from Beyond Burger and beef burger.

Table ES1. Comparison of total cradle-to-distribution impacts of quarter pound lb. Beyond Burger and U.S. beef.

<table>
<thead>
<tr>
<th>Impact category</th>
<th>Unit</th>
<th>Beyond Burger</th>
<th>beef patty</th>
</tr>
</thead>
<tbody>
<tr>
<td>GHGE</td>
<td>kg CO₂ eq.</td>
<td>0.4</td>
<td>3.7</td>
</tr>
<tr>
<td>Energy use</td>
<td>MJ</td>
<td>6.1</td>
<td>11.4</td>
</tr>
<tr>
<td>characterized land use</td>
<td>m² a eq.</td>
<td>0.3</td>
<td>3.8</td>
</tr>
<tr>
<td>characterized water use</td>
<td>liter eq.</td>
<td>1.1</td>
<td>218.4</td>
</tr>
</tbody>
</table>

The distribution of impacts across the Beyond Burger product chain is shown in Figure ES1. Production of the dominant ingredients – pea protein, canola oil, coconut oil – represent important contributions to greenhouse gas emissions (GHGE), energy use and land use. Packaging also is an important contributor across all impact categories: the polypropylene tray is the largest contributor to packaging’s share of GHGE, energy use, and water use, whereas fiber production for cardboard and pallets make notable contributions to land use. We estimate that switching to a
polypropylene tray made of 100% postconsumer recycled content could reduce the overall GHGE of the BB life cycle by 2% and reduce energy use by 10%.

Figure ES1. Distribution of impacts across life cycle stages for the Beyond Burger.
1. Introduction and Goal of the study

Beyond Meat has commissioned the Center for Sustainable Systems to conduct a life cycle assessment (LCA) of their Beyond Burger (BB) and compare it against a typical American ground beef patty. The primary reason for the study is to advance knowledge on the environmental impact of plant-based protein alternatives. In addition, Beyond Meat is interested in sharing results on the potential environmental benefits of BB publicly to consumers and provide scientifically based evidence to support claims of the environmental impacts of consuming BB versus beef. A secondary goal is to provide Beyond Meat with a benchmark against which to measure future improvements in the environmental performance of the BB product chain as well as to highlight hotspots within the product chain. The impact categories of interest include greenhouse gas emissions, cumulative energy demand, water use, and land use.

The intended audience is both internal stakeholders at Beyond Meat, as well as external customers, consumers, and interested stakeholders.

A goal of the study is to conduct a comparative assessment of BB and beef and support comparative assertions intended for public communication. Accordingly, Critical review was conducted per Section 6.3 of the ISO 14044-2006 Standard. The ISO standard requires LCA studies to undergo a Critical Review by a panel of no less than three (3) reviewers when the results are intended to support comparative assertions that are intended to be disclosed to the public.

2. LCA Methodology

2.1. Scope of the Study

The following sections describe the general scope of the project to achieve the stated goals. This includes the identification of specific product systems to be assessed, the product function(s), functional unit and reference flows, the system boundary, allocation procedures, and cut-off criteria of the study.

2.1.1. Product Systems

This cradle-to-distribution LCA study compares a plant-based protein burger with a typical beef burger produced in the U.S.
- The Beyond Burger (BB) is a pea protein-based patty designed to look, cook and taste like fresh ground beef. It is sold in one quarter pound (4 oz.) patties. The product system is defined and informed through direct communications with the product developer and manufacturer, Beyond Meat.
- The U.S. beef industry is complex and multi-faceted. Here, we rely on existing LCA studies of beef production in the U.S. in order to quantify impacts of a beef burger patty. See Section 3.3 for further details on studies employed to evaluate the environmental impact of beef production.

2.1.2. Product Functions and Functional Unit

Establishing the function of foods, and in turn, the functional unit, is difficult (Schau and Fet, 2008) as foods supply a variety of functions. Supplying human nutrition can be considered the primary function of food, but nutrition is multi-dimensional and quite complex, and not easily reduced to a straightforward quantifiable parameter. Foods also provide additional non-nutritional
functions including pleasure, emotional and psychological value, and cultural identity. While important, these additional functions are equally challenging to quantify. In the case of the Beyond Burger, as its flavor and texture profiles are designed to mimic beef, it is reasonable to assume qualitatively that the two products provide similar non-nutritional functions.

As Table 1 demonstrates, the BB has a similar nutritional profile to typical 80/20 beef. This means that a direct comparison between equal weights of BB and beef is reasonable from a nutritional function perspective, and a straightforward mass-based functional unit is appropriate for this study. In addition, quarter pound beef patties may be considered consumer standards.

<table>
<thead>
<tr>
<th>Table 1. Nutritional comparison of Beyond Burger and 80/20 beef</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
</tr>
<tr>
<td>Protein (g)</td>
</tr>
<tr>
<td>Iron (DV)</td>
</tr>
<tr>
<td>Saturated fat (g)</td>
</tr>
<tr>
<td>Cholesterol (mg)</td>
</tr>
<tr>
<td>Total fat (g)</td>
</tr>
<tr>
<td>Calories</td>
</tr>
</tbody>
</table>

The functional unit for this study is therefore defined as one 4 oz. (¼ pound, 0.113 kg) uncooked burger patty delivered to retail outlets. As the BB is currently only marketed in pre-formed ¼ pound patties, this functional unit serves equally well for comparisons with beef and to establish baseline environmental performance for the BB product chain.

2.1.3. System Boundaries

Figure 1 provides a graphical representation of the system boundaries considered in this study. The study represents a cradle-to-distribution assessment of the BB product chain. As such, the study will exclude activities at the retail and consumer level. This cradle-to-distribution boundary scope was chosen primarily because, especially given the uncertainties present in generic modeling of these downstream stages, retail and consumer activities are are considered to be equivalent between the BB and beef product systems. Further, the "cradle-to-distribution" boundary also corresponds with the supply chain controlled by Beyond Meat. Table 2 provides additional detail of items included and excluded from system boundaries. System boundaries for the beef LCA used in comparison are shown later in Figure 4.

<table>
<thead>
<tr>
<th>Table 2. Description of items included and excluded from Beyond Burger system boundary.</th>
</tr>
</thead>
<tbody>
<tr>
<td>included</td>
</tr>
<tr>
<td>• Raw material supply, including ingredients, primary, secondary and tertiary packaging</td>
</tr>
<tr>
<td>• Processing and packaging operations</td>
</tr>
<tr>
<td>• Lighting in processing facilities</td>
</tr>
<tr>
<td>• Transport of ingredients and packaging materials</td>
</tr>
<tr>
<td>• Cold storage prior to distribution</td>
</tr>
<tr>
<td>• Refrigerated transport of finished product to retailer/distributor</td>
</tr>
<tr>
<td>• Packaging disposal</td>
</tr>
</tbody>
</table>
Figure 1. Life cycle stages included in cradle to distribution system boundary of the Beyond Burger product.

2.1.3.1. Time Coverage

Market-scale production of the BB began in May of 2016, and processing moved to a new facility in June, 2017. Therefore, a limited data history is available. For this study, ingredients and suppliers are representative of 2017 production and no significant formulation or supplier changes were made over the year. Baseline product distribution data were aggregated from third quarter 2017 (6/15/2017 to 9/15/2017). Production/processing energy demands were measured during fourth quarter 2017.

2.1.3.2. Technology Coverage

The study is to represent Beyond Meat’s production of BB in the U.S. in 2017.

2.1.3.3. Geographical Coverage

The study is to represent BB production in the continental US, with electricity grid data specific to the production location. At this point, the BB is only distributed in the U.S. Where known, ingredient production are representative of their place of origin, and transportation is included to Beyond Meat production facilities. Packaging disposal is representative of the U.S. average as described in Section 3.2.7.

2.1.4. Allocation principles

In choosing datasets for the BB LCA model, consistent allocation approaches were selected. For processes from Ecoinvent v. 3, the “allocation, default” system model was chosen. According to Ecoinvent, this system model:

---

**Legend**
- **Transportation**
- **Material inputs**
- **energy/electricity inputs**

**Primary data**
- Pre-treatment
- Mixing
- Portioning
- Primary & secondary packaging
- Tertiary packaging
- Cold storage

**Secondary data**
- All ingredients
- Water

**Includes upstream background data**
- Liner paper
- Plastic tray
- Lid film
- Paperboard sleeve
- Cases
- Pallets
- Wrapping

**Processing**
- Distribution to retailer or distributor receiving gate

**Packaging**
- Wrapping

**LEGEND**
- Transportation
- Material inputs
- Energy/electricity inputs
contains two methodological choices: 1) it uses the average supply of products, as described in market activity datasets and 2) it uses partitioning (allocation) to convert multi-product datasets to single-product datasets. The flows are allocated relative to their 'true value', which is the economic revenue corrected for some market imperfections and fluctuations.

For Agrifootprint v. 3.0 processes, economic allocation was consistently selected, however the influence of these allocation choices are explored in Section 5.3.5.

The LCA of pea protein isolate, provided under confidentiality by the manufacturer as described in Section 3.2.2.1, used a mass allocation assignment.

Shared cold-room warehousing of ingredients and finished product at the co-packing processing facility were allocated to the BB on the basis of fraction of total refrigerated volume occupied.

2.1.5. Cut-off Criteria

All efforts have been made to be as inclusive as possible, and no cut-off criteria are defined for this study. Instead, we follow the guidance of the European Commission's Product Environmental Footprint program (EC, 2012) by using a proxy approach. For the processes within the system boundary, all available energy and material flow data have been included in the model. In cases where no matching life cycle inventories are available to represent a flow, proxy data have been applied based on conservative assumptions regarding environmental impacts.

The choice of proxy data is documented in Section 3.2.

2.2. Life Cycle Impact Assessment Methodology and Impact Categories

The impact categories chosen for this study include: greenhouse gas emissions (global warming potential), non-renewable energy use (cumulative energy demand), water use and land use. Primary impact assessment methods were chosen to coordinate exactly with those used in the beef comparison (Thoma et al., 2017) as follows (brief descriptions of the impact assessment methods are provided for background):

• GHGE: IPCC 2007 100a (IPCC, 2007)
• Energy use: Cumulative energy demand (Frischknecht et al., 2007)
  Results reported are the sum of non-renewable fossil, nuclear and biomass energy as well as renewable, biomass, wind, solar, geothermal and water energy. Gross calorific energy content of biomass materials (e.g., corrugated cardboard) has been excluded from the renewable biomass and reported cumulative energy demand.
• Water use impact: (Pfister et al., 2009)
  In this method, consumptive water use – the amount of water used that is not eventually returned to the system – is multiplied by a water scarcity indicator based on the ratio of withdrawn water to available water in a given region. The scarcity indicator is country-specific.
• Land use impact: Ecosystem Damage Potential (Koellner and Scholz, 2008)
  This impact assessment method depends on the area and duration of occupation for specified land-cover types in order to calculate the total ecosystem damage. The amount of occupied land of a specific type and the length of time of the occupation is multiplied by a characterization factor between negative one (indicating a positive contribution to the ecosystem) and one, specific to each land-cover type. The result is a land use impact that is smaller than the total land area occupied, so it is important to note that these values are not simply the land use inventory, and do not include land transformation impacts.
Inventory data (e.g., emissions of individual greenhouse gases) were not reported in Thoma et al. (2017), and therefore we were unable to update impact assessment methods to IPCC 2013. To consider the influence of the outdated methods, results for the BB are reported using the updated IPCC 2013 100a method. We also include absolute water use (consumptive water use without impact assessment) and absolute annual land use (land occupation).

2.3. Data Quality Requirements

Data quality has been considered throughout the LCA process and has been qualitatively assessed in Section 5.4.1. In situations where data quality was questionable, sensitivity analysis has been performed to assess the influence of uncertainty on overall results.

2.4. Type and Format of the Report

In accordance with the ISO requirements (ISO, 2006) the results, data, methods, assumptions and limitations from this study are presented in a transparent manner and in sufficient detail to convey the complexities, limitations, and trade-offs inherent in the LCA to the reader. This allows the results to be interpreted and used in a manner consistent with the goals of the study.

2.5. Software and Database

The LCA model was created using SimaPro 8 software system, developed by PRé Sustainability. LCI databases accompanying SimaPro, including Ecoinvent, Agrifootprint, and USLCI were utilized for background materials and processes in the model.

2.6. Critical Review

The ISO 14040/14044 standards require a critical review when the study results are intended to support comparative assertions intended to be disclosed to the public. The primary goals of a critical review are to provide an independent evaluation of the LCA study and to provide input on how to improve the quality and transparency of the study. The benefits of employing a critical review are to ensure that:

- The methods used to carry out the LCA are consistent with ISO 14040 and 14044,
- The methods used to carry out the LCA are scientifically and technically valid,
- The data used are appropriate and reasonable in relation to the goal of the study,
- The interpretations reflect the limitations identified and the goal of the study, and
- The study report is transparent and consistent.

If applicable, the critical review panel can comment on suggested priorities for potential improvements. For this study, the critical review panel consisted of

- Prof. Roland Geyer, University of California, Santa Barbara (chair)
- Prof. H. Scott Matthews, Carnegie Mellon University
- Prof. Alissa Kendall, University of California, Davis

The review was performed according to section 6.3 of ISO 14044 on comparative assertions to be disclosed to the public. A draft copy of this report was made available to the panel. The panel provided feedback on the methodology, assumptions, and interpretation. The draft report was subsequently revised and a final copy submitted to the review panel along with responses to comments.
The Critical Review Statement can be found in Annex A. The Critical Review Report containing the comments and recommendations of the independent experts as well as the practitioner's responses is also available in the Annex.

3. Life Cycle Inventory Analysis

3.1. Data Collection Procedure

Most data were provided by Beyond Meat, including information on product formulation, processing, process energy use, packaging, storage and distribution. Additional information on key ingredients, production consumables and packaging were collected from respective vendors.

3.2. Beyond Burger Product System

3.2.1. Electricity grid

Electricity grid inventory data for the US were represented at the regional level by specific North American Electric Reliability Corporation (NERC) interconnection regions for year 2012 mix of fuels (the most recent available in Ecoinvent 3), as modeled in Ecoinvent 3 (process="Electricity, medium voltage {*NERC region*} market for | Alloc Def, S"). Activities in each processing facility were modeled using a dataset representative of that electricity grid region.

3.2.2. Beyond Burger ingredients

The ingredients contained in the BB patty are listed in Table 3, along with the data approach used to model each. All ingredients were included in the LCA. Where indicated, information and/or data were gathered from the actual purveyor or manufacturer of the product, but are considered proprietary. Further details of prominent ingredients follow.

3.2.2.1. Pea protein pre-treatment

The primary ingredient, and protein source for the BB, is a pea protein isolate which undergoes pre-treatment prior to mixing with other ingredients. The manufacturer of the pea protein isolate supplies a number of products with similar transformation processes and has performed a simplified LCA for this product family, which has been validated by the PricewaterhouseCoopers certification authority. Impact assessment results for the pea protein product family, along with a methodological description, were provided under confidentiality. The impact indicators provided included global warming (kg CO₂ eq/tonne dry solids (t DS) via 2007 IPCC 100-year method), non-renewable energy (MJ primary/t DS via IMPACT+ 2002 method), consumed ground water (m³/t DS) and mobilized land (ha/t DS). These results have been used directly to represent production of the pea protein isolate. Transportation legs from the place of manufacture of the pea protein isolate have also been included. Water used in the pre-treatment step is modeled as municipal treated water from groundwater (the dominant source at processing facility). The electricity requirements of the pre-treatment process were measured directly via current clamp meter over short collection times. A 5% loss rate is assumed across this pre-treatment stage to account for material left in equipment at the end of production runs, etc.
3.2.2.2. Canola oil

Expeller-pressed non-GMO canola oil originates from the US/Canada, with approximately 70% coming from Canada’s Western provinces (Alberta, Saskatchewan, Manitoba) and 30% from North Central U.S. (Dakotas, Montana, Minnesota). It is pressed in Manitoba, re-packaged in Hammond, IN, and delivered (via truck) to the BB processing facility. Existing Agrifootprint processes were modified to properly reflect growing regions (i.e., 70% Canadian production, 30% U.S. production), the electricity grid at pressing facility (MRO region), and proper transport distances (1500 km by rail from Winnipeg, Manitoba to Hammond, IN and 3254 km by truck to BB processing facility).

Table 3. Summary of Beyond Burger ingredients and data used in modeling ingredient production*.

<table>
<thead>
<tr>
<th>Ingredient</th>
<th>Data approach utilized</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water</td>
<td>[ELCD] Drinking water, water purification treatment, production mix, at plant, from surface water RER S System</td>
</tr>
<tr>
<td>Pea Protein</td>
<td>Pea protein isolate (LCA data from manufacturer) + water</td>
</tr>
<tr>
<td>Expeller-Pressed Canola Oil</td>
<td>[Agrifootprint] Refined rapeseed oil, from crushing (pressing), at plant/** Mass (Source of canola oil was known, including processing facility location. Process modified to reflect 70% Canadian, 30% U.S. production, MROE electricity grid, and appropriate transport distances)</td>
</tr>
<tr>
<td>Refined Coconut Oil</td>
<td>[Agrifootprint] Refined coconut oil, at plant/ID Mass, (Indonesia production) with transport to BB processing facility via ocean freight (22224 km) (port of entry: New York or Boston) and truck (4835 km)</td>
</tr>
</tbody>
</table>

Formulation contains less than 2% of the following ingredients:

- Citrus extract acidulant: Based on ingredients as given by manufacturer
- Flavor components: Facility-level average impact data from manufacturer
- Potato Starch: [Agrifootprint] Potato starch dried, from wet milling, at plant/DE Mass
- Cellulose from Bamboo: Bamboo plantation LCI data from (Wang et al., 2014) (no processing included due to lack of information on extraction and processing)
- Methylcellulose: PROXY: [Ecoinvent] Carboxymethyl cellulose, powder (GLO)/ market for / Alloc Def, S (proxy suggested by Rich Helling at Dow as reasonable for small concentrations)
- Beet-based colorant: Based on ingredient estimates from manufacturer (see below)

* Formulation composition provided, but not revealed here for proprietary reasons (the “less than 2%” declaration is made on the product label).

3.2.2.3. Coconut oil

Coconut oil was identified as originating in Malaysia and Indonesia. An existing Agrifootprint dataset for coconut oil in Indonesia was used as proxy, adding appropriate shipping to the BB processing facility.
3.2.2.4. Beet juice extract colorant

Color in the BB is based on a red beet juice extract. Based on information from the supplier, it takes approximately 6-10 kg of raw beets to make 1 kg of concentrated juice. As raw beets are ~88% water (USDA, 2015), assuming the 10:1 ratio, this concentration requires removal of ~7.8 kg water. No reasonable quality LCI data on red beet production could be found, so carrot production was used as a proxy ([Agrifootprint] Carrot, at farm/NL Mass). Growing and production requirements are expected to be similar between carrots and beets. This proxy choice was confirmed as appropriate through personal communication with the Agrifootprint database developers. The concentrating step was modeled in the LCA with a milk evaporation process ([Ecoinvent] Evaporation of milk {CA-QC} | milk evaporation \ Alloc Def, S)

The final colorant, used in the BB formulation at less than 2%, contains 2-10% (modeled at 10%) of this concentrated beet extract, 40% water, and 50% glycerine.

3.2.3. Beyond Burger processing & packaging

Processing in the processing facility occurs in three primary stages: mixing, patty forming, and packaging. These stages occur in a processing room maintained at 40°F or below. Electricity requirements were measured via current clamp meter over short collection times for processing room air conditioning, mixing, burger forming, and packaging. A 5% loss rate is assumed across processing stages (applied at the primary packaging stage) to account for material left in equipment at the end of production runs, etc.

Retail packaging of BB consists of a thermoformed polypropylene (PP) tray with an extruded polyethylene (PE) sealant layer that receives two ¼ pound BB patties. Figure 2 offers an image of the retail packaging. A PE lid film is sealed over the top, and wrapped with a paperboard sleeve. Each patty sits in the tray on a square of wax coated paper. Eight retail units are aggregated in a corrugated cardboard carton, and 156 cartons are stacked on a pallet and wrapped with linear low density polyethylene for distribution. Table 4 supplies the specific weights and modeling details for this primary and tertiary packaging. Figure 3 shows the specific modeling approach used for production of the PP tray, which was informed by personal communication with representatives at the tray manufacturer and represent industry averages for this kind of production. In the base scenario, the PP tray is assumed to be made of 100% virgin polypropylene. The influence of postconsumer recycled content is considered in Section 5.3.4.
Figure 2. Photograph of Beyond Burger retail packaging.

<table>
<thead>
<tr>
<th>component</th>
<th>quantity</th>
<th>Modeling approach/ LCI processes utilized</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermoformed tray</td>
<td>23.5 g</td>
<td>See Figure 3</td>
</tr>
<tr>
<td>PE lid film</td>
<td>1.68 g per tray</td>
<td>See Figure 3</td>
</tr>
<tr>
<td>Cardboard sleeve</td>
<td>27.4 g per tray, plus 12% board scrap rate during manufacturing; 0.33g printing ink</td>
<td>[Ecoinvent] Folding boxboard/chipboard {US-LA}</td>
</tr>
<tr>
<td>Patty paper</td>
<td>1.3 g per tray</td>
<td>90% paper ([Ecoinvent] Tissue paper {GLO}</td>
</tr>
<tr>
<td>Corrugated carton</td>
<td>239 g per 8 trays</td>
<td>[Ecoinvent] Corrugated board box {GLO}</td>
</tr>
<tr>
<td>Wood pallet</td>
<td>1 per 156 cartons</td>
<td>[Ecoinvent] EUR-flat pallet {GLO}</td>
</tr>
<tr>
<td>Pallet wrap</td>
<td>1 lb per pallet</td>
<td>[USLCI] Linear low density polyethylene resin, at plant/RNA + [Ecoinvent] Extrusion, plastic film {CA-QC}</td>
</tr>
</tbody>
</table>
After packaging, the BB product is placed in cold storage (-10°F) where the product is frozen and stored for an average of 1.5 weeks before distribution.

### 3.2.4. Cold storage modeling

Because cold storage facilities were shared across multiple products and data on energy requirements of operation were unavailable, a reasonable annual Specific Energy Consumption (SEC) of 28 kWh/m³ was assumed. This value was drawn from an “Energy Benchmarking of Warehouses for Frozen Foods,” conducted for the California Energy Commission (Prakash and Singh, 2008). The influence of this assumption is evaluated over a wide range of possible SEC values in Section 5.3.1.

Electricity requirements were calculated by:

\[
\text{electricity (kWh)} = \text{SEC} \times \frac{\text{(days in storage)}}{365} \times \text{(occupied volume)}
\]

In addition to the above electricity demand, the thermal demand of cooling and freezing the final packaged product to storage temperature, which occurs in the cold storage unit, was included. This was calculated by the following:
\[ Q = \left( m_{BB}C_{pBB} + m_{pack}C_{pPack} \right) \Delta T + m_{H2O}\Delta H_{fusion} \]

where:
- \( m_{BB} \) = mass of Beyond Burger (=283 kg per pallet)
- \( m_{pack} \) = mass of packaging (=123 kg per pallet)
- \( m_{H2O} \) = mass of water in BB
- \( C_{pBB} \) = specific heat of BB (assumed to be same as beef) = 2.24 kJ/kg K
- \( C_{pPack} \) = specific heat of packaging = \( \sim 2 \) kJ/kg °C (1.3 for paper, 2.3 for PE)
- \( \Delta T \) = (250-277K) = -27K
- \( \Delta H_{fusion} \) = 0.334 kJ/g H₂O

The thermal demand was converted to electricity requirements of the cold room compressor by dividing by an assumed energy efficiency ratio of 0.7. Sensitivity to this assumption is considered in Section 5.3.1.

### 3.2.5. Processing facility lighting

Energy use for overhead lighting was estimated based on the square footage of facilities used by the BB processing line.

The illuminance requirement of a food processing facility is 500-1000 lumen/m² (lux) on the working surface\(^1\). Assuming 750 lux, a light loss factor of 0.85 (industry standard), and a coefficient of utilization of 0.85 (from downlight), the lumens required from the light source is 1038 lux. The efficacy of high intensity discharge metal halide lamps (identified lighting in BB processing facilities) is 115-104 lumen/Watt (including ballast losses) (US Department of Energy, 2016). Assuming 110 lumen/W, the energy requirement is 9.44 W/m² = 0.877 W/ft².

The lighting is assumed to be on 24 hours/day and is related to the product reference flow using typical daily throughput rates.

### 3.2.6. Beyond Burger distribution

Actual product distribution data from third quarter 2017 (6/15/2017 to 9/15/2017) were used to generate a weighted average transportation distance. Distance by land (in miles) between "ship from" and "ship to" zip codes was estimated via: [https://www.freemaptools.com/distance-between-usa-zip-codes.htm](https://www.freemaptools.com/distance-between-usa-zip-codes.htm). These distances were then weighted by the quantity of product shipped to each location (total product weight of 634,200 lbs.) to arrive at a weighted average shipping distance of 1346 miles.

The following processes were used to model distribution transport via refrigerated truck, combining a transport process with units of ton*km and a freezing temperature refrigeration operation in units of kg*day. In order to estimate the time of refrigeration operation, an average speed of 56.3 mph (Statista, 2015) plus 6 hours of idle time per day (Gaines et al., 2006) were assumed.

- [USLCI] Transport, combination truck, long-haul, diesel powered/tkm/RNA
- [Ecoinvent] Operation, reefer, freezing {GLO}| market for | Alloc Def, U (units of kg*day)

Sensitivity to distribution distance is considered in Section 5.3.3.

---

\(^1\) [https://www.engineeringtoolbox.com/light-level-rooms-d_708.html](https://www.engineeringtoolbox.com/light-level-rooms-d_708.html)
3.2.7. Packaging disposal modeling

End of life processes are not included for the main food product in this study. However, in order to facilitate future comparisons of different packaging formats, disposal of packaging materials is included.

Modeling of packaging disposal follows EPA’s Waste Reduction Model (WARM, version 14) (USEPA, 2016). The WARM model uses a life cycle approach to estimate energy use (or credit) and GHGE associated with recycling, combustion, composting and landfilling of different materials. While the WARM model uses the avoided burden approach to credit recycling by the offset of virgin material, in our model we account for the influence of recycled content in material production via a recycled content (or cut-off) method. Thus, recycling aids the system by avoiding end-of-life burdens from landfill or incineration, but does not result in a material displacement credit at the end-of-life process.

US EPA Municipal Solid Waste data (U.S. EPA, 2016) were used to establish the default fractions distributed to recycling, landfill, and combustion pathways. These fractions are based on US national averages for 2014. The fractions used in the model are shown in Table 5; that is, disposal of BB primary and tertiary packaging materials are assumed to follow national pathway fractions.

### Table 5. Modeled fractions of disposal pathways for various materials.

<table>
<thead>
<tr>
<th>Material</th>
<th>Recycled</th>
<th>Landfilled</th>
<th>Combusted</th>
</tr>
</thead>
<tbody>
<tr>
<td>LDPE</td>
<td>12.3%</td>
<td>70.5%</td>
<td>17.2%</td>
</tr>
<tr>
<td>PP</td>
<td>3.5%</td>
<td>77.6%</td>
<td>18.9%</td>
</tr>
<tr>
<td>Corrugated cardboard</td>
<td>89.5%</td>
<td>8.4%</td>
<td>2.1%</td>
</tr>
<tr>
<td>Other paper</td>
<td>25.6%</td>
<td>59.8%</td>
<td>14.6%</td>
</tr>
<tr>
<td>wood</td>
<td>25.1%</td>
<td>60.2%</td>
<td>17.7%</td>
</tr>
</tbody>
</table>

*a* recycling rates for the year reported (2014) from US EPA MSW data tables (U.S. EPA, 2016)

*c* derived by subtracting recycling fraction and distributing remaining by national average MSW disposal ratio: 80.4% landfill, 19.6% incineration.

3.3. U.S. beef production: baseline for comparison

Beef production has been studied extensively via LCA (De Vries et al., 2015), and a number of studies on various aspects of U.S. production exist (Battagliese et al., 2013; Battagliese et al., 2015; Capper and Hayes, 2012; Dudley et al., 2014; Eshel et al., 2014; Kannan et al., 2017; Lupo et al., 2013; Pelletier et al., 2010; Stackhouse-Lawson et al., 2012; Thoma et al., 2017; Tichenor et al., 2017). The U.S. beef industry is composed of a diverse set of production practices and norms that have not yet been fully captured and represented in an LCA study. However, recent studies sponsored by the National Cattlemen’s Beef Association (NCBA) and conducted initially by BASF (Battagliese et al., 2013; Battagliese et al., 2015) and later adapted and corroborated by University of Arkansas (Thoma et al., 2017) offer an appropriate baseline for beef production in the U.S. These studies are full “cradle to grave” assessments of the US beef product chain (see Figure 4), and include feed production, cow-calf operation, feedlot operation, harvesting (slaughter), case-ready processing and packaging, distribution, retail operations, and at home consumer operations. The primary (acknowledged) limitation in the studies stems from the fact that on-farm operations (cow-calf and feedlot) are based on data from the USDA’s Roman L Hruska Meat Animal Research Center (USMARC) located in Clay Center, Nebraska (Battagliese et al., 2015). This modeling choice was made because of extensive data availability, and while it is acknowledged that USMARC is not representative of the beef industry as a whole, the crop, feed and animal management practices are typical of the practices used in that region of the country.
The following is a representative list of inputs considered in this study. Note that energy and water consumption as well as air, water, and waste emissions are considered throughout.

- Feed
  - Pasture
  - Chemical inputs to crops & soil
  - Lubricants
  - Manure
  - Land
- Cow-calf
  - Supplemental feed
  - Lubricants
  - Land
- Feedlot [incl. backgrounding]
  - Supplemental feed
  - Lubricants
  - Land
- Retail
  - Packaging
  - Refrigerants
  - Consumables / Wear items (gloves, hair and beard nets)
  - Land
  - Beef Waste
- Restaurant consumption
  - Packaging
  - Refrigerants
  - Beef waste
  - Cleaning chemicals
  - Consumables / Wear items (knives, spoons, forks, gloves)
  - Land
- At-home consumption
  - Cooking energy
  - Refrigeration energy
  - Packaging waste
  - Beef waste
- Harvesting
  - Cattle & By-Products
  - Chemicals (only for cleaning plant & animals)
  - Paper used to separate hides from animal
  - Packaging
  - Lubricants
  - Laundering
  - Consumables / Wear items (knives, saw blades, gloves, frocks, boots, aprons, hair and beard nets)
  - Refrigerants
  - Land
  - Beef Waste

*Transportation
† Data for farm phases are specific to USMARC.

Exclusions: Office & administrative impacts, employee commutes, capital equipment, buildings & infrastructure, repair & maintenance materials, parts & supplies, seeds for feed, cattle veterinary medicines. These were determined not to significantly impact the final results.

Figure 4. System boundary for U.S. beef LCA, as presented by Battagliese et al., 2015. The red border represents the portion of the modeled system used for comparison against the Beyond Burger. Distribution to retail (orange box) is included in the comparison, but are modeled identically to the Beyond Burger case.

The functional unit basis of these NCBA studies is one pound of consumed boneless, edible beef, and as such the analysis includes impacts due to food loss and waste, primarily at the retail and consumer stages. Food loss rates of 4% at retail and 20% at consumer were assumed. In order to adjust published results to a basis of one pound of boneless, edible beef delivered to retail, impacts at each life cycle stage (feed, cow-calve, feedlot, harvesting, case ready, retail, consumer, restaurant) were multiplied by \( (1-0.04) \times (1-0.2) \). Then, only stages up to retail (feed, cow-calve, feedlot, harvesting, case ready: red border in Figure 4) were utilized to generate new totals to retail gate. Results were then adjusted from a “one pound” to “one quarter pound” functional unit.

For the purposes of this study, results have all been drawn from the University of Arkansas adaption (Thoma et al., 2017), 2011 linear model, and are presented in Table 7. The LCA model built by Thoma et al. was executed in SimaPro using unit process datasets with extensive upstream networks (specific inventory data sources are detailed in Appendix A of (Thoma et al., 2017)); thus the upstream boundary conditions involving secondary data are considered to be equivalent to those in the BB LCA. Distribution (transport from case-ready processing to retail) could not be separated from other stages in the beef study. Thus, we have used the same distribution model described in Section 3.2.6 as a conservative comparison. In addition, while the cumulative energy demand results presented in (Thoma et al., 2017) included the caloric energy content of feeds, this approach was not used in the current study, and results excluding the energy content of feedstuffs were provided by the authors, as presented in Table 7 (personal communication, 2018). Table 6 offers a high-level comparison of the system boundaries and data sources between the BB and beef LCAs.
Table 6. Comparison of system boundaries and data sources between the Beyond Burger LCA and beef LCA.

<table>
<thead>
<tr>
<th>Stage/component</th>
<th>Beyond Burger LCA</th>
<th>Beef LCA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Upstream ancillary processes</td>
<td>Included via SimaPro/Ecoinvent LCI data matrix</td>
<td>Included via SimaPro/Ecoinvent LCI data matrix</td>
</tr>
</tbody>
</table>
| Agricultural production | Ingredient production modeled using secondary data (primarily Agrifootprint) | Feed production: primary data on production input quantities, input production represented by secondary databases  
Animal production: primary data from IFSM\(^1\) model scenario representing USMARC; inputs represented by secondary databases |
| processing | Primary data on formulation, processing stages, and energy requirements | Harvest: primary data from facility processing 1.5 million animals/year |
| packaging | Primary data on ALL specific packaging materials and weights; materials via secondary databases | Generic "case ready" primary data; materials via secondary databases |
| Final product distribution | Primary data from 4\(^{th}\) Q. 2017 distribution records; secondary data processes as described in Section 3.2.6 | in comparison, assumed same as BB LCA |
| Packaging disposal | Landfill & incineration impacts according to WARM model | Embedded in retail and consumer stages and therefore not included in comparison |
| Electricity production | Ecoinvent 3 processes representing specific regional grid for 2012 | US average grid mix (USLCI dataset) for 2000 |

\(^1\)IFSM=Integrated Farm System Model (https://www.ars.usda.gov/northeast-area/upper-pa/pswmru/docs/integrated-farm-system-model/)

It is important to note that these US beef studies included "case ready" processing and packaging of all retail cuts (not just ground beef patties). We do not differentiate or allocate between beef cuts, as the dominant on-farm impacts apply to the whole animal (however, by-products of the harvesting process, such as hides, tallow, bonemeal, etc. were allocated impacts based on economic value in the original study). Including only “case-ready” processing introduces a conservative assumption, since processing of only ground beef would likely require slightly more

\(^2\)Case ready refers to meat that has been processed (cut) and packaged at a central facility and delivered to the store ready to be put directly into the meat case. This is in contrast to whole or partial carcasses or “boxed meat” (wholesale cuts) that require further processing and packaging into retail cuts by butchers at the retail outlet.
processing energy. We assume that there are not significant differences in impacts between ground beef packaging and the average “case ready” packaging included in the NCBA studies. The beef used as a comparison point in this study is assumed to be from dedicated beef operations. The influence of beef from dairy operations in the U.S. marketplace is considered in Section 5.2.3.

Table 7. Summary of LCA results for U.S. beef production, per quarter pound boneless, edible beef (modified from (Thoma et al., 2017) to remove the effect of food loss).

<table>
<thead>
<tr>
<th>Per quarter pound boneless, edible beef</th>
<th>Feed</th>
<th>Cattle</th>
<th>Harvesting</th>
<th>Case ready</th>
<th>Distribution</th>
<th>Total (delivered to retail)</th>
</tr>
</thead>
<tbody>
<tr>
<td>GHGE kg CO2-eq.</td>
<td>0.6</td>
<td>3.0</td>
<td>0.1</td>
<td>0.0</td>
<td>0.0</td>
<td>3.7</td>
</tr>
<tr>
<td>Cumulative energy demand MJ</td>
<td>6.6</td>
<td>2.2</td>
<td>0.7</td>
<td>1.4</td>
<td>0.4</td>
<td>11.4</td>
</tr>
<tr>
<td>Absolute water use liter-abs.</td>
<td>433.5</td>
<td>3.8</td>
<td>0.4</td>
<td>0.0</td>
<td>0.0</td>
<td>437.7</td>
</tr>
<tr>
<td>characterized water use liter-eq.</td>
<td>216.3</td>
<td>1.9</td>
<td>0.2</td>
<td>0.0</td>
<td>0.0</td>
<td>218.4</td>
</tr>
<tr>
<td>Land use m2a-eq.</td>
<td>3.7</td>
<td>0.0</td>
<td>0.0</td>
<td>0.1</td>
<td>0.0</td>
<td>3.8</td>
</tr>
</tbody>
</table>

*Distribution impacts per quarter pound delivered are taken directly from the BB LCA and applied here.

As is typical in LCA studies of beef production, farm gate contributions – that is the “feed” and “cattle” stages in Table 7 – dominate all impacts. These on-farm stages represent 96%, 78%, 99% and 98% of the cradle-to-distribution GHGE, cumulative energy use, characterized water use, and land use, respectively.

4. Life Cycle Impact Assessment Results

4.1. Beyond Burger LCA results

The results of the Beyond Burger LCA are summarized in Table 8 and Figure 5. Note that “0.00” in Table 8 indicate values less than 0.005 whereas “x” indicates that the model used to represent packaging disposal does not include water and land use inventories. Note also that the terms “absolute land use” and “absolute water use” refer to raw inventories of these resources: m² per year occupied and liters of water consumed. “Characterized land use” and “characterized water use” refer to indicators where the impact assessment methods described in Section 2.2 have been applied. The following sections supply additional details, including dominant processes, for each impact category.
Figure 5. Distribution of four impacts across life cycle stages for the Beyond Burger.
Table 8. Cradle to distribution LCA results for a one quarter pound Beyond Burger.

<table>
<thead>
<tr>
<th>Impact category</th>
<th>Unit</th>
<th>Ingredients</th>
<th>Processing</th>
<th>Packaging</th>
<th>cold storage</th>
<th>Final Product Distribution</th>
<th>Packaging disposal</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>GHGE (2007 100a)</td>
<td>kg CO₂ eq</td>
<td>0.22</td>
<td>0.05</td>
<td>0.08</td>
<td>0.01</td>
<td>0.02</td>
<td>0.00</td>
<td>0.38</td>
</tr>
<tr>
<td>GHGE (2013 100a)</td>
<td>kg CO₂ eq</td>
<td>0.22</td>
<td>0.05</td>
<td>0.08</td>
<td>0.01</td>
<td>0.02</td>
<td>0.00</td>
<td>0.38</td>
</tr>
<tr>
<td>cumulative energy demand</td>
<td>MJ</td>
<td>2.86</td>
<td>0.75</td>
<td>2.07</td>
<td>0.12</td>
<td>0.37</td>
<td>-0.03</td>
<td>6.14</td>
</tr>
<tr>
<td>Percentage renewable</td>
<td>%</td>
<td>0%</td>
<td>5%</td>
<td>6%</td>
<td>16%</td>
<td>0%</td>
<td>0%</td>
<td>3%</td>
</tr>
<tr>
<td>characterized land use</td>
<td>m²·a eq.</td>
<td>0.22</td>
<td>0.00</td>
<td>0.05</td>
<td>0.00</td>
<td>0.00</td>
<td>x</td>
<td>0.27</td>
</tr>
<tr>
<td>Absolute land use</td>
<td>m²·a</td>
<td>0.37</td>
<td>0.00</td>
<td>0.08</td>
<td>0.00</td>
<td>0.00</td>
<td>x</td>
<td>0.45</td>
</tr>
<tr>
<td>characterized water use</td>
<td>liter eq.</td>
<td>0.22</td>
<td>0.51</td>
<td>0.38</td>
<td>0.02</td>
<td>0.00</td>
<td>x</td>
<td>1.12</td>
</tr>
<tr>
<td>Absolute water use</td>
<td>liters</td>
<td>0.49</td>
<td>1.11</td>
<td>1.64</td>
<td>0.04</td>
<td>0.00</td>
<td>x</td>
<td>3.27</td>
</tr>
</tbody>
</table>
4.1.1. Greenhouse gas emissions

The GHGE associated with producing and delivering a ¼ pound Beyond Burger to retail are 0.384 kg CO₂eq/quarter pound BB (or 3.4 kg CO₂eq./kg BB). There is no difference between the IPCC 2007 and 2013 global warming potential (GWP) factors, driven by the fact that CO₂ emissions dominate the inventory (CO₂ = 87% of total GWP; methane = 5%, nitrous oxide = 7%). More than half of this impact is associated with producing and delivering ingredients; packaging represents 22%, and processing steps represent 13%. Additional details on the percent contributions to GHGE are given in Table 9.

Table 9. Percent contributions to GHGE from different stages and processes in the BB lifecycle.

<table>
<thead>
<tr>
<th>Ingredients</th>
<th>% of total</th>
<th>% of stage</th>
</tr>
</thead>
<tbody>
<tr>
<td>ingredients</td>
<td></td>
<td></td>
</tr>
<tr>
<td>pea protein production</td>
<td>57</td>
<td></td>
</tr>
<tr>
<td>canola (for oil), on-farm production</td>
<td>20</td>
<td>36</td>
</tr>
<tr>
<td>coconut (for oil), on-farm production</td>
<td>12</td>
<td>20</td>
</tr>
<tr>
<td>ingredient transport (all forms)</td>
<td>6</td>
<td>11</td>
</tr>
<tr>
<td>packaging</td>
<td>22</td>
<td></td>
</tr>
<tr>
<td>thermoformed PP tray</td>
<td>11</td>
<td>52</td>
</tr>
<tr>
<td>cardboard sleeve</td>
<td>4</td>
<td>18</td>
</tr>
<tr>
<td>tertiary corrugated cardboard</td>
<td>4</td>
<td>19</td>
</tr>
<tr>
<td>processing</td>
<td>13</td>
<td></td>
</tr>
<tr>
<td>direct electricity demand</td>
<td>2.5</td>
<td>19</td>
</tr>
<tr>
<td>distribution</td>
<td>6</td>
<td></td>
</tr>
<tr>
<td>cold storage (intermediate and final product)</td>
<td>2</td>
<td></td>
</tr>
</tbody>
</table>

4.1.2. Cumulative energy demand (energy use)

Distribution of energy demand across life cycle stages follows that of GHGE fairly well, with the exception that packaging represents a larger percentage of the whole due to the embodied energy in packaging materials that are not reflected in GHGE. Energy required to produce the pea protein represents the single greatest contributor at 33% of the total, but the thermoformed tray is a close second at 21%. Direct processing electricity demand represent 3.5% of total energy demand (this includes electricity demand for cold storage). Distribution of final product represents 6.0% of total energy demand. The renewable content of cumulative energy demand is primarily reflective of the renewable portions of regional electricity grids.

4.1.3. Land use (occupation)

Land use is assessed using a method designed to characterize the ecosystem damage potential of each land-cover type. In this impact assessment method, land area and duration of occupation (absolute land use) is multiplied by a characterization factor between negative one (indicating a positive contribution to the ecosystem) and positive one for each land-cover type (Koellner and Scholz, 2008). The result is a land use impact that is smaller than the total land area occupied. Land transformation impacts are not included. A simple land use inventory (m² of land occupied annually for all land-cover types) is provided in Table 8 (absolute land use) to supplement the characterized land use impact. Interestingly, the distribution of land use across the life cycle stages shown in Figure 5 do not differ between characterized and raw land use.
As may be expected, ingredient production dominates land use (81%) with packaging representing most of the remainder (18.5%). Contributors include pea protein (16%), canola (46%), coconut (17%), wood for pallet (10%), and corrugated board for tertiary packaging (3.5%).

### 4.1.4. Consumptive water use

As described in Section 2.2, the method used to assess the impact of water use takes into account the water scarcity (ratio of water withdrawn to water available) in a given region. These characterization factors range from 0 to 1, with 1 indicating extreme water scarcity (Pfister et al., 2009). Thus, while it is expected that the characterized water use value in Table 8 be lower than the absolute water use, the degree to which it is smaller gives an indication of the relative level of water scarcity. It must be noted, however, that this assessment relies on country average characterization factors, which for countries like the U.S., can have significant inter-regional variability. In addition, “water use” in this context refers to consumptive blue water use: that is, surface or ground water used for irrigation, industrial processes or cooling that is not returned back to the watershed. Green water (precipitation) is not included.

The processing stage accounts for 45% of the characterized water use. Production of the thermoformed tray accounts for 14% of total characterized water use, the cardboard sleeve is another 6%, the pattsy paper 5.7%, and corrugated board in tertiary packaging is 6% of the total. Canola oil grown, processed and delivered is 13% of the total characterized water use.

### 4.2. Comparison with beef

Table 10 provides a direct comparison of the impacts attributable to a ¼ pound Beyond Burger with a ¼ pound beef patty. Relative impacts are shown in Figure 6. Based on the results of this study, production, packaging and distribution of the Beyond Burger generates 90% less greenhouse gas emissions, and requires 46% less energy, 99.5% less water (in competition), and 93% less land use (as characterized by ecosystem damage potential) than production, packaging and distribution of U.S. beef.

<table>
<thead>
<tr>
<th>Impact category</th>
<th>Unit</th>
<th>Beyond Burger</th>
<th>beef patty</th>
</tr>
</thead>
<tbody>
<tr>
<td>GHGE</td>
<td>kg CO₂ eq.</td>
<td>0.4</td>
<td>3.7</td>
</tr>
<tr>
<td>Energy use</td>
<td>MJ</td>
<td>6.1</td>
<td>11.4</td>
</tr>
<tr>
<td>characterized land use</td>
<td>m²a eq.</td>
<td>0.3</td>
<td>3.8</td>
</tr>
<tr>
<td>characterized water use</td>
<td>liter eq.</td>
<td>1.1</td>
<td>218.4</td>
</tr>
</tbody>
</table>

Note that the land use values presented here are characterized by the ecosystem damage potential of different land use types. Since (Thoma et al., 2017) does not report raw land use inventory, it is not possible to make direct comparisons between uncharacterized (i.e., absolute) land occupation. In addition, the water use characterization utilized by Thoma et al. relies on national average water stress values, and therefore does not necessarily capture the regional variation that may be present in feed production used in beef rations.
5. Interpretation

5.1. Identification of Relevant Findings

Based on the cradle-to-distribution LCA findings presented here, the Beyond Burger generates 90% less greenhouse gas emissions, and requires 46% less non-renewable energy use, >99% less (characterized) water use, and 93% less (characterized) land use than a U.S. beef burger.

This study also identified a number of interesting findings regarding “hotspots” in the BB life cycle. As may be expected, the production of ingredients in the BB made notable contributions to GHGE, energy use, and land use, and roughly speaking, these contributions followed the mass fractions in the formulation: that is, there were no standout contributions from minor ingredients. Primary packaging, and especially the thermoformed PP tray, was a notable hotspot across all indicators (tray is 11% of total GHGE, 21% of energy use, 14% of water use). These results are relevant because it presents an opportunity to re-design the primary packaging and make significant reductions in the overall product footprint. Section 5.3.4 considers the influence of postconsumer recycled content in the PP tray.

The BB processing stage has a disproportionate contribution to water use, driven by the production of materials consumed within this stage.

5.2. Assumptions and Limitations

5.2.1. Boundary condition limitations

The boundary conditions employed in this study follow the products up to the point of delivery to retail (or wholesale distributors), and therefore do not include retail and at-home use stages. In addition, the contribution from food waste at the retail and consumer level, as well as potential waste through processing and distribution, are not included. Excluding the retail and consumer stages is appropriate as there are unlikely to be major differences between BB and beef. BB is distributed frozen, but is typically displayed in retail alongside fresh meat in a refrigerated counter.
Cooking is similar to that of beef. Waste rates are extremely difficult to estimate, but there is no indication that significant differences would exist between the two products. If anything, because the BB is distributed and stored frozen, there may be reduced retail-level waste compared to beef.

5.2.2. Spatial and temporal assumptions

BB production was modeled based on current practices, including specific ingredient supply chains, where known. Such specifics could be subject to market shifts such as, for example, a shift in pea production regions that could influence environmental performance, especially of highly regionally dependent indicators such as water use. In addition, BB processing efficiencies are based on current production practices, and efficiencies can be expected to improve as production volume increases, leading to decreasing impacts. Further, future production scenarios may include more geographically distributed production, thus influencing transportation distances (see Section 5.3.3 for a consideration of the sensitivity to transportation distances).

5.2.3. Beef comparison assumptions: considering beef from dairy and grass-fed beef

The baseline beef production scenario used as a comparison point was developed to represent a dedicated beef cattle operation that is “typical” for the Midwest and Great Plains of the U.S. This baseline was chosen because, based on expert judgment, it is the most complete and representative LCA of US beef conducted to date. However, beef production methods vary widely, and this variation can reflect in environmental performance. Cradle-to-farm gate GHGE for beef production from an exhaustive LCA literature review ranged from 16 to 118 kg CO₂ eq./kg boneless edible beef, with the mean of 95 data points at 33 kg CO₂ eq./kg and a standard deviation of 12.6. Beef derived from dairy herds varied from 7 to 28 kg CO₂ eq./kg with the mean of 10 data points at 19 kg CO₂ eq./kg and a standard deviation of 8.7 (Heller et al., 2018). Granted, these studies vary both in production methods and geographical location as well as methodological specifics. The point remains, however, that large variation in LCA-based assessments of beef exist. The following sections offer an indication of the influence of key production variants – namely beef from dairy and grass-fed beef – on the beef environmental impact values used as a comparative baseline in this study.

In addition, the baseline beef scenario assumes “case ready” processing and packaging, meaning that the variety of cuts typically found in a retail case are included. This is likely a conservative estimate for processing impacts of all ground beef. Ground beef represented 42% of retail beef sales in 2017 (Statista, 2018). Other estimates place the fraction of US beef consumption in ground beef form at 50%³ or 60%⁴. While it is difficult to accurately determine the amount of additional energy required if baseline beef scenario were represented by all ground beef, an upper bound can be estimated by simply adding the energy requirements of beef grinding to the life cycle values in table 6. In a study aimed at examining different operating conditions on the characteristics of meat grinding, (Kamdem and Hardy, 1995) report grinding energy requirements ranging from 7.5 – 66.6 J/g. Even at the high end of this range, and assuming that electricity generation and transmission increase primary energy demand by a factor of three, this is still less than 0.2 MJ/kg, or 0.2% of the cradle-to-distribution cumulative energy demand reported in Table 7.

---
⁴ [http://www.beefmagazine.com/beef-quality/has-us-become-ground-beef-nation](http://www.beefmagazine.com/beef-quality/has-us-become-ground-beef-nation)
5.2.3.1. Beef from dairy

Beef originating from dairy operations often demonstrates reduced environmental impact in LCA studies than beef from dedicated beef operations because the impacts associated with maintaining a breeding herd are shared between the milk and meat co-products (Tichenor et al., 2017). Reliable data on the fraction of dairy-sourced beef in the U.S. market are hard to come by, meaning that estimates are derived by various means. One recent estimate (Goldstein et al., 2017) assumes that all culled dairy cattle go to ground beef due to the lower quality of the meat, and estimates that between 10.9% and 20.0% of U.S. ground beef originates from the dairy herd. A summary of cradle-to-farm gate LCA results from a recent study of dairy beef production in the Northeastern U.S. (Tichenor et al., 2017) are shown in Table 11. While the GHGE and energy use reported in Table 11 can be reasonably compared to farm-gate (feed + cattle) impacts in Table 7, the land use and water depletion indicators use different impact assessment methods and are not directly comparable.

Table 11. Cradle-to-farm gate LCA results for dairy beef production in the Northeastern U.S.

<table>
<thead>
<tr>
<th></th>
<th>Per kg hot carcass weight(^1)</th>
<th>Per kg boneless edible beef(^2)</th>
<th>Per quarter pound edible beef</th>
</tr>
</thead>
<tbody>
<tr>
<td>GHGE</td>
<td>kg CO(_2) eq.</td>
<td>12.7</td>
<td>19.0</td>
</tr>
<tr>
<td>Fossil fuel depletion(^4)</td>
<td>kg oil-eq.</td>
<td>1.33</td>
<td>1.99</td>
</tr>
<tr>
<td>(converted to energy units)</td>
<td>MJ (42 MJ per kg oil-eq.)</td>
<td>55.9</td>
<td>83.4</td>
</tr>
<tr>
<td>Land use(^3)</td>
<td>m(^2)a</td>
<td>17</td>
<td>25</td>
</tr>
<tr>
<td>Water depletion(^4)</td>
<td>liters</td>
<td>111</td>
<td>166</td>
</tr>
</tbody>
</table>

\(^1\) As reported by (Tichenor et al., 2017)

\(^2\) assuming 33% losses at harvest & case ready, as used in NCBA sponsored studies

\(^3\) land use calculated via the livestock feed requirement model by (Peters et al., 2014). While values were reported as “m\(^2\)” in Tichenor, this model gives annual land use (occupation), so units have been changed here to “m\(^2\)a”

\(^4\) water depletion (i.e., water withdrawal) and fossil fuel depletion calculated via the ReCiPe Midpoint (H) method (Goedkoop et al., 2009)

Using the high-end estimate of US ground beef from dairy (20%) and assuming that downstream impacts (harvest and case-ready) are unchanged when utilizing beef carcasses originating from dairy, we estimate the resulting GHGE for US ground to be:

\[0.8 \times (3.6) + 0.2 \times (2.1) + 0.1 = 3.4 \text{ kg CO}_2 \text{ eq/quarter pound boneless edible beef delivered to retail.} \]

(or 30.2 kg CO\(_2\) eq/kg)

Energy use, calculated in a similar fashion, is 11.4 MJ/quarter pound boneless edible beef delivered to retail.

These estimates are 5% lower for GHGE than the baseline beef values and about the same for energy use. Such calculations across studies are ill-advised as data sources and modeling parameters can have significant influences. This approximation, however, demonstrates that at an expected fraction of the US beef supply, the effect of beef from dairy on GHGE and energy use is not
reflects the range found in a survey of refrigerated warehouses in California.

Cold store of 11 days)

cold store decreased
Cold room compressor energy efficiency ratio increased 20% (to 84%)
Cold room compressor energy efficiency ratio decreased 20% (to 56%)
cold store for 21 days (91% increase from baseline of 11 days)
cold store for 4 days (64% decrease from baseline)

\[ \text{BB processing loss rate hi (10%)} \]
\[ \text{BB processing, no losses (0%)} \]
\[ \text{SEC hi (132 kWh/m}^3; 371\% \text{ increase from baseline)} \]
\[ \text{SEC low (15 kWh/m}^3; 46\% \text{ decrease from baseline)} \]

<table>
<thead>
<tr>
<th>BB processing loss rate hi (10%)</th>
<th>GHGE</th>
<th>energy use</th>
<th>land use</th>
<th>water use</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.93%</td>
<td>4.99%</td>
<td>4.71%</td>
<td>5.32%</td>
<td></td>
</tr>
<tr>
<td>BB processing, no losses (0%)</td>
<td>-4.78%</td>
<td>-4.80%</td>
<td>-4.64%</td>
<td>-5.12%</td>
</tr>
<tr>
<td>SEC hi (132 kWh/m$^3$; 371% increase from baseline)</td>
<td>0.57%</td>
<td>0.65%</td>
<td>0.02%</td>
<td>0.60%</td>
</tr>
<tr>
<td>SEC low (15 kWh/m$^3$; 46% decrease from baseline)</td>
<td>-0.07%</td>
<td>-0.08%</td>
<td>0.00%</td>
<td>-0.07%</td>
</tr>
<tr>
<td>Cold room compressor efficiency ratio increased 20% (to 84%)</td>
<td>-0.25%</td>
<td>-0.29%</td>
<td>-0.01%</td>
<td>-0.28%</td>
</tr>
<tr>
<td>Cold room compressor efficiency ratio decreased 20% (to 56%)</td>
<td>0.37%</td>
<td>0.43%</td>
<td>0.01%</td>
<td>0.42%</td>
</tr>
<tr>
<td>cold store for 21 days (91% increase from baseline of 11 days)</td>
<td>0.14%</td>
<td>0.16%</td>
<td>0.00%</td>
<td>0.15%</td>
</tr>
<tr>
<td>cold store for 4 days (64% decrease from baseline)</td>
<td>-0.10%</td>
<td>-0.11%</td>
<td>-0.00%</td>
<td>-0.10%</td>
</tr>
</tbody>
</table>

\[ \text{SEC = Specific energy consumption of cold storage facility. The range used here (15-132 kWh/m}^3\text{) reflects the range found in a survey of refrigerated warehouses in California (Singh, 2008)} \]
5.3.2. Sensitivity to measured electricity use

Because the BB processing occurs in facilities shared with other production lines, processing energy demand could not be taken from utility purchase records or other longitudinal records. Instead, electricity use during processing stages was measured in situ with inductive current clamp meters, and in some instances of low-energy demand equipment, averaged over only minutes. Thus, it is anticipated that this data have notable uncertainty. Sensitivity of the LCA model to these 18 measured electricity values was performed in order to demonstrate the influence this measurement uncertainty may have on overall results. This sensitivity assessment, shown in Table 13, demonstrates that a 10% change in the required electricity during these processing steps leads to a 0.2–0.3% change in GHGE, energy use, and water use, and negligible change in land use. Since these effects are linear, a 20% variability in electricity demand would result in ~0.4–0.6% change in overall impacts, etc.

Table 13. Sensitivity of total BB results to changes in measured electricity

| % change in overall impact from 10% change in (measured) electricity demand* |
|------------------|-----------------|------------------|-----------------|
| GHGE             | 0.24%           |
| cumulative energy demand | 0.26%        |
| characterized land use | 0.00%         |
| characterized water use     | 0.19%          |

*In this sensitivity assessment, all 18 measured electricity values were varied together by the same amount. Thus, this should be interpreted as a maximum effect from a given level of uncertainty.

5.3.3. Final product distribution sensitivity

The average transportation distance from the BB processing location to retail/wholesale customers across the country was modeled as 1346 miles, based on distribution records for third quarter 2017. This average distance will likely change as production volume and market demand changes. Table 14 offers an indication of the sensitivity of overall results to this transport distance. In addition to a 20% increase and decrease from the baseline distance, a “population weighted” average distance was calculated from the processing facility to the 1000 most populated cities in the continental US, based on data from [http://www.mileage-charts.com/chart.php?p=chart&a=NA&b=US](http://www.mileage-charts.com/chart.php?p=chart&a=NA&b=US). Table 14 demonstrates that even in this extreme case, the total GHGE associated with the BB only increases by 3%.

Table 14. Influence of distribution distance on total BB LCA results. All values are shown relative to the totals in Table 8.

<table>
<thead>
<tr>
<th></th>
<th>GHGE</th>
<th>energy use</th>
<th>Land use</th>
<th>Water use</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average distribution distance increased 20% (to 1627 miles)</td>
<td>1.27%</td>
<td>1.20%</td>
<td>0.00%</td>
<td>0.01%</td>
</tr>
<tr>
<td>Average distribution distance decreased 20% (to 1084 miles)</td>
<td>-1.27%</td>
<td>-1.20%</td>
<td>0.00%</td>
<td>-0.01%</td>
</tr>
<tr>
<td>Population weighted distribution (1836 miles)</td>
<td>2.25%</td>
<td>2.13%</td>
<td>0.00%</td>
<td>0.02%</td>
</tr>
</tbody>
</table>

5.3.4. Post-consumer recycled content of tray

In the baseline case, it is assumed that the polypropylene (PP) tray (primary packaging) is made from 100% virgin PP. Here, we estimate the impact of post-consumer recycled content in the PP
tray. SimaPro does not currently contain a process for recycled postconsumer PP. However, the recycling process is quite similar regardless of polymer. For the sake of this estimate, therefore, we utilize a process from the USLCI dataset for recycled HDPE ([USLCI] Recycled postconsumer HDPE pellet/RNA) as a proxy for recycled postconsumer PP. This recycled material is assumed to displace virgin material in the PP tray at various rates, as shown in Table 15. Based on this estimate, a tray with 100% postconsumer recycled PP could decrease the GHGE associated with the BB by 2% and cumulative energy demand by 10%.

Table 15. Influence of postconsumer recycled content of PP tray on overall BB LCA results.

<table>
<thead>
<tr>
<th>Percent postconsumer recycled PP content in tray</th>
<th>GHGE</th>
<th>Energy use</th>
</tr>
</thead>
<tbody>
<tr>
<td>10%</td>
<td>-0.2%</td>
<td>-1.0%</td>
</tr>
<tr>
<td>25%</td>
<td>-0.5%</td>
<td>-2.5%</td>
</tr>
<tr>
<td>50%</td>
<td>-1.0%</td>
<td>-5.1%</td>
</tr>
<tr>
<td>75%</td>
<td>-1.5%</td>
<td>-7.6%</td>
</tr>
<tr>
<td>100%</td>
<td>-2.0%</td>
<td>-10.2%</td>
</tr>
</tbody>
</table>

5.3.5. Allocation sensitivity

Allocation is required in LCA when an indivisible system produces two or more outputs. Canola is a good example: agricultural production of canola seed results in both canola oil and a protein-rich seed meal that has value as an animal feed, among other things. As the means of producing these co-products are inseparable, “allocating” the burdens of production between the two is necessary. ISO 14044-2006 guidelines offer allocation method guidance, suggesting that partitioning should be first based on physical relationships and secondly on other relationships such as economic value, but no clear rule is established. The Agrifootprint database, which is used for important ingredients including canola oil, coconut oil, and potato starch, offers three allocation options for all processes: mass, energy, and economic allocation. Economic allocation was chosen as the baseline case to be consistent with the allocation methods used in other chosen processes as well as the beef comparison study.

Table 16. Percent differences from values in Table 8 for the “ingredient” stage and total impacts, when changing all Agrifootprint processes from economic-based allocation to either energy allocation or mass allocation.

<table>
<thead>
<tr>
<th>Agrifootprint energy allocation</th>
<th>Ingredients</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>GHGE</td>
<td>-21.6%</td>
<td>-13.8%</td>
</tr>
<tr>
<td>cumulative energy demand</td>
<td>-14.0%</td>
<td>-11.3%</td>
</tr>
<tr>
<td>characterized land use</td>
<td>-28.6%</td>
<td>-23.3%</td>
</tr>
<tr>
<td>characterized water use</td>
<td>-25.4%</td>
<td>-9.5%</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Agrifootprint mass allocation</th>
<th>Ingredients</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>GHGE</td>
<td>-25.6%</td>
<td>-14.4%</td>
</tr>
<tr>
<td>cumulative energy demand</td>
<td>-9.4%</td>
<td>-4.4%</td>
</tr>
<tr>
<td>characterized land use</td>
<td>-40.9%</td>
<td>-33.3%</td>
</tr>
<tr>
<td>characterized water use</td>
<td>-36.5%</td>
<td>-7.1%</td>
</tr>
</tbody>
</table>
Table 16 demonstrates the influence of allocation choice on overall results, and shows that choosing energy or mass allocation would decrease impacts across all categories. Thus, economic allocation in this case is not only the most consistent choice, it is also the most conservative.

5.4. Data Quality Assessment

5.4.1. Additional inventory data quality assessment

A qualitative analysis of the uncertainty due to variability of the inventory data was carried out using the pedigree matrix approach for groups of data, based on expert opinion of the study researchers. The significance of data quality scores in the pedigree matrix is presented in Table 17. The data quality evaluation is presented in Table 18. The importance of data to the life cycle impacts was also evaluated by expert opinion based on contribution analysis and sensitivity analyses.

Table 17. Pedigree matrix used for data quality assessment derived from (Weidema and Wesnaes, 1996)

<table>
<thead>
<tr>
<th>Indicator score</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reliability</td>
<td>Verified data based on measurements</td>
<td>Verified data partly based on assumptions or non-verified data based on measurements</td>
<td>Non-verified data partly based on assumptions</td>
<td>Qualified estimate (e.g. by industrial expert)</td>
<td>Non-qualified estimate</td>
</tr>
<tr>
<td>Completeness</td>
<td>Representative data from a sufficient sample of sites over an adequate period to even out normal fluctuations</td>
<td>Representative data from a smaller number of sites over adequate periods</td>
<td>Representative data from an adequate number of sites over shorter periods</td>
<td>Representative data from a smaller number of sites and shorter periods or incomplete data from an adequate number of sites and periods</td>
<td>Representativeness unknown or incomplete data from a smaller number of sites and/or over shorter periods</td>
</tr>
<tr>
<td>Temporal correlation</td>
<td>Less than 3 years’ difference to year of study</td>
<td>Less than 6 years’ difference</td>
<td>Less than 10 years’ difference</td>
<td>Less than 15 years’ difference</td>
<td>Age of data unknown or more than 15 years’ difference</td>
</tr>
<tr>
<td>Geographic correlation</td>
<td>Data from study area</td>
<td>Average data from larger area that includes the studied area</td>
<td>Data from areas with similar production conditions</td>
<td>Data from areas with slightly similar production conditions</td>
<td>Data from unknown areas or areas with very different production conditions</td>
</tr>
<tr>
<td>Further technological correlation</td>
<td>Data from studied businesses, processes and materials</td>
<td>Data from studied processes and materials from different businesses</td>
<td>Data on studied processes and materials from a different technology</td>
<td>Data on related processes or materials with the same technology</td>
<td>Data on related processes or materials with different technology</td>
</tr>
</tbody>
</table>

The analysis shows that, overall, the quality of the data used for the LCA modeling is of high to medium data quality. This conclusion derives from the fact that data of greatest importance to the results (i.e., to which the assessment is most sensitive) receives low scores in the pedigree quality assessment. Descriptive data of the BB composition, processing, packaging and distribution came directly from Beyond Meat, and is considered reliable. Electricity use during processing was measured over relatively short time periods and therefore may not be highly representative. However, these electricity demands do not have large importance on overall system results. Production of the PP tray (the dominant packaging contribution) was informed by the manufacturer and is considered representative of industry averages.
Table 18. Data quality evaluation and importance of data contribution to life cycle impacts.

<table>
<thead>
<tr>
<th>Source</th>
<th>Importance</th>
<th>Reliability</th>
<th>Completeness</th>
<th>Temporal correlation</th>
<th>Geographic correlation</th>
<th>Further technological correlation</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Ingredients</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>BB formulation</td>
<td>B</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Pea protein isolate production</td>
<td>S</td>
<td>1</td>
<td>1</td>
<td>5</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Canola oil production</td>
<td>D</td>
<td>1</td>
<td>2</td>
<td>1</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>Coconut oil production</td>
<td>D</td>
<td>2</td>
<td>3</td>
<td>1</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>Minor ingredients</td>
<td>S, D, P</td>
<td>3</td>
<td>4</td>
<td>5</td>
<td>1</td>
<td>3</td>
</tr>
<tr>
<td><strong>Processing</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Processes</td>
<td>B</td>
<td>2</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Electricity demand</td>
<td>B</td>
<td>2</td>
<td>1</td>
<td>5</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td><strong>Packaging</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Packaging weights/quantity</td>
<td>B</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>PP tray production</td>
<td>S</td>
<td>1</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Other packaging production</td>
<td>S, D</td>
<td>3</td>
<td>4</td>
<td>5</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td><strong>Cold storage</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Electricity demand of cold storage</td>
<td>M</td>
<td>3</td>
<td>3</td>
<td>5</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>Storage residence time</td>
<td>B</td>
<td>3</td>
<td>4</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td><strong>Distribution transport</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>distance</td>
<td>B</td>
<td>3</td>
<td>2</td>
<td>3</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Modeled truck</td>
<td>D</td>
<td>3</td>
<td>2</td>
<td>1</td>
<td>3</td>
<td>2</td>
</tr>
<tr>
<td><strong>Packaging disposal</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Disposal pathways</td>
<td>D</td>
<td>3</td>
<td>2</td>
<td>1</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>Impact model</td>
<td>M</td>
<td>3</td>
<td>2</td>
<td>1</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td><strong>Beef comparison</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Overall study</td>
<td>1</td>
<td>1</td>
<td>4</td>
<td>1</td>
<td>2</td>
<td>4</td>
</tr>
</tbody>
</table>

Sources: B = Beyond Meat; S = supplier; D = databases; P = proxy; M = modeled
Importance: 1 = high; 2 = medium; 3 = low
5.5. Model Completeness and Consistency

All relevant process steps within the boundary conditions of the study were considered and modeled. The process chain is considered to be sufficiently complete and detailed with regard to the goal and scope of this study.

Assumptions, methods and data are consistent across the BB LCA. To the extent possible based on the level of description of the beef study used as comparison, boundaries, allocation rules, and impact assessment methods have been applied consistently.

5.6. Conclusions, Limitations, and Recommendations

Part of the goal of this study was to provide an estimate of the potential benefit of replacing beef consumption with the plant-based Beyond Burger consumption. A robust LCA of the Beyond Burger was conducted and environmental impact results were compared with a representative study of beef that was modified to cover an equivalent boundary condition (cradle to distribution). The resulting comparative statement from this study is as follows:

*Based on a comparative assessment of the current Beyond Burger production system with the 2017 beef LCA by Thoma et al, the Beyond Burger generates 90% less greenhouse gas emissions, requires 46% less non-renewable energy, has >99% less impact on water scarcity and 93% less impact on land use than a ¼ pound of U.S. beef.*

While uncertainty and sensitivity analysis suggest that the absolute values of these comparative numbers may vary somewhat, there is no indication that a situation or condition may arise in which the environmental performance, as indicated by the categories considered here, of the Beyond Burger would be worse than that of a beef burger. To demonstrate this point, literature values for the GHGE from cradle-to-farm gate production of beef vary, due to production practices and locations as well as modeling assumptions, from 7 to 118 kg CO\(_2\) eq./kg boneless edible beef (Heller et al., 2018). Beyond Burger cradle-to-distribution GHGEs (thus including more of the product chain) are 3.4 kg CO\(_2\) eq./kg BB.

In addition, this study has highlighted a number of hotspots in the Beyond Burger product chain that may warrant attention. These include the polypropylene tray used as primary packaging and specific processing procedures.

Limitations of the study include the following:

- Some data on the BB process chain was collected over a limited timeframe, thus perhaps limiting its long-term representativeness. In particular, electricity use during BB processing and final product distribution patterns and distances are perhaps the most relevant.
- Energy use of cold storage was modeled rather than measured. This was due to the fact that cold storage occurred in a shared facility, and access to actual energy requirements was not possible.
- Some minor ingredients were represented by fairly coarse proxies. Based on these estimates, contribution to system impacts of these minor ingredients is negligible.
- The beef study used as a comparative point was conducted by a 3\(^{rd}\) party. While every effort was made to assure consistent boundary conditions and impact assessment methods based on careful study of project reports and through personal communication with the study authors, such indirect comparison introduces a potential limitation. While the comparative beef assessment represents the best available study of beef production in the US, it does not necessarily accurately reflect average US market ground beef production. However, efforts...
in this report to bound some of the potential variance in beef production suggest that significant differences from the conclusions drawn here are unlikely.

Recommendations from the study include the following:

- Communication of the relative environmental benefits of Beyond Burger over beef shall occur with acknowledgement of the uncertainties present in this study.
- Alternatives to the polypropylene tray, including PP with increased postconsumer recycled content, should be considered in an effort to further improve the environmental performance of the Beyond Burger.

6. References


Annex A: Critical Review Statement

Critical Review of the Study “Beyond Meat’s Beyond Burger Life Cycle Assessment: A detailed comparison between a plant-based and an animal-based protein”

Commissioned by: Beyond Meat (Savage River), Los Angeles, CA

Performed by: Martin C. Heller, Senior Research Specialist, Center for Sustainable Systems, University of Michigan

Supervised by: Gregory A. Keoleian, Professor and Director Center for Sustainable Systems, University of Michigan

Critical Review Panel\(^5\): Roland Geyer, Professor, UC Santa Barbara, CA (Chair) Alissa Kendall, Professor, UC Davis, CA H Scott Matthews, Professor, Carnegie Mellon University, Pittsburgh, PA

Draft Date: 14 September, 2018


The Scope of the Critical Review

The review panel had the task to assess whether

- the methods used to carry out the LCA are consistent with ISO 14044:2006 and ISO/TS 14071: 2014
- the methods used to carry out the LCA are scientifically and technically valid,
- the data used are appropriate and reasonable in relation to the goal of the study,
- the interpretations reflect the limitations identified and the goal of the study, and
- the study report is transparent and consistent.

The review was performed according to ISO 14044 and ISO/TS 14071 in their strictest sense as the results of the study are intended to be used for comparative assertions to be disclosed to the public.

The extent to which the unit process data are appropriate and representative, given the goal and scope of the study, was determined by a critical review of the available metadata, i.e.

\(^5\) While the professional affiliations of the peer reviewers have been provided, their effort was personally compensated. Thus, their reviews do not represent any endorsements by their Universities.
process descriptions, etc. Analysis and validation of the process inputs and outputs themselves was outside the scope of this review.

General evaluation

The defined scope for this LCA study was found to be appropriate to achieve the defined goals. The Life Cycle Inventory models are suitable for the purpose of the study and are thus capable to support the goal of the study. All primary and secondary data are adequate in terms of quality, and technological, geographical and temporal coverage. The data quality is found to be mostly high for the most important processes and at least adequate for all others. Study results are reported using four impact categories and two inventory-level indicators. This selection was found to be appropriate and reasonable in relation to the goal of the study, which includes comparative assessment relative to previous studies with limited use of impact categories. As a result, the report is deemed to be representative and complete. The study is reported in a transparent manner. Various assumptions were addressed by uncertainty and sensitivity analyses of critical data and methodological choices. The interpretations of the results reflect the identified limitations of the study (and past literature) and are considered to be conservative.

The critical review process was open and constructive. The LCA commissioner and practitioner were cooperative and forthcoming and addressed all questions, comments, and requests of the review panel to its full satisfaction.

This Review Statement summarizes the review process and its outcome. The review process is documented in the Review Report, which is available as a separate document (following this Review Statement) and contains all reviewer comments and practitioner responses.

Conclusion

The study has been carried out in compliance with ISO 14044 and ISO/TS 14071. The critical review panel found the overall quality of the report high, its methods scientifically and technically valid, and the used data appropriate and reasonable. The study report is transparent and consistent, and the interpretation of the results reflects the goal and the identified limitations of the study.

Roland Geyer
Alissa Kendall
H Scott Matthews
<table>
<thead>
<tr>
<th>Comments</th>
<th>Suggested modifications</th>
<th>Suggestions and rationale</th>
<th>Placement/numbering</th>
<th>Recommendations</th>
<th>Placement/numbering</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>suggested</td>
<td>suggested and in parenthesis.</td>
<td>Figure 3</td>
<td>suggested</td>
<td>Figure 3</td>
</tr>
<tr>
<td>2</td>
<td>suggested</td>
<td>suggested and in parenthesis.</td>
<td>Figure 3</td>
<td>suggested</td>
<td>Figure 3</td>
</tr>
<tr>
<td>3</td>
<td>suggested</td>
<td>suggested and in parenthesis.</td>
<td>Figure 3</td>
<td>suggested</td>
<td>Figure 3</td>
</tr>
<tr>
<td>4</td>
<td>suggested</td>
<td>suggested and in parenthesis.</td>
<td>Figure 3</td>
<td>suggested</td>
<td>Figure 3</td>
</tr>
<tr>
<td>5</td>
<td>suggested</td>
<td>suggested and in parenthesis.</td>
<td>Figure 3</td>
<td>suggested</td>
<td>Figure 3</td>
</tr>
<tr>
<td>6</td>
<td>suggested</td>
<td>suggested and in parenthesis.</td>
<td>Figure 3</td>
<td>suggested</td>
<td>Figure 3</td>
</tr>
<tr>
<td>7</td>
<td>suggested</td>
<td>suggested and in parenthesis.</td>
<td>Figure 3</td>
<td>suggested</td>
<td>Figure 3</td>
</tr>
<tr>
<td>8</td>
<td>suggested</td>
<td>suggested and in parenthesis.</td>
<td>Figure 3</td>
<td>suggested</td>
<td>Figure 3</td>
</tr>
<tr>
<td>9</td>
<td>suggested</td>
<td>suggested and in parenthesis.</td>
<td>Figure 3</td>
<td>suggested</td>
<td>Figure 3</td>
</tr>
<tr>
<td>10</td>
<td>suggested</td>
<td>suggested and in parenthesis.</td>
<td>Figure 3</td>
<td>suggested</td>
<td>Figure 3</td>
</tr>
<tr>
<td>11</td>
<td>suggested</td>
<td>suggested and in parenthesis.</td>
<td>Figure 3</td>
<td>suggested</td>
<td>Figure 3</td>
</tr>
<tr>
<td>12</td>
<td>suggested</td>
<td>suggested and in parenthesis.</td>
<td>Figure 3</td>
<td>suggested</td>
<td>Figure 3</td>
</tr>
<tr>
<td>13</td>
<td>suggested</td>
<td>suggested and in parenthesis.</td>
<td>Figure 3</td>
<td>suggested</td>
<td>Figure 3</td>
</tr>
<tr>
<td>14</td>
<td>suggested</td>
<td>suggested and in parenthesis.</td>
<td>Figure 3</td>
<td>suggested</td>
<td>Figure 3</td>
</tr>
<tr>
<td>15</td>
<td>suggested</td>
<td>suggested and in parenthesis.</td>
<td>Figure 3</td>
<td>suggested</td>
<td>Figure 3</td>
</tr>
<tr>
<td>16</td>
<td>suggested</td>
<td>suggested and in parenthesis.</td>
<td>Figure 3</td>
<td>suggested</td>
<td>Figure 3</td>
</tr>
<tr>
<td>17</td>
<td>suggested</td>
<td>suggested and in parenthesis.</td>
<td>Figure 3</td>
<td>suggested</td>
<td>Figure 3</td>
</tr>
<tr>
<td>18</td>
<td>suggested</td>
<td>suggested and in parenthesis.</td>
<td>Figure 3</td>
<td>suggested</td>
<td>Figure 3</td>
</tr>
<tr>
<td>19</td>
<td>suggested</td>
<td>suggested and in parenthesis.</td>
<td>Figure 3</td>
<td>suggested</td>
<td>Figure 3</td>
</tr>
<tr>
<td>20</td>
<td>suggested</td>
<td>suggested and in parenthesis.</td>
<td>Figure 3</td>
<td>suggested</td>
<td>Figure 3</td>
</tr>
<tr>
<td>21</td>
<td>suggested</td>
<td>suggested and in parenthesis.</td>
<td>Figure 3</td>
<td>suggested</td>
<td>Figure 3</td>
</tr>
<tr>
<td>22</td>
<td>suggested</td>
<td>suggested and in parenthesis.</td>
<td>Figure 3</td>
<td>suggested</td>
<td>Figure 3</td>
</tr>
<tr>
<td>23</td>
<td>suggested</td>
<td>suggested and in parenthesis.</td>
<td>Figure 3</td>
<td>suggested</td>
<td>Figure 3</td>
</tr>
<tr>
<td>24</td>
<td>suggested</td>
<td>suggested and in parenthesis.</td>
<td>Figure 3</td>
<td>suggested</td>
<td>Figure 3</td>
</tr>
<tr>
<td>25</td>
<td>suggested</td>
<td>suggested and in parenthesis.</td>
<td>Figure 3</td>
<td>suggested</td>
<td>Figure 3</td>
</tr>
<tr>
<td>26</td>
<td>suggested</td>
<td>suggested and in parenthesis.</td>
<td>Figure 3</td>
<td>suggested</td>
<td>Figure 3</td>
</tr>
<tr>
<td>27</td>
<td>suggested</td>
<td>suggested and in parenthesis.</td>
<td>Figure 3</td>
<td>suggested</td>
<td>Figure 3</td>
</tr>
<tr>
<td>28</td>
<td>suggested</td>
<td>suggested and in parenthesis.</td>
<td>Figure 3</td>
<td>suggested</td>
<td>Figure 3</td>
</tr>
</tbody>
</table>

---

**Notes:**
- **HSM** indicates Human Subject Matter.
- **ED/TE** indicates Environmental Design/Technology.
- **Text(s)** indicates the specific text being commented on.
- **Figure(s)** indicates the specific figure being commented on.
- **Table(s)** indicates the specific table being commented on.
- **ES-1** indicates the specific section being commented on.
- **Page numbers** are referenced to the original document.
I ask though the GAG the impact assessment (daily intake) four ways to be. There is no question that the results of the final study are not the same as all the previous research. For example, for most of the impacts, final and raw data are used. It is important to note that this study only includes the impacts of beef production. For example, the cattle and beef industry are used to assess the impacts. The method used to assess the impacts of beef production was used in the previous LCA study. The method used to assess the impacts of beef production was used in the previous LCA study. The method used to assess the impacts of beef production was used in the previous LCA study. The method used to assess the impacts of beef production was used in the previous LCA study. The method used to assess the impacts of beef production was used in the previous LCA study. The method used to assess the impacts of beef production was used in the previous LCA study.
Is this just for primary or all packaging? Re primary: I think it's more realistic to eliminate renewables and to count biomass and non-renewable. Why not use assume that it's landfilled entirely. Re recycled content: Do you assume that Are citrus extract acidulant and favor components excluded from the study? Is the 0.7 from el. to heat or the other way round? Do you have a source for that value by the EDP. Also, don't you need a reference state for the land in all about the avoided burden approach, so if you don't use avoided burden The cumulative energy use results reported are the sum of non-renewable production of all the inputs are included. There might be an opportunity to clarify data sources by distinguishing between primary and secondary data, respectively. Consider using the notions of primary and secondary data. Consider whether this cumulative energy demand calculation will allow comparison of this study to future studies. Consider the allocation methods used in the pea protein isolate LCA. Consider adding detail and describing each of the factors Consider using the LCA of pea protein isolates, provided under confidentiality by the manufacturer as described in SI 3.2.1, used a mass allocation assignment.