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Beyond Meat's Beyond Burger Life Cycle Assessment:

A detailed comparison between a plant-based and an animal-based protein source

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

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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.

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 energy, has >99% less impact on water scarcity and 93% less impact on land use than a ¼ pound of U.S. beef.

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

Impact category	Unit	Beyond Burger	beef patty
GHGE	kg CO_2 eq.	0.4	3.7
Energy use	MJ	6.1	11.4
characterized land use	m^2a eq.	0.3	3.8
characterized water use	liter eq.	1.1	218.4

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%.

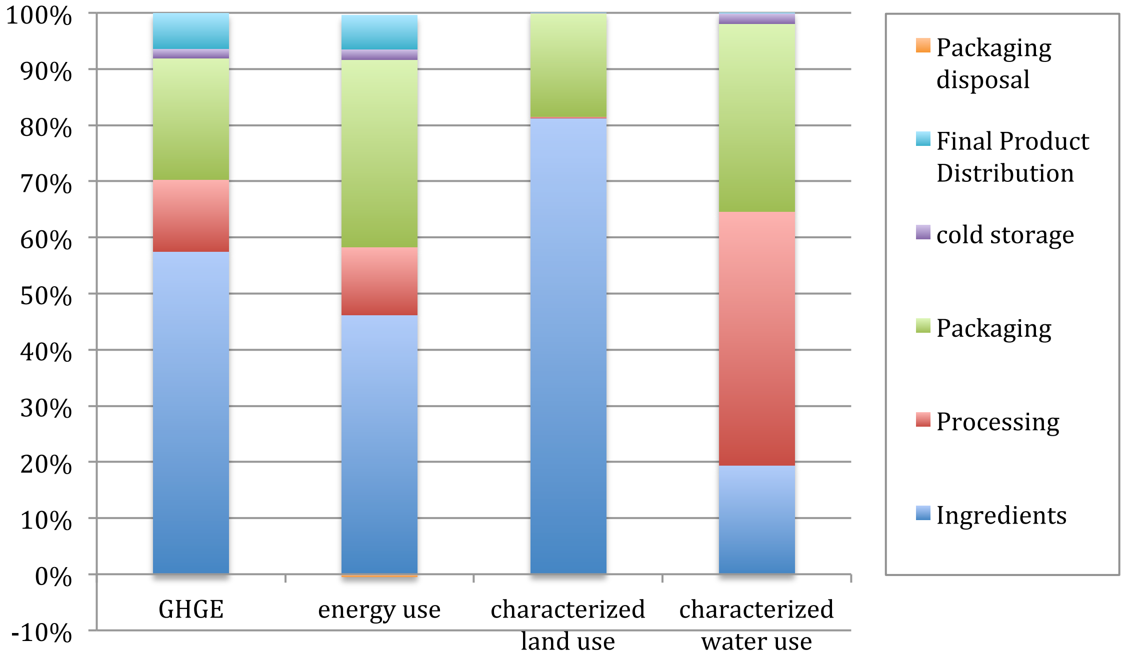

Figure ES1. Distribution of impacts across life cycle stages for the Beyond Burger.

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 publically 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 1. Nutritional comparison of Beyond Burger and 80/20 beef

	4 oz. BB patty	4 oz. 80/20 beef (USDA, 2015)
Protein (g)	20	19
Iron (DV)	25%	12%
Saturated fat (g)	5	9
Cholesterol (mg)	0	80
Total fat (g)	22	23
Calories	290	287

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 2. Description of items included and excluded from Beyond Burger system boundary.

included	excluded
• Raw material supply, including ingredients, primary, secondary and tertiary packaging • Processing and packaging operations • Lighting in processing facilities • Transport of ingredients and packaging materials • Cold storage prior to distribution • Refrigerated transport of finished product to retailer/distributor • Packaging disposal	• Retail and consumer stages • Food waste disposal • Capital goods and infrastructure • Employee travel • Water use for processing line cleaning (typically unheated) • Additional processing facility overhead such as forklift operation • Bamboo fiber (ingredient) processing

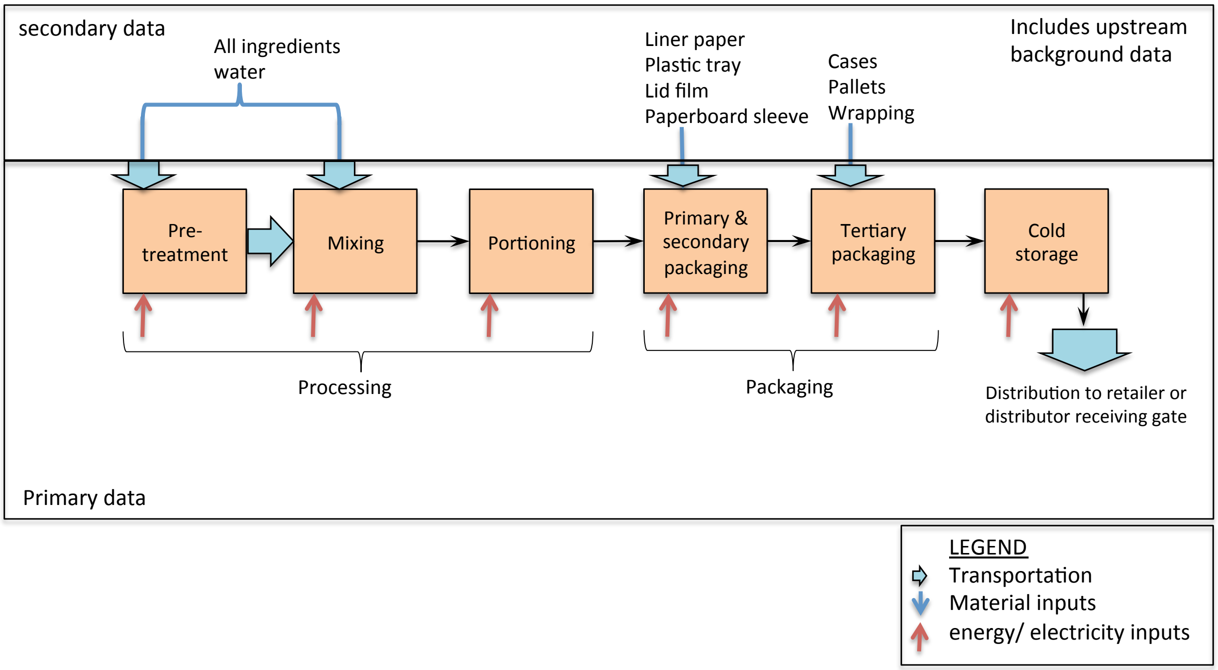

Figure 1. Life cycle stages included in cradle to distribution system boundary of the Beyond Burger product.

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:

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 CO_2 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 (m^3/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*.

Ingredient	Data approach utilized [xxx] = source database
Water	[ELCD] Drinking water, water purification treatment, production mix, at plant, from surface water RER S System
Pea Protein	Pea protein isolate (LCA data from manufacturer) + water
Expeller-Pressed Canola Oil	[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)
Refined Coconut Oil	[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)
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 4. Beyond Burger packaging materials and modeling approaches

component	quantity	Modeling approach/ LCI processes utilized
Thermoformed tray	23.5 g	See Figure 3
PE lid film	1.68 g per tray	See Figure 3
Cardboard sleeve	27.4 g per tray, plus 12% board scrap rate during manufacturing; 0.33g printing ink	[Ecoinvent] Folding boxboard/chipboard {US-LA}| chipboard production, white lined | Alloc Def, U (modified to represent WECC elec. grid and US water sourcing.; [Ecoinvent] Printing ink, offset, without solvent, in 47.5% solution state {GLO}| market for | Alloc Def, S.
Patty paper	1.3 g per tray	90% paper ([Ecoinvent] Tissue paper {GLO}| market for | Alloc Def, S) 10% wax ([Ecoinvent] Paraffin {GLO}| market for | Alloc Def, S)
Corrugated carton	239 g per 8 trays	[Ecoinvent] Corrugated board box {GLO}| market for corrugated board box | Alloc Def, S
Wood pallet	1 per 156 cartons	[Ecoinvent] EUR-flat pallet {GLO}| market for | Alloc Def, S
Pallet wrap	1 lb per pallet	[USLCI] Linear low density polyethylene resin, at plant/RNA + [Ecoinvent] Extrusion, plastic film {CA-QC}| market for | Alloc Def, S

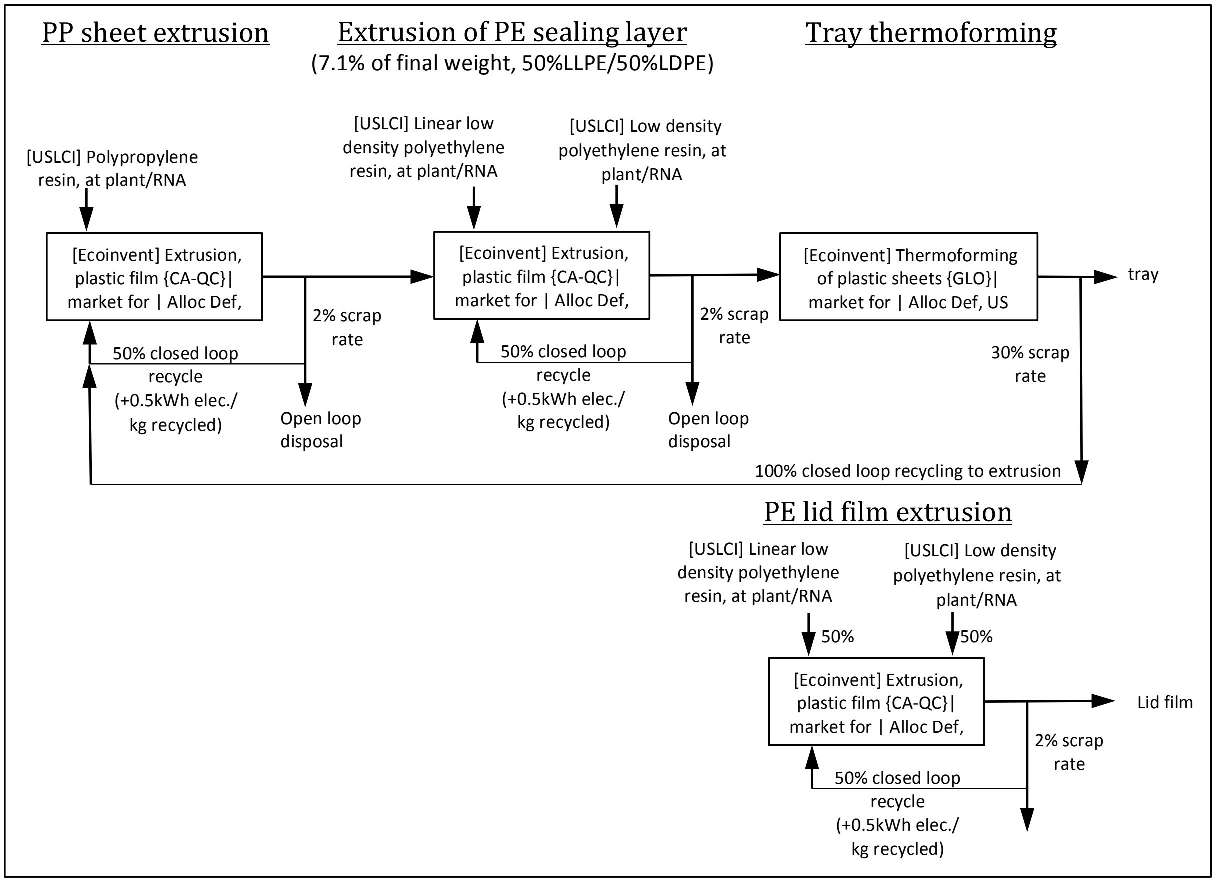

Figure 3. BB tray modeling details. Processes informed by personal communication with representatives at tray manufacturer and represent industry averages for this type of production.

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/m^3 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:

$$electricity\ (kWh) = SEC * \frac{(days\ in\ storage)}{365} * (occupied\ volume)$$

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:

$$Q = \left(m_{BB}Cp_{BB} + m_{pack}Cp_{pack}\right)\Delta T + m_{H_2O}\Delta H_{fusion}$$

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
Cp_{BB} = specific heat of BB (assumed to be same as beef) = 2.24 kJ/kg K
Cp_{pack} = specific heat of packaging = ~2 kJ/kg °C (1.3 for paper, 2.3 for PE)
ΔT = (250-277K) = -27K
ΔH_{fusion} = 0.334 kJ/g H_2O

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/m^2 (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/ m^2 = 0.877 W/ft^2.

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. 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

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) (US EPA, 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.

Material	Recycled[a]	Landfilled[c]	Combusted[c]
LDPE	12.3%	70.5%	17.2%
PP	3.5%	77.6%	18.9%
Corrugated cardboard	89.5%	8.4%	2.1%
Other paper	25.6%	59.8%	14.6%
wood	25.1%	60.2%	17.7%

[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.

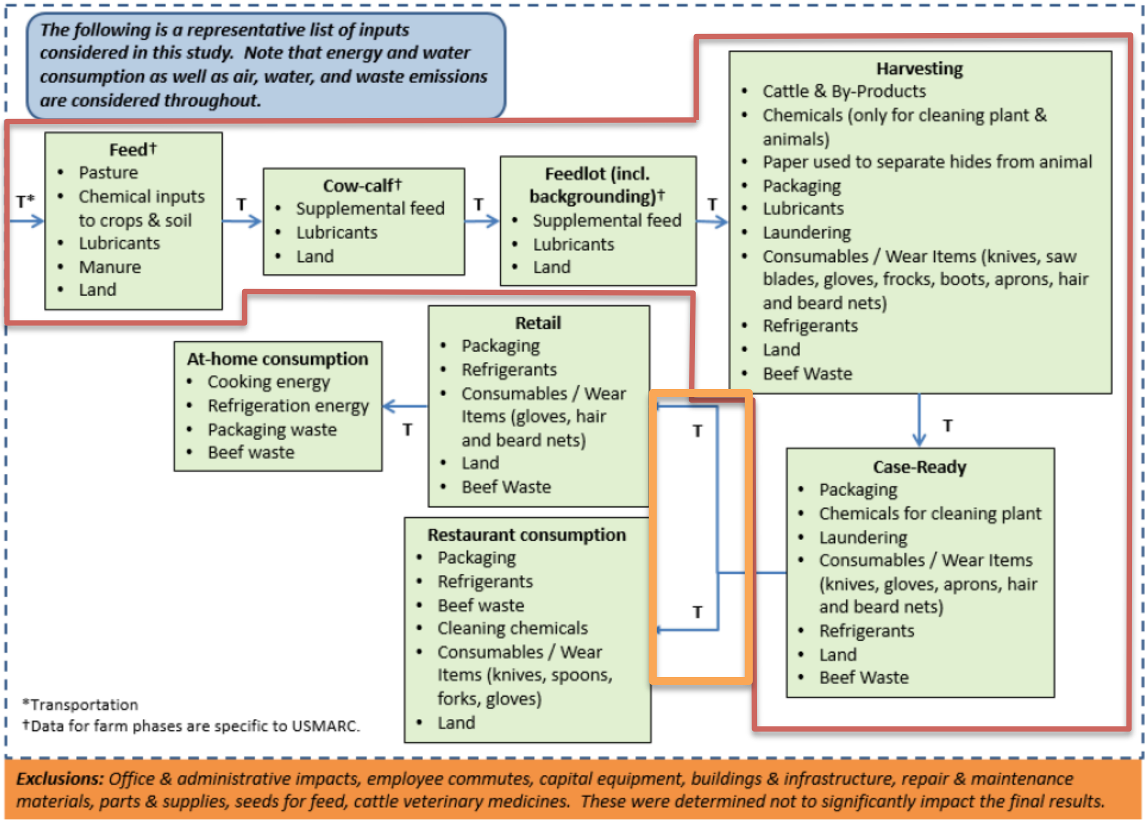

Figure 4. System boundary for U.S. beef LCA, as presented by Battagliese et al., 2015. The red border represents the portion of the modeled system used for comparison against the Beyond Burger. Distribution to retail (orange box) is included in the comparison, but are modeled identically to the Beyond 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-calf, feedlot, harvesting, case ready, retail, consumer, restaurant) were multiplied by (1-0.04)*(1-0.2). Then, only stages up to retail (feed, cow-calf, 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.

Stage/component	Beyond Burger LCA	Beef LCA
Upstream ancillary processes	Included via SimaPro/Ecoinvent LCI data matrix	Included via SimaPro/Ecoinvent LCI data matrix
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 4th 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
Intermediate transport	[USLCI] Transport, combination truck long-haul, diesel powered /tkm/RNA	[USLCI] Transport, single unit truck long-haul, diesel powered /tkm/RNA

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

It is important to note that these US beef studies included "case ready[2]" 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).

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

*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: m^2 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.

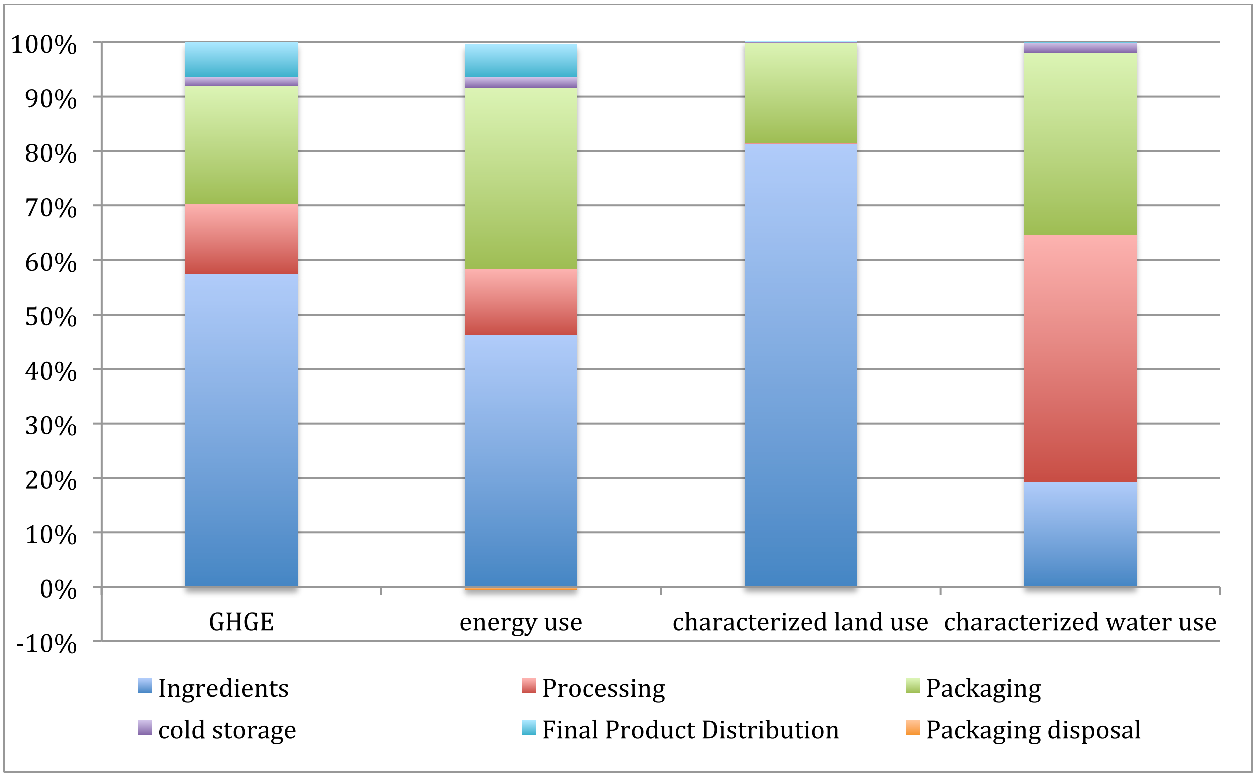

Figure 5. Distribution of four impacts across life cycle stages for the Beyond Burger.

Table 8. Cradle to distribution LCA results for a one quarter pound Beyond Burger.

Impact category	Unit	Ingredients	Processing	Packaging	cold storage	Final Product Distribution	Packaging disposal	Total
		Per quarter pound Beyond Burger						
GHGE (2007 100a)	kg CO_2 eq	0.22	0.05	0.08	0.01	0.02	0.00	0.38
GHGE (2013 100a)	kg CO_2 eq	0.22	0.05	0.08	0.01	0.02	0.00	0.38
cumulative energy demand	MJ	2.86	0.75	2.07	0.12	0.37	-0.03	6.14
Percentage renewable	%	0%	5%	6%	16%	0%	0%	3%
characterized land use	m^2a eq.	0.22	0.00	0.05	0.00	0.00	x	0.27
Absolute land use	m^2a	0.37	0.00	0.08	0.00	0.00	x	0.45
characterized water use	liter eq.	0.22	0.51	0.38	0.02	0.00	x	1.12
Absolute water use	liters	0.49	1.11	1.64	0.04	0.00	x	3.27

4.1.1. Greenhouse gas emissions

The GHGE associated with producing and delivering a ¼ pound Beyond Burger to retail are 0.384 kg CO_2eq/quarter pound BB (or 3.4 kg CO_2eq. /kg BB). There is no difference between the IPCC 2007 and 2013 global warming potential (GWP) factors, driven by the fact that CO_2 emissions dominate the inventory (CO_2 = 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 lifec cycle.

	% of total	% of stage
ingredients	57	-
pea protein production	20	36
canola (for oil), on-farm production	12	20
coconut (for oil), on-farm production	7	12
ingredient transport (all forms)	6	11
packaging	22	-
thermoformed PP tray	11	52
cardboard sleeve	4	18
tertiary corrugated cardboard	4	19
processing	13	-
direct electricity demand	2.5	19
distribution	6	-
cold storage (intermediate and final product)	2	-

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 (m^2 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 patty 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 10. Comparison of total cradle-to-distribution impacts of quarter pound Beyond Burger and quarter pound U.S. beef.

Impact category	Unit	Beyond Burger	beef patty
GHGE	kg CO_2 eq.	0.4	3.7
Energy use	MJ	6.1	11.4
characterized land use	m^2a eq.	0.3	3.8
characterized water use	liter eq.	1.1	218.4

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.

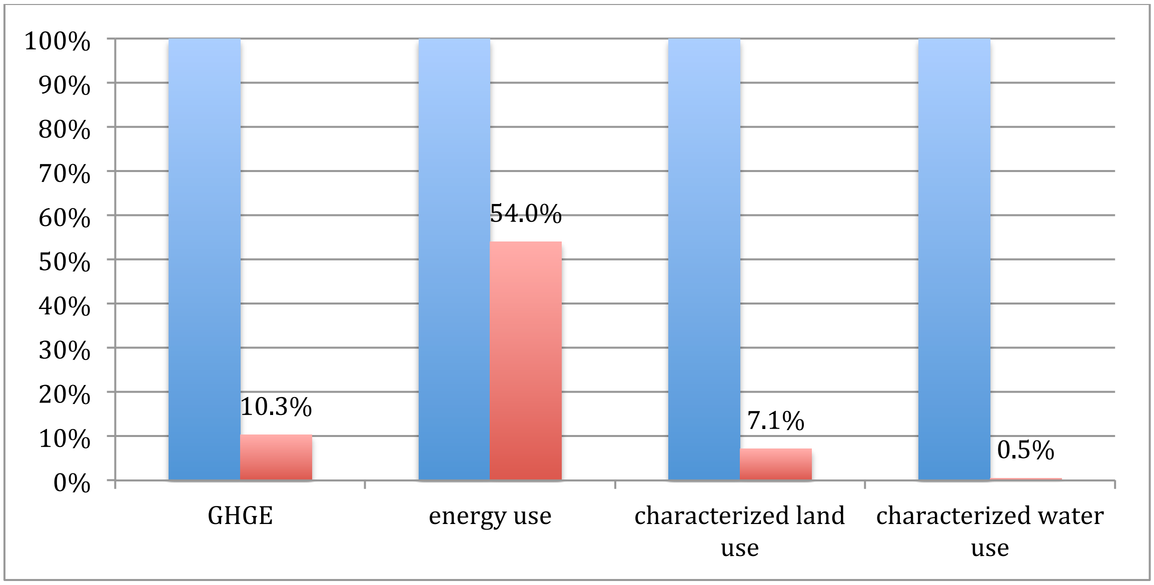

Figure 6. Relative comparison of impacts between beef (blue bars, set at 100% for each indicator) and Beyond Burger (red bars).

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 CO_2eq./kg boneless edible beef, with the mean of 95 data points at 33 kg CO_2eq./kg and a standard deviation of 12.6. Beef derived from dairy herds varied from 7 to 28 kg CO_2eq./kg with the mean of 10 data points at 19 kg CO_2eq./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.

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[3] http://beef2live.com/story-ground-beef-united-states-0-104332

[4] 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.

		Per kg hot carcass weight[1]	Per kg boneless edible beef[2]	Per quarter pound edible beef
GHGE	kg CO_2 eq.	12.7	19.0	2.1
Fossil fuel depletion[4]	kg oil-eq.	1.33	1.99	0.22
(converted to energy units)	MJ (42 MJ per kg oil-eq.)	55.9	83.4	9.5
Land use[3]	m^2a	17	25	2.8
Water depletion[4]	liters	111	166	18.8

[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^2a"
[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*(3.6) + 0.2*(2.1) + 0.1 = 3.4 kg CO_2 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 great enough to change the directional conclusions drawn in this study. Even if 100% dairy beef is assumed, BB performs significantly better.

5.2.3.2. Grass-fed beef

Grass-fed beef, typically defined as beef raised without the use of concentrated feedstuffs such as corn or soybean, has grown in popularity and is often lauded as an environmentally sound alternative. While there may local benefits of grass-fed over grain-fed beef such as reduced nutrient losses and increased biodiversity, this benefit does not always hold true for the environmental indicators considered in this study. (Tichenor et al., 2017) also studied the impacts of grass-fed beef and reported GHGE to be 33.7 kg CO_2 eq/kg hot carcass weight, which, using the conversion in Table 11, is equal to 50 kg CO_2 eq/kg boneless edible beef. When potential pasture carbon sequestration and lower enteric methane emissions are considered, this value dropped to 20 kg CO_2 eq/kg hot carcass weight (30 kg CO_2 eq/kg boneless edible beef). Similar values have been reported in other studies of grass-fed beef in the US (Lupo et al., 2013; Stackhouse-Lawson et al., 2012). (Tichenor et al., 2017) reports energy use and water use for grass-fed beef as slightly lower than the dairy beef scenarios from that study, suggesting water and energy impacts near or slightly below the values reported by Thoma et al. (2017).

5.3. Results of Sensitivity Analysis

5.3.1. Modeling parameter sensitivity

The influence of a number of key modeling parameters on overall system environmental performance is shown in Table 12. With the exception of processing loss rates, these sensitivity results demonstrate negligible changes in total impacts due to sizable variation in cold storage modeling parameters and assumed material recycling rates. Processing loss rates directly increase the ingredients and processing energy required to generate a given quantity of finished product. Therefore, increases or decreases of 5% from the baseline assumption of 5% losses (implemented at both pre-treatment and final processing stages) result in roughly 5% changes in impacts (including the loss factor at two successive stages results in slightly non-linear behavior).

Table 12. Sensitivity of BB LCA model to a variety of assumed parameters. All values are shown relatve to the totals in Table 8.

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

[a]SEC = Specific energy consumption of cold storage facility. The range used here (15-132 kWh/m^3) 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). 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 relatve to the totals in Table 8.

	GHGE	energy use	Land use	Water use
Average distribution distance increased 20% (to 1627 miles)	1.27%	1.20%	0.00%	0.01%
Average distribution distance decreased 20% (to 1084 miles)	-1.27%	-1.20%	0.00%	-0.01%
Population weighted distribution (1836 miles)	2.25%	2.13%	0.00%	0.02%

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.

	Percent change from Totals in Table 8	
Percent postconsumer recycled PP content in tray	GHGE	Energy use
10%	-0.2%	-1.0%
25%	-0.5%	-2.5%
50%	-1.0%	-5.1%
75%	-1.5%	-7.6%
100%	-2.0%	-10.2%

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.

	Ingredients	**Total**
Agrifootprint energy allocation		
GHGE	-21.6%	-13.8%
cumulative energy demand	-14.0%	-11.3%
characterized land use	-28.6%	-23.3%
characterized water use	-25.4%	-9.5%
Agrifootprint mass allocation		
GHGE	-25.6%	-14.4%
cumulative energy demand	-9.4%	-4.4%
characterized land use	-40.9%	-33.3%
characterized water use	-36.5%	-7.1%

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)

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

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.

			Indicator score (see Table 17 for interpretation)				
	source	Importance	reliability	completeness	Temporal correlation	Geographic correlation	Further technological correlation
Ingredients							
BB formulation	B	1	1	1	1	1	1
Pea protein isolate production	S	1	1	5	1	1	1
Canola oil production	D	1	2	1	2	1	1
Coconut oil production	D	2	3	1	2	3	2
Minor ingredients	S, D, P	3	4	5	1	3	4
Processing							
Processes	B	2	1	1	1	1	1
Electricity demand	B	2	1	5	1	1	1
Packaging							
Packaging weights/quantity	B	1	1	1	1	1	1
PP tray production	S	1	2	2	1	1	1
Other packaging production	S, D	3	4	5	2	3	4
Cold storage							
Electricity demand of cold storage	M	3	3	5	2	1	1
Storage residence time	B	3	4	1	1	1	1
Distribution transport							
distance	B	3	2	3	1	1	1
Modeled truck	D	3	2	1	3	2	4
Packaging disposal							
Disposal pathways	D	3	2	1	1	2	4
Impact model	M	3	2	1	1	2	4
Beef comparison							
Overall study		1	1	4	1	2	4

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_2eq. /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 3rd 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

Battagliese, T., J. Andrade, I. Schulze, B. Uhlman and C. Barcan. 2013. More Sustainable Beef Optimization Project: Phase 1 Final Report. BASF. Available from http://bit.ly/NCBA_Report.

Battagliese, T., J. Andrade, R. Vinas, K. Stackhouse-Lawson, C. A. Rotz and J. Dillon. 2015. U.S. Beef - Phase 2 Eco-efficiency Analysis. BASF. Available from https://goo.gl/LtqAsD.

Capper, J. L. and D. J. Hayes. 2012. The environmental and economic impact of removing growth-enhancing technologies from U . S . beef production. Journal of Animal Science 90: 3527-3537.

De Vries, M., C. van Middelaar and I. de Boer. 2015. Comparing environmental impacts of beef production systems: A review of life cycle assessments. Livestock Science 178: 279-288.

Dudley, Q. M., A. J. Liska, A. K. Watson and G. E. Erickson. 2014. Uncertainties in life cycle greenhouse gas emissions from U.S. beef cattle. Journal of Cleaner Production 75: 31-39.

Eshel, G., A. Shepon, T. Makov and R. Milo. 2014. Land, irrigation water, greenhouse gas, and reactive nitrogen burdens of meat, eggs, and dairy production in the United States. Proceedings of the National Academy of Sciences 111(33): 11996-12001.

Frischknecht, R., N. Jungbluth, H. J. Althaus, G. Doka, R. Dones, R. Hischier, S. Hellweg, S. Humbert, M. Margni, T. Nemecek and M. Spielmann. 2007. Implementation of Life Cycle Impact Assessment Methods: Data V. 2.0 Duebendorf, CH. Swiss Centre for LCI. Available from http://www.ecoinvent.ch.

Gaines, L., A. Vyas and J. L. Anderson. 2006. Estimation of Fuel Use by Idling Commercial Trucks. 85th Annual Meeting of the Transportation Research Board. Washington, D.C.

Goedkoop, M., R. Heijungs, M. Huijbregts, A. De Schryver, J. Struijs and R. Van Zelm. 2009. ReCiPe 2008. A life cycle impact assessment method which comprises harmonised category indicators at the midpoint and the endpoint level 1.

Goldstein, B., R. Moses, N. Sammons and M. Birkved. 2017. Potential to curb the environmental burdens of American beef consumption using a novel plant-based beef substitute. PloS one 12(12): e0189029.

Heller, M. C., A. Willits-Smith, R. Meyer, G. A. Keoleian and D. Rose. 2018. Greenhouse gas emissions and energy use associated with production of individual self-selected U.S. diets. Environmental Research Letters 13(4).

IPCC. 2007. Synthesis Report. Contribution of Working Groups I, II, and III to the Fourth Assessment, Geneva, Switzerland. International Panel on Climate Change.

ISO. 2006. Environmental management - life cycle assessment - requirements and guidelines. International Organization for Standardization, ISO 14044: 2006.

Kamdem, A. T. K. and J. Hardy. 1995. Influence of various conditions on meat grinding characteristics. Journal of Food Engineering 25(2): 179-196.

Kannan, N., E. Osei, O. Gallego and A. Saleh. 2017. Estimation of green water footprint of animal feed for beef cattle production in Southern Great Plains. Water Resources and Industry 17: 11-18.
Koellner, T. and R. W. Scholz. 2008. Assessment of land use impacts on the natural environment. The International Journal of Life Cycle Assessment 13(1): 32.
Lupo, C. D., D. E. Clay, J. L. Benning and J. J. Stone. 2013. Life-Cycle Assessment of the Beef Cattle Production System for the Northern Great Plains, USA. Journal of Environmental Quality 42(5): 1386-1394.
Pelletier, N., R. Pirog and R. Rasmussen. 2010. Comparative life cycle environmental impacts of three beef production strategies in the Upper Midwestern United States. Agricultural Systems 103(6): 380-389.
Peters, C. J., J. A. Picardy, A. Darrouzet-Nardi and T. S. Griffin. 2014. Feed conversions, ration compositions, and land use efficiencies of major livestock products in US agricultural systems. Agricultural Systems 130: 35-43.
Pfister, S., A. Koehler and S. Hellweg. 2009. Assessing the Environmental Impacts of Freshwater Consumption in LCA. Environmental Science and Technology 43(11): 4098-4104.
Prakash, B. and R. P. Singh. 2008. Energy Benchmarking of Warehouses for Frozen Foods. California Energy Commission. University of California, Davis. Available from http://ucce.ucdavis.edu/files/datastore/234-1194.pdf.
Schau, E. M. and A. M. Fet. 2008. LCA studies of food products as background for environmental product declarations. International Journal of Life Cycle Assessment 13(3): 255-264.
Singh, R. P. 2008. Benchmarking study of the refrigerated warehousing sector in California. Public Interest Energy Research Program. California Energy Commission. Available from http://ucce.ucdavis.edu/files/datastore/234-1193.pdf.
Stackhouse-Lawson, K. R., C. A. Rotz, J. W. Oltjen and F. M. Mitloehner. 2012. Carbon footprint and ammonia emissions of California beef production systems 1. Journal of Animal Science 90(12): 4641-4655.
Statista. 2015. Average operating truck speed on selected U.S. interstate highways in 2009. [Online], Available at http://www.statista.com/statistics/195100/average-operating-truck-speed-on-selected-us-interstate-highways/ Accessed August 12, 2015.
Statista. 2018. Category share of beef sales in the United States in 2017, by cut type, online. Available from https://www.statista.com/statistics/191269/fresh-beef-category-share-in-2011/.
Thoma, G., B. Putman, M. Matlock, J. Popp and L. English. 2017. Sustainability Assessment of U.S. Beef Production Systems. Resilience Services, PLLC and the University of Arkansas. Available from https://goo.gl/8ttBo6.
Tichenor, N. E., C. J. Peters, G. A. Norris, G. Thoma and T. S. Griffin. 2017. Life cycle environmental consequences of grass-fed and dairy beef production systems in the Northeastern United States. Journal of Cleaner Production 142: 1619-1628.
U.S. EPA. 2016. Advancing Sustainable Materials Management: 2014 Tables and Figures. United States Environmental Protection Agency. Available from https://www.epa.gov/sites/production/files/2016-11/documents/2014_smm_tablesfigures_508.pdf.
US Department of Energy. 2016. Solid-State Lighting R & D Plan. US DOE Off ice of Energy Efficiency & Renewable Energy Available from https://www.energy.gov/sites/prod/files/2016/06/f32/ssl_rd-plan_ jun2016_2.pdf.
US EPA. 2016. Waste Reduction Model (WARM), version 14. [Online], Available at https://www.epa.gov/warm/versions-waste-reduction-model-warm Accessed August 12, 2017.

USDA. 2015. USDA National Nutrient Database for Standard Reference, Release 28. US Department of Agriculture, Agricultural Research Service, Nutrient Data Laboratory. Available from http://www.ars.usda.gov/nea/bhnrc/ndl.
Wang, L., J. Littlewood and R. Murphy. 2014. An economic and environmental evaluation for bamboo-derived bioethanol. RSC Advances 4(56): 29604-29611.
Weidema, B. P. and M. S. Wesnaes. 1996. Data quality management for life cycle inventories—an example of using data quality indicators. Journal of cleaner production 4(3-4): 167-174.

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
Reference	ISO 14044: 2006. Environmental Management - Life Cycle Assessment – Requirements and Guidelines ISO/TS 14071: 2014. Environmental management — Life cycle assessment — Critical review processes and reviewer competencies: Additional requirements and guidelines to ISO 14044:2006

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

Critical Review Report 1

Initials	Index	Line number	Clause / subclause	Paragraph / Figure / Table	Type of comment	Reviewer comment	Reviewer recommendation	Practitioner repsonse	line number in new report version 3.0
HSM	1	172-3 (also 247)	x	x	ed	Probably a minor thing, but as discussed on the call might be worth "calling out" that this is a standard size product (any consumer knows this – people don't go out looking to buy a 1/8th pound patty). OK if only changed on 247 and not here (but both might help)	suggested edit (not critical or required)	suggested edit made in both locations.	179 & 262
HSM	2	176			ed	Maybe stipulate here (as below) "because they're assumed equal"?	suggested edit (not critical or required)	suggested edit made: "...as they were considered equivalent in both product systems."	184
HSM	3			ES-1	te	As I said on the call, this is a major comment of mine (just noted here since its the first place results are mentioned. Are the upstream boundaries the same in the Beef and BB LCIs? i.e., when NCBA did their study, what database/model was used to capture the effects? e.g., if Simparo was used the US LCI matrix model then a large upstream network was included by default beyond the small list of direct suppliers. Did Thoma et all do the same? THis is potentially a significant source of discrepancy between the studies and should be clarified. Hopefully, the beef study did a similarly comprehensive model and its easy to address here.	needs to be clarified (not necessarily here in ES but definitely in the paper)	Thoma et al's adaption of the beef LCA performed originally by BASF involved rebuilding the model in SimaPro rather than with the proprietary data used by BASF. Throughout, they have used SimaPro processes from Ecoinvent, Agrifootprint and USLCI databases, all of which have extensive upstream data incorporated. To clarify this in the text, the following sentence has been added to Section 3.3 U.S. beef: "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. "	606
HSM	4	207			ed	Instead of just saying 'externally', Be more clear that they mean publicly? Externally could otherwise mean with clients or supplier.	suggested edit (not critical or required)	replaced "externally" with "publically to consumers"	218
HSM	5	252			ed	I would add "ONE" before 4 oz. Its probably obvious, but helps.	suggested edit (not critical or required)	accepted suggested edit	243
HSM	6	260			ed/te	How do these inclusions/exclusions compare to the NCBA studies? Having all text to describe these throughout the study is challenging to review/read. A single comprehensive table or graphic that helped to show the original (and included) boundaries woul really help. eg as we see later, the Beef study actually included more steps (that you then remove for comparison sake).	strongly suggested edit	A figure showing the beef LCA system boundaries (new Figure 4) as well as a table making high level comparisons of system boundaries and data sources for the two studies(new Table 6) has now been included in Section 3.3.	584 (Figure 4) & 600 (Table 6)
HSM	7			2	te	The process water and bamboo exclusions should get a little more discussion. Why do you think its ok to exclude them?	suggested edit (not critical or required)	bamboo fiber is included in the Beyond Burger as an ingredient at 1.5%. I have represented this with LCI data for a bamboo plantation (agricultural production). I was unable to find information or data on processing of bamboo into the food ingredient fiber. I am assuming this would be a negligible contribution to the overall results. Cleaning water was excluded because we did not have reliable estimates for quantity.	
HSM	8	309-330			ed/te	Why? (Is this also what Thoma did?) In this section, If all of these bullets are just "repeating" the choices Thoma made, I think its fine, but I would revise the opening 2.2 paragraph to be clear that the impact methods are identical to those used by thoma, and those choices and assumptions are repeated below. To me, as its currently written, its not clear what some of the sentence mean (ie, did you add it?) If you do have "separate thoughts" they could be in a separate part below all of these.	strongly suggested edit , just to prevent confusion	Edits have been made to this section to clarify that the bullets here are merely descriptions of the LCIA methods used, and do not reflect "choices" made. Further, the cumulative energy demand indicator has been updated to include renewable and non-renewable energy (with the exception of removing caloric content of biomass materials). This is in line with the results used from Thoma.	330-331
HSM	9	332			te	Are you not able to do this for the beef results? Why?	suggested edit (not critical or required)	Correct. Thoma does not report inventory data, only results in CO2 eq. This has been clarified in the text: "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."	354
HSM	10	383			te	re: grid mix 2012.. Is this the latest available? What was the mix used in Beef study? Also – I am confused by the paragraph. Is electricity modeled at the region and/or US level?	suggested edit (not critical or required)	Electricity is modeled at the regional level in the Beyond Burger LCA when specific electricity use locations were known. The 2012 grid mix is indeed the most recent data available in Ecoinvent 3 (we have specified this in the text). The Thoma study utilizes an average US electricity grid dataset from USLCI database, representative of year 2000 mix of fuels. Their choice of this data is unjustified.	406
HSM	11	389			ed	Several of these aren't in Figure 1, so its hard to figure out how they fit.	suggested edit (not critical or required)	Uncertain what the concern is here. All ingredients to the BB are included in figure 1 as "ingredients". Figure 1 has been modified slightly in hopes of minimizing the confusion here.	
HSM	12	395-6			ed	Can this be re-worded to be more accessible to an outside audience? (is this a proxied study? Not sure what similarity of processes is trying to say)	suggested edit (not critical or required)	re-worded as follows: "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. "	416
HSM	13	398-9			te	Why does this matter? How comprehensive was their LCI? Was that not sufficient for you to include in your model to aggregate into the rest of the results? (Point is why did you need to use "final LCIA results" rather than just take their LCI and fold it into yours?	strongly suggested edit , just to prevent confusion	We did not receive LCI results. The supplier was only willing to provide final results with a methodological description. I am uncertain how to make this more clear: the sentence prior states: "Impact assessment results for the pea protein product family, along with a methodological description, were provided under confidentiality."	419
HSM	14	402			ed	Origin of WHAT? A figure might help with this particular sub-model.	suggested edit (not critical or required)	replaced "origin" with "manufacture of the pea protein isolate". Much of this generic language is included because of concern with revealing product source. I do not feel a figure will assist; it would be a box with "pea protein isolate production" and a transportation arrow.	424
HSM	15	411-13			ed	Should probably provide another sentence or three describing how this was done, including the values used	suggested edit (not critical or required)	this detail is included in the reviewer supplementary material (Table s1) and was considered proprietary and thus not included in detail in the public report.	
HSM	16			T3	ed/te	Minor point but where is this being sent from LA that it is 3000 miles away?	suggested edit (not critical or required)	the coconut oil produced in Indonesia, shipped via ocean freight to a port of entry of either New York or Boston and then shipped via truck to the BB processing facility. Added: "(port of entry: New York or Boston)".	440 (Table 3)
HSM	17			T3	ed/te	re: 2% header and values below it.. So does this mean they were excluded? Why note they are less than 2% (esp since you claim the mix is proprietary)..	strongly suggested edit , just to prevent confusion	All of the ingredients are included in the model. This statement: "less than 2% of the following ingredients" is included as part of the ingredients list on the product packaging. The distinction is made here because proxies are used for some of these minor ingredients. Added (the "less than 2%" declaration is made on the product label) to the table note.	441
HSM	18			T3	ed	I don't think you need the first column (which is hidden anyway and just reminds the reader you are hiding this). Just keep the caption at the bottom.	suggested edit (not critical or required)	Column removed as suggested.	
HSM	19	428-30			ed	This isn't a major part of the model, but is there some further justification you can find for this? (I know nothing about carrots and beets)	suggested edit (not critical or required)	We did check this proxy assumption with Jasper Scholten at Blonk Consultants, who agreed with the appropriateness. Added the following text: "This proxy choice was confirmed as appropriate through personal communication with the Agrifootprint database developers."	454
HSM	20	452			ed	I don't think you have referenced this figure in the text	suggested edit (not critical or required)	added the sentence: "Figure 2 offers an image of the retail packaging."	468
HSM	21			F3	ed/te	It seems especially odd now to not have something similar for the ingredient mixing and combination above.	strongly suggested edit , just to prevent confusion	The specifics of the ingredient mixing and processing are considered proprietary and can not be detailed in the public report.	
HSM	22	478			ed	I don't have any issue with how this was done, but also have never seen it before. Did you "follow someones lead" on how to do this? If so, say "following XXX, we…"	suggested edit (not critical or required)	no, not following anyone's lead. Just straightforward energy balance considerations.	
HSM	23	502			ed	Is the square footage of the facility considerd to be proprietary? If not say that size here.	suggested edit (not critical or required)	this information will remain excluded from the public report due to proprietary concerns.	
HSM	24	509			ed	Why not represent this as a range for an uncertainty analysis?	suggested edit (not critical or required)	We have included a sensitivity assessment for distribution distance in Section 5.3.4. The full range of shipped product is 14 miles to 2902 miles, but these extremes represent very small fractions of total product distributed during the 4th quarter 2017 (0.1% and 0.5%, respectively) and are fealt to be an inappropriate representation of distribution of the "average" product.	
HSM	25	517-8			te	I have never modeled frozen product. Is this how its done (these 2 processes)?	suggested edit (not critical or required)	Ecoinvent contains processes for reefer transport, but they are all built around European trucking parameters. In order to use a US-specific truck transport process, we chose to model the operation of the refrigeration unit separately using the indicated process. As far as we are aware, there is no "standard" way to model refrigerated transport.	
HSM	26	564			ed	A few comments on how its written (I don't think it affects the results): • Didn't you also have to adjust down to 4 oz functional unit? • Might state that the Beef studies were sufficiently robust in detail such that you could actually "pick and choose" the categories that were consistent to align with the Beyond Meat product. • That said, why did you choose to have the smaller boundary if Beef data had more? (worth noting that in here somewhere too)	suggested edit (not critical or required)	The adjustment of functional unit from 1 pound to 1/4 pound seemed self-explanatory, but for the sake of clarity we have added the sentence: "Results were then adjusted from a "one pound" to "1/4 pound" functional unit." The "sufficient robustness" statement seems unneccesary since, if this were not the case, we would be unable to do the adjustment that we did. We have chosen to address the question of boundary condition choice in the system boundaries section (2.1.3) with the addition of the following text: "This cradle-to-distribution boundary scope was chosen primarily because, especially given the uncertainties present in generic modeling of these downstream stages, they 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. "	598 & 273-277
HSM	27	567			ed/te	As suggested above, it might help to have a comparative table or figure showing (relatively high level) processes included in the two models. This paragraph(s) pretty hard to read without that	strongly suggested edit , just to prevent confusion	a comparative table has been added (new Table 6), as well as a system boundary diagram for the beef LCA (new Figure 4)	584 (Figure 4) & 600 (Table 6)
HSM	28	574			ed	re: "case ready" What does this mean, and is it equivalent to what you have done for Beyond Meat?	suggested edit (not critical or required)	the following footnote was added to define/describe case ready: "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	bottom of page 22

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HSM	29			T6	ed	Even though this is just the “inventory” section of the report, I think its fine/appropriate to qualitatively discuss the results in the Beef study, especially as they related to setting up your comparison. For example, for most of the impacts, Feed and Cattle dominate (no surprise)	suggested edit (not critical or required)	added a brief statement after the table: "As is typical in LCA studies of beef production, farm gate contributions – that is the “feed” and “cattle” stages in Table 6 – 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. "	634
HSM	30			T6	ed	This is a really minor point, but even though they may have published per kg, to make it easier to envision the comparison you’re gonna do below, I would scale these down to ¼ pound basis (divide by 2.2 then 4).	strongly suggested edit , just to prevent confusion	suggested edit made.	Table 7 (line 629)
HSM	31	603			ed	This just looks weird (I know what you’re trying to do. Maybe make a new acronym QPBB for quarter pound patty so it doesn't look like 0.33/1/4?	suggested edit (not critical or required)	We've chosen to write out quarter pound, only to avoid confusion between referring to Beyond Burger (BB) and beef burger (which also could be interpretted as BB)	
HSM	32	607			ed	Why not have a table for ingredient level detail?	suggested edit (not critical or required)	added table per suggestion (now Table 9)	667
HSM	33	627			ed	I can’t tell if you are discussing how the land use impact method works, or if you are doing something different or as needed to use into the method. Meaning are you the one assigning the -1 to +1 scores? (Similar comment for the next few subsections too)...	strongly suggested edit , just to prevent confusion	we are discussing how the impact method works to provide some interpretative context for the reader.We have attempted to clarify this by adding the phrase, "In this impact assessment method, a characterization factor…" Attempts to clarify this have been added to subsequent sections as well, and a brief statement about the diffeences between absolute and characterized values has been included in Section 4.1	681, 643
HSM	34	640			ed	Is this the right section reference? Its below not above. It might also be worth adding a better general statement about the difference between characterized and absolute impacts (these are not popular LCIA metrics, and most of the audience wont be familiar with them).	suggested edit (not critical or required)	The section numbers were incorrect in the version sent to reviewers. This has been corrected, and all section references have been checked.	
HSM	35	672			ed	Odd to describe that way? aren’t the blue bars set at the normalized level of the beef impact?	suggested edit (not critical or required)	We are unsure how to respond here. This is a *relative* representation of the differences between beef and BB. In all cases, the beef impacts are given a value of 100%, and the BB results are shown relative to this. The purpose is to give a visual representation of the differences across all 4 indicators.	
HSM	36	678			ed	I wouldn't round up. Cant say 100%.	strongly suggested edit	changed to >99%. Sticky spot, because including the decimal point implies greater accuracy than we feel comfortable with.	730
HSM	37	696			ed/te	So this statement surprised me – for how you have modeled Beef and how it was in my head before you got to this point. So the beef is assumed to be grown and then slaughtered and shipped to a grocery store where it is locally processed? You make it sound like theres no frozen chain for beef. Its worth clarifying somewhere along the way (or here) what the retail difference would be (even though you’re not modeling it). If this is true I would go back near the beginning and clarify all of this.	I thin you need to make this statement earlier	We are unclear what the surprising piece is here…No, the beef is not assumed to be locally processed; that is what "case ready" means: processing and packaging in a central facility. Although a notable percentage of beef is still locally processed. Further, case ready beef is shipped and sold to retailers both fresh and frozen; We can't find data on how much goes through each of these channels, but our impression is fresh is more popular. In other words, our impression is that "typically", case ready beef is not frozen. It is not clear from the beef LCA documentation how this was modeled.	
HSM	38	706			ed	I’d be more blunt – you’d expect efficiencies to IMPROVE (meaning impacts would decrease)	suggested edit (not critical or required)	Sentence changed to the following: "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."	758
HSM	39	716			ed/te	I thought we discussed this on the prep call, but.. I think youre really setting yourself up for trouble if the overall comparison results you show are only BB vs avg, especially if you have the comparative detail for dairy versus grass. I would recommend having a “triple coparison” of BB, average dairy-fed, average grass-fed (and if you want, an overall avg like you have now). BB is still going to be better, but you help your cause I think by noting that its better than any of these. If you wanted to get fancy you could add error bars (and still here stipulate that some of the outliers could be better)	must do something about this	the challenge here is that we do not have consistent results across all of the impact categories and impact assessment methods usedin our BB study. This is primarily why we have not included alternative scenarios in the final results and left as a discussion point: since the "baseline" beef study we're using currently does not include these different options, we would have to combine multiple studies, further opening the errors in unmatched boundary conditions, modeling assumptions, etc. There isn't a clean way to do this and our feeling was that it would take away from, rather than raise, the credibility of the study. Indeed, it requires in-depth reading of the report, but we feel that addressing alternative beef scenarios in this way offers sufficient coverage of the breadth of possible beef scenarios.	
HSM	40	793			ed/te	Why only sens analysis on the BB side of the model?	suggested edit (not critical or required)	We do not have a beef LCA model. We are using results as reported in Thoma. Therefore, we cannot do sensitivity on their model.	
HSM	41			13		You should probably add another sentence or two discussing the “big numbers” in the table. They really whittle away at the comparative differences.	suggested edit (not critical or required)	Per comments of all reviewers, we have chosen to make economic allocation (rather than mass allocation) the baseline scenario. Thus the differences seen here (in what is now Table 16) are all *reductions* from the baseline (i.e., using other allocations would result in less impact for BB) and the choice of economic allocation becomes a conservative approach. This influences the final results throughout.	
HSM	42	858			te	I don't think the simulation adds much, especially when youre only doing it on only one side of the comparison. (To reveal my bias, I don't think Simapro simulations of uncertainty using pedigree matrices are of much value - its an arbitrarily defined distribution, etc.)	suggested edit (not critical or required)	Thank you for this suggestion. We have removed the Monte Carlo simulation from the report.	
HSM	43	862			ed	that said, If youre going to keep in the simulation you need to say more here – eq quantitative comparisons. Also – if youre going to do a simulation for BB, then you need to consider the range of values for dairy and grass fed beef in the LCIs.	strongly suggested edit	Simulation has been removed.	
HSM	44	881			ed	Why? How? Say more.	suggested edit (not critical or required)	The following has been added: "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. "	941
HSM	45	914			ed	Again I think you need to be careful here – what about the low dairy beef values? If those were considered that contradicts what you have written. You are making the point more strongly than is warranted (BB is generally better, agreed, no problem).	suggested edit (not critical or required)	We disagree here. If we take the dairy beef values from Tichenor, GHGE are 19 kg CO2eq/kg + 1.0 kg CO2eq/kg from harvest and case-ready impacts (same as conv. Beef) =20 kg CO2eq/kg=2.3 kg CO2eq/quarter pound (vs. 0.4 kgCO2eq/quarter pound for BB). Tichenor's energy use values are acutally greater than conventional beef. Water use values are not easily compared because of differences in accounting and LCIA methods, but if we look only at farm gate water depletion from Tichenor, dairy beef uses 18.9 L/quarter pound (vs. 3L/quarter pound for BB). Similarly, absolute land use is 2.8m^2/quarter pound for dairy beef and 0.5m^2/quarter pound for BB. Even at the extreme low end of the ranges seen in the literature for dairy beef (7 kg CO2eq/kg at farm gate), BB performs better(3.4 kg CO2eq/kg distributed to retailer). A statement was included in the conclusions to further drive home this point: "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 CO2 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 CO2eq. /kg BB."	979
AK	1	241-242			ge	This sentence refers to non-nutritional values of food, such as cultural value. This is a good point, but seems to be unconnected with what follows	Consider addressing some of the non-nutritional functions in the description of the BB product, if important.	the following edits/ additions have been made: "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."	254-258
AK	2	271-272			te	Why rely on mismatched data with respect to time horizon of data collection between the distribution and production/packaging? This may not be particularly important if few changes occur in pathways.	Consider explaining the inconsistency and/or indicating whether it is likely to affect results.	We relied on the data available to us in conducting the study. There is no reason to believe that mis-matched time horizon data will significantly influence results as no notable changes in production occurred during the time horizon. We are merely sampling from a congruent but shorter time window for distribution and energy demand. As the Beyond Burger is a relatively new product with growing demand, it is anticipated that specifics of distribution will change in the future (as indicated in the report), but there is no reason to believe that this is closely linked to production impacts under the current facility arrangement.	
AK	3	305-308			te	The scope of the impact assessment is chosen based on the selected comparative study by Thoma et al., but is by no means complete	While this narrow set of impact categories may be acceptable, it is unclear why additional impact categories weren't also tracked. The fact that the comparative study is narrow does not require that the current study be narrow.	The impact categories considered were determined in the early scoping stages of the project; these were the categories considered most relevant and important by both the client and practitioner. Specific assessment methods were made to align with the beef study, but the impact categories of interest were determined before this. In fact, the beef study considers other impacts that we did not track in the BB LCA, due to lack of data for many of the ingredients for which external (to Ecoinvent databases) data were used.	
AK	4	411-413		Table 3	te	for bamboo cellulose only the bamboo plantation stage is included. The extraction stage, I believe, requires chemical or thermal treatment, and may be more impactful than cultivation	Because this material is used in small quantities it may not be necessary to include additional steps. However, if information is available on how this material is extracted, it is worth adding to the table or text.	We were unable to find information on the extraction and processing of bamboo cellulose, which was the primary reason that production only is used as a proxy. This has been made more clear in the text.	Table 3
AK	5	387-401			te	The choice of mass-based allocation has some potential problems. In particular the effect of mass allocation on vegetable derived oils, here canola, has a significant effect on attributed impacts. I infer that pea-protein is also treated this way, but am not entirely sure based on the text. Does the beef study use economic allocation for non-meat cow parts or does it also use mass-based allocation? If so, this is an inconsistency likely to favor the BB study.	Clarify the allocation methods used across the study, and the allocation methods used in the beef LCA.	Thank you. This comment has been well received, and we have switched to using economic allocation of Agrifootprint processes in the basecase scenario. The beef study also uses economic allocation, so this improves consistency. The pea protein LCA used mass allocation. This has been specified in Section 2.1.4 as well.	314

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AK	6	311-312				The cumulative energy use results reported are the sum of non-renewable fossil, nuclear and biomass energy and do not include renewable sources. Though I see a reference to a source for this method, it seems a bit strange to eliminate renewables and to count biomass and non-renewable. Why not use a more common cumulative energy accounting approach?	Consider whether this cumulative energy demand calculation will allow comparison of this study to future studies.	Thank you for the comment. The change to using a full cumulative enery accounting has been made. On exception is that the "caloric content" of some packaging materials, which show up as "renewable biomass" have been removed.	335
RG	1	259, 442		Table 2	ed	The cardboard carton is secondary packaging	say "primary, secondary, and tertiary"…	suggested edit made.	Table 2
RG	2			Table 2	ed	"Transport of major materials" Materials means ingredients or includes other inputs?	Clarify	changed "major materials" to "ingredients and packaging materials"	Table 2
RG	3			Figure 1	ed	Potentially misleading figure. Important to make it visually clear, that production of all the inputs are included. There might be an opportunity to visually distinguish between forground and background system, using secondary and primary data, respectively.	Consider adding detail and improving clarify of this figure.	figure has been updated to differentiate between primary and secondary data sources in hopes of clarifying the inclusion of background systems	284 (Fig 1)
RG	4			2.1.4 Allocation Principles	ed	You should add something about the allocation methods used in the pea protein isolate LCA.	Explain the allocation methods used in the pea protein isolate LCA.	added the following: "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."	314
RG	5			Section 3 LCI	ge	There is an opportunity to clarify data sources by distinguishing between primary and secondary data. I think this could be done without too much effort in Figure 1.	Consider using the notions of primary and secondary data.	see response above. The new Table 6 also contributes to this clarification.	
RG	6			Table 3	ed	Are citrus extract acidulant and favor components excluded from the study?	Clarify.	All ingredients are included. This has been explicitly stated in Section 3.2.2. Perhaps these two (citrus extract acidulant and flavor components) are confusing because I am unable to reveal additional information about components or impacts due to confidentiality.	411
RG	7			Figure 3	te	It looks like PP and PE get mixed when the 30% scrap traus are recycled. Is that not a problem.	Clarify	This is the process as described to me by the tray manufacturer. This figure was shared via personal communication with conacts at the tray manufacturer, and was confirmed as accurate for industry average production	
RG	8			Figure 3	te	The closed-loop recycling hs been confirmed by Beyond Meat?	Confirm	this Figure refers only to the manufacture of the tray; the information contained was supplied and confirmed by the tray manufacturer	
RG	9	473			ed	"freezing and cooling" isn't the keeping at -10F accounted for by the SEC?	change to "freezing"	The logic here is as follows: there is senible and latent heat that must be removed from the product when it first enters cold storage: this energy requirement can be calculated specifically for the product. It is then assumed that the SEC accounts for keeping the product at -10C. At worst, this is over-accounting for the energy demand of refrigeration, which has a minimal contribution to the overall system impacts.	
RG	10	484-485			ed	Is the 0.7 from el. to heat or the other way round? Do you have a source for that?	Clarify, mention source.	The statement has been clarified with the following: "The thermal demand was converted to electricity requirements of the cold room compressor by dividing by an assumed energy efficiency ratio of 0.7. " This efficiency ratio has been assumed as a conservative estimate, with sensitivity assessment demonstrating 20% changes in the value leading to less than 1% changes in total results. No direct source is available.	516
RG	11	512-532		Packaging Disposal Modeling	ed/te	Is this just for primary or all packaging? Re primary: I think it's more realistic to assume that it's landfilled entirely. Re recycled content: Do you assume that any of your packaging has recycled content? That was not made clear. How do you model eol for secondary and tertiary packaging? The WARM model is all about the avoided burden approach, so if you don't use avoided burden what parts of the WARM model are you using?	Clarify. Consider changing your disposal model. Having said that, it's unlikely to matter much.	Since disposal of packaging materials has a very minimal effect on overall results, we have chosen to maintain the current model. It is true that the WARM model as packaged is about "avoided burden". However, it contains impact factors (GHGE and energy use) for incineration and landfill of various materials. We have extracted these impact factors from WARM and used them directly in our modeling. Recycling rates have very minimal effect on results, so we have chosen to maintain the "US average" recycling rates. However,per your suggestion, we have added sensitiity scenarios considering the "postconsumer recycled content" of the PP tray.	postconsumer recycled content in Section 5.3.4 (Line 893)
RG	12	620-631		Land use (occupation)	ed	Absolute occupation is in area*years, so characterization is simply multiplying that value by the EDP. Also, don't you need a reference state for the land in question, so it's actually a difference between actual and reference EDP?	Clarify	the wording here has been changed, which hopefully clarifies the intended message: "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)." We do not feel it's valuable to discuss the reference EDP here, as this methodological detail isn't helpful in interpreting results. We primarily want the reader to be clear that characterized land use will be smaller than absolute, due to the nature of the characterization method.	681
RG	13	625-627		Land use (occupation)	ed	"A simple land use inventory (m2 of land occupied annual for all land-cover types) is provided […]". Where? In your report?	Clarify	added "…is provided in Table 7 (absolute land use) "	686
RG	14	743-744		Table 9	ed	Might be worth specifying the land use and water depletion indicators used. Also, land use in m2 or m2*a, i.e. transformation or occupation?	Consider edit. Clarify.	the following notes have been added to the table (now Table 11): land use calculated via the livestock feed requirement model by {Peters, 2014 #943}. While values were reported as "m2" in Tichenor, this model gives annual land use (occupation), so units have been changed here to "m2a" 4water depletion (i.e., water withdrawal) and fossil fuel depletion calculated via the ReCiPe Midpoint (H) method {Goedkoop, 2009 #1090}	811-816
RG	15	780-782			ed	That sentence is hard to understand.	Reword for clarity.	Reworded as follows: "(Tichenor et al., 2017) reports energy use and water use for grass-fed beef as slightly lower than the dairy beef scenarios from that study, suggesting water and energy impacts near or slightly below the values reported by Thoma et al. (2017)."	843
RG	16	782-785		Table 10	te	As you say yourself, the recycling rate scenarios are kind of pointless. Why not have a 100% recycled content scenario?	Consider changing the packaging sensitivity analysis.	This has been added as Section 5.3.4	
RG	17	829-838		Table 13	te	If I interpret Table 13 correctly, economic allocation generates the highest environmental impact results. You chose economic allocation foe the ecoinvent processes, why not for the agrifootprint processes? I think the baseline result would be stronger, while still being very low, if they were based economic allocatsion across all processes.	Consider using economic allocation as baseline for the agrifootprint processes.	Thank you for the suggestion. This has been implemented.	
RG	18			Section 3.4.1	ed	I don't use SimaPro and am not sure what gets varied in the Monte Carlo simulation.	Add additional explanation.	per concerns with the Monte Carlo simulation, it has been removed from the report. SimaPro allows for "uncertainty" of all inputs, by defining ranges or distributions. Many of the datasets included have this uncertainty included, but as Matthews points out in comment 42, many of these are based on the "pedigree matrix" approach, which may be of questionable value.	
RG	19	873		Table 16	ed/te	How do you derive from Table 16 that the overall data quality is high? The numbers seem all over the place.	Add a clarifying sentence.	The following sentence has been added: 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.	941
RG	20	900-903			ed	It's good that the source of the beef LCA is mentioned. Might be wise to change the language around "[…] an equivalent U.S. beef patty." to indicate what kind of beef and beef production the Thoma et al. 2017 study actually assesses.	Consider clarifying the comparative statement.	yes, this has been updated to "than a 1/4 pound of U.S. beef."	974

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