COMPARATIVE ENVIRONMENTAL LCA OF THE IMPOSSIBLE BURGER WITH CONVENTIONAL GROUND BEEF BURGER

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Executive Summary

The global community is facing an imperative to feed 10 billion people by 2050, and an urgent need to sustain a food secure future while also preserving and strengthening the natural environment. Over the next several decades, world food demand is expected to increase by 50%, and demand for animal products by at least 70%, entailing risks for human resilience due to the intensive resource use associated with animal-derived food (Alexandratos & Bruinsma, 2012).

The current agricultural system pushes many environmental thresholds past what can be considered sustainable or scalable. To preserve existing land and water resources, and to implement strategies needed to keep global warming below a 1.5 °C rise as adopted by the international 2016 Paris Agreement, more sustainable consumer options are needed to meet the growing demand for meat and dairy products without relying on the inefficiencies of translating plants through an animal and onto a plate. Alternatives to cattle products in particular will be critical.

Impossible Foods has developed one such product: The Impossible Burger®, made directly from plants. This analysis uses life cycle assessment (LCA) methodology to compare the potential environmental impacts of Impossible Burger® 2.0 to those of a conventional, industrial ground beef burger produced in the U.S. Comparison is possible due to the culinary and nutritional equivalence of the Impossible Burger® with that of animal-derived ground beef.

Animal farming is the largest resource user within agriculture. It requires between 1/3 to 1/2 of all ice-free land, about one third of fresh water, contributes close to a fifth of global GHGs, and generates nutrient pollution creating enormous ‘dead zones’ in coastal ecosystems (Herrero, et al., 2016; Eshel, Martin, & Bowen, 2010; Reid, et al., 2008). Meat from ruminants is particularly impactful, occupying about 2/3 of global agricultural land and generating about half of agriculture’s total GHG emissions. Animals convert plants into meat and dairy, yet do so within the constraints of an animal metabolism, thus losing the vast majority of the protein and calories contained in the plants consumed. This report focuses on the resource-sparing potential of bypassing the animal entirely, and creating equivalent products directly from plants.

This analysis finds that the Impossible Burger® requires 87% less water, 96% less land, and produces 89% fewer GHG emissions than the animal version. Additionally, it contributes 92%

less aquatic pollutants. These numbers reflect the latest Impossible Burger® recipe (2.0), launched in 2019.

These unit-level, or 'per burger', LCAs are important to test product-based impact, yet must be considered within the broader context of animal agriculture's environmental impact and the opportunity cost of relying on animals for meat and dairy. For example, 40% of the continental US land is used to produce beef, thus LCA results are most meaningful when considered within the global or national consumption context (Eshel, Shepon, Makov, & Milo, 2014).

We compare the cradle-to-gate potential impacts per kg of final product of the Impossible Burger® and a U.S. ground beef burger. Nutritional desirability is outside our resource-focused scope; further, the Impossible Burger® has a comparable nutritional content to the beef burger. At the same time, the Impossible Burger® has a similar cooking time, shelf-life, and distribution system to the beef burger, hence these activities were excluded from the study.

Data from lifecycle inventory (LCI) databases (e.g., ecoinvent v3.3, allocation – recycled content SCLCI 2014, World Food Lifecycle Database v3.1) are used to calculate the potential environmental impact of both products, focusing on four environmental impact indicators: aquatic eutrophication potential, global warming potential, land occupation, and water consumption. We have reported on other midpoint and endpoint indicators using IMPACT 2002+ method in the appendix, for broader understanding rather than as the focus of the study.

Table 1. Baseline results for a kg of Impossible Burger® and beef burger (IMPACT 2002+ v2.28). Italic number in parenthesis represent 95% confidence intervals.

Impact Category	Unit	Impossible Burger®	Beef Burger	Difference %
Aquatic eutrophication potential	g PO4-eq	1.3 *(2.3-9.7)*	15.1 *(14.3-60.6)*	-92%
Global warming potential	kg CO2-eq	3.5 *(3.1-4.0)*	30.6 *(25.3-37.5)*	-89%
Land occupation*	m2.y	2.5 *(1.6-3.7)*	62.0 *(37.0-102.5)*	-96%
Water consumption	l	106.8 *(56.9-203.3)*	850.1 *(617.9-1238.1)*	-87%

** Land occupation is reported at an LCI level.*

This assessment relies on the best available LCA-related information on food production and conforms with the ISO 14044 standard. For all studied impacts, the Impossible Burger® offers substantial impact reductions ranging from 87% to 96% compared to U.S. beef burger. The study results show that per kilogram of frozen, ready-to-ship burger patty:

- Aquatic eutrophication potential decreases from 15 g PO_4-eq for beef burger to 1.3 g PO_4-eq for the Impossible Burger®. The reduction is due to the avoided manure emissions from raising beef cattle, avoided fertilizer emissions during feed production, and a reduction in electricity consumption by avoiding slaughtering activities.

- **Global warming potential** impacts reduced by 27.2 $kgCO_2$-eq in favor of the Impossible Burger®. The most significant reductions come from the avoided emissions associated with manure and enteric emissions resulting from raising beef cattle.
- **Land occupation** reduced from 62.0 m^2 per year for the beef burger to 2.5 m^2 per year for the Impossible Burger®. In the case of the Impossible Burger®, avoiding raising beef cattle not only reduces pasture land occupation for grazing, which represents 86% of beef burger land occupation; but also reduces agricultural land demand from 6.8 m^2 per year to 2.4 m^2 per year. This is because of the decreased agricultural products demand for beef cattle feed.
- **Water consumption** savings are estimated at 743 liters in favor of Impossible Burger®. The largest water savings are a result of the avoided burden associated with irrigation in the cultivation of feed crops for beef cattle.

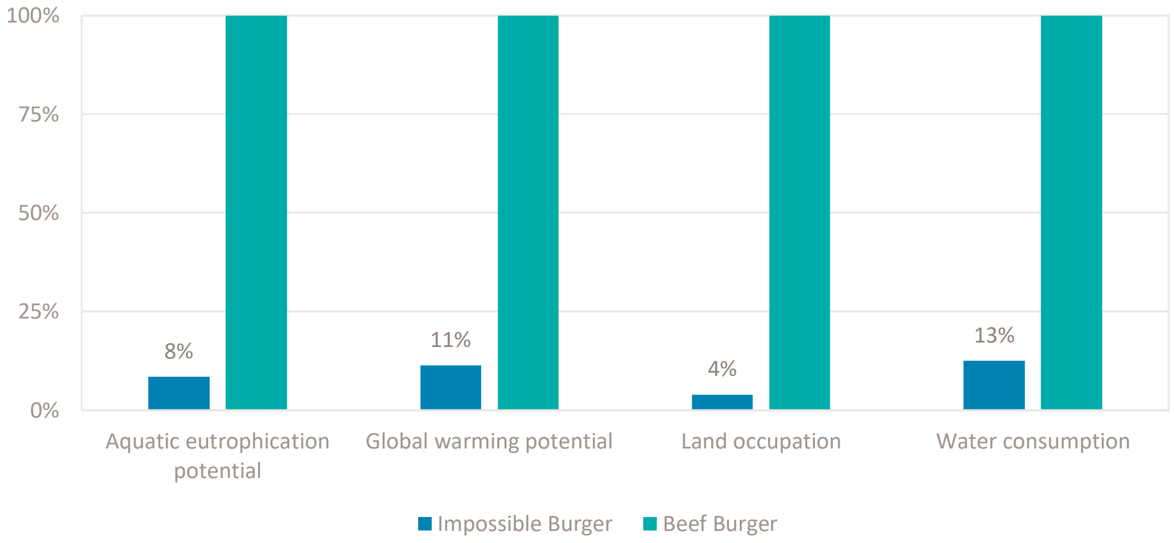

Figure 1: Results comparison of Impossible Burger® and Beef Burger (Impact 2002+ v2.28).

For both products, the raw material production stage contributes the most to the total environmental impacts studied across the four impact indicators. The results demonstrate that raw material production stage contribution to total impacts are >78% for aquatic eutrophication, >60% for GHG emissions, >99% for land occupation and >79% of water consumption for both beef burger and the Impossible Burger®. For the beef burger, cattle raising and feed production are the primary contributing activities in raw material production. For the Impossible Burger® the main contributing activities in the raw material production stage were plant-based ingredient production and manufacturing. The Impossible Burger® has a dramatically lower resource demand than that of beef. As a result, the proportion of total impact contributions contained within the production stages is higher than the proportion of total impact contributions from the same stages within the cattle system.

The result shows that raising beef cattle for human consumption requires growing a much larger amount of upstream primary plant material than if humans directly consumed plants or plant-based products. Additionally, shifting to plant-based food options avoids the impacts associated with raising beef cattle like manure emissions and enteric emissions, which typically contribute to relatively high global warming potential and aquatic eutrophication among other environmental impacts.

Sensitivity analysis was conducted for priority inputs where assumptions had to be made such as the potato protein inputs, refrigeration life, and coconut irrigation etc. for Impossible Burger®. The sensitivity analysis, explored in depth in Section 4.6, details that these assumptions do not considerably affect total results and overall conclusions of the study. The same conclusions were drawn from the uncertainty analysis, where no overlap between the impact categories studied has occurred.

After considering uncertainty and alternative production scenarios, we find that the Impossible Burger® offers clear and meaningful reductions over that of the conventional beef burger in the four environmental impacts studied.

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Acronyms

FAO – Food and Agriculture Organization of the United Nations

GHG – Greenhouse Gas

IB – Impossible Burger®

IFSM – Integrated Farm System Model

IPCC – Intergovernmental Panel on Climate Change

ISO – International Organization for Standardization

LCA – Life Cycle Assessment

LCI – Life Cycle Inventory

LCIA – Life Cycle Impact Assessment

PG&E – Pacific Gas and Electric Company

SCLCI – Swiss Center for Life Cycle Inventories

TVP – Textured Vegetable Protein

US(A) – United States (of America)

USDA – United States Department of Agriculture

USMARC – US Meat Animal Research Center

WECC – Western Electricity Coordinating Council

WFLDB – World Food Lifecycle Database

1. Introduction

The food and agriculture sector has become a focal area in the debate around strategies to sustainably feed a growing population, expected to reach nearly 10 billion by 2050. To meet this demand, total food production will need to increase an estimated 50% to 70% compared to 2009 levels, increasing annual cereal production to 3 billion tons and meat production to 470 million tons (Alexandratos & Bruinsma, 2012; FAO, 2009; Searchinger, et al., 2018). Total demand for meat and dairy will increase even more dramatically. At the same time, global agriculture and food production contributes more than 25% of all global greenhouse gas (GHG) emissions, inflicts significant negative impacts on fresh and marine water through use of agrochemicals, and uses nearly half of the ice-free land on the planet (Tilman & Clark, 2014; Reid, et al., 2008; Steinfeld, et al., 2006; Eshel, Martin, & Bowen, Land use and reactive nitrogen discharge: Effects of dietary choices, 2010). This begs the question: how can the food sector meet demand without significantly increasing its impact on the environment?

The question must be examined through the dual lens of consumption and production: *what will people eat,* and *how will the food be produced?* Consumption behavior is driven by factors of individual dietary preferences and purchasing power, quantities of food eaten, and by changes in food utilization and waste. On the food production front, agricultural technology, access to inputs and training, and adoption of best management practices can boost material efficiency as food is brought from the farm to the dinner table. While efficiency in yield per acre and yield per input is important, there also exists a wide spectrum of agricultural management practices that include application of agroecological theory and diversified farming which can also contribute to environmental health (Searchinger, et al., 2018).

Plant-based transitions span both production and consumption in the toolkit of sustainably meeting future food demand.

Dietary choices can lead to a meaningful reduction of overall environmental impacts. Recent studies have shown that eliminating or reducing meat consumption can reduce GHG emissions from 15% to 77%, water consumption up to 84%, and help lessen cropland demand by 540 million hectares by 2050 compared to a business-as-usual scenario (Dettling, Tu, Faist, DelDuce, & Mandlebaum, 2016; Tilman & Clark, 2014; Heller, Willits-Smith, Meyer, Keoleian, & Rose, 2018; van de Kamp, Seves, & Temme, 2018; Goldstein, Moses, Sammons, & Birkved, 2017; Eshel, Martin, & Bowen, Land use and reactive nitrogen discharge: Effects of dietary choices, 2010).

Market interventions will be necessary to reduce reliance on animal farming. Specifically, products that can be readily exchanged for animal-based equivalents can provide a viable option for meeting rapidly increasing animal product consumption in emerging economies, while supporting existing demand in current high consumption markets. In turn, once production increases and an array of plant-based meat and dairy alternatives become both available and desirable to consumers, current and future resource extraction and greenhouse gas emissions resulting from animal agriculture can be mitigated and abated. Increased scale of production is necessary to achieve the environmental goals associated with plant-based diets, and in turn, to meet widely recognized international commitments to maintain climate and biodiversity within safe planetary thresholds. Access to alternative plant-based options for popular food products such as burgers, sausages, steaks, and other relatively low efficiency meat categories will be particularly important (Searchinger, et al., 2018; Shepon, Eshel, Noor, & Milo, 2016).

The average American eats approximately three burgers worth of ground beef per week, equivalent to 50 billion burgers annual consumption (Center for Investigative Reporting, 2012). Impossible Foods targets this existing ground beef market, leveraging innovation to offer the Impossible Burger®, a plant-based ground beef alternative offering reduced environmental impacts while delivering similar nutrition content, flavor, aroma, and “beefiness” to traditional beef (Impossible Foods Inc., 2018).

The goal of this study is to understand the environmental impacts associated with the Impossible Burger®, and how those environmental metrics compare to those of a conventional U.S. beef burger. The results will provide credible, transparent information for external communication purposes and for internal footprint quantification at Impossible Foods, backed by a science-based life cycle assessment (LCA) approach.

2. Goal of the study

2.1. Objectives

The objective of this study is to support Impossible Foods in making strategic business decisions and external communications regarding the environmental benefits of the Impossible Burger® in comparison with a conventional U.S. beef burger.

More specifically, the study seeks to fulfill the following specific objectives:

1. Understand whether the Impossible Burger® provides an environmental benefit relative to conventional beef burger, and the magnitude of this benefit; the focus of the environmental impact assessment includes primarily aquatic eutrophication potential, global warming potential, land occupation, and water consumption.
2. Understand the main impact drivers for both burger products and articulate the impact differences.

3. Provide transparent and credible information to support Impossible Foods in making strategic communications.

2.2. Intended audiences

This project report is intended to support Impossible Foods® in quantitating full life cycle environmental impact of Impossible Burger® production, and in communicating the comparative environmental performance of its Impossible Burger® against the environmental performance of a traditional beef burger. Specific audiences may include the company’s employees, business partners, customers, and the general public.

The International Standards Organization (ISO) standard 14044 on LCA includes a set of specific requirements for LCAs whose intent is to report specific product-to-product comparisons to a broad audience. It is the intent of this assessment to meet those requirements in cases where explicit statements are made comparing the environmental impact of the products under study (International Standard Organization, 2006; International Standard Organization, 2006).

3. Scope and system boundaries

This section includes the LCA methodology, a description of the products’ function, the system and its boundaries, and data sources including the requirements for data quality and analysis.

3.1. General description of the products studied

3.1.1. Impossible Burger®

Impossible Foods’® main product is the Impossible Burger®, which falls into the category of *beef substitutes for human consumption*. These products are intended to be included in recipes and meals as direct and equivalent substitutes for ground beef, such as in hamburger patties, meatballs, taco filling, sauces, and other culinary applications. Plant-based proteins, fats, oils, and binders are the primary recipe components, as well as the innovative ingredient known as *heme,* which gives the product its characteristic meat flavor, color, and behavior.

Heme is manufactured through a fermentation and isolation process. It is then shipped to the Impossible Foods manufacturing facilities, where it is mixed and processed with other plant-based proteins and fats. This mixture is then molded, frozen, and packaged for sale. The frozen packaged product is then modeled as distributed in 20-pound boxes across the U.S.

The model use of 20-pound boxes was selected as a representation of multiple different pack-out configurations for patties and bricks.

The scope of the system studied includes all activities necessary to produce frozen packaged Impossible Burger®, from "cradle to manufacturers gate." Figure 2 further details the system under study, including raw materials manufacturing, heme production, Impossible Burger® production, and packaging.

Retail, distribution, use, and end-of-life stages are excluded from the study, as these do not differ significantly between the Impossible Burger® and a traditional beef burger, and therefore bear similar environmental impacts. The Impossible Burger® has been designed to have nutritional content similar to a beef burger. Moreover, Impossible Foods product has similar cook-time and shelf-life. Finally, the environmental impacts of these stages have not shown to be a significant driver of the overall life cycle of such food products. (Impossible Foods Inc., 2018; Heller & Keoleian, 2018; Dettling, Tu, Faist, DelDuce, & Mandlebaum, 2016; Asem-Hiablie, Battagliese, Stackhouse-Lawson, & Rotz, 2018; USDA, 2018).

Table 2: 4 oz nutrition content for Impossible Burger® and beef burger with 80% lean meat and 20% fat. Sources: Impossible Foods Inc. (2018), USDA (2018)

Nutrition Content	Impossible Burger® (4 oz.)	Beef burger 20% fat (4 oz.)
Calories	240	254
Total fat (g)	14	20
Cholesterol (mg)	0	71
Protein (g)	19	17.17
Total Carbohydrate (g)	9	0
PDCAAS*	0.83	0.85

** Protein Digestibility-Corrected Amino Acid Score: measure to evaluate protein quality based on humans' amino acids requirements and its digestibility*

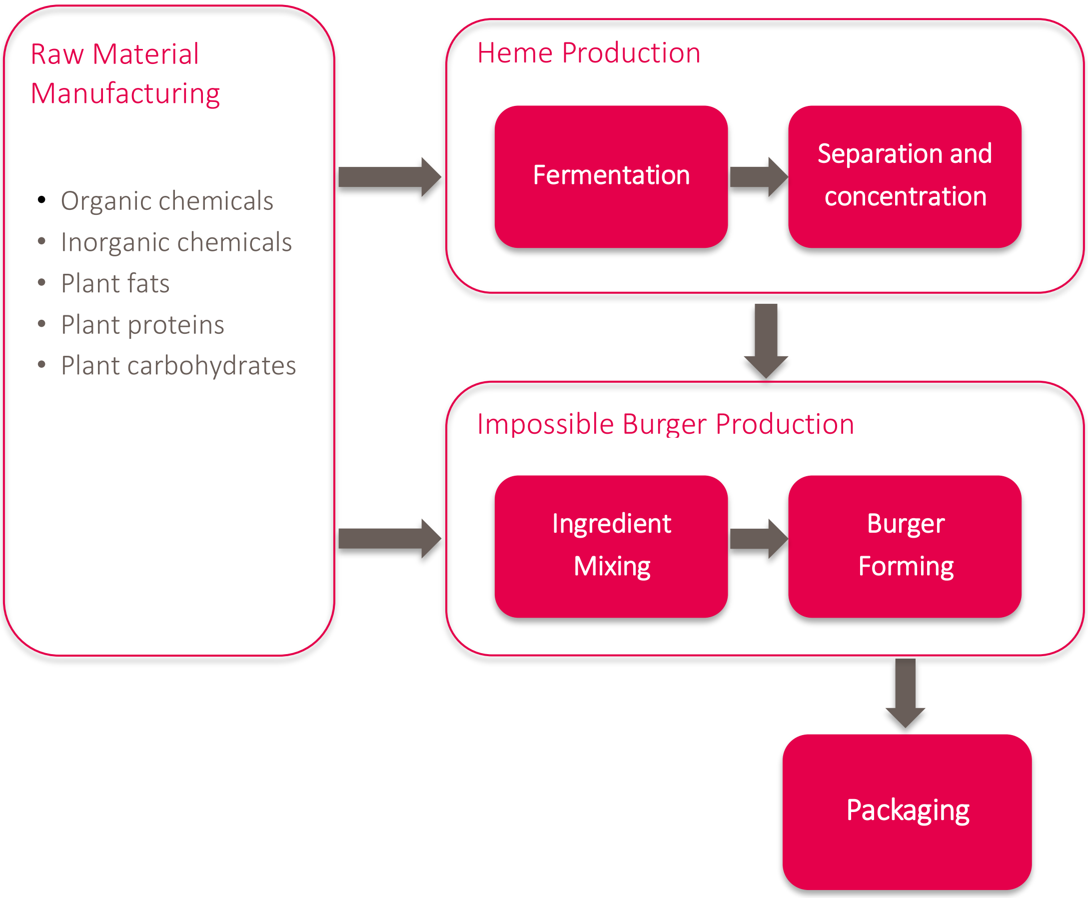

Figure 2: Manufacturing process of the Impossible Burger® under study. Material and energy inputs, transportation of ingredients, as well as emissions to air, water, and soil, and generation of waste are considered throughout the supply chain

3.1.1. Beef burger

Cattle production generates the greatest economic value of any commodity in the U.S. food sector, with an estimated valuation of $60 billion in 2016 (Field, 2017). Moreover, beef burgers are among the most popular food products in the U.S., with an estimated annual consumption of 50 billion burgers (Center for Investigative Reporting, 2012).

Beef production in the U.S. typically consists of a cow-calf operation on pasture, lasting six to eight months, followed by an optional phase of backgrounding with a high forage diet, and finally 5- to 8-month on feedlot with a high concentrate diet (Field, 2017). Feedlot finishing diets rely predominantly on corn, with some wheat or barley. Industrial byproducts like distiller's grains or gluten feed are also important in feedlot diets, representing 10-40% of the dry matter content depending on commodity prices and market conditions (Drouillard, 2018). After the finishing phase, cattle are slaughtered, with dressing weights around 63% of live weight (Asem-Hiablie, Battagliese, Stackhouse-Lawson, & Rotz, 2018).

Table 3: Impossible Burger® main data sources, assumptions, and background dataset sources

	Heme Production	Impossible Burger® Mix	Burger Manufacturing	Packaging
Data sources	Impossible Foods provided all primary information.	Impossible Foods provided all primary information.	Impossible Foods provided necessary information.	Impossible Foods provided all necessary information.
Assumptions	Chemicals ingredients representing less than 1% by mass are modeled by generic chemical organic or inorganic dataset if exact match unavailable.	Processed food ingredients are represented by the closest dataset available. When unavailable, they are modeled by the raw material which is derived if they represent <1% by mass. Chemicals ingredients representing less than 1% by mass are modeled by generic chemical organic or inorganic dataset if exact match was unavailable.	Plant-based and beef burger share similar production and packaging practices. All refrigerants are recharged every 8 years, with a 0.1% leak at end-of-life.	Plant-based and beef burger share similar production and packaging practices.

Table 4: Beef burger main data sources, assumptions, and background dataset sources

	Feed Production	Cattle raising and fattening	Cattle slaughtering and processing	Burger Manufacturing	Packaging
Data sources	Rotz, Isenber, Stackhouse-Lawson, & Pollak (2013	Asem-Hiablie, Battagliese, Stackhouse-Lawson & Rotz, (2018); Rotz, Isenber, Stackhouse-Lawson & Pollak (2013); FAO (2018); (Rotz, Asem-Hiablie, Place & Thoma (2019)	Bengoa, Rossi & Mouron (2017)	Impossible Food burger manufacturing process	Impossible Food burger packaging
Assumptions	Processed food ingredients are represented by the closest dataset available. When unavailable, they are modeled by the raw material which is derived if they represent <1% by mass.	Impacts of supporting herd (cows, heifers, and bulls) are assigned to cow-calf operations. Manure and enteric emissions are calculated using Tier 2 IPCC (2006) and WFLDB v3.3 (2017) guidelines.	It's assumed that there are no significant differences in carcass yield and revenue between the European and the U.S. cattle market. No distinctions are made between different fresh beef meat cuts. An estimated 22% of beef comes from dairy operations.	Plant-based and beef burger share similar production and packaging practices. There's a 5% loss at manufacturing.	Plant-based and beef burger share similar production and packaging practices.

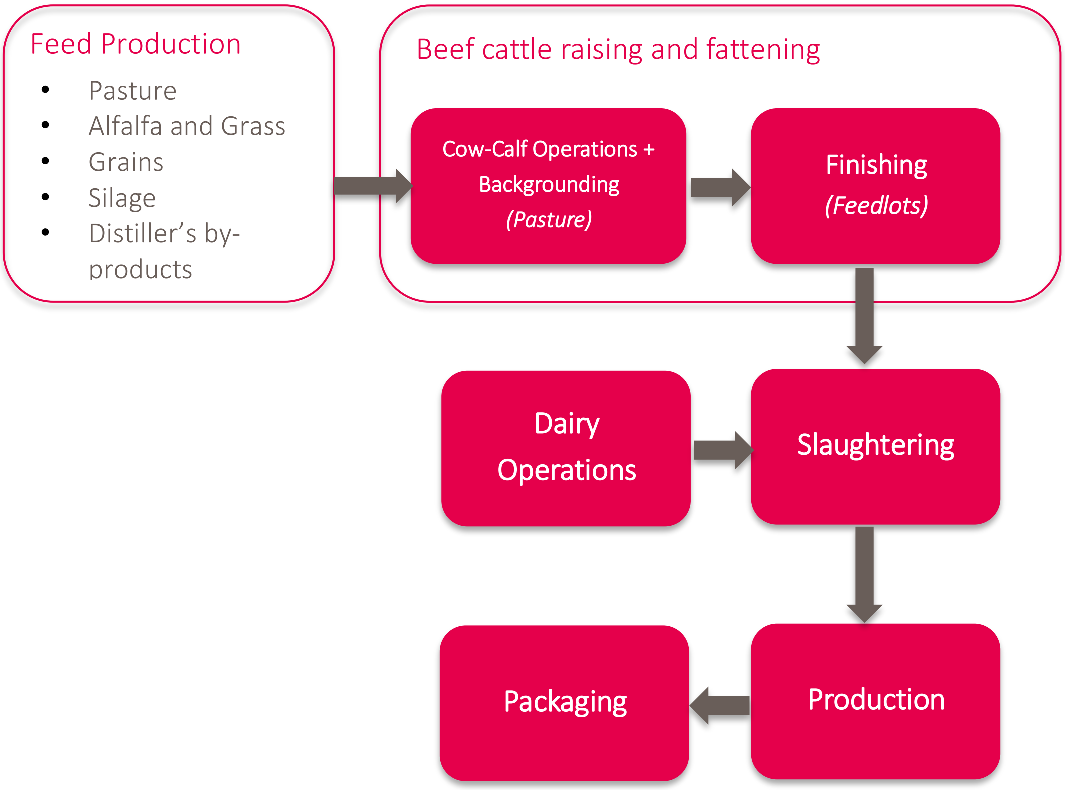

Figure 3: Process diagram of beef burger under study. Material and energy inputs, transportation of ingredients, as well as emissions to air, water, and soil, and generation of waste are considered throughout the supply chain

A significant portion of beef consumed in the U.S. comes from the dairy sector. In 2002, approximately 18% of beef consumed in the US was sourced from dairy cull and breeding overhead, up to around 23% in 2016 (Boetel, 2017). Given that dairy cattle meat is a significant portion of the total beef consumption, this input is considered in the scope of the study.

Ground beef is commonly made from either ground chuck, round, or sirloin, in proportions reflecting the desired product fat content. In this study, we do not distinguish individual cuts, as ground meat mass weighted-average pricing offers a close approximation of the mass weighted-average revenue of beef cuts (Cattlemen's Beef Board and National Cattlemen's Beef Association, 2014; Cattlemen's Beef Board and National Cattlemen's Beef Association, 2018).

The scope of the studied system includes all the activities necessary to produce boneless retail-ready ground beef, i.e. from "cradle to manufacturers gate". Figure 3 depicts the studied system, which includes feed production, cow-calf, backgrounding, and feedlot operations, beef from dairy production, slaughtering, and packaging.

3.2. Comparative basis: Function and functional unit

Life cycle assessment relies on a “functional unit” as a reference for evaluating the components within a single system, or among multiple systems, on a common basis. It is therefore critical that this parameter is clearly defined and measurable.

It is acknowledged that there is not a single clear and agreed-upon measurement on which to set a functional basis for food consumption, due to the multiple functions that food serves (to provide nutrition, alleviate hunger, support social interactions, and other psychological reasons), as well as the difficulty of quantifying how many of these needs are met.

The functional unit for this study is cradle-to-gate assessment of 1 kg of Impossible Burger®, which will be benchmarked against 1 kg of boneless retail-ready U.S. conventional ground beef burger.

The purpose of this study is to compare the respective cradle-to-gate environmental impacts across four priority environmental impact areas: aquatic eutrophication, climate change, land occupation and water consumption. All infrastructure processes have been left out of the study, as they typically do not significantly contribute to the overall impact categories named.

Beyond nourishment, any other functions of the products are not considered here. For example, taste, enjoyment, relief of psychological stress, providing a basis for social interactions and others may all be reasons that people consume food in certain contexts. No attempt is made here to compare these products based on these alternative functions.

3.3. System characterization and data sources

A reference flow refers to the quantity and type of material needed to fulfill a functional unit. The following sections provide details on the data used to define these reference flows for the products assessed in this study.

When modeling the two product systems under study, the ecoinvent v3.3, allocation – recycled content, unit database is prioritized as the default source for background data. In the absence of a representative agricultural dataset, a dataset from the Quantis World Food Life Cycle Database 3.1 processes is used in its place; whenever possible, appropriate country inventories are selected. In the absence of country specific inventories, region specific inventories that have similar technology and climate conditions are used. When neither country specific or region-specific inventories are available, global inventories are used. Global inventories are typically average datasets of all the country specific datasets available in the database for the specific product/process. This is assumed to be a reasonable alternative in the absence of country or region-specific datasets (Swiss Center for Life Cycle

Inventories, 2016; Bengoa, Rossi, & Mouron, 2017; Durlinger, Koukouna, Broekema, van Paassen, & Scholten, 2017).

Additionally, inputs representing a high proportion of mass or environmental impacts for either product are adapted to relevant country conditions. This includes changing to country or region specific electricity grid, updating crop yields, irrigation water and fertilizer inputs. Each background process dataset is identified in Appendix B (section **Error! Reference source not found.**) and changes to existing datasets are been described in subsections 3.3.1 and 3.3.2.

3.3.1. Impossible Burger®

Required inventory data for modeling the Impossible Burger® life cycle, including heme production, burger ingredients, manufacturing, and packaging data are provided by Impossible Foods with few exceptions. Primary packaging of a 20 lb. Impossible Burger® box consists of separation paper leaves used to keep individual patties from sticking to one another and plastic wrapping film. Packaging and burger production are collocated, obviating transportation emissions between these steps. Electricity and water consumption are fully considered in the production process.

3.3.1.1. Heme Production

Heme is produced through fermentation, in which a genetically modified yeast strain expresses the naturally occurring leghemoglobin protein. Following fermentation, the leghemoglobin protein is isolated and concentrated from the fermentation media.

Two wastewater streams exit the process: one with a high suspended solids content which is diverted to agricultural land application (high solid waste), the other has a lower suspended solids concentration and is treated in municipal wastewater (low solid waste).

3.3.1.2. Impossible Burger® production.

The product is comprised of a variety of plant-based materials and ingredients which are used as flavor, fat, texture, or other purposes. The production entails protein and oils preparation, burger forming, cooling, assembly and packaging. Electricity consumption in all processing steps, including refrigeration, has been considered.

In this study, transportation of the eight highest-mass ingredients, representing 91% of the dry mass of the total product, was modeled in detail; the transport distance of the remaining ingredients was assumed to be 786 km by truck, based on information provided by Impossible Foods. Transportation by truck for distances up to 100 km was modeled using EURO3 3.5-7.5 metric ton truck, and above 100km using >32t EURO 4 truck.

One important component of the Impossible Burger® is the potato protein, for which Impossible Foods' supplier provided background life cycle information. The estimated impact incorporated into the baseline model was considered conservative estimate, as it assumes that 100% of the potato's environmental impacts are allocated to the potato protein (and no other co-products). A sensitivity analysis addressing this assumption is described in Section 4.6.

Coconut oil, another essential component of the Impossible Burger®, is sourced from the Philippines. Based on personal communications with suppliers, Philippine coconut researchers and on data provided by the Philippine Coconut Authority, irrigation and irrigation infrastructure is very rarely included in coconut production (Magat S. S., 2011; Quieta, 2012; Magat S. ; Dy & Reyes, 2007). Therefore, the study assumes no water withdrawals for irrigation management of this crop. Further, because specific oil processing data for coconut oil does not exist in ecoinvent v3.3, oil processing was modeled as a simple average of palm oil processing, soybean oil processing, and cottonseed oil datasets available, adapting electricity sourcing to the Philippines.

In the California-based manufacturing plant, refrigerants are kept in circulation to maintain freezer operation and refrigerated storage at an optimal temperature. These refrigerants are estimated to be changed every 8 years based on conservative estimates by Impossible Foods. The study, which takes place over the course of one production year, allocates the refrigerant production, end of life processing, and 0.1% leakage at the end of life, evenly by mass across 8 years of production. Essentially applying 1/8 of the associated burdens to 1 year of production. Water is used in the process, primarily for cleaning, and is treated as municipal wastewater.

A small fraction of electricity is from unspecified origin, whose emission intensity was conservatively modeled as California's average mix. Transmission and voltage conversion environmental impacts were incorporated using Ecoinvent's Western Electricity Coordinating Council (WECC) processes as an approximation (PG&E, 2016; PG&E, 2015; PG&E, 2017; PG&E, 2018).

Table 5: Electricity mix from PG&E.

PRODUCT	**100 kWh of PG&E Electricity Production**	
Input	**Quantity**	**Unit**
Solar	11.5	kWh
Wind	7.75	kWh
Biomass and Waste	4.25	kWh
Hydroelectricity, Run-off	2	kWh
Natural Gas	21.5	kWh
Nuclear	23.75	kWh
Hydroelectricity, reservoir	11	kWh

Unspecified*	13.25	kWh

** PG&E cannot track the source of this amount of electricity.*

3.3.1.3. Packaging

Table 6: Impossible Burger® Packaging LCI

PRODUCT	**1 kg of Packaged IF Burger, at factory**	
Input	**Quantity**	**Unit**
Impossible Food Burger	1	kg
Paper, patty paper	1.6	g
Plastic Film	2.3	g
Corrugated cardboard	10	g
Outputs	**Quantity**	**Unit**
Plastic Film	0.4	g

3.3.2. Beef burger

3.3.2.1. Animal feed production and animal-raising

Cattle raising is modeled based on Asem-Hiablie, Battagliese, Stackhouse-Lawson & Rotz (2018) and Rotz, Isenber, Stackhouse-Lawson & Pollak (2013), both using data from the U.S. Meat Animal Research Center (USMARC) in combination with an Integrated Farm System Model (IFSM). This represents typical crop, feed, and animal management practices from Nebraska, one of the largest beef feedlots producing state in the country (Field, 2017), however it is important to note that this data does not represent the average US beef production.

The model includes cow-calf operations lasting the 6 months on pasture, 3 months of backgrounding, and 7 months of feedlot finishing. The backgrounding diet was based on hay and distiller’s grain, while the finishing diet was primarily grain-based. The herd being raised at the facilities included 5,050 calves, 5,498 cows, 285 bulls, and 1180 replacement heifers in the cow-calf operation; 3,724 cattle were finished in the feedlot with an average weight of 581 kg. In addition to finished cattle, it was assumed that 1100 cows and 80 bulls, according to a 20% replacement rate, with average weights of 636 kg and 908 kg respectively, were also sent to slaughter, for a total output of 3,213 ton of live weight (Asem-Hiablie, Battagliese, Stackhouse-Lawson, & Rotz, 2018; Rotz, Isenber, Stackhouse-Lawson, & Pollak, 2013).

The environmental impacts associated with additional inputs necessary for supporting the herd, including feed, water, operations energy, as well as facility outputs including manure and enteric emissions, were assigned to the total cattle sent to slaughter. Fuel and electricity for pumped water and other cattle raising operations were *included; electricity being modeled using a U.S. MRO grid dataset. An inbound transport distance of 100 km was used for cattle feed, and the study assumes that this feed was produced entirely in the U.S. (Table 7 and* Table 8) (Rotz, Isenber, Stackhouse-Lawson, & Pollak, 2013).

Feed production was modeled using background processes from Ecoinvent 3.3, allocation – recycled content, unit and the World Food Lifecycle Database (WFLDB) 3.1. Ecoinvent´s “Maize grain, feed {CA-QC}” was modified to more closely represent “Maize grain, feed {US}”, based on a U.S. maize input, as well as a U.S. MRO electricity input. A grazing dataset from WFLDB 3.1 representing average global conditions was adapted to U.S. conditions, with 15.49 ton/ha of fresh matter yield and 20 N kg/ha of additional nitrogen fertilizer based on Rotz, Isenber, Stackhouse-Lawson, & Pollak (2013).

Table 9 reports emissions factors used per kg of live weight. 100% of manure produced by the entire herd is left on the pasture during cow-calf and backgrounding operations, while 95% of manure produced on feedlots is spread on feed fields. Enteric emissions were calculated based on dry mass intake by IPCC, 2006 Tier 2, using a 6.5% and 3% methane conversion factor for grazing and feedlot animals respectively. Manure management emissions, including methane and nitrogen, were calculated following IPCC, 2006 Tier 2 and WFLDB 3.1 guidelines. Methane emissions were also calculated according to dry matter intake through volatile solid emissions calculation. Ammonia, nitrogen oxides, and dinitrogen monoxide emissions from manure management were also calculated, starting from a daily nitrogen emission factor of 0.31 kg per ton of live weight. Phosphorus manure emissions were estimated using emissions factors for the whole operation from Rotz, Asem-Hiablie, Place & Thoma (2019). Nitrate emissions were outside the scope of the 4 priority impact categories and were not estimated (FAO, 2018; Asem-Hiablie, Battagliese, Stackhouse-Lawson, & Rotz, 2018; Dettling, Tu, Faist, DelDuce, & Mandlebaum, 2016; IPCC, 2006; Pelletier, Pirog, & Rasmussen, 2010).

Finally, Soil Organic Carbon (SOC) changes, which might be relevant during grazing were not included in this study due to limited science and data availability to conduct such calculations. SOC changes are highly contextual and variable, depending on grazing intensity and duration, pasture management, grass type, precipitation and other climate conditions. A combination of all these factors can lead to either an increase, decrease, or neutral effect on SOC (McSherry & Ritchie, 2013; Derner & Schuman, 2007; Hewins, et al., 2018).

Table 7: Feed inputs for cow-calf + backgrounding and feedlot operations to produce 3,123 ton of beef cattle. Sources: Rotz, Isenber, Stackhouse-Lawson & Pollak (2013)

	Quantity (ton)	
Feed	**Cow-calf + Backgrounding**	**Feedlot**
Pasture	23,808	0

Alfalfa and grass hay	4,833	707
Corn silage	2,416	2,507
High moisture corn	104	2,718
Corn grain	56	1,596
Distillers grain	45	1,623

Table 8: Water, feed transportation, fuel and energy consumption to produce 3,123 ton of beef cattle. Sources: Asem-Hiablie, Battagliese, Stackhouse-Lawson & Rotz (2018); Rotz, Isenber, Stackhouse-Lawson & Pollak (2013)

Input	Quantity	Unit
Electricity	1,070,441	kWh
Fuel	16,571,820	MJ
Natural gas	11,161,800	MJ
Water, for drinking	371,495	m^3

Table 9: Emissions factor for manure management and enteric emissions for beef cattle per unit of live-weight. All flows but phosphorus calculated using IPCC (2006) Tier 2 and WFLDB v3.1 guideline, phosphorus per Rotz, Asem-Hiablie, Place & Thoma (2019)

Input	Quantity (g/kg LW)
CH_4, enteric fermentation	360
CH_4, manure management	4.4
NH_3-N, manure management	2.1
NO_2, manure management	4
N_2O, manure management	2.9
Phosphorus runoff, manure management	0.25

The allocation approach applied in this study is described in section 4.1. Economic allocation was used in this study as this is one of the widely used allocation method for multi-output agricultural systems and is one of the most viable allocation methods for animal co-products. The demand for meat has been identified as the main driver to produce meat, and thus drive related environmental impacts. Economic allocation was applied to assign impacts between fresh meat and co-products, based on information from the European Fat Processors and Renderers Association – this is not adjusted to reflect the U.S. scenario, as it is assumed that the market and costs associated with beef and coproducts is similar between the U.S. and European markets (Table 11). It is important to note that allocation decisions affect results, to investigate allocation and result dynamics, an APOS sensitivity analysis was conducted, as described in section 4.6. The study consistently uses the same allocation method across the two databases and the products under study.

Table 10: Beef cattle slaughtering LCI. Source: Bengoa, Rossi & Mouron (2017)

PRODUCT	1 kg of slaughtered beef cattle	
Input	**Quantity**	**Unit**
Beef, cattle, for slaughter, at beef farm	780	g
Culled dairy cows	70	g
Male calves	150	g
Slaughtering activities	1	kg
Cattle transportation	0.2	tkm

22% of beef was estimated to come from dairy operations: 7% from culled dairy cows and 15% from male calves. These environmental impacts are modeled using WFLDB datasets, which follows the International Dairy Federation principles to allocate impacts between dairy (88%) and beef meat (12%), as well as the same guidelines used in this study to calculate direct emissions, including manure management and enteric emissions[1]. Finally, 200 km is assumed between the feedlot and the slaughterhouse. (Bengoa, Rossi, & Mouron, 2017; Boetel, 2017; Rotz, Isenber, Stackhouse-Lawson, & Pollak, 2013; Geiger, 2016; USDA, 2018).

Table 11: Beef cattle slaughtering products and allocation factors. Source: Bengoa, Rossi & Mouron (2017)

Product	Quantity (g)	Economic allocation factor (%)
Beef, fresh meat	460	93.2
Beef, food grade offal	30	0.61
Beef, food grade bones	80	0.7
Beef, food grade fat	70	1.42
Beef, food grade blood	30	0.32
Beef, cat. 3 slaughter by-products	30	0.01
Beef, hides and skins	70	3.78
Beef, cat. 1 and 2 materials and waste	230	0

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[1] Please visit https://quantis-intl.com/wp-content/uploads/2017/02/wfldb_methodologicalguidelines_v3.0.pdf for detailed calculation guidelines followed by WFLDB and this report

3.3.2.2. Beef burger production and packaging

Because burger production and packaging generally have a low contribution to the total environmental footprint of ground beef, these processes are modeled using the same assumptions as are used for the Impossible Burger® (Heller & Keoleian, 2018). A 5% meat loss during these production steps is used according to Dettling et al, 2016.

3.4. Temporal and geographic boundaries

This assessment is intended to be representative of food production in the U.S. during the year that the study is conducted (2018). Data and assumptions are intended to reflect current equipment, processes, and market conditions. Data has been selected where possible to best match these geographic and temporal conditions, although relevant geography data may not always be available, most data being at least a year old and, in many cases, several years old. Main databases and key reports used in this study are all from 2013 or later, which is considered to represent current conditions in the industry. Considerable efforts were made to better represent current production conditions for high contribution processes in mass or environmental impacts terms. Production yields, current irrigation practices and electricity sources were updated as a result of prioritizing applicable and representative inventories for the study.

It should be noted that some processes within the system boundaries might in fact take place anywhere in the world and over a much wider range of time than the current year. For example, the processes associated with manufacturing food products consumed in the U.S., and their raw materials, take place both in the U.S. as well as in a wide variety of other countries. The information to represent food production in this assessment has been selected with a preference for data representing U.S. production. To the extent that such data is not available in all cases, it is assumed that the use of data from other geographies, when needed, balances in part the actual sourcing of products from both within and outside the U.S.

Regarding the temporal boundaries, certain processes may generate emissions over a longer period than the reference year. Regardless of such considerations, all data has been selected to as closely represent conditions in 2018 as is practical.

3.5. Cut-off criteria

Processes may be excluded if their contributions to the total system's environmental impact are expected to be less than 1%. Materials that are less than 1% by mass are assumed to also contribute less than 1% of the environmental impact, except in cases where there is a reason to expect otherwise, such as with hazardous substances. Despite this criterion for allowing components to be excluded, all product components and production processes are included when the necessary information is readily available, or a reasonable estimate can be made.

The following are just a few examples of items excluded from the study due to lack of reliable data and expected contribution lower than the cut-off criteria: infrastructure processes, seals and stickers on packaging or used in retail, shipping pallets and other ancillary services not directly linked to the product production system such as executive travel, legal, accounting etc.

4. Assessment methodology

4.1. Allocation methodology

A common methodological decision point in LCA occurs when the system being studied creates co-products. When systems are linked in this manner, the boundaries of the system of interest must be widened to include using all co-products, or the impacts of producing the linked product must be distributed—or allocated—across the systems. While there is no clear scientific consensus regarding an optimal method for handling this in all cases, many possible approaches have been developed, and each may have a greater level of appropriateness in certain circumstances (Reap, Roman, Duncan, & Bras, 2008).

ISO 14044 prioritizes methodologies related to multi-functionality processes, which can deliver more than one product, including allocation and system expansion. It is best to avoid allocation through system subdivision or expansion whenever possible. If not, then one should perform allocation using an underlying physical relationship. If allocation using a physical relationship is not possible or does not makes sense, then one can use another relationship, such as economic, or other characteristic.

In alignment with the cut-off allocation approach for addressing systems that donate or receive material or energy source from an upstream or downstream system, applied in the foreground modeling described above, the ecoinvent life cycle inventory system model chosen to apply in this study is that called cutoff by classification. This approach is explained in detail on the ecoinvent website and in an ecoinvent v3 overview and methodology paper (Wernet, et al., 2016). In summary, the burdens of producing primary materials are always assigned to the first user of those materials, and recyclable materials are burden- and credit-free to those users.

Ecoinvent 3.3 typically uses economic allocation for multi-product systems. WFLDB 3.1 also uses economic allocation for multi-product systems, except when stated otherwise, as in the case of dairy system where it follows International Dairy Federation allocation guidelines. The economic allocation principle was used for crop co-products, animal feed, and animal co-products specifically and agricultural production systems in general, and has been widely used for this products (Bengoa, Rossi, & Mouron, 2017; Dettling, Tu, Faist, DelDuce, & Mandlebaum, 2016; Rotz, Asem-Hiablie, Place, & Thoma, 2019; de Vries & de Boer, 2010; Wiedemann, et al., 2015). Nguyen et al. (2012) and Nguyen et al. (2013) investigated the influence of the allocation rule for animal feed in carbon footprints of meat. Although for the single feed components the allocation rule is very important, on the level of meat, the influence is relatively small. The study intends to consistently use the same allocation classification for similar processes across the two databases used for this comparative study.

Furthermore, many of the processes in the ecoinvent database also provide multiple functions, and allocation is required to provide inventory data per function. This study consistently uses the allocation method used by ecoinvent v3.3 in its cutoff by classification approach and the allocation used by WFLDB v 3.1 as previously described. Most products in this category are allocated on a revenue basis. As described in section 3.3, economic allocation is one of the widely used allocation method for multi-output agricultural systems and is considered to be addressing the main driver for these production systems- revenue and demand. The choice of allocation metric and factors can be highly influential to the resulting environmental indicator impact of each product. The allocation choices influence on the study results was tested through a sensitivity analysis using "point of substitution" allocation version of ecoinvent, further described in section 4.6. No significant differences (less than 0.1%) was observed in the study results as per the APOS results.

4.1.1. Transport allocation

Transport vehicles have both a weight and a volume capacity. These are important aspects to consider when allocating the impacts of an entire transportation journey to one product. Vehicles transporting products with a high density (high mass-per-volume ratio) will reach their weight capacity before reaching their volume capacity. Vehicles transporting products with a low density (low mass-per-volume ratio) will reach their volume capacity before reaching their weight capacity. Therefore, the density of the product is critical for determining whether to model transportation as volume-limited or weight-limited.

In this study, all transport is assumed to be weight-limited and the transportation of the cargo within the vehicle is therefore allocated based on its weight.

Transportation by truck for distances up to 100 km was modeled using EURO3 3.5-7.5 ton truck, and above 100km using >32 ton EURO 4 truck. Refrigerated transport was modeled using 7.5-16 ton EURO4 R134a refrigerated truck.

4.2. Impact assessment

Impact assessment classifies and combines the flows of materials, energy, and emissions into and out of each product system by the type of impact their use or release has on the environment. The method used here to evaluate the environmental impacts is the peer-reviewed and internationally recognized life cycle impact assessment (LCIA) method IMPACT 2002+ vQ2.28 (Humbert, De Schryver, Margni, & Jolliet, 2012). This method assesses seventeen different potential impact categories (midpoints)[2] and then aggregates them into endpoint categories.

The final report considers most heavily the four impact categories shown and described in Figure 4. These are aquatic eutrophication potential, climate change, land occupation and water consumption. Land occupation is mostly reported at an inventory level, unless indicated otherwise, with complete LCIA results in section 8.2. These 4 environmental indicators are international accepted and widely used for assessing livestock and agricultural products environmental impacts. Most meat related environmental studies identify carbon footprint, land occupation, aquatic eutrophication and water consumption as priority hotspots (Asem-Hiablie, Battagliese, Stackhouse-Lawson, & Rotz, 2018; Heller & Keoleian, 2018; McClelland, Arndta, Gordon, & Thoma, 2018; Tilman & Clark, 2014; Rotz, Isenber, Stackhouse-Lawson, & Pollak, 2013; Goldstein, Moses, Sammons, & Birkved, 2017).

It is the aim of this study to concentrate on the most relevant identified impact indicators for comparison and discussions. The study doesn't intend to omit other mid-point indicators, which are available in the report Appendix C. However other indicators are not the focus of this study and are added in the appendix for the sake of transparency. Appendix C (8.3) includes the contribution of each midpoint indicator per Impact 2002+ v2.28 method, in determining the overall result for all endpoint indicators for the products under study. Impact 2002+ V2.28 method is a scientifically reviewed, published and widely used environmental impact assessment method that has characterization factors for over 1500 different LCI results, which are included as supplementary material. The method is regularly updated and discusses assumptions, limitations and uncertainty in the website and the methodology document. Overall the fate exposure and effect related uncertainty of the method is high for land occupation and low for aquatic eutrophication, global warming potential and water consumption. The specific method related assumptions and limitations are as described below:

- Aquatic Eutrophication: The eutrophication potential does not include nitrates.
- Global Warming Potential: The timescale in which the GWP is assessed is considered a valid choice (100yr GWP). The impact will be significantly higher in a shorter

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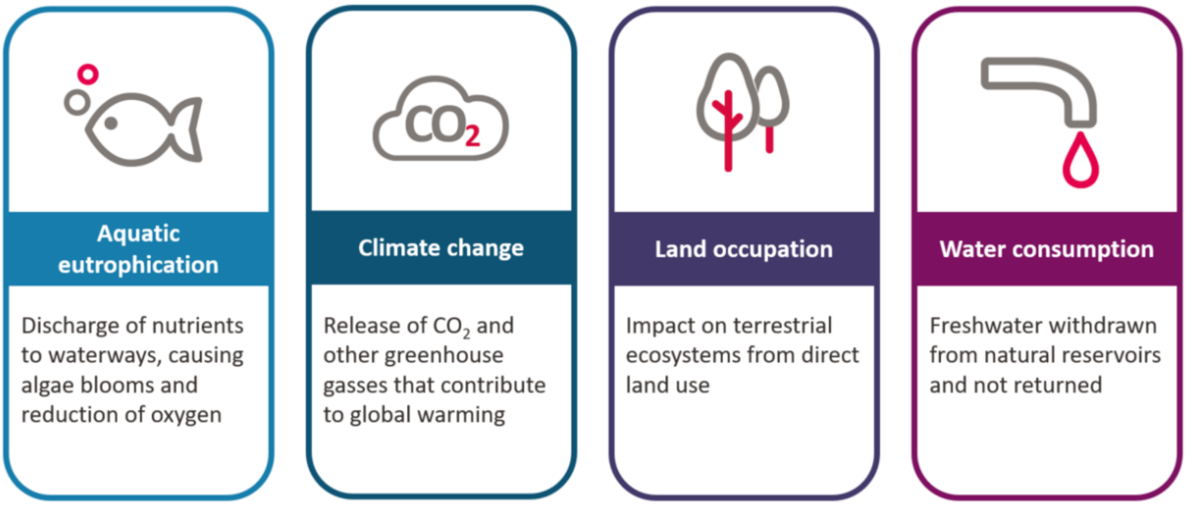
[2] The Human Toxicity midpoint category is divided between carcinogenic and non-carcinogenic effects, hence a total of 17 midpoint indicators (Humbert et al. 2012).

timeframe and lower in a longer timeframe. While GWP has a low uncertainty in general. The uncertainty for beef could be higher due to methane emissions.

- Land Occupation: The method potentially overestimates the impact of grazing compared to plowing
- Water Consumption: The study does not consider local water stress.



Discharge of nutrients to waterways, causing algae blooms and reduction of oxygen

Release of CO_2 and other greenhouse gasses that contribute to global warming

Impact on terrestrial ecosystems from direct land use

Freshwater withdrawn from natural reservoirs and not returned

Figure 4: Description of the four environmental impact indicators given primary focus in this assessment (Impact 2002+ v2.28).

A more detailed description of the impact categories than what is shown in Figure 4 is provided in Appendix A (8.1).

No results normalization is conducted with the exception being those results presented on a relative basis (%) compared to the reference for each system. No endpoint or midpoint category weighting is done; being presented individually and not as a single score, as there is no objective method by which to achieve this.

The LCA results represent an estimation of the potential environmental impacts that can occur and do not represent a measurement of actual environmental impacts that have occurred. They are relative expressions, which are not intended to predict the final impact, or whether standards or safety margins are exceeded. Additionally, these categories do not cover all the environmental impacts associated with human activities. For example, impacts such as noise pollution, odor production, and electromagnetic field generation are not included in the present assessment, as the methodological developments regarding such impacts are not sufficient to allow for their consideration within the scope of this life cycle assessment.

4.3. Calculation tool

SimaPro 8.4 software, developed by PRé Consultants (2017) is used to assist the LCA modeling, link the reference flows with the life cycle inventory database, and compute the complete inventory of the systems. Results are calculated by combining foreground data (intermediate products and elementary flows) with generic datasets providing cradle-to-gate background elementary flows to create a complete inventory of the two systems. Microsoft Excel is used to help with processing the results from the LCA.

Foreground data are defined as data/processes that are in the control of the study commissioner; these include primary data available for Impossible Burger®. Background data are defined as data/processes which are not under the control of the commissioner of the study, or indirect in nature due to the lack of specific information available, which in this case include beef burger processes. Although ground beef foreground data was sourced from the published paper, which uses primary data, while this data was not in control of the study commissioner, the referred study does gather and use primary data. Ecoinvent 3.3 is the most widely used, published and reviewed third party dataset available and is considered to the best choice for background datasets. Similarly, WFLDB datasets are used for agricultural datasets only when a suitable ecoinvent dataset was not available, a total of five instances. Based on the documentation and available information, it is observed that ecoinvent 3.3 and WFLDB 3.1 are consistent. Effort has been made to use the most specific country-level datasets throughout the modeling choices made. Where specific country-specific datasets were not available, datasets from similar technological countries/regions were used. Global datasets (average of all available regional/ country datasets) were used when relevant country specific or similar regional datasets were not available. Appendix B (8.2) details all the datasets used for the study.

4.4. Contribution analysis

In addition to the comparative assessment, a contribution analysis is calculated to determine the extent to which each modeled process contributes to the overall impact of the Impossible Burger®. Lower quality data may be suitable in the case of a process whose contribution is minimal. Similarly, processes with a great influence on the study results are characterized by high-quality information. In this study, the contribution analysis is a simple observation of the relative importance of the different processes to the overall potential impact.

4.5. Uncertainty analysis

Three types of uncertainty related to the LCA models are typically discussed and defined: uncertainty in inventory data, uncertainty in the impact characterization models and choice related uncertainty. With assessment of comparative results, it is important to note the difference between the uncertainty in the impact of a given product and the uncertainty in comparing the impact between two products. It is possible for the uncertainty in the absolute impact of two given products to each be relatively high and yet the uncertainty of how they compare to be very low. The more similar two products are in terms of the processes and materials that comprise them, the more the factors that contribute to the uncertainty in the absolute impact of each will cancel each other out when comparing them. Choice related uncertainties are typically investigated using sensitivity analysis.

4.5.1. Inventory data uncertainty analysis and data quality assessment

An analysis of the uncertainty due to the variability of inventory data is performed. Data sources are assessed based on time-related coverage, geographical coverage, technology coverage, precision, completeness, representativeness, consistency, reproducibility, source description and uncertainty of the information as prescribed in ISO 14044. The pedigree matrix for rating inventory data appears below, and a complete discussion of this topic can be found in Frischknecht & Jungbluth (2007) (Table 12).

Table 12: Pedigree matrix used data quality assessment, derived from Weidema & 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 qualified estimates	Qualified estimate (e.g., by industrial expert)	Non-qualified estimate
Completeness	Representative data from all sites relevant to the market considered, over an adequate period to even out normal fluctuations	Representative data from >50% of the sites relevant for the market considered, over an adequate period to even out normal fluctuations	Representative data from only some sites (<<50%) relevant for the market considered or >50% of sites but from shorter periods	Representative data from only one sites relevant for the market considered or some sites but from shorter periods	Representativeness unknown or incomplete data from a smaller number of sites and from shorter periods
Temporal differences	Less than 3 years of difference to the time-period of the dataset	Less than 6 years difference to the time period of the dataset	Less than 10 years difference to the time period of the dataset	Less than 15 years difference to the time period of the dataset	Age of data unknown or more than 15 years of difference to the time-period of the dataset
Geographical differences	Data from area under study	Average data from larger area in which the area under study is included	Data from area with similar production conditions	Data from area with slightly similar production conditions	Data from unknown or distinctly different area
Further technological differences	Data from enterprises, processes and materials under study	Data from processes and materials under study but from different enterprises	Data from processes and materials under study but from different technology	Data on related processes or materials	Data on related processes on laboratory scale or from different technology

Data quality assessment results are included in Appendix D (**Error! Reference source not found.**), listing each indicator score for processes and flows.

Further, SimaPro 8.4 software (PRé 2017) includes a module for Monte Carlo simulation, which allows assessment of the uncertainty and variability embedded in inventory data. Most of the data here is drawn from the ecoinvent 3.3 database, which has a thorough characterization of the uncertainty for most of the flows of energy and material within the life cycle inventory data that it provides. Adapted ecoinvent and WFLDB datasets' DQI were recalculated in the context of the study application and its role in the model based on the pedigree matrix explained in Table 12.

Monte Carlo analysis is used to understand the uncertainty within the product systems. 1,000 iterations for each product system was performed to understand the range of LCIA results, by randomizing LCI data using geometric standard deviations reported in Appendix D for each flow. A 1,000 iterations comparative Monte Carlo analysis was also performed.

4.5.2. Characterization model uncertainty analysis

In addition to the inventory data uncertainty described above, there are two types of uncertainty related to the LCIA method. The first is about the characterization of the LCI results into mid-point indicators, and the second is about the subsequent characterization of those midpoint scores into end-point indicators. The uncertainty ranges associated with characterization factors at both levels vary from one mid-point or end-point indicator to another. The accuracy of characterization factors depends on the ongoing research in the many scientific fields behind life cycle impact modeling, as well as on the integration of current findings within operational LCIA methods.

There are presently no systematic methods available for quantifying or evaluating the influence of the uncertainty in these characterization models within the comparative assessments made here. Without consideration of the uncertainty in LCIA characterization factors, the uncertainty assessment results derived here should be seen as something like a lower bound on the level of uncertainty in the systems and the uncertainty would be higher if uncertainty in these characterization factors are also considered.

4.6. Sensitivity analysis

The parameters, methodological choices, and assumptions used when modeling the systems present a certain degree of uncertainty and variability. It is important to evaluate whether these selections significantly influence the study’s conclusions and to what extent the findings are dependent upon certain sets of conditions. Following the ISO 14044 standard, a series of sensitivity analyses are used to study the influence of uncertainty and variability, thereby evaluating the robustness and reliability of the results and conclusions.

As described in the previous section, uncertainty analysis allows for the identification of influential factors and parameters that warrant further investigation through sensitivity analyses. The following scenarios are identified as important based on its contribution to the total impacts and the data quality/uncertainty known:

1. **Potato protein:** An alternative scenario using this dataset was run and compared to the baseline model. The results are then evaluated to identify Impossible Burger®’s total impact and potato protein’s contribution to it.
2. **Coconut oil:** Oils have shown to contribute more than 10% of total water consumption for plant-based burgers; the country of origin may have wide implications on water

consumption in the production of coconut oil (Heller & Keoleian, 2018; Bengoa, Rossi, & Mouron, 2017). As the Philippines is identified as the country of origin for coconut oil in this study, and regional variations could exist despite prevailing lack of irrigation, a sensitivity analysis exploring currently present in ecoinvent dataset is included.

3. **Ground beef with and without meat from dairy:** Beef coming from dairy tends to have a lower impact than beef cattle (Heller & Keoleian, 2018). To understand how Impossible Burger® compares to conventional meat from beef cattle, a sensitivity analysis excluding beef coming from dairy, as well as a scenario where all the meat is derived from dairy, are conducted. This scenario is performed using the same cattle proportion as described in Table 10.
4. **Refrigerants lifetime:** 8 years is the base assumption for refrigerant lifetime, established on conservative estimates provided by Impossible Foods. Nevertheless, refrigerants lifetime may vary. Therefore, a 6 years and 12 years scenario were run to see their effect in results, predominantly on global warming potential.
5. **Impossible Burger®'s Electricity Source:** To explore how much Impossible Burger®'s potential environmental impacts may increase by using less clean electricity sources, an alternative scenario using U.S. average electricity grid was explored.
6. **Alternative LCIA method for land occupation:** ReCiPe 2016 – Midpoint (Hierarchical) was used to assess the range of land occupation impacts, as both methods, widely recognized by the international LCA community, has significant different characterization factors for pasture land occupation: ReCiPe has a characterization factor of 0.55 m^2 crop/yr/m^2, while Impact2002+ has a factor of 1.037m^2 org.arab./yr/m^2.

An additional sensitivity analysis was run to test the influence of ecoinvent 3.3 allocation method, substituting cut-off by classification to allocation at the point of substitution (APOS). Results differed less than 0.1% for both products under study, and thus no further analysis was done.

4.7. Critical review

Because the results of this study are intended to be used to support a comparative assertion disclosed to the public, a critical review must be conducted by a panel of interested, relevant parties, particularly an LCA expert and other stakeholders.

The peer review panel is intended to comprise of experts in beef environmental impacts assessment, agricultural environmental impact assessment and ISO 14040/14044 standard requirements. The selected critical review committee comprises the following members:

Table 13: Reviewer's names, affiliations, and areas of expertise

Name	Affiliation	Expertise

Gidon Eshel	Bard College	Geophysical processes, Numerical analysis, Science based disclosures
Greg Thoma	University of Arkansas	Life Cycle Analysis, Food Systems
Nathan Pelletier	University of British Columbia	Life Cycle Analysis, Food Systems

Detailed resumes of each of the peer review panel member is described in appendix 8.3

In accordance with 14040 and 14044 ISO standards (2006a, b), the goal of the critical review process is to check that the report follows the following stipulations:

- The methods used by Quantis to carry out the LCA are as follows:
  - consistent with the 14044 International Standards, and
  - scientifically and technically valid;
- The data used are appropriate and reasonable in relation to the goal of the study;
- The interpretations of Quantis reflect the limitations identified and the goal of the study; and
- The study report is transparent and consistent.

The critical review process will be carried out in two steps:

1. Final report submitted (Dec 2018);
2. Corrections and clarification of points raised by the reviewers in step 1 (January 2019).

The reviewers' comments will be provided to Quantis as distinct review reports. The critical review reports and the responses to reviewers' recommendations will be presented in the appendix.

5. Results

The following section presents the study results. The first part focuses on the comparison of the impacts of Impossible Burger® to the traditional beef burger. The second part presents a more detailed analysis of the Impossible Burger® results.

5.1. Impossible Burger® vs. beef burger comparison

Results show that potential environmental impacts of producing the Impossible Burger® are lower than those of the traditional beef burger in the 4 priority impact categories. Most of the impacts associated with the beef burger, and thus most of beef's environmental liabilities relative to the Impossible Burger®, come from the cattle-raising stage that represents between 41% and 93% of the potential environmental impacts of the beef burger.[3]

Table 14: LCIA results for priority categories for 1kg of Impossible Burger® and 1 kg of beef burger. Italic numbers in parenthesis represent 95% confidence interval. (Impact 2002+ v2.28)

Impact Category	Unit	Impossible Burger®	Beef Burger	Difference %
Aquatic eutrophication potential	g PO4-eq	1.28 *(2.3-9.7)*	15.1 *(14.3-60.6)*	-92%
Global warming potential	kg CO2-eq	3.5 *(3.1-4.0)*	30.6 *(25.3-37.5)*	-89%
Land occupation*	m2.y	2.5 *(1.6-3.7)*	62.0 *(37.0-102.5)*	-96%
Water consumption	l	106.8 *(56.9-203.3)*	850.1 *(617.9-1238.1)*	-87%

** Land occupation is at the inventory level.*

The largest potential impact savings is seen in the land occupation indicator, where the traditional beef burger occupies 62 m^2 per year compared to the Impossible Burger®'s 2.5 m^2 per year. For the beef burger, 90% of this impact comes from pasture needs for the beef cattle raising, mainly in the grazing phase. Regarding land occupation related to agricultural production, the beef burger occupies 6.4 m^2 per year compared to 2.3 m^2 per year for the Impossible Burger®.

The second most significant impact savings offered by the Impossible Burger® over beef burger is the aquatic eutrophication impact category, which is 92%. This difference stems from eliminating phosphorus emissions from cattle operations, including emission from manure, fertilizers use during feed production, and electricity consumption for slaughtering.

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[3] Complete results can be found in Annex B for all endpoint and midpoint categories.

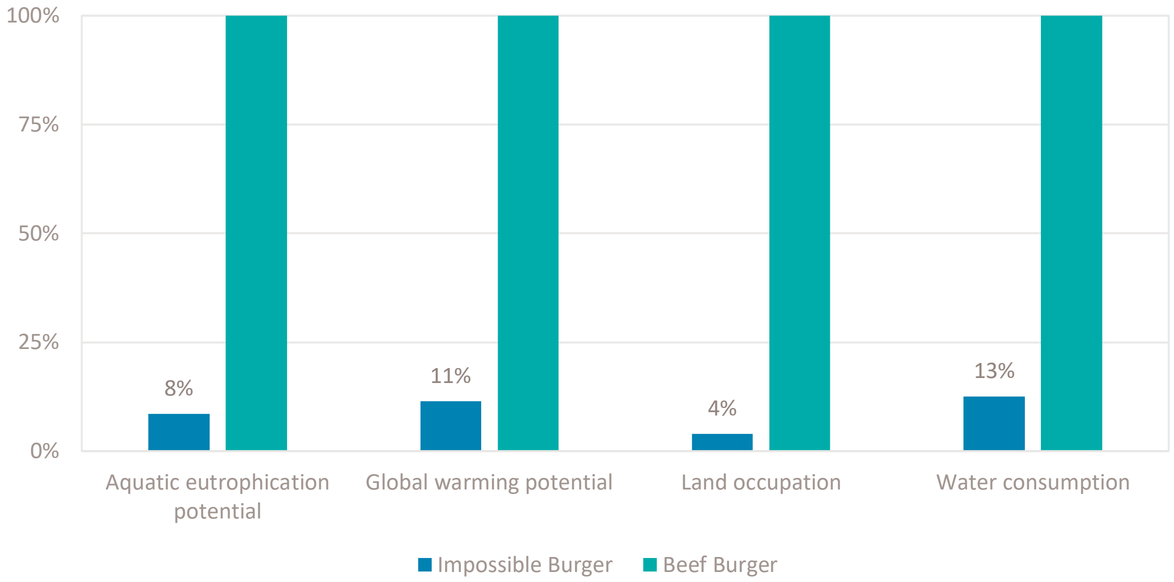

Figure 5: Impossible Burger® vs. beef burger life cycle impact assessment relative results comparison, with results normalized to beef burger impacts for each indicator (Impact 2002+ v2.28).

Water consumption and global warming potential impacts are 87% and 89% lower respectively in the Impossible Burger® than in the beef burger, with 743 fewer liters of water consumed and 27.1 fewer kg CO_2-eq. emitted per kilogram of beef. Lower water consumption is driven by the fact that a large amount of water (82% of the total) is consumed in the production of maize for cattle feed, which is not used in the Impossible Burger®.

Also, as the Impossible Burger® production does not include production of cattle, this leads to a reduction of 26.3 kg CO_2-eq per kg of beef burger not produced. From this, roughly 79% comes from emissions associated with manure management and enteric fermentation, 11% from feed production and transportation, while an extra 10% comes from cattle slaughtering.

5.2. Detailed Impossible Burger® results

The two lifecycle stages that represent the most significant impacts for the Impossible Burger® are production and manufacturing of the ingredient mix, with the packaging stage adding negligible contributions to all impact categories (Figure 6).

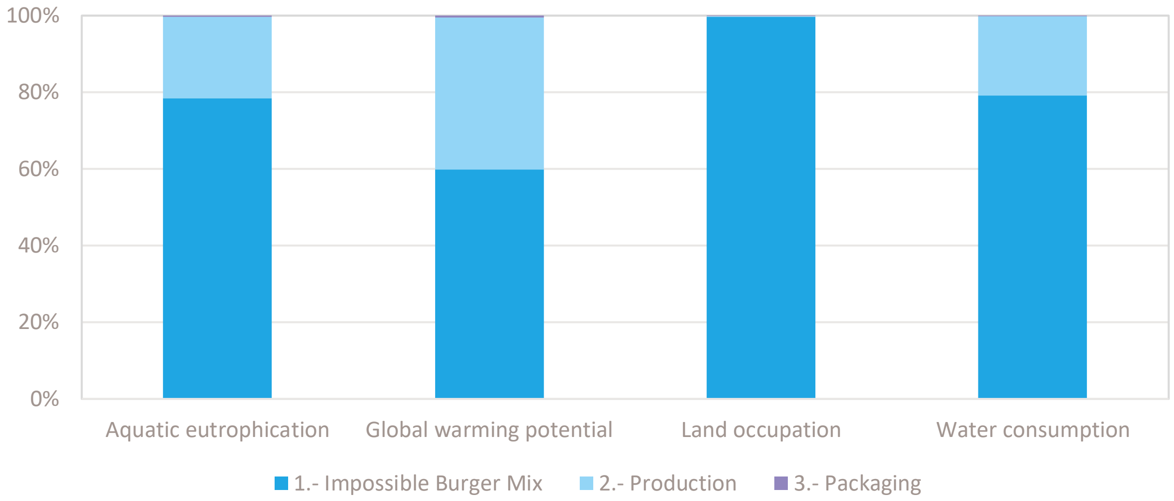

Figure 6: Impossible Burger® life cycle impact assessment distribution among life cycle stages (Impact 2002+ v2.28)

Impacts generated at the production stage are mainly explained by electricity consumption, along with production of nitrogen and carbon dioxide for refrigeration purposes. Impacts associated with electricity consumption lead to 21% of total global warming potential emissions, 14% of total water consumption impacts, and 15% of total aquatic eutrophication impacts due to emissions associated with fossil fuel production and consumption, contributing just around 0.1% to overall land occupation. Refrigerant emissions at the end-of-life add up to 0.19 kgCO_2-eq, which is equivalent to 5% of total potential global warming potential emissions, due to small leakages at end-of-life stage.

Table 15: LCIA Priority results for 1 kg of Impossible Burger® per life cycle stage (Impact 2002+ v2.28).

Impact Category	Unit	Total	1.- Impossible Burger® Mix	2.- Production	3.- Packaging
Aquatic eutrophication potential	g PO4-eq	1.28	1.00	0.27	<0.1
Global warming potential	kg CO2-eq	3.50	2.09	1.38	0.02
Land occupation*	m2.y	2.5	2.46	0.01	<0.1
Water consumption	l	106.82	84.49	22.13	0.19

* *Land occupation is at the inventory level.*

Much of the remaining impacts arise in the Impossible Burger® Mix production, with three ingredients—heme, fats, and texture agents—accounting for 42-82% of all impacts across the Impossible Burger® life cycle.

5.2.1. Impossible Burger® ingredient analysis

Ingredient contributions to GHG emissions are led by leghemoglobin, followed by potato protein and coconut oil. Potato protein is also the largest contributor to water use by ingredient, followed by coconut oil, then heme. Coconut oil is the highest land-using ingredient, followed by soy protein and sunflower oil.

Aquatic eutrophication potential	Global warming potential	Land Occupation	Water consumption
Potato protein	LegH protein	Coconut oil	Potato protein
Coconut oil	Potato protein	Soy protein	Coconut oil
LegH protein	Coconut oil	Sunflower oil	LegH protein
Sunflower oil	Flavor mix	Potato protein	Flavor mix
Soy protein	Sunflower oil	LegH protein	Soy protein
Flavor mix	Soy protein	Flavor mix	Sunflower oil

Figure 7: Impossible Burger® Ingredients Rank Order Impact Categories over total life cycle impacts (Impact 2002+ v2.28)

The production of potato protein leads to a total consumption of 62 liters of water, equivalent to 54% of Impossible Burger® total, mainly due to the use of heavy irrigation in potato production. At the same time, it occupies 0.38 m^2 of land per year, equivalent to 14% of land occupation impacts, which were primarily driven by land occupation during the crop production. It's also associated with 30% of the total aquatic eutrophication impacts, due to phosphorus leaching from fertilizers use, and 9% of global warming potential impacts, due to fertilizer use emissions. Given that this ingredient was modeled using conservative assumptions, it's possible that these high potential impacts are overestimated.

Sunflower oil and coconut oil significantly contribute to land occupation, leading to 0.89 and 0.46 m^2 of land occupied per year respectively, for crop production. The refining stage of coconut oil also requires 8.5 liters of water.

Texturized vegetable protein from soybean meal contributes 24% of the land occupation footprint in the Impossible Burger® total, also due to land occupation during crop production.

5.3. Sensitivity analysis

Sensitivity analyses were conducted across impact categories to investigate alternative modeling choices and methodologies. A summary figure is presented below.

Using an average U.S. electricity grid rather than PG&E grid would increase global warming potential to 4.7 $kgCO_2$-eq per kg and aquatic eutrophication potential by 39% of Impossible Burger® driven by the relatively higher use of fossil fuel in the electricity grid across the rest of the country.

An alternative, less conservative model, of potato protein produces significant changes for almost all impact categories, and particularly for water consumption, which sees an absolute reduction of 52 liters compared to the baseline assumptions. This model uses a wet milling multi-output process, in which impacts are economically-allocated across potato protein and other co-products, rather than assigning 100% of the burden to potato protein. Differences in aquatic eutrophication potential, global warming potential, and land occupation can be similarly attributed.

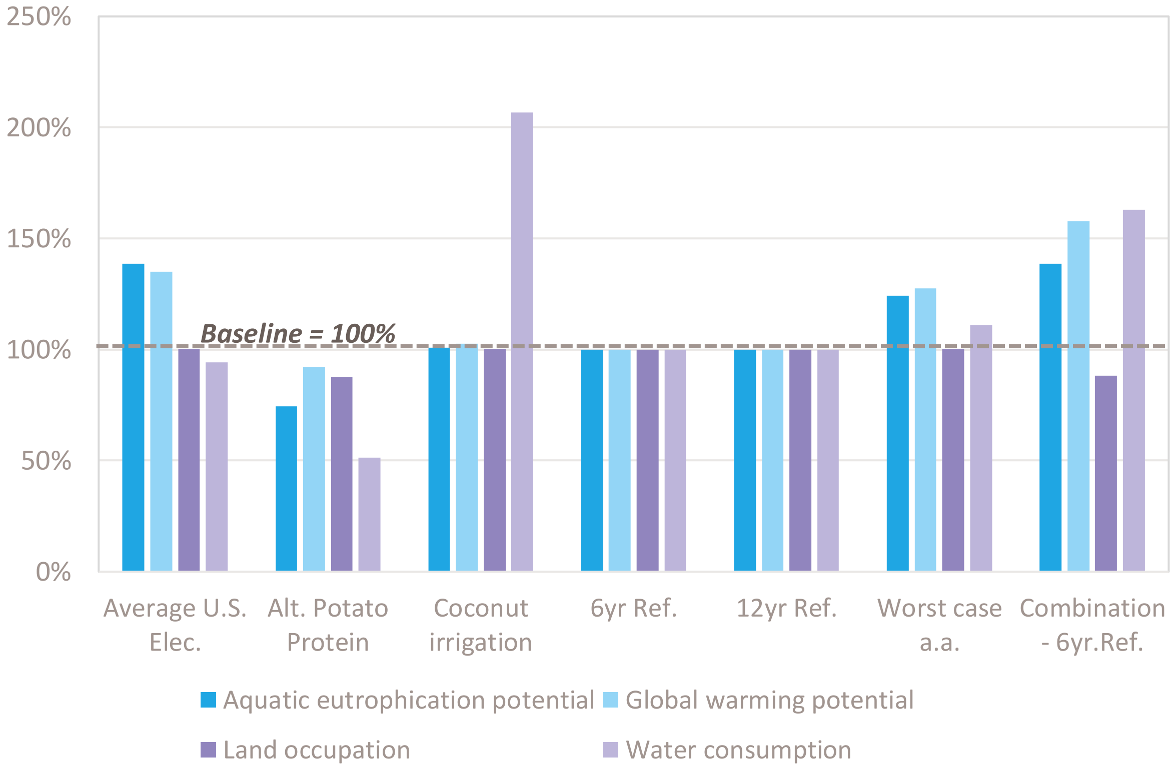

Figure 8: Results comparison for Impossible Burger® sensitivity analysis scenarios. 100% represents baseline results (Impact 2002+ v2.28).

Assuming coconut was irrigated 1.96 m^3 ha-$y^{-1,}$ leads to more than doubling total water consumption. Actual water consumption of irrigated coconut depends on yield, which was not adjusted in this sensitivity analysis. If modeled more realistically, the expected added yield may offset the higher water consumption due to irrigation. Other impact categories are less sensitive to this assumption, increasing by only 1-3%.

Changing refrigerant lifetimes to either 6 or 12 years does not significantly change results. The GWP contribution from refrigerants remains approximately 5%. No other changes were observed due to modification in refrigerants lifetime (less than 0.1%).

In the case of all alternative scenarios occurring simultaneously, water consumption increases by 63% to 174 liters, with higher consumption due to irrigated coconut oil offsetting potato protein consumption reductions; global warming potential and aquatic eutrophication potential also increases 58% and 39% respectively, due to increased use of energy and resources in general as a combination of switching the electricity source and amino acids and vitamin background dataset. On the other side, land occupation would be reduced by 12% due reduced land occupation attributed to potato protein.

Regarding land occupation sensitivity analysis, ReCiPe 2006 Midpoint (H) delivers a total of 2.4 and 37.4 m^2 crop eq./yr per kg of product for Impossible Burger® and beef burger respectively, compared to 2.4 and 59.2 m^2 org. arab./yr given by Impact2002+ v2.28. While this shows moderate changes to the animal-derived ground beef, the general differential of impact between the two products remains similar. The beef burger still uses 2.7 times more land with agricultural purposes (6.4 versus 2.4 for m^2 crop eq./yr per kg) than the Impossible Burger®. Note that both methods calculate land occupation differently, have different units and as such are not exactly comparable.

Since the conclusion of this sensitivity analysis does not change the results, it is not considered important to investigate and justify the implications of such methodological differences.

Alternative scenarios were also examined in the case of dairy herd allocations. Although sourcing beef entirely from the dairy herd is not industry practice, the scenario is analyzed here. The results show the environmental impacts reduce for all the four priority indicators. Land occupation has the biggest reduction, with 37% of the baseline occupation – a large portion of dairy cows are modeled to be fed without grazing, reducing pasture land occupation to 9.6 m2 per year, while increasing crop land occupation to 14.3 m2 per year as more feed crop is needed. Global warming potential would be reduced to 24.7 kg CO_2-eq, aquatic eutrophication to 7.7 g PO_4-eq, and water consumption to 631 liters.

Given that milk is the main product in the dairy industry and generates the primary revenue, beef products from dairy receive, a lower allocation of environmental impacts, between 10%-35% depending on method chosen, compared to beef cattle, where main revenue driver is beef meat production (Bengoa, Rossi, & Mouron, 2017; Thoma, et al., 2013). Land occupation changes can be attributed to dietary differences between each type of cattle, where beef cattle spend more time on pastures instead of consuming feed mix. Diet is the main cause of increased pasture land occupation and the reduction in crop related land occupation.

5.1. Uncertainty analysis

Uncertainty assessments have been conducted for the two systems. The uncertainty assessment considers the range of uncertainty in estimating the flows of material and energy in the systems and the uncertainty in the emissions of pollutants or other impacts associated with each of these. It excludes the uncertainty associated with the characterization factors used to transform the inventory results into impact indicator results. Figure 9 presents each system's individual uncertainty results based on Monte Carlo simulations for the Impossible Burger® and beef burger, in terms of global warming potential, water consumption, land occupation, and aquatic eutrophication potential.

Results show that there is no overlap between any of the analyzed midpoint categories, despite significant variability in them. Further, comparative Monte Carlo simulation resulted in 100% runs with beef burger impacts being higher than Impossible Burger®. For both products, 97.5% whiskers extend further than 2.5%, meaning that there is higher probability of impacts being larger than current average.

Global warming potential demonstrates lower coefficient of variation (COV), calculated as the standard deviation divided by the mean, for both products – COV being 6.7% for Impossible Burger® and 10.3% for the Beef burger, as GHG emissions has a lower basic uncertainty than other emissions estimated. Beef burger's larger COV can be explained by the higher uncertainty present in manure management and enteric fermentation calculated emissions.

Water consumption shows higher uncertainty, with a COV of 37.3% and 40%, which stems from a general large uncertainty in water flows throughout the different background processes used in the model.

Land occupation exhibits similar COV for both products, that is 21.3% for Impossible Burger® and 29.2% for beef burger, with a long low-probability tail to larger impacts, and a shorter higher-probability tail for smaller impacts. Variation in crop yields drives the distribution.

Finally, aquatic eutrophication has the highest COV for both products -- 41.5% for the Impossible Burger® and 35.3% for the beef burger, exhibiting a similar behavior to land occupation uncertainty, stemming from electricity consumption and crop production P-emissions uncertainty. Higher COV for Impossible Burger® can be explained as uncertainty on electricity generation emissions tend to have a larger influence on results, when compared to the small potential impact reported.

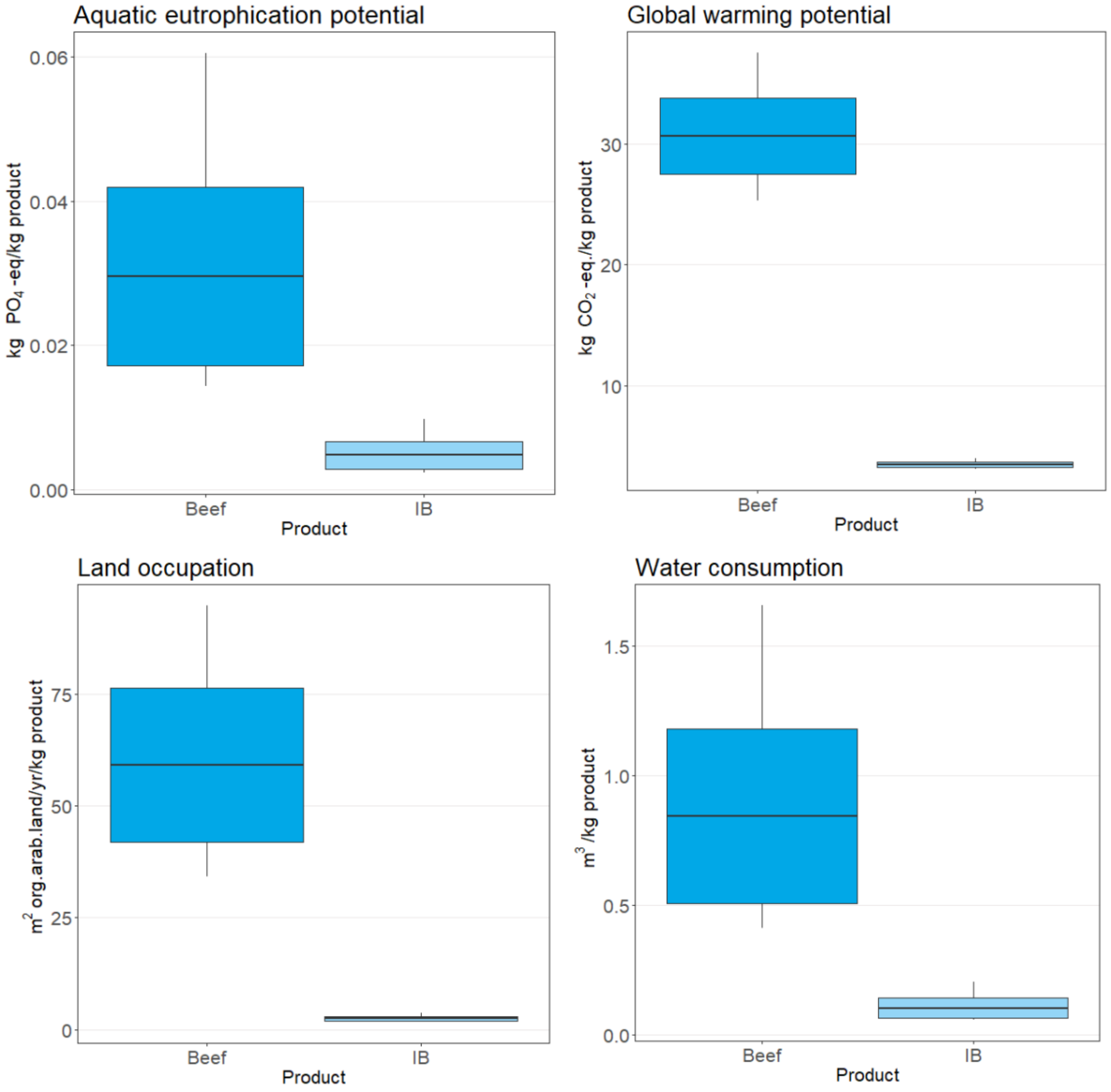

Figure 9: Statistics of MC based distribution estimates for beef burger (Beef) and Impossible Burger® (IB). Mean impact is represented by the dark line bisecting the box. The boxes span ± 1 standard deviation around mean (horizontal line at box vertical centers). The whiskers span the central 95% of the expected distribution, between the 2.5th and the 97.5th percentiles. Because these are empirical and apparently skewed rather than theoretically normal distributions, these percentiles are not equidistant from the respective means.

5.2. Inventory data quality assessment

Inventory data quality assessment procedure and results are summarized in full. From this assessment, it is evident that overall, data used for the analysis are acceptable.

Criteria for evaluation included data sources, data accuracy, technology coverage, time-related coverage, data age, and geographical coverage. These criteria, for both systems under comparison, are met with acceptable and consistent assessment.

The main data for which either further verification or improvement in quality would be particularly useful to increase the robustness of the results are related to the following processes:

- Potato protein model to accurately represent manufacturing practices.
- Manure emissions at grazing during cow-calf operations, due to large uncertainties in the emissions factors and the influence it has over beef burger results.
- Coconut oil processing is modeled using an average of three different oil refining processes as previously described. Greater specificity would be of value, given the contribution to water consumption overall.

5.3. LCA applications and limits

This LCA performed for Impossible Foods compares the production of the Impossible Burger® against a traditional U.S. ground beef burger. Any conclusion described by this report must be considered only within the context of the study and with considerations of the assumptions made and study limitations.

Results of this exercise can be used to accomplish the following:

- Characterize the environmental profile of the Impossible Burger®, as well as its "hot spots" and key parameters driving its results;
- Identify strengths and weaknesses of both products; and identify conditions for which one alternative seems preferable to another.

There are limitations in the current study that should be reiterated and that might be made the focus of future work. The study's assumptions and limitations are listed below:

- The potato protein model is created under basic assumptions of protein content in potatoes and GHG emissions from energy use disclosed from suppliers. A more rigorous model that more closely represents reality would result in improved, and likely lower, potential impacts for the Impossible Burger®;
- The use of the USMARC production model may represent a best-case scenario in U.S. beef production. Although being representative of U.S. production, it does not constitute a national average, and other production systems in other parts of the

country, like 100% pasture-raised beef may affect the degree of environmental benefits the Impossible Burger® has over the beef burger.
- Impossible Foods supplies its electricity from PG&E Company. Reverting back to a utility supplier with a higher carbon footprint could increase potential environmental impacts, as shown in the sensitivity analysis;
- Use of dataset from Canadian agricultural practices and natural gas consumption technology may change results, either positively or negatively, for both products, although not the conclusions due to large difference in results;
- Several ingredients in the Impossible Burger® mix are modeled generically as organic or inorganic chemicals due to lack of more precise datasets, each represent 0.6% or less and altogether 3%. Results may change if more accurate models are made available;
- Soil Organic Carbon changes were not included in the study. Literature shows that this might benefit or worsen beef burger global warming potential, dependent on pasture management, grazing density, climate, and other conditions, thus exhibiting a wide variation in results. SOC is not assessed in this study due to lack of reliable science, data and method to build a usable reasonable impact assessment.

Finally, LCIA results are relative expressions and do not predict impacts on category endpoints, the exceeding of thresholds, safety margins, or risks.

6. Conclusions

This assessment compares the Impossible Burger®, a plant-based alternative to beef, with a traditional U.S. beef burger. Because of their similar function and nutritional values, these two products are considered substitutable. The goal of the study is to understand whether the Impossible Burger® has a lower environmental impact footprint compared to animal-derived ground beef, and to what extent. In turn, this assessment estimates the degree to which substitution of beef for plant-based meat might aid U.S. consumers who want to shift their diet toward less environmentally costly options. The following are the key findings from this work, focused on the assessments made here on both products.

When U.S. consumers choose to replace a kilogram of beef burger with a kilogram of Impossible Burger®, they are reducing environmental impacts across every impact category focused on in the study between 87%-96%.

Regarding global warming potential, replacing a kilogram of beef burger with the equivalent amount of Impossible Burger® will reduce 27.1 kg CO_2-eq, mainly due to the lack of manure and enteric emissions in the plant-based burger’s lifecycle. Soil Organic Carbon changes during beef cattle grazing were not included due it’s high variability and might increase or reduce this benefit. A worst-case scenario for the Impossible Burger®, where it would be produced with a higher input of fossil fuels through electricity and highly impactful amino acids manufacturing technologies, would reduce this benefit by 2 kg CO_2-eq per kg at most. Further, a best-case scenario for the beef burger, where all meat comes from dairy cattle, would further reduce the difference by 5.9kg of CO_2-eq. Overall, the Impossible Burger® would reduce a minimum, but meaningful, 19.2 kg of CO_2-eq/kg.

Water consumption impacts for the Impossible Burger® are 87% lower than its beef counterpart, largely due to a reduced demand for feed agricultural products and their associated irrigation water.

Land occupation for the Impossible Burger® is 96% lower than that for the beef burger, where for every kilogram of beef replaced, 66.5 m^2 per year for land can be saved from occupation. Disaggregating this number, 4.2 m^2 comes from agricultural use for the beef burger, and thus its production requires 2.8 times more land for crop production than the Impossible Burger®. Another 55.2 m^2 comes from pasture used for grazing, where many arguments that no other agricultural activity could be performed on them.

At the same time, aquatic eutrophication potential associated with the Impossible Burger® is more than 10 times lower than the beef burger, as it avoids manure emissions and much of the phosphorus emissions related to feed crops, and electricity use during cattle slaughtering.

For both products, production of raw inputs contributes >50% of environmental impacts: >50% GHG emissions, >78% of water consumption, >84% for aquatic eutrophication, and >99% for land occupation. Burger manufacturing impacts are only nontrivial for the Impossible Burger®, whose overall impacts are much smaller than that of beef's.

Put simply, raising beef cattle to feed humans requires far more resources in the upstream cultivation of cattle feed than if humans use those crops directly to manufacture food products. Additionally, shifting to plant-based options avoids environmental impacts associated with cattle rearing, like land occupation for grazing, manure management, and enteric emissions. Also, even in the best-case scenario for beef, being entirely dairy-sourced, and worst-case for the Impossible Burger®, as shown in the climate change impact category, benefits are still substantial with plant-based burger impacts one order of magnitude lower.

In considering the results of this study, it should again be noted that nutritional content, an important feature of food, has not been considered directly as both exhibit similar characteristics. The intention here is to portray an environmental comparison as accurately and clearly as possible, which can be used along with nutritional considerations, and other considerations such as taste, cost and convenience, in helping U.S. consumers make their food choices.

In summary, the study has found that there are clear and unambiguous environmental benefits to replacing beef with Impossible Burger®.

7. References

Alexandratos, N., & Bruinsma, J. (2012). *World Agriculture Towards 2030/2050 - The 2012 Revision.* Rome: Global Perspective Studies Team. FAO Agricultural Development Economics Division.

Asem-Hiablie, S., Battagliese, T., Stackhouse-Lawson, K. R., & Rotz, C. A. (2018). A life cycle assessment of the environmental impacts of a beef system in the USA. *The International Journal of Life Cycle Assessment*, 1-15. doi:10.1007/s11367-018-1464-6

Asem-Hiablie, S., Battagliese, T., Stackhouse-Lawson3, K. R., & Rotz, C. A. (2018). A life cycle assessment of the environmental impacts of a beef system in the USA. *The International Journal of Life Cycle Assessment*, 1-15. doi:10.1007/s11367-018-1464-6

Bengoa, X., Rossi, V., & Mouron, P. (2017). *World Food LCA Database Documentation v3.1.*

Blonk Milieu Advies BV. (2010). *Environmental impacts of synthetic amino acid production.* Gouda.

Boetel, B. (2017, October 31). *In The Cattle Markets: Dairy Cattle Impact on Beef Supplies*. (Department Of Agricultural Economics, University Of Wisconsin-River Falls) Retrieved from Dairy Herd Management: https://www.dairyherd.com/article/cattle-markets-dairy-cattle-impact-beef-supplies

Cattlemen’s Beef Board and National Cattlemen’s Beef Association. (2018, October 22). *Wholesale Prce Update*. Retrieved from Beef. It's what's for dinner: https://www.beefitswhatsfordinner.com/sales-data/wholesale-price-update

Cattlemen's Beef Board and National Cattlemen's Beef Association. (2014). *BeefCuts. Primal & Subprimal Weights and Yields.* Retrieved from http://www.beefissuesquarterly.com/CMDocs/BeefResearch/PE/BeefCutsGuide.pdf

Center for Investigative Reporting. (2012, August 2). *The Hidden Costs of Hamburgers*. Retrieved from Public Broadcasting Service: https://www.pbs.org/newshour/science/the-hidden-costs-of-hamburgers

College of Engineering. University of Arkansas. (2019). *Faculty Directory - Greg Thoma*. Retrieved February 5, 2019, from College of Engineering. University of Arkansas: https://engineering.uark.edu/directory/index/uid/gthoma/name/Greg-Thoma/

de Vries, M., & de Boer, I. (2010). Comparing environmental impacts for livestock products: A review of life cycle assessments. *Livestock Science*, 1-11.

Derner, J., & Schuman, G. (2007). Carbon sequestration and rangelands: A synthesis of land management and precipitation effects. *Journal of Soil and Water Conservation, 62*(2), 77-85. Retrieved from http://www.jswconline.org/content/62/2/77.short

Dettling, J., Tu, Q., Faist, M., DelDuce, A., & Mandlebaum, S. (2016). *A comparative Life Cycle Assessment of plant-based foods and meat foods.* Quantis. Boston: Morning Star Farm. Retrieved from https://www.morningstarfarms.com/content/dam/morningstarfarms/pdf/MSFPlantBasedLCAReport_2016-04-10_Final.pdf

Drouillard, J. S. (2018, July). Current situation and future trends for beef production in the United States of America — A review. *Asian-Australas Journal of Animal Science, 31*(7), 1007-1016. doi:10.5713/ajas.18.0428

Durlinger, B., Koukouna, E., Broekema, R., van Paassen, M., & Scholten, J. (2017). *Agri-footprint 3.0.* Gouda: Blonk Consultants.

Dy, R., & Reyes, S. (2007). *The Philippine Coconut Industry Performance, Issues and Recommendations.*

Eshel, G., Martin, P. A., & Bowen, E. E. (2010). Land use and reactive nitrogen discharge: Effects of dietary choices. *Earth Interactions, 14*(21), 1-15. doi:10.1175/2010EI321.1

Eshel, G., Shepon, A., Makov, T., & Milo, R. (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.

FAO. (2009). *How to Feed the World in 2050.* Rome.

FAO. (2018). *Global Livestock Environmental Assessment Model (GLEAM).*

Field, T. (2017). An overview of the U.S. Beef Industry. In T. Field, *Beef Production and Management Decisions* (6th ed., pp. 1-25). New York, New York: Pearson. Retrieved from https://www.pearsonhighered.com/assets/samplechapter/0/1/3/4/0134602692.pdf

Food Systems PRISM Lab. (2019). *Dr. Nathan Pelletier*. Retrieved February 5, 2019, from Food Systems PRISM Lab: https://prismlab.weebly.com/dr-nathan-pelletier.html

Frischnecht, R., & Jungbluth, N. (2007). *Overview and Methodology. Ecoinvent.* Dubendorf: Ecoinvent Centre.

Geiger, C. (2016, May 2). *One in five hamburgers come from dairy*. Retrieved from Hoard's Daryman: https://hoards.com/article-18581-one-in-five-hamburgers-come-from-dairy.html

Goedkoop, M., & Spriensma, R. (2001). *The Eco-Indicator 99: A Damage Oriented Method for Life Cycle Impact Assessment.* Amersfoort: PRé Consultants B.V.

Goldstein, B., Moses, R., Sammons, N., & Birkved, M. (2017). Potential to curb the environmental burdens of American beef consumption using a novel plant-based beef substitute. *PLOS One*. doi:10.1371/journal.pone.0189029

Heller, C., & Keoleian, G. A. (2018). *Beyond Meat's Beyond Burger Life Cycle Assessment: A detalied comparison between a plant-based and an animal-based protein source.* Center for Sustainable Systems. Universitiy of Michigan.

Heller, M., Willits-Smith, A., Meyer, R., Keoleian, G. A., & Rose, D. (2018). Greenhouse gas emissions and energy use associated with production of individual self-selected US diets. *Environmental Research Letters, 13*(4). doi:044004

Herrero, M., Henderson, B., Havlík, P., Thornton, P., Conant, R., Smith, P., . . . Butterbach-Bahl, K. (2016). Greenhouse gas mitigation potentials in the livestock sector. *Nature Climate Change, 6*(5), 452-461.

Hewins, D., Lyseng, M., Schoderbek, D., Alexander, M., Willms, W., Carlyle, C., . . . Bork, E. (2018). Grazing and climate effects on soil organic carbon concentration and particle-size association in northern grasslands. *Scientific Reportsvolume*, 1336.

Humbert, S., De Schryver, A., Margni, M., & Jolliet, O. (2012). *IMPACT 2002+: User Guide. Draft for version Q2.2 (version adapted by Quantis).* Retrieved from https://www.quantis-intl.com/pdf/IMPACT2002_UserGuide_for_vQ2.2.pdf

Impossible Foods Inc. (2018). *Food.* Retrieved from Impossible Foods: https://impossiblefoods.com/food

International Standard Organization. (2006). *ISO 14040:2006(E) - Environmental management — Life cycle assessment — Principles and framework.* International Standard Organization, Geneva.

International Standard Organization. (2006). *ISO 14044:2006(E) - Environmental management — Life cycle assessment — Requirements and guidelines.* Geneva.

IPCC. (2006). Volume 4. Agriculture, Forestry and Other Land Use. Chapter 10: Emissions from Livestock and Manure Management. In E. H. National Greenhouse Gas Inventories Programme, *2006 IPCC Guidelines for National Greenhouse Gas Inventories* (pp. 10.1-10.87). Hayama: Institute for Global Environmental Strategies (IGES).

Magat, S. S. (2011). *Productive and Sustainable Coconut Farming Ecosystems as Potential Carbon "Sinks" in Climate-Change Minimization:(A Review and Advisory Notes).* Retrieved from http://www.pca.da.gov.ph/coconutrde/images/gen11.pdf

Magat, S. (n.d.). *Understanding right, the productivity (yield) of coconut from the Philippines' Research and Field Experience: A knowledge tool for industry development and management (A research notes).* Retrieved from http://www.pca.da.gov.ph/coconutrde/images/yield.pdf

McClelland, S., Arndta, C., Gordon, D., & Thoma, G. (2018). Type and number of environmental impact categories used in livestock life cycle assessment: A systematic review. *Livestock Science*, 39-45. doi:10.1016/j.livsci.2018.01.008

McSherry, M., & Ritchie, M. (2013). Effects of grazing on grassland soil carbon: a global review. *Global Change Biology*, 1347-1357.

Nguyen, T., Doreau, M., Corson, M., Eugène, M., Delaby, L., Chesneau, G., . . . van der Werf, H. (2013, May 15). Effect of dairy production system, breed and co-product handling methods on environmental impacts at farm level. *Journal of Environmental Manangement, 120*, 127-137. doi:0.1016/j.jenvman.2013.01.028

Nguyen, T., van der Werf, H., Eugène, M., Veysset, P., Devun, J., Chesnau, G., & Doreau, M. (2012). Effects of type of ration and allocation methods on the environmental impacts of beef-production systems. *Livestock Science*, 239-251.

Pelletier, N., Pirog, R., & Rasmussen, R. (2010). Comparative life cycle environmental impacts of three beef production strategies in the Upper Midwestern United States. *Agricultural Systems, 103*, 380–389.

PG&E. (2015). *PG&E's 2014 Power Mix.* Retrieved from https://www.pge.com/includes/docs/pdfs/myhome/myaccount/explanationofbill/billinserts/11.15_PowerContent.pdf

PG&E. (2016). *PG&E's 2015 Power Mix.* Retrieved from https://www.pge.com/pge_global/common/pdfs/your-account/your-bill/understand-your-bill/bill-inserts/2016/11.16_PowerContent.pdf

PG&E. (2017). *PG&E's Power Mix. Understanding our clean energy solutions.* Retrieved from https://www.pge.com/pge_global/local/assets/data/en-us/your-account/your-bill/understand-your-bill/bill-inserts/2017/november/power-content.pdf

PG&E. (2018). *Corporate Reponsibility and Sustainability Report.* Retrieved from http://www.pgecorp.com/corp_responsibility/reports/2018/?WT.mc_id=Vanity_crsr

Quieta, J. (2012). *Coco Levy Funds: A Fiscal Stimulus to the Coconut Industry?* Congressional Policy and Budget Research Department (CPBRD) Policy Brief.

Radcliffe Institute for Advanced Study. Harvard University. (2017). *Fellows - Gidon Eshel*. Retrieved February 5, 2019, from Radcliffe Institute for Advanced Study Harvard University: https://www.radcliffe.harvard.edu/people/gidon-eshel

Reap, J., Roman, F., Duncan, S., & Bras, B. (2008). A survey of unresolved problems in life cycle assessment. Part 1: Goal and scope and inventory analysis. *The International Journal of Life Cycle Assessment, 13*(4), 290-300. doi:10.1007/s11367-008-0008-x

Reid, R., Gichohi, H., Said, M., Nkedianye, D., Ogutu, J., Kshatriya, M., . . . Bagine, R. (2008). Fragmentation of a Peri-Urban Savanna, Athi-Kaputiei Plains, Kenya. *Fragmentation in Semi-Arid and Arid Landscapes*, 195-224.

Rotz, C., Asem-Hiablie, S., Place, S., & Thoma, G. (2019). Environmental footprints of beef cattle production in the United States. *Agricultural Systems*, 1-13. doi:10.1016/j.agsy.2018.11.005

Rotz, C., Isenber, B., Stackhouse-Lawson, K., & Pollak, E. (2013). A simulation-based approach for evaluating and comparing the environmental footprints of beef production systems. *Journal of animal science, 91*(11), 5427-5437. doi:10.2527/jas.2013-6506

Searchinger, T., Waite, R., Hanson, C., Ranganathan, J., Dumas, P., & Matthews, E. (2018). *Creating a Sustainable Food Future. A Menu of Solutions to Feed Nearly 10 Billion People by 2050.* World Resource Institute. Retrieved from https://www.wri.org/publication/creating-sustainable-food-future

Shepon, A., Eshel, G., Noor, E., & Milo, R. (2016). Energy and protein feed-to-food conversion efficiencies in the US and potential food security gains from dietary changes. *Environmental Research Letters, 11*(10), 105002.

Steinfeld, H., Gerber, P., Wassenaar, T., Castel, V., Rosales, M., & de Haan, C. (2006). *Livestock's long shadow. Environmental issues and options.* FAO. Roma: FAO. Retrieved from http://www.europarl.europa.eu/climatechange/doc/FAO%20report%20executive%20summary.pdf

Swiss Center for Life Cycle Inventories. (2016). *Ecoinvent database v3.3, "cut-off system model".*

Thoma, G., Popp, J., Nutter, D., Shonnard, D., Ulrich, R., Matlock, M., . . . Adom, F. (2013). Greenhouse gas emissions from milk production and consumption in the United States: A cradle-to-grave life cycle assessment circa 2008. *International Dairy Journal*, S3-S14. doi:10.1016/j.idairyj.2012.08.013

Tilman, D., & Clark, M. (2014, November 12). Global diets link environmental sustainability and human health. *Nature, 515*, 518-522. doi:10.1038/nature13959

USDA. (2018, September 26). *Livestock & Meat Domestic Data.* Retrieved from United States Department of Agriculture. Economic Research Service: https://www.ers.usda.gov/data-products/livestock-meat-domestic-data/livestock-meat-domestic-data/#Livestock%20and%20poultry%20slaughter

USDA. (2018). *WeightChart.* Retrieved from Beef, ground, 80% lean meat / 20% fat, raw (hamburger): http://www.weightchart.com/nutrition/info-beef-ground-80-lean-meat-20-fat-raw.aspx van de Kamp, M. E., Seves, S. M., & Temme, E. H. (2018). Reducing GHG emissions while improving diet quality: exploring the potential of reduced meat, cheese and alcoholic and soft drinks consumption at specific moments during the day. *BMC Public Health, 18*(1), 264. doi:10.1186/s12889-018-5132-3

Weidema, B., & Wesnaes, M. (1996). Data quality management for life cycle inventories – an example of using data quality indicators. *Journal of Cleaner Production, 4*(3-4), 167-174.

Wernet, G., Bauer, C., Steubing, B., Reinhard, J., Moreno-Ruiz, E., & Weidema, B. (2016). The ecoinvent database version 3 (part I): overview and methodology. *The International Journal of Life Cycle Assessment, 21*(9), 1218-1230. doi:10.1007/s11367-016-1087-8

Wiedemann, S., McGahan, E., Murphy, C., Yan, M., Henry, B., Thoma, G., & Legard, S. (2015). Environmental impacts and resource use of Australian beef and lamb exported to the USA determined using life cycle assessment. *Journal of Cleaner Production*, 67-75. doi:10.1016/j.jclepro.2015.01.073

8. Appendices

8.1. Appendix A: Description of impact categories

Aquatic eutrophication potential

Aquatic eutrophication refers to the excessive addition of nutrients, primarily nitrogen and phosphorous, to aquatic ecosystems. In freshwater ecosystems, phosphorous is usually the driving nutrient, while in marine and terrestrial ecosystems, nitrogen is usually the driving nutrient. These nutrients often enter water bodies from agricultural runoff or from wastewater treatment facilities. This excessive nutrification ("eutrophication" is also sometimes referred to as "nutrification" or "over-nutrification") encourages biomass growth such as algae blooms. When these blooms die off, their decomposition removes oxygen from the water body, resulting in hypoxic or even anaerobic conditions, contributing to fish kills and decline or death of other aquatic life. Aquatic eutrophication is measured in kg of PO_4 (Phosphate) equivalents.

Global warming potential

Alterations in the statistical distribution of weather patterns of the planet over time that last for decades or longer; global warming potential is represented based on the International Panel on Global warming potential's 100-year weightings of the global warming potential of various substances (IPCC 2013). Substances known to contribute to global warming are weighted based on an identified global warming potential expressed in grams of CO_2 equivalents. This indicator covers all greenhouse gas emissions.

Because the uptake and emission of CO_2 from biological sources can often lead to misinterpretations of results, it is not unusual to omit this biogenic CO_2 from consideration when evaluating global warming potentials. Here, the recommendation of the PAS 2050 product Carbon Footprint guidance is followed in not considering either the uptake or emission of CO_2 from biological systems and correcting biogenic emissions of other gases accordingly by subtracting the equivalent value for CO_2 based on the carbon content of the gas (BSI 2008).

Land occupation

Land occupation measures the potential impact on terrestrial ecosystems caused by direct land use associated with a product, process or organization. It takes into account the contribution of various types of land. It is measured in m2 organic arable land for one year.

Water consumption

Sum of all volumes of fresh water used in the life cycle of the product, except for water used in turbines (for hydropower production), less the amount of water returned to the freshwater systems. This includes the volume of water taken from freshwater reservoirs (lakes, rivers, aquifers, etc.) that is evaporated during industrial or agricultural processes, embedded in products or otherwise consumed. Drinking water, irrigation water and water for and in industrialized processes (including cooling water) are all considered. Use of seawater is not considered. Neither is the use of rainwater, which has not yet reached a lake, river or aquifer.

8.2. Appendix C: Complete LCIA results

8.2.1. Detailed Impossible and beef burger results

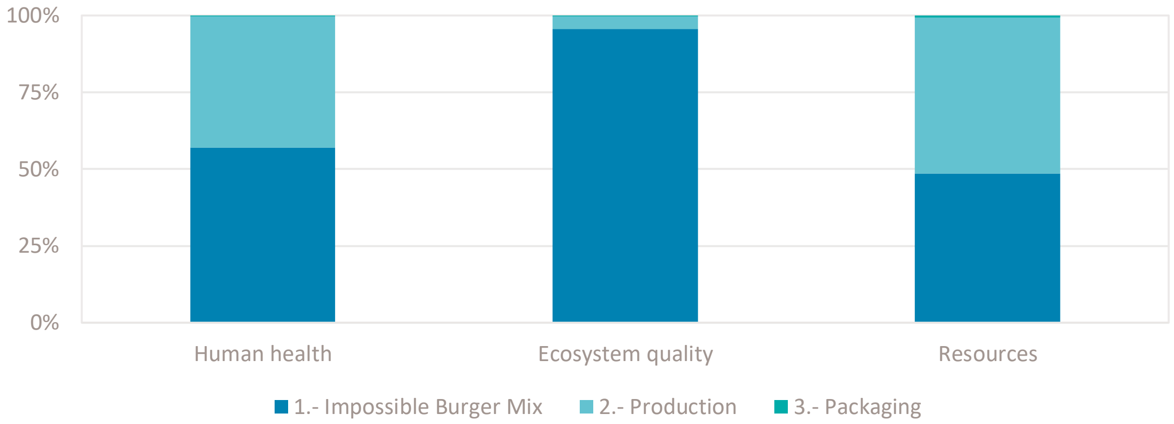

Figure 10: Detailed endpoint results for 1 kg of Impossible Burger® (Impact 2002+ v2.28)

Table 16: Detailed endpoint results for 1 kg of Impossible Burger®

Damage category	Unit	Total	1.- Impossible Burger® Mix	2.- Burger Production	3.- Packaging
Human health	10-6 * DALY	4.77	2.72	2.04	0.01
Ecosystem quality	PDF.m2.y	4.83	4.61	0.20	0.02
Resources	MJ	57.06	27.69	28.97	0.40

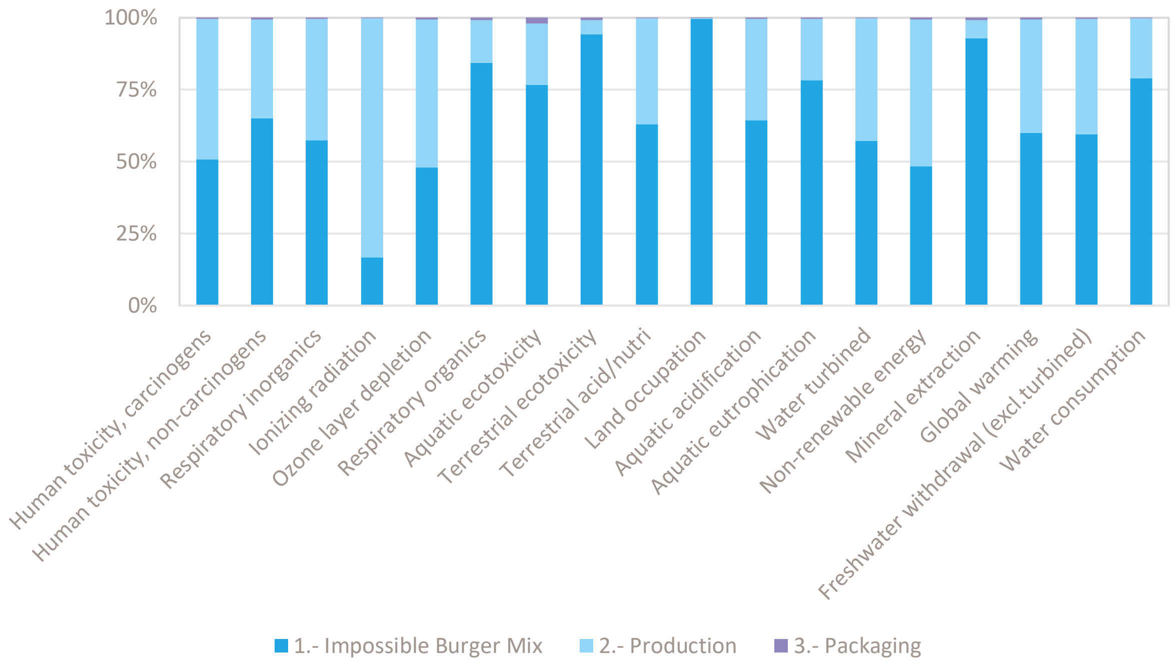

Figure 11: Midpoint results by life cycle stage for 1 kg of Impossible Burger® (as percentage of each midpoint's total result) (Impact 2002+ v2.28).

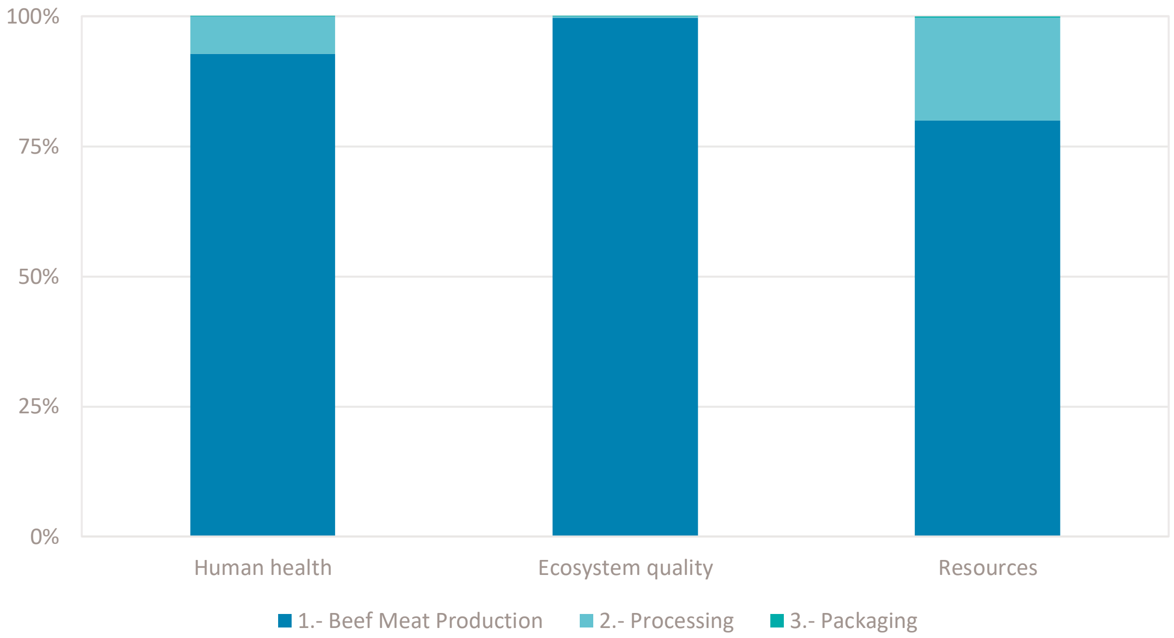

Figure 12: Detailed endpoint results for 1 kg of beef burger (Impact 2002+ v2.28).

Table 17: Detailed endpoint results for 1 kg of beef burger (Impact 2002+ v2.28).

Damage category	Unit	Total	1.- Beef Meat	2.- Burger Production	3.- Packaging
Human health	10^{-6} * DALY	28.5	26.4	2.0	0.0
Ecosystem quality	PDF.m2.y	72.5	72.3	0.2	0.0
Resources	MJ	146.9	117.5	29.0	0.4

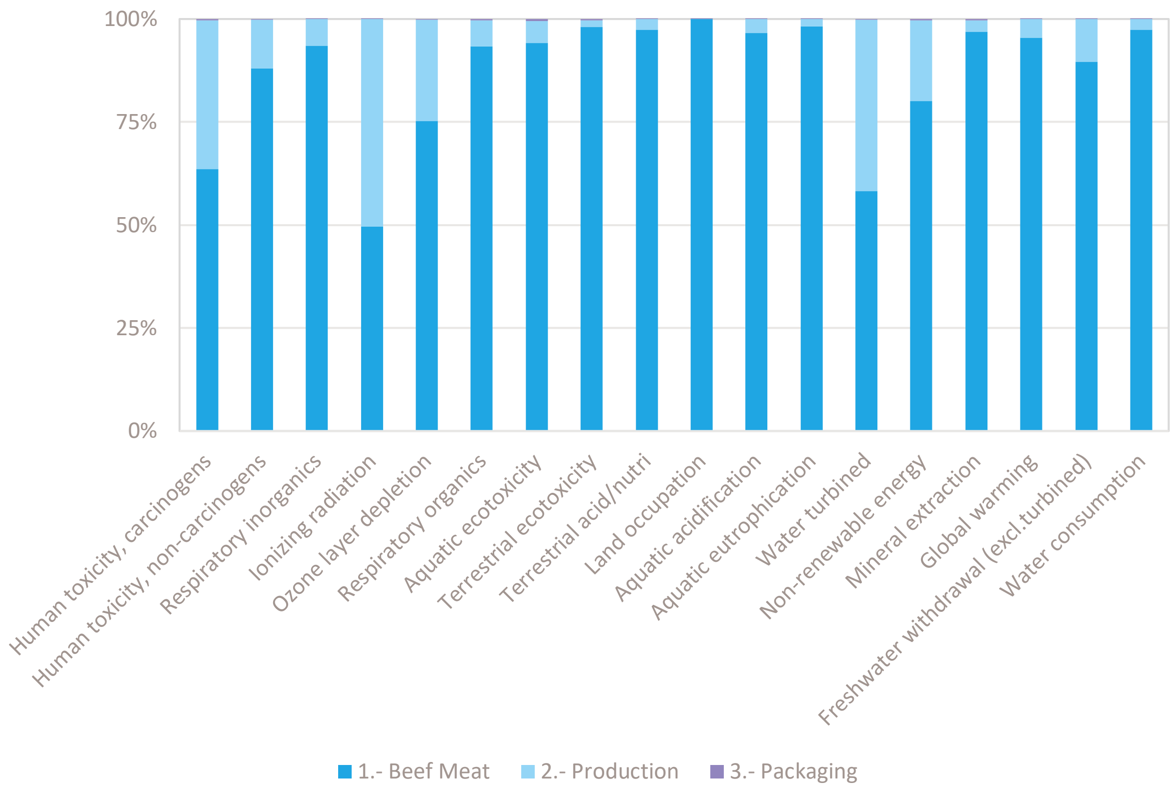

Figure 13: Detailed midpoint results for 1 kg of beef burger (Impact 2002+ v2.28).

Table 18: Complete endpoint results for 1.0526 kg of Burger Production (Impact 2002+ v2.28).

Damage category	Human health	Ecosystem quality	Resources
Unit	DALY	PDF.m^2.y	MJ
Total	**2.0E-06**	**1.97E-01**	**28.97**
Electricity	1.7E-06	5.88E-02	20.92
Nitrogen	9.3E-08	1.93E-02	2.96
Carbon dioxide production	2.4E-07	4.46E-02	1.50
Gas	4.6E-08	1.96E-03	3.53
Refrigerant Production	1.0E-09	1.13E-04	0.01
Refrigerant Emissions	3.3E-13	6.82E-10	0.00
Water	1.3E-09	2.47E-04	0.04
Wastewater	4.0E-09	7.23E-02	0.02

Table 19: Detailed endpoint results for 1kg of burger packaging (Impact 2002+ v2.28).

Damage category	**Human health**	**Ecosystem quality**	**Resources**
Unit	DALY	PDF.m^2.y	MJ
Total	**1.42E-08**	**1.82E-02**	**3.98E-01**
Paper	2.36E-09	2.32E-03	4.48E-02
Packaging film, low density polyethylene	4.35E-09	4.11E-04	2.10E-01
Corrugated board box	7.54E-09	1.55E-02	1.43E-01
Waste polyethylene	2.54E-13	3.27E-08	1.56E-06

Table 20: Detailed endpoint results for 1kg of fresh beef meat (Impact 2002+ v2.28).

Damage category	Unit	Total	Beef cattle, for slaughter	Slaughtering	Transport	Culled dairy cow	Dairy calves
Human health	DALY	2.6E-05	1.6E-05	6.6E-06	6.1E-08	5.4E-07	2.9E-06
Ecosystem quality	PDF.m^2.y	72.3	67.1	0.2	0.0	2.4	2.5
Resources	MJ	117.5	54.1	44.9	0.9	2.9	14.7

Table 21: Detailed endpoint results for 1 kg of live beef cattle (Impact 2002+ v2.28).

Impact Category	Unit	Total	Cattle Emissions	Grazing[4]	Alfalfa-grass silage	Maize silage	Maize grain, feed	Distiller's Dried Grains	Electricity and fuels	Feed Transport
Human health	DALY	9.8E-06	2.1E-06	3.8E-06	4.6E-07	6.5E-07	6.1E-07	3.6E-07	1.6E-08	5.6E-08
Ecosystem quality	PDF.m^2.y	40.4	0.4	30.2	2.4	3.9	0.6	0.3	0.0	0.0
Resources	MJ	32.5	0.0	4.2	2.3	2.2	5.0	2.9	0.2	1.3

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[4] Grazing includes manure emissions during cow-calf operations. It does not include enteric emissions, which are under "Cattle emissions"

8.3. Appendix E: Review panel biographies

8.3.1. Gidon Eshel

Gidon Eshel, Ph.D., is a research professor of environmental physics at Bard College and runs the website environmentalCalculations.com. He is best known for his work quantifying the geophysical consequences of agriculture and diet. Most recently, he has compared various livestock in terms of land and water use, fertilizer-based water pollution, and greenhouse gas emissions per unit product and compared the global-warming consequences of different beef-production strategies (including grass- versus trough-fed beef). His widely varied scientific interests also include the development of algebraic tools for simultaneous optimization of health and environmental outcomes through dietary choices, climate physics, and measures of time scale–specific ecosystem stability.

Eshel studied physics and earth sciences at the Technion and the University of Haifa, in Israel, before getting an MA, an MPhil, and a PhD at Columbia University in mathematical geophysics. Before his post at Bard, he was a NOAA Climate & Global Change Postdoctoral Fellow hosted by Harvard, a staff scientist at the Woods Hole Oceanographic Institute, and a faculty member of the Department of the Geophysical Sciences at the University of Chicago.

Adapted from *Radcliffe Institute for Advanced Study. Harvard University (2017)*

8.3.2. Greg Thoma

Greg Thoma, Ph.D., has been on the faculty at the University of Arkansas since receiving his Ph.D. in Chemical Engineering in 1994 from Louisiana State University, and is a Registered Professional Engineer in the state of Arkansas. He has held the Ray C. Adam Chair in Chemical Engineering and is currently the Bates Teaching Professor in Chemical Engineering. He also served as director for research and is currently senior advisor to The Sustainability Consortium, which focuses on measuring and improving the sustainability of consumer goods, including food.

His research focuses on the application of chemical engineering principles to find solutions to environmental problems. He is currently lead investigator for several life cycle initiatives in the food and agriculture sector including studies on fluid milk, cheese, milk delivery systems, and U.S. swine production. Dr. Thoma also consults on other LCA work focusing on rice, cotton, corn, and sweet corn. Recently he became the scientific lead for the UNFAO Partnership on the Environmental Benchmarking of Livestock Supply Chains technical advisory group for poultry which is working to create guidance in the application of LCA for assessment of sustainable poultry and egg production. He is currently serving on the steering committee for the Swiss National Science Foundation's National Research Program titled, "Healthy Nutrition and Sustainable Food Production".

Adapted from *College of Engineering. University of Arkansas (2019)*

8.3.3. Nathan Pelletier

Nathan Pelletier, Ph.D., is an Assistant Professor, jointly appointed in the Faculties of Arts and Sciences (Biology) and Management at the University of British Columbia - Okanagan. He currently holds the Endowed Chair in Bio-economy Sustainability Management / Egg Industry Chair in Sustainability and NSERC/Egg Farmers of Canada Industrial Research Chair in Sustainability.

His work is broadly situated in the fields of ecological economics and industrial ecology, emergent research areas focused on understanding and managing the sustainability dimensions of economic activity.

Areas of research interest are theory and practical application of ecological economic instruments in bio-economy (food, feed, and biomass) sustainability measurement, management and communication initiatives. He has contributed to the development of methodological frameworks for evaluation and management of the scale, resource efficiency, and social dimensions of sustainability - in particular, life cycle-based product and organization-level accountancy tools for supply chain sustainability management.

Adapted from *Food Systems PRISM Lab (2019)*

9. External panel review

An external panel review has been performed for the present study, based on the guidelines in the ISO 14044 standard for assessments intending to support public disclosure of comparative statements. This external review was chaired by Nathan Pelletier, PhD, from University of British Columbia, Greg Thoma, PhD, from University of Arkansas, and Gidon Eshel, Ph.D., from Bard College. Below is the final statement issued by the panel.

9.1. Panel statement of conformance with ISO 14044

The review panel has concluded that the study is, in the majority of instances, in compliance with the ISO 14040 and 14044 standards for LCA studies used to support comparative assertions to be disclosed to the public. There are no major outstanding methodological or technical issues upon completion of this review, and the general findings of the review panel are summarized below. Summary statements from individual reviewers describing outstanding minor issues are provided at the end of this report. More detailed comments on the study methodology and technical assumptions, including the panel's responses, can be found in the attached review summary.

Are the methods used to carry out the LCA consistent with the international standards (ISO 14040, 14044)?

The review panel finds that the study is largely consistent with the ISO LCA standards, and in particular, the reporting requirements under Section 5.3 for studies used to support comparative assertions. The methodology is clearly described, and most modeling assumptions are documented and adequately explained.

Sensitivity analyses were conducted to verify key assumptions and few of the sensitivity analyses showed results that varied significantly from the primary results, generally supporting the study conclusions. A detailed data quality assessment was also conducted, and the study conclusions were supported by uncertainty analysis using Monte Carlo simulations in the SimaPro software program.

Are the methods used to carry out the LCA scientifically and technically valid?

The review panel finds that the methods used are scientifically and technically valid. The IMPACT 2002+ V2.28 impact assessment methods were used, which consist of a suite of an internationally-accepted environmental impact assessment methods spanning a variety of resource and emissions-related impact categories. The environmental indicators reported are relevant to the production systems under study, including a mix of selected mid-point and end-point indicators. The limitations of the impact assessment methods are described, and the chosen impact assessment methods were tested by also generating results with the ReCiPe method for comparison. The technical accuracy of the system descriptions, assumptions, and modeling were verified by the panel and found to be acceptably representative of the production systems under study.

Are the data used appropriate and reasonable in relation to the goal of the study?

The review panel finds that the data used are appropriate with respect to the study objectives. Primary data were used to characterize the Impossible Foods burger and represent the best available data to characterize its production. Published data drawn largely from two sources (Ecoinvent and the WFLDB) were generally used to characterize the beef production system (including "upstream" production systems such as provision of feed inputs for beef production. The sources of data and the rationale for the data used has been documented in the report to the extent allowed under confidentiality agreements. The review panel reviewed these data and supporting assumptions and is confident that these represent appropriate data to achieve the study objectives.

The report provides a great deal of discussion around data quality, and in instances where data quality was less than desirable, sensitivity analysis has been conducted to show that there is no impact on the overall study results.

Do the interpretations reflect the limitations identified and the goal and scope of the study?

The review panel finds that the interpretation of the results reflects the limitations identified and the sensitivity analyses and uncertainty analysis provided support the conclusions.

Is the study report transparent and consistent?

The review panel finds that the study report is transparent and consistent. A high-level of detail is provided in the description of the product systems, key assumptions, and data used.