KEY FINDINGS AND OPPORTUNITIES:

Comparative life cycle assessment of plant- and animal-based meats

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Supplement to: This white paper summarizes the key results and opportunities of the ISO-certified LCA report, "Comparative Life Cycle Assessment of Plant-Based Meats and Conventional Animal Meats" (Bonales et al. 2024; herein referred to as "the LCA report"). The LCA report, including the detailed processes, life cycle inventory, and an interactive data dashboard with data available for download are available at gfi.org.

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About the Good Food Institute

The Good Food Institute is a nonprofit think tank working to make the global food system better for the planet, people, and animals. Alongside scientists, businesses, and policymakers, GFI's teams focus on making plant-based and cultivated meat delicious, affordable, and accessible. Powered by philanthropy, GFI is an international network of organizations advancing alternative proteins as an essential solution needed to meet the world's climate, global health, food security, and biodiversity goals. All of GFI's open-access insights and data are made possible by gifts and grants from our global community of donors. If you are interested in learning more about giving to GFI, please visit here or contact philanthropy@gfi.org.

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Executive summary

This report presents the key findings and opportunities from the ISO-certified comparative life cycle assessment of plant-based and animal-based meat (Bonales et al. 2024) conducted by the Good Food Institute (GFI) and EarthShift Global. It is the most comprehensive, open-access analysis of plant-based meat's environmental impacts to date.

Reducing the environmental impacts of food production, particularly meat production, is critical to support global food security and address climate change, pollution, and resource depletion. Alternative proteins—meat made from plants, cultivated from animal cells, or produced via fermentation—offer more sustainable protein sources while maintaining the meat-eating experience. Plant-based meat, with its growing market share and widespread accessibility, is positioned as a key part of a reimagined protein supply.

Life cycle assessment (LCA) is an internationally recognized method used to quantify the environmental impacts of a product across its life cycle, including all relevant inputs and outputs. Policymakers, investors, companies, and consumers rely on LCA data to guide decisions that promote sustainable agricultural practices and a secure food supply.

To evaluate the potential of plant-based meat to reduce the environmental impacts of the food system, GFI commissioned a comprehensive, ISO-certified LCA with two primary goals:

- To compare the environmental impacts of plant-based meat and animal-based meat production
- To evaluate the environmental impacts of plant-based meats produced using different raw materials and production methods.

LCA scope

This report summarizes the major findings from the ISO-certified LCA report, which evaluates and compares three plant-based meats with three animal-based meats (chicken, pork, and beef) among 18 environmental impact categories, from cradle-to-manufacturing gate, on a one-kilogram raw ground meat basis.

Data was sourced from plant-based meat manufacturers, ingredient and equipment manufacturers, scientific papers, and the commercially available datasets, ecoinvent 3.9.1, and the World Food LCA Database. Sensitivity analyses were performed on plant-based meat systems to understand how mass versus economic allocation methodology, extrudate crop geography, and energy source and efficiency affect their environmental footprints.

Key findings

1. Plant-based meat provides the same amount of meat while reducing pressure on the environment:

Plant-based meat has, on average, 89% less environmental impact than animal-based meat across the impact categories evaluated in this study (see table below). When averaged across the three plant-based meat recipes, plant-based meat has 91% lower impacts than beef, 88% lower impacts than pork, and 71% lower impacts than chicken. These trends remain consistent when considering economic versus mass allocation, uncertainty of input data, and plant-based crop geography.

Average percent impact reduction of three plant-based meats compared to animal-based beef, pork, and chicken meats.

Plant-based meat reduces impact by...	*compared to* Beef	*compared to* Pork	*compared to* Chicken
Global warming *kg CO_2 eq*	94%	88%	67%
Fine particulate matter formation *kg PM2.5 eq*	91%	91%	83%
Marine eutrophication *kg N eq*	96%	90%	84%
Land use *m^2a crop eq*	91%	60%	10%
Fossil resource scarcity *kg oil eq*	81%	86%	69%
Water consumption *m^3*	93%	96%	94%
Avg of 18 impact categories	91%	88%	71%

***2. Plant-based meat production provides significant environmental benefits, across a range of inputs and production methods*:**

This report provides a uniquely granular view of the environmental impacts of plant-based meat, comparing dominant inputs and processing methods and using real-world, commercial-scale data.

Three plant-based recipes were evaluated, all made with coconut oil, canola oil, potato starch, spices, wheat gluten, and water and differentiated by their protein extrudate made with:

Pea DL:
Dry fractionated (D), low-moisture extruded pea protein (L)

Pea WH:
Wet fractionated (W), high-moisture extruded pea protein (H)

Soy WH:
Wet fractionated (W), high-moisture extruded soy protein (H)

While the different inputs and processes have some effect on the environmental impact values, overall, the LCA demonstrates that plant-based meat systems have relatively low impacts on the environment and can be scaled with minimal natural resource use. Moreover, the study shows that crop geography, ingredient choices, fractionation strategies, and extrusion methods can be optimized to maximize the environmental benefits of plant-based meats.

Future directions

Diversifying the protein supply with plant-based meat would reduce the environmental impacts of meat production between 79 and 99.8%, on average. However, for plant-based meats to realize their full environmental benefits, they must be incorporated into the global protein supply at a higher percentage than current production scale allows.

Having demonstrated significant environmental advantages over animal meat production, plant-based meat innovation should prioritize improving the scale, taste, and cost of products while maintaining sustainability benefits. The ISO-certified LCA summarized herein provides an impartial baseline that helps stakeholders across government, non-governmental organizations, academics, and the private sector understand which strategies for protein production to prioritize to meet rising global meat demand.

Introduction

Food production has far-reaching environmental effects. The food system accounts for between 26% and 34% of anthropogenic greenhouse gas (GHG) emissions, 45% of habitable land use, and around 70% of freshwater withdrawals globally.

Animal agriculture alone accounts for 12 to 20% of total global GHG emissions and 80% of agricultural land use, though it supplies only 9% of the world's calorie supply and 20% of the world's protein supply. In addition to these impacts, animal agriculture contributes to some of the world's most pressing challenges concerning global health, food security, and biodiversity. As global demand for meat is rising and projected to increase significantly by 2050, finding more sustainable ways to produce meat is essential.

A shift toward alternative proteins—meat made from plants, cultivated from animal cells, or produced via fermentation—offers more sustainable protein sources while conserving meat-eating experiences. Plant-based meat sits at the leading edge of alternative proteins with its growing market share and widespread accessibility and will be an important part of a reimagined protein supply.

Numerous life cycle assessments (LCAs) have demonstrated the significant environmental benefits of plant-based meat products, reporting 46-99% reductions in GHG emissions, land use, and air pollution compared to animal-based meat. However, many plant-based meat LCAs do not disclose real-world commercial scale data for key processes and ingredients or lack access to this data, resulting in the use of analogs and assumptions. Further, many limit their assessment of impacts to a few key impact categories. Therefore, there is a need for a comprehensive and open-access LCA that represents plant-based meat production and products on the market.

To this end, GFI commissioned a comparative, International Organization for Standardization (ISO)-certified LCA of plant-based meat and animal-based meat. The LCA was conducted by EarthShift Global following the ISO 14040 and 104044 standards for comparative assertion and public disclosure, including critical review by a panel of three independent LCA experts.

The goals of the plant-based meat LCA are:

- To compare the environmental impacts of plant-based meat and animal-based meat production.
- To compare the environmental impacts of plant-based meats made using different raw materials and production methods.

This white paper summarizes the key results, learnings, and recommendations of the LCA. The ISO-certified LCA report, including the detailed processes, life cycle inventory, and an interactive data dashboard with data available for download, are available here.

Life cycle assessments are critical to understanding the environmental impact of foods

Life cycle assessment (LCA) is an internationally recognized methodology that quantifies the environmental impacts of a product during its entire life cycle, including all relevant inputs and outputs. When conducted accurately, LCAs are impartial analyses that help people and businesses better understand how their choices in goods or services impact their environmental footprint. Consumers and investors can use LCA results to objectively compare products and use their buying power to make sustainable decisions. Companies benefit from LCA results by applying them to environmental, financial, and operational decision-making to bolster:

- Innovation and optimization
- Marketing and communication
- Supplier management
- Regulatory compliance
- Risk management
- Business performance

For example, LCAs are critical in identifying environmental hotspots in processes, informing targeted resource optimization. Moreover, LCAs can be leveraged by companies to connect to consumers by building brand credibility, making environmental claims, and demonstrating commitment to social responsibility and transparency. GFI's LCA guide for alternative protein manufacturers describes these benefits in more detail. Further, GFI and Foodsteps's LCA tool provides alternative protein companies the opportunity to estimate the environmental impacts of their products.

While there are international standards applicable to LCAs, there are often variations in functional units, system boundaries, allocation methods, impact categories, and other parameters between independently conducted LCAs. Sensitivity and uncertainty analyses are necessary to test LCA assumptions and reduce methodology bias. Still, conducting, comparing, and interpreting LCAs can be difficult, so LCA results should be well-understood and clearly communicated when disseminated to the public.

LCA approach and scope

Systems description

Three plant-based and three animal-based meat systems are evaluated (Table 1). The systems are compared on a functional unit of producing one kilogram (2.2 lbs, 35.3 oz) of ground meat as they have similar marketed portions, consumption methods, and macronutrient profiles. Table 2 provides the estimated nutritional attributes of each recipe based on the cumulative nutrition of individual ingredients.

While calorie and protein content are similar, plant-based meat contains high amounts of fiber and no cholesterol, in direct contrast to animal meats which contain high amounts of cholesterol and no fiber.

The plant-based meat consists of hypothetical recipes chosen for their market representativeness and technological readiness (Table 3). Of the top 75 plant-based meat products in the United States, soy protein concentrate, pea protein, wheat gluten, coconut oil, and canola oil are six of the eight most common ingredients (GFI's Plant-based meat: Anticipating 2030 production requirements report). Texturized, extruded meat analog or "extrudate" made with pea or soy protein is the primary ingredient and contributes 15 grams of protein per 100 grams of plant-based meat in all three plant-based systems. The remaining secondary ingredients, such as gluten, oils, spices, binders, and water, would realistically be added to a final product and also provide small amounts of protein.

Table 1. Overview of the systems evaluated in the LCA report, their meat type, primary input, and primary processing methods.

System		Primary input	Primary processing methods
Plant-based	Pea DL	Pea	Dry fractionation Low-moisture extrusion
	Pea WH	Pea	Wet fractionation High-moisture extrusion
	Soy WH	Soy	Wet fractionation High-moisture extrusion
Animal-based	Beef	Cattle	Slaughtering Grinding
	Pork	Swine	Slaughtering Grinding
	Chicken	Broilers	Slaughtering Grinding

While these recipes are representative of some plant-based meat products currently on the market, many plant-based ingredients are used to create a wide variety of meat products. For example, unlike the recipes explored here, most commercially available plant-based chicken products typically do not contain coconut oil, instead relying on canola, corn, or soybean oil, which provide less than 1.6 grams of saturated fat per 100 gram serving.

Coconut oil is more commonly used in plant-based beef products to mimic red meat adipose tissue. Including both coconut oil and canola oil in the plant-based recipes evaluated in the LCA is intended to be conservative (i.e., inclusive of potentially environmentally impactful ingredients) and encompass the potential impacts of a wide range of plant-based meat products.

Table 2. Nutritional attributes of meat recipes assessed in the LCA (Reference for animal-based meat and secondary plant-based meat ingredients: https://fdc.nal.usda.gov/index.html)

Nutrient	Pea/Soy meat	Beef meat	Pork meat	Chicken meat
Protein *g/100g*	19	17	17	17
Fat *g/100g*	9	20	21	8
Saturated Fat *g/100g*	4	8	8	2
Cholesterol *mg/100g*	0	71	72	86
Iron *mg/100g*	3	2	1	1
Fiber *g/100g*	2	0	0	0
Calories *kcal/100g*	179	254	263	143

Table 3. Plant-based ground meat recipes evaluated in the LCA, chosen to represent commercially produced plant-based meats.

Ingredient	wt%
Extruded meat analog *pea or soy protein base*	28–71%*
Coconut oil	4%
Canola oil	4%
Potato starch	3%
Spices**	3%
Wheat gluten	5%
Water	10–53%***

**15% protein total, water content varies, **Spice mix: glutamic acid, salt, yeast, dried shiitake, citric acid, ***66% water total*

System boundaries and pathways

The system boundaries established for this study are cradle-to-manufacturing gates, including cultivation of crops, transportation to facilities, and processing. Downstream activities related to final distribution, such as packaging, cold storage, transport to retail, and consumer losses, are excluded because they are assumed to be comparable for all product systems as they are all designed to be used, cooked, and consumed in similar ways.

Plant-based meat production, as modeled for the ISO-certified LCA (Figure 1) begins at the farm with soybean or pea cultivation and harvest, which are then transported for ingredient production. First, crops are pre-processed by cleaning, drying, dehulling, and grinding or milling to produce flour. Next, the flours undergo either dry or wet fractionation processes to isolate protein.

Dry fractionation by air classification is modeled for the first recipe (Pea DL), wherein the finely ground flour is separated into a fine protein-rich fraction and a coarse starch-rich fraction. For the second and third plant-based recipes, wet fractionation is applied to improve pea (Pea WH) or soy (Soy WH) protein content, then spray drying to remove moisture. Following fractionation, the resulting protein isolates and concentrates are texturized using high- or low-moisture extrusion (see: "Plant-based meat production technology" box for more details on the fractionation and extrusion techniques modeled in this study) and finally mixed with the secondary ingredients to form a ready-to-cook plant-based meat product.

As noted in Figure 1, production processes are modeled using a mix of primary data gathered specifically for this study from plant-based meat and ingredient producers and secondary data from commercially available datasets. Plant-based meat production processes are largely based on primary data (Table 4).

Plant-based meat production technology

Meat is made up of proteins, fats, vitamins and minerals, and water. While this combination of nutrients is difficult to find outside of animal muscle, each is available in plant sources. Combining the right mix of plant-based ingredients results in meat produced with the same building blocks. Given the diversity of plant sources, there are a number of ways to create plant-based meat ingredients. The LCA focuses on primary protein ingredients isolated by fractionation methods:

Wet fractionation: Extraction of protein begins with soaking flour in water or ethanol, followed by separation based on solubility or pH and drying. Wet fractionation typically yields protein isolates, which have a protein content above 80%.

Dry fractionation: Separation of fine protein-rich granules from coarse starch-rich granules is achieved by air classification, which exploits differences in particle density, particle size, and powder dispersibility. Dry fractionation typically yields protein concentrates, which have a protein content between 37 and 60%.

Animal muscle proteins form their fibrous structures through movement (Bomkamp et al. 2022; Sha and Xiong 2020). Plant proteins typically lack these fibrous structures but can be texturized by applying heat and shear force.

The ISO-certified LCA focuses on extrusion, the dominant technology used to texturize plant proteins for plant-based meat. Extrusion entails feeding the protein isolate or concentrate through a horizontal barrel with one or more screws and then through a shaped die to form the desired product. Here, two types of extrusion processes are modeled, namely:

Low-moisture extrusion: This process results in a dry product that requires rehydration before use. It results in a porous structure to the final product with a moisture content below 40%.

High-moisture extrusion: This process results in a wet product that requires cold storage. It provides a more fibrous structure to the final product with a moisture content above 50%.

Photo courtesy of Beyond Meat

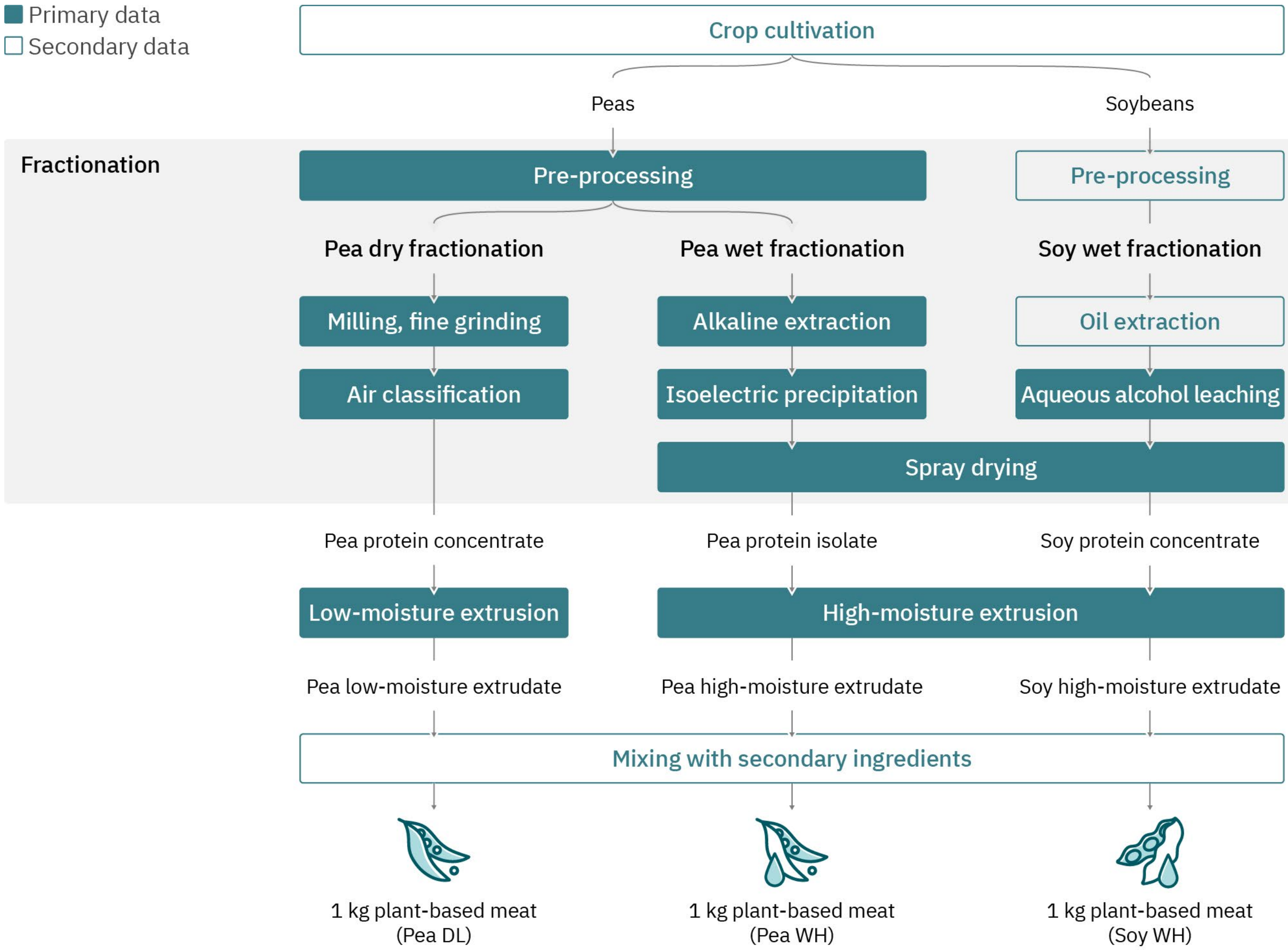


Figure 1. LCA pathways for plant-based meat production, including all processes from crop cultivation to fractionation, extrusion, and mixing.

Animal meat production, as modeled here, includes all processes from crop cultivation to final grinding and mixing (Figure 2). Animal husbandry begins with crop cultivation for feed production and ends with feedlot operation. Different feed baskets are provided for beef, pork, and chicken with maize and soy contributing to all of the feeds.

In the case of beef, breeding weaned calves is modeled as a separate input to the intensive feedlot operation because calf raising is independent from feedlot operations. For the LCA, weaned calves input reflects the U.S. market mix of 77% intensive and 23% mixed and extensive systems on pasture. Pork and chicken systems reflect 100% intensive systems following U.S. statistics. After the animals reach a certain weight in the feedlot, they are slaughtered to produce fresh meat and several coproducts. The fresh meat is then ground and mixed to produce ready-to-cook ground meat.

The animal-based meat production modeled in the ISO-certified LCA reflects a highly optimized intensive farming system, representative of how the majority of meat is raised in the United States. While extensive farming systems (e.g., grass-fed or grass-finished beef, free-range chicken) are an alternative to intensive farming systems (e.g., feedlot finishing, concentrated animal feeding operations), current studies demonstrate that the extensive systems have higher GHG and land use footprints than intensive systems (Nijdam, Rood, and Westhoek 2012) and GHG emissions cannot be offset by solely relying on carbon sequestration in pasture lands (Wang et al. 2023).

Compared to data from Poore and Nemecek (2018), the largest meta-analysis of food environmental impacts to date, the impacts of the systems analyzed here are much lower than systems used around the world (see: "How does this life cycle analysis compare to other environmental assessments of meat?" box).

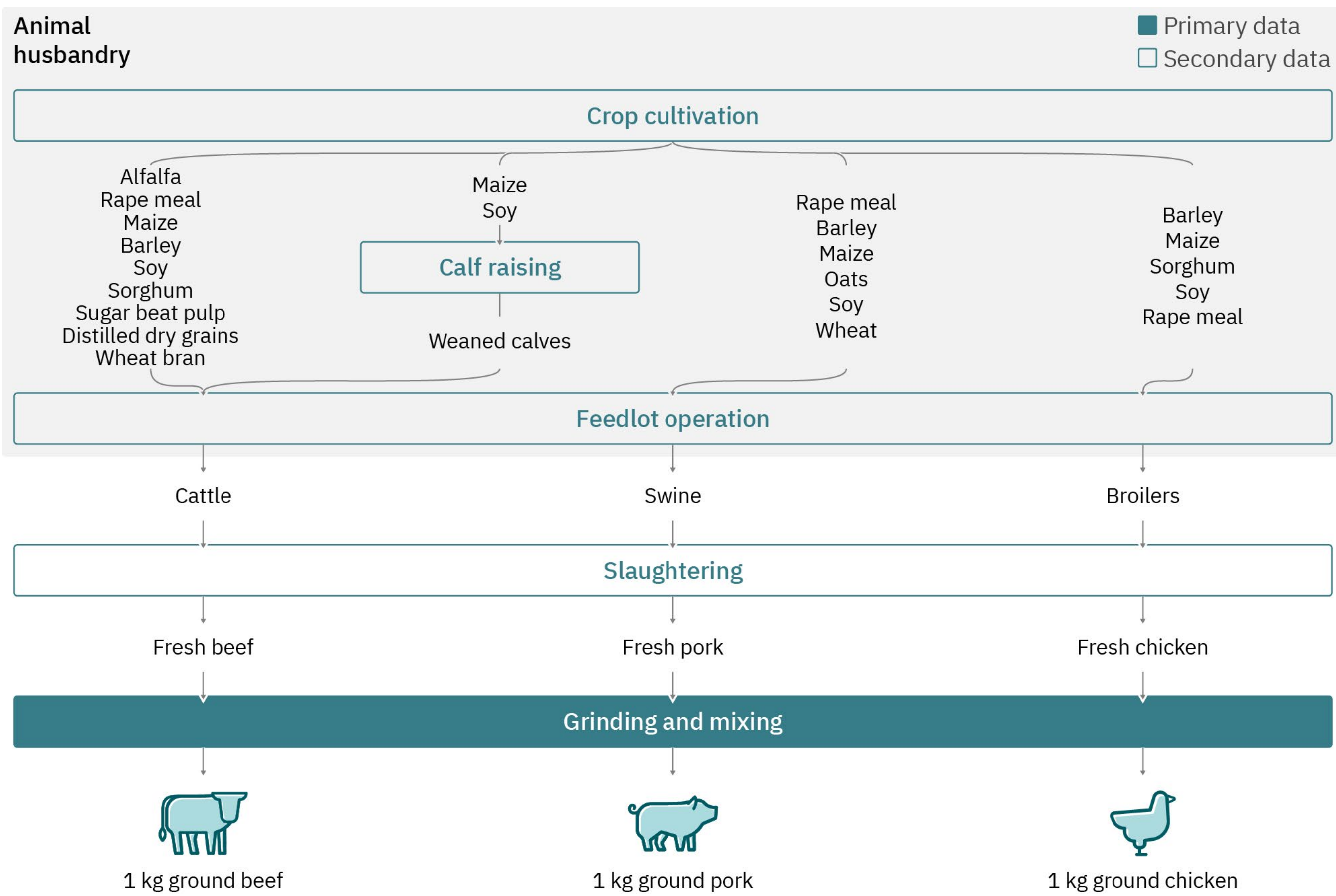


Figure 2. LCA pathways for animal meat production based on U.S. intensive farming practices, from crop cultivation to final grinding and mixing.

Data sources

Data from plant-based meat manufacturers, ingredient and equipment manufacturers, scientific papers, and ecoinvent 3.9.1 was used to model plant-based meat production (Table 4). Animal-based meat production was modeled using scientific papers and commercially available datasets including ecoinvent 3.9.1 and the World Food LCA Database. Primary data from industry partners was checked for consistency, aggregated, and anonymized. Secondary data from scientific papers and commercially available datasets was chosen to represent North American geography when available.

Allocation criteria and impact method

Due to the animal meat production process resulting in more than one product, mass allocation criteria were applied as the baseline to share the burden among all products produced; the sensitivity of the results to economic allocation criteria was also evaluated. The set of 18 environmental impact results were characterized using ReCiPe 2016 Midpoint (H) assessment method, as detailed in Appendix A of the LCA report.

Table 4. Number of industry and scientific paper data sources per plant-based system evaluated in the LCA report. All other data was collected from ecoinvent 3.9.1.

System and process		Anonymized industry data sources	Scientific papers reference sources
Pea DL	Dry fractionation	2	5
	Low moisture extrusion	2	1
Pea WH	Wet fractionation	1	6
	High moisture extrusion	2	0
Soy WH	Wet fractionation	2	1
	High moisture extrusion	3	1

Photo courtesy of United Soybean Board

Key results

Comparison of the environmental impacts of animal and plant-based meat

Plant-based meat provides the same amount of meat while reducing environmental impact by 89% compared to animal-based meat.

Plant-based meat has, on average, 89% less environmental impact than animal-based meat across the 18 impact categories evaluated in this study. Compared separately, the plant-based meat recipes, when averaged, have 91% lower impacts than beef, 88% lower impacts than pork, and 71% lower impacts than chicken. Beef production has the highest impacts in 11 of 18 categories, while pork has the highest impacts in the remaining seven categories (Figure 3).

The main impact drivers of beef production are direct field emissions from cattle enteric metabolism, feed production, manure management, and fertilizer input. For pork, the environmental impacts are driven by animal housing operations,[1] manure management, and feed production. Chicken impacts are primarily driven by direct emissions from broiler production, slaughtering, and feed cultivation. Chicken water consumption and fossil resource scarcity are primarily driven by high maize usage in feed, which requires large quantities of irrigated water and diesel for cultivation. For a detailed breakdown of the animal-based system impacts and process contributions, please see Sections 5.4-5.6 in the LCA report and "Animal husbandry drives the high global warming impacts of meat production" box in this summary.

[1] "Animal housing operations" category includes infrastructure, energy, and maintenance.

Impact category	Pea DL	Pea WH	Soy WH	Beef	Pork	Chicken
Fine particulate matter formation *kg PM2.5 eq*	$1.59e^{-03}$	$1.89e^{-03}$	$1.67e^{-03}$	$1.91e^{-02}$	$1.86e^{-02}$	$1.01e^{-02}$
Fossil resource scarcity *kg oil eq*	$1.24e^{-01}$	$1.98e^{-01}$	$1.42e^{-01}$	$8.02e^{-01}$	$1.07e^{+00}$	$5.05e^{-01}$
Freshwater ecotoxicity *kg 1,4-DCB*	$3.47e^{-02}$	$3.75e^{-02}$	$3.36e^{-02}$	$3.52e^{-01}$	$2.82e^{-01}$	$9.95e^{-02}$
Freshwater eutrophication *kg P eq*	$3.76e^{-04}$	$4.44e^{-04}$	$3.61e^{-04}$	$7.85e^{-03}$	$2.74e^{-03}$	$1.83e^{-03}$
Global warming *kg CO_2 eq*	$7.47e^{-01}$	$9.82e^{-01}$	$8.57e^{-01}$	$1.45e^{+01}$	$7.01e^{+00}$	$2.59e^{+00}$
Human carcinogenic toxicity *kg 1,4-DCB*	$2.94e^{-02}$	$3.68e^{-02}$	$3.13e^{-02}$	$4.47e^{-01}$	$1.00e^{+00}$	$1.36e^{-01}$
Human non-carcinogenic toxicity *kg 1,4-DCB*	$4.64e^{-01}$	$7.01e^{-01}$	$9.28e^{-01}$	$1.09e^{+03}$	$4.65e^{+00}$	$2.10e^{+00}$
Ionizing radiation *kBq Co-60 eq*	$2.28e^{-02}$	$3.05e^{-02}$	$2.51e^{-02}$	$2.09e^{-01}$	$1.98e^{-01}$	$1.40e^{-01}$
Land use *m^2a crop eq*	$2.20e^{+00}$	$1.90e^{+00}$	$2.09e^{+00}$	$2.21e^{+01}$	$5.20e^{+00}$	$2.30e^{+00}$
Marine ecotoxicity *kg 1,4-DCB*	$3.25e^{-02}$	$3.63e^{-02}$	$3.12e^{-02}$	$4.08e^{-01}$	$3.70e^{-01}$	$1.24e^{-01}$
Marine eutrophication *kg N eq*	$7.59e^{-04}$	$7.69e^{-04}$	$8.10e^{-04}$	$1.95e^{-02}$	$7.45e^{-03}$	$4.98e^{-03}$
Mineral resources scarcity *kg Cu eq*	$2.12e^{-03}$	$2.17e^{-03}$	$1.90e^{-03}$	$1.93e^{-02}$	$5.02e^{-02}$	$5.77e^{-03}$
Ozone formation, Human health *kg NO_x eq*	$1.46e^{-03}$	$1.65e^{-03}$	$1.85e^{-03}$	$9.39e^{-03}$	$1.36e^{-02}$	$5.00e^{-03}$
Ozone formation, Terrestrial ecosystems *kg NO_x eq*	$1.51e^{-03}$	$1.72e^{-03}$	$2.00e^{-03}$	$9.66e^{-03}$	$1.42e^{-02}$	$5.16e^{-03}$
Stratospheric ozone depletion *kg CFC-11 eq*	$2.47e^{-06}$	$2.49e^{-06}$	$4.11e^{-06}$	$1.21e^{-04}$	$2.43e^{-05}$	$2.38e^{-05}$
Terrestrial acidification *kg SO_2 eq*	$4.24e^{-03}$	$4.43e^{-03}$	$4.28e^{-03}$	$8.80e^{-02}$	$6.90e^{-02}$	$3.97e^{-02}$
Terrestrial ecotoxicity *kg 1,4-DCB*	$1.91e^{+00}$	$1.97e^{+00}$	$2.06e^{+00}$	$1.67e^{+01}$	$2.36e^{+01}$	$5.52e^{+00}$
Water consumption *m^3*	$1.79e^{-02}$	$1.85e^{-02}$	$1.70e^{-02}$	$2.45e^{-01}$	$4.64e^{-01}$	$3.24e^{-01}$

Figure 3. Heat map indicating the environmental impacts of producing one kilogram of beef, pork, chicken, pea (DL and WH), and soy (WH) meat across 18 categories, presented on a spectrum from lower system impacts (green) to higher system impacts (red). Values represent the absolute impact values for each category and system.

Comparing key impact categories highlights the differences in animal- and plant-based meat production

While 18 impact categories were assessed in the LCA, this summary report focuses on global warming, water consumption, land use, fossil resource scarcity, fine particulate matter formation, and marine eutrophication.

These categories, representing climate, resource consumption, and pollution (Table 5), allow for closer examination of the drivers of plant-based meat's lower overall environmental impact.

Additionally, these categories are commonly reported in other plant-based meat LCAs, allowing for easier comparison between this study and other independently conducted studies (see: "How does this life cycle analysis compare to existing environmental assessments of meat?" box).

Importantly, when assessing the environmental impacts of products or processes, it is critical to holistically consider various aspects of sustainability, rather than focus on one or two metrics.

Table 5. Key impact categories explored in this summary report. These represent six of 18 impact categories explored in the full LCA.

Category		Description
Climate	Global warming	Impact of greenhouse gas emissions on global climate change
Resource consumption	Water consumption	Use of freshwater resources, including direct and indirect use
	Land use	Land occupation and transformation
	Fossil resource scarcity	Depletion of finite fossil fuel resources such as coal, oil, and natural gas
Pollution	Fine particulate matter formation	Formation of fine particles in the atmosphere
	Marine eutrophication	Excessive nutrient enrichment of marine ecosystems

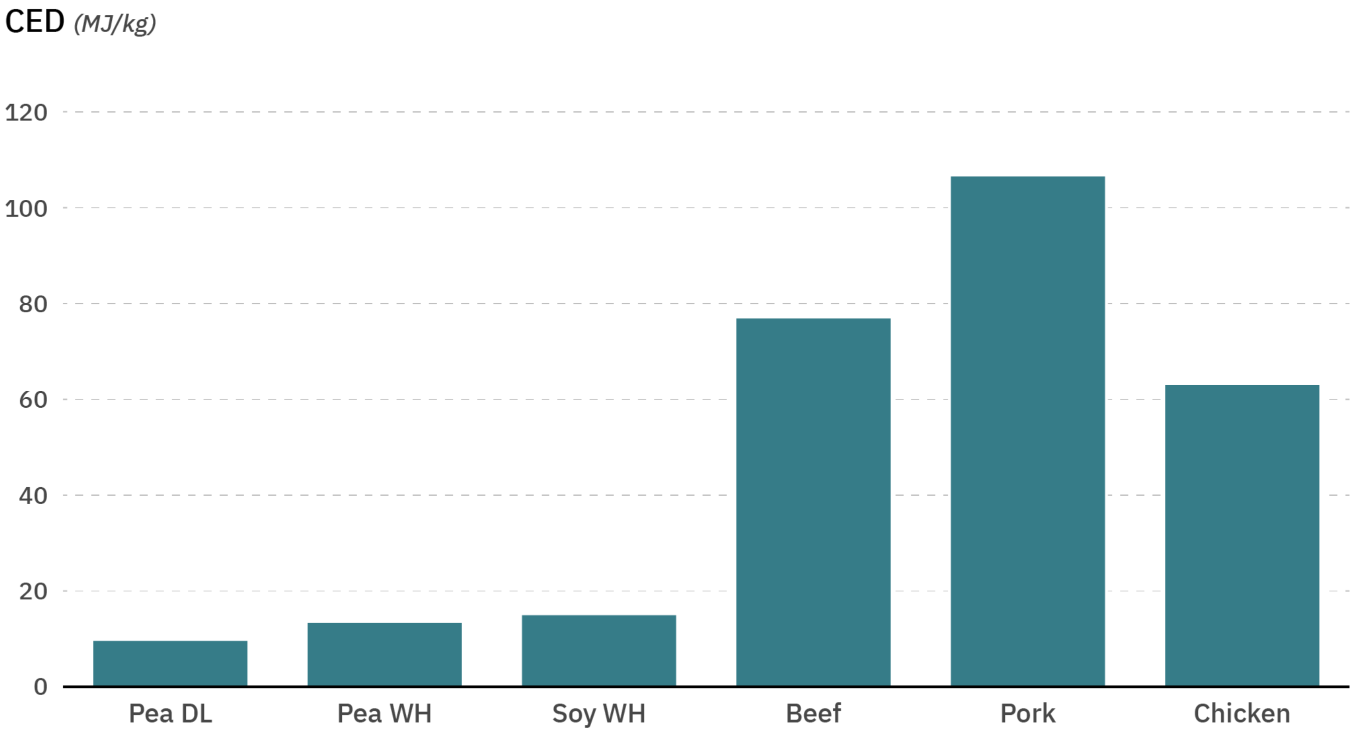


Figure 4. Cumulative energy demand (MJ/kg) of producing one kilogram of beef, pork, chicken, pea (DL and WH), and soy (WH) meat.

On average, plant-based meat systems have 89% less CO_2eq, 89% less fine particulate matter, and 81% less fossil resource scarcity than animal meat systems. The lower cumulative energy demand (CED) of plant-based systems explains much of this result (Figure 4), as well as the absence of emissions from enteric fermentation and manure management, which is a large contributor to the global warming impact of beef and pork (see: "Animal husbandry drives the high global warming impacts of meat production" box).

Additionally, due to lower feedstock requirements and subsequent reliance on crops, plant-based meat production relies less on land, water, fertilizer, and pesticide resources, thus consuming significantly less land and water and resulting in lower marine eutrophication (i.e., aquatic pollution).

On average, plant-based systems have 79% less land use, 95% less water consumption, and 93% less marine eutrophication than animal meat systems. Within each of these impact categories, plant-based meat has between 60 and 96% less environmental impact than conventional meat except for land use of chicken production (Table 6; Figure 5).

Table 6. Average percent impact reduction of three plant-based meats compared to animal-based beef, pork, and chicken meats.

Plant-based meat reduces impact by...	*compared to* Beef	*compared to* Pork	*compared to* Chicken
Global warming *kg CO_2 eq*	94%	88%	67%
Fine particulate matter formation *kg PM2.5 eq*	91%	91%	83%
Marine eutrophication *kg N eq*	96%	90%	84%
Land use *m^2a crop eq*	91%	60%	10%
Fossil resource scarcity *kg oil eq*	81%	86%	69%
Water consumption *m^3*	93%	96%	94%
Avg of 18 impact categories	91%	88%	71%

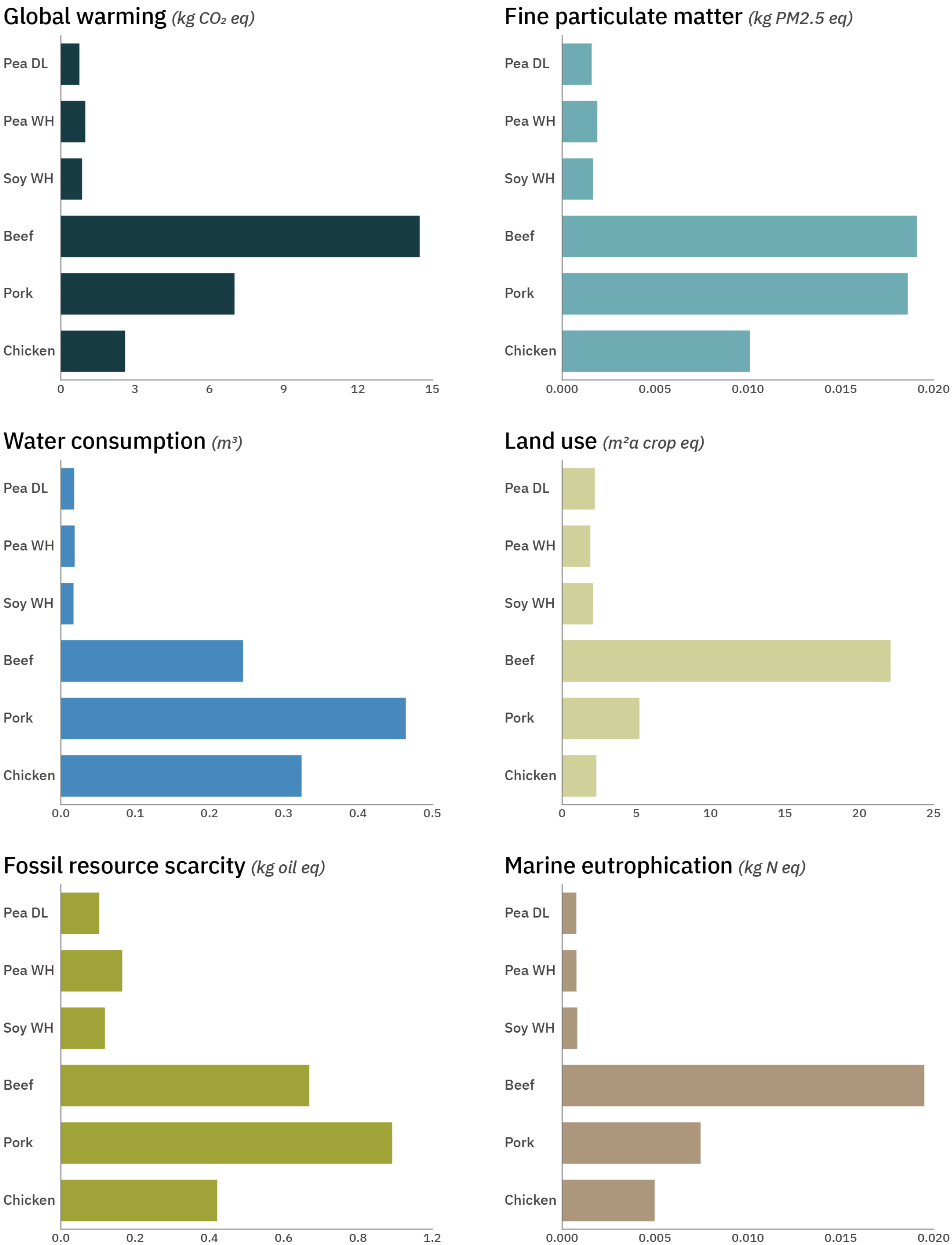


Figure 5. The environmental impacts of producing one kilogram of beef, pork, chicken, pea (DL and WH), and soy (WH) meat.

In this study, plant-based systems have comparable land use to chicken production, a result that contrasts with LCAs comparing plant-based chicken to conventional chicken and which report land use reductions of 82% and 84% (Saerens et al. 2021; Dettling et al. 2016). A closer look at the land use impacts of chicken and plant-based meat systems reveals several variables contributing to this result.

The chicken production system modeled in this study represents one of the most efficient animal production systems in the world, with the average of chicken systems globally using much more land than that of chicken meat production reported here (see: "How does this life cycle analysis compare to existing environmental assessments of meat?" box). The chicken land use impacts in this study are primarily the result of feed production, which relies primarily on land-efficient crops, maize (9.31 ton/ha) and soy (2.76 ton/ha).

The plant-based meat land use impacts are spread over several ingredients, primarily the extrudate, coconut oil, and canola oil (Figure 6). While the extrudate is derived from land-efficient crops like soy (2.76 ton/ha) and pea (3.87 ton/ha), coconut and canola oils rely on less land-efficient coconut (1 ton/ha) and canola (1.9 tons/ha). As mentioned above, many plant-based chicken recipes do not contain coconut oil so the results presented in this study may overestimate land use impacts of plant-based chicken. This demonstrates that as plant-based meat scales, land use efficiency can be maximized by selecting more land-use efficient ingredients, particularly for fats and oils.

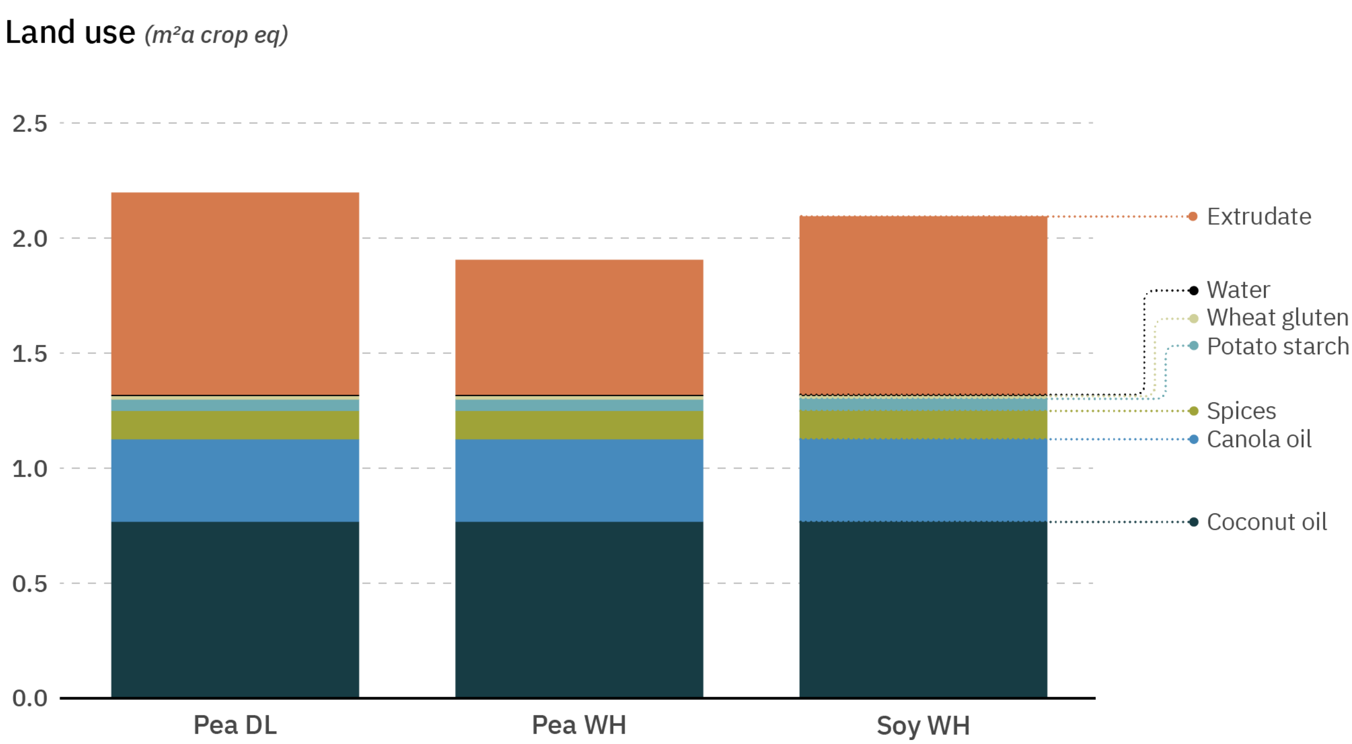


Figure 6. Ingredient contributions to land use impacts of the plant-based meat systems.

Mass and economic allocation both emphasize the lower environmental impacts of plant-based meat

When conducting LCAs, allocation is applied to calculate the portion of environmental impact assigned to a product or process. Many systems produce multiple useful products. For example, soy can be used to make food, animal feed, and oil. Mass-based and economic-based allocation methods are typically used to allocate proportionate impacts to each product made in a system. Economic allocation results in more allocation of the system's environmental impact to higher monetary value products, which recognizes consumer demand as a primary driver of production systems but is subject to fluctuations over time. Mass allocation instead proportionally distributes the environmental impacts to the mass of each coproduct. Allocation method choices can affect environmental impact results and should be considered carefully.

The baseline results presented in this study are modeled on mass allocation criteria. Following ISO guidelines, all systems were also compared using economic allocation using the allocation factors shown in Table 7. While economic allocation increased impacts of the meat for all systems, plant-based meat continues to demonstrate reduced environmental impact compared to animal-based meat (Figure 7).

With economic allocation, plant-based meat shows on average 91% less environmental impact than animal-based meat across 18 impact categories, compared to 89% less environmental impact with mass allocation criteria.

Animal meat systems, particularly beef and pork, show higher sensitivity to the allocation approach than plant-based meat primarily because fresh animal meat has a higher economic value compared to the other animal coproducts. Beef continues to show the largest impacts in the same 11 of 18 categories, with pork showing the largest impacts in the remaining seven categories.

Table 7. Mass and economic allocation factors used to evaluate animal and plant-based meat in the LCA.

System	Product	Mass allocation factor (%)	Economic allocation factor (%)
Beef	Fresh meat	49.00	92.90
Pork	Fresh meat	67.00	98.67
Chicken	Fresh meat	65.70	86.60
Pea DL	Pea protein concentrate	23.38	52.90
Pea WH	Pea protein isolate	21.73	54.97
Soy WH	Soy protein concentrate	62.54	97.41

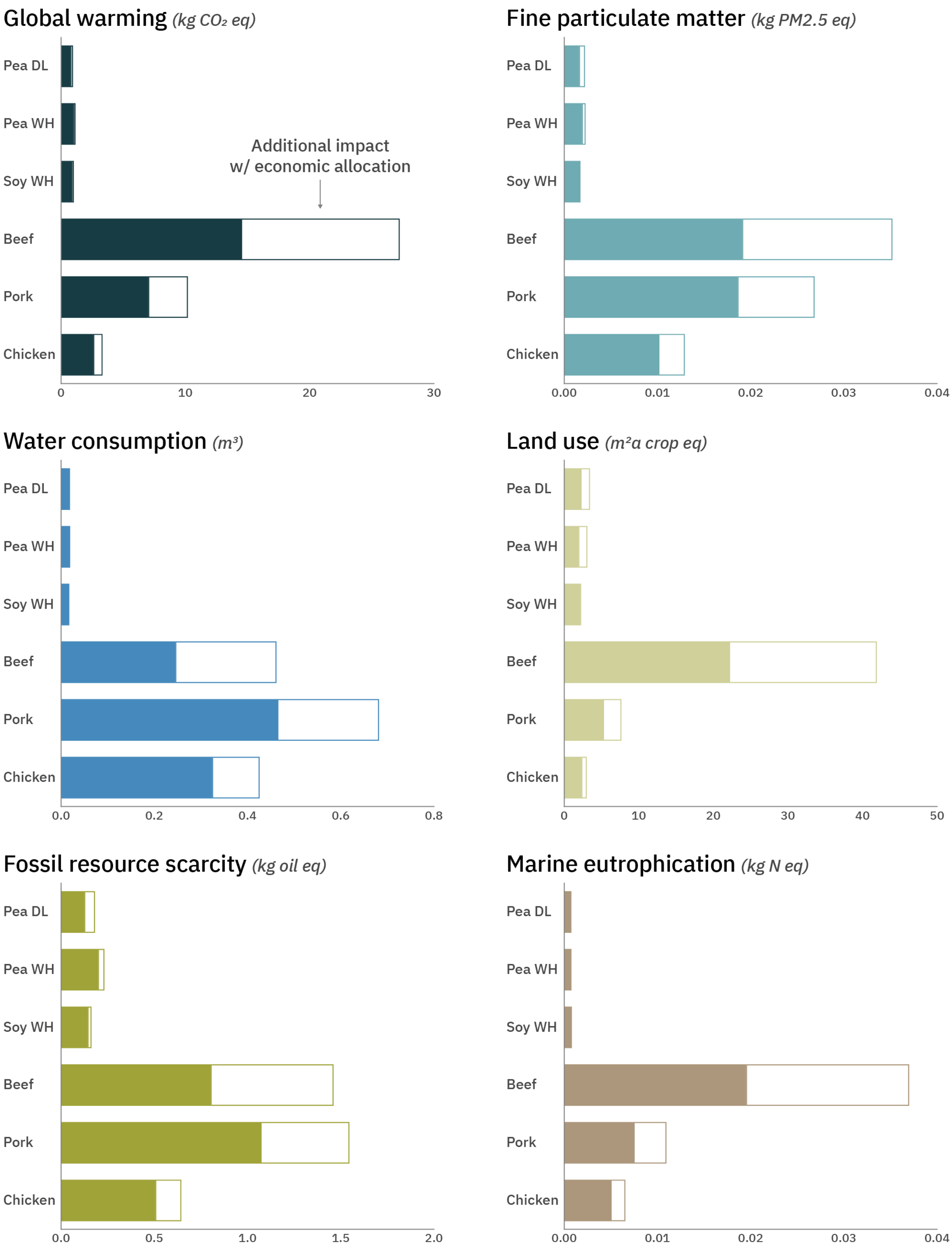


Figure 7. Mass versus economic allocation criteria application to determine environmental impacts of beef, pork, chicken, pea (DL and WH), and soy (WH) production.

How does this LCA compare to existing environmental assessments of meat?

The economic allocation-derived LCA data from this study allows more direct comparison to other environmental assessments of animal-based and plant-based meats. For example, Poore and Nemecek (2018), the largest meta-analysis of food environmental impacts to date, is a well-respected benchmark for understanding global variations in food production footprints and reports results derived using economic allocation. The analysis includes GHG emissions, land use, terrestrial acidification, eutrophication, and scarcity-weighted freshwater withdrawals within and between 40 major foods, including beef, pork, and chicken, comparing 724, 116, and 326 farm regional inventories, respectively, across the globe. The system boundaries between Poore and Nemecek's meta-analysis differ slightly from that represented in this LCA but comparisons can be made by adjusting for post-manufacturing gate contributions. Generally, the environmental impacts of conventional meat demonstrated here align with or are lower than the lowest percentiles of impacts from Poore and Nemecek. For example, the adjusted lowest 5th percentile of GHG emissions for 1 kg of beef in Poore and Nemecek's analysis, at 28.6 kg CO_2eq, is approximately equal to the 27.2 kg CO_2eq presented in this study for 1 kg of beef, when relevant contributions are adjusted.[1] Similarly, the lowest 5th percentile of land use for 1 kg of poultry meat is 6.5 m^2, which is more than double the chicken land use reported in this LCA.[2] This is expected given the selection of the highly optimized intensive U.S. farming and animal production systems for this analysis. This study demonstrates that, even compared to some of the most optimized animal-based productions in the world, plant-based meat production is much more efficient and environmentally sustainable. When compared to animal-based systems less efficient than those evaluated in the ISO-certified LCA, plant-based meat would provide even larger benefits than those described here.

The study parameters, carbon footprint, land use, and water consumption of the plant-based meats evaluated in this study (Pea DL, Pea WH, and Soy WH) are also compared to other plant-based meat LCAs (Figure 8) (Heller and Salim 2023; Khan et al. 2019; Smetana et al. 2021). Comparing the results using economic allocation, the impacts reported in all studies are relatively similar.

[1] Poore and Nemecek estimates that, for products such as beef, distribution and retail losses contribute up to 15% of emissions (see Poore and Nemecek, 2018, Fig. S13), whereas the emissions from packaging, transport, and retail contribute up to 9%, for a total of up to 24% of emissions occurring after the manufacturing gate. The lowest 5th percentile of GHG emissions for 1 kg of beef in Poore and Nemecek is 37.6 kg CO_2eq. Removing 24% of emissions after the manufacturing gate equals 28.6 kg CO_2eq.

[2] Assumes transportation, distribution, and losses are not major contributors to land use in Poore and Nemecek's analysis.

Plant-based meat	Functional unit	Boundaries	Geography	Impact assessment method	Ingredients
Beyond Burger 3.0	1/4 lb burger patty	Cradle to distribution	North America	ReCiPe 2016 midpoint (H)	Pea protein, rice protein, canola oil, natural flavors, dried yeast, other
Impossible Burger	1 kg burger patty	Cradle to manufacturing gate	United States	IMPACT 2002+ vQ2.28	Soy protein, potato protein leghemoglobin protein, coconut oil, sunflower oil, flavor mix, other
Smetana et al. 2021	113 g burger patty	Cradle to manufacturing gate	Europe	IMPACT 2002+	Soy protein, wheat gluten, rapeseed oil, other
Pea DL, Pea WH, Soy WH *(this study)*	1 kg ground meat	Cradle to manufacturing gate	North America	ReCiPe 2016 midpoint (H) V1.03	See Table 3

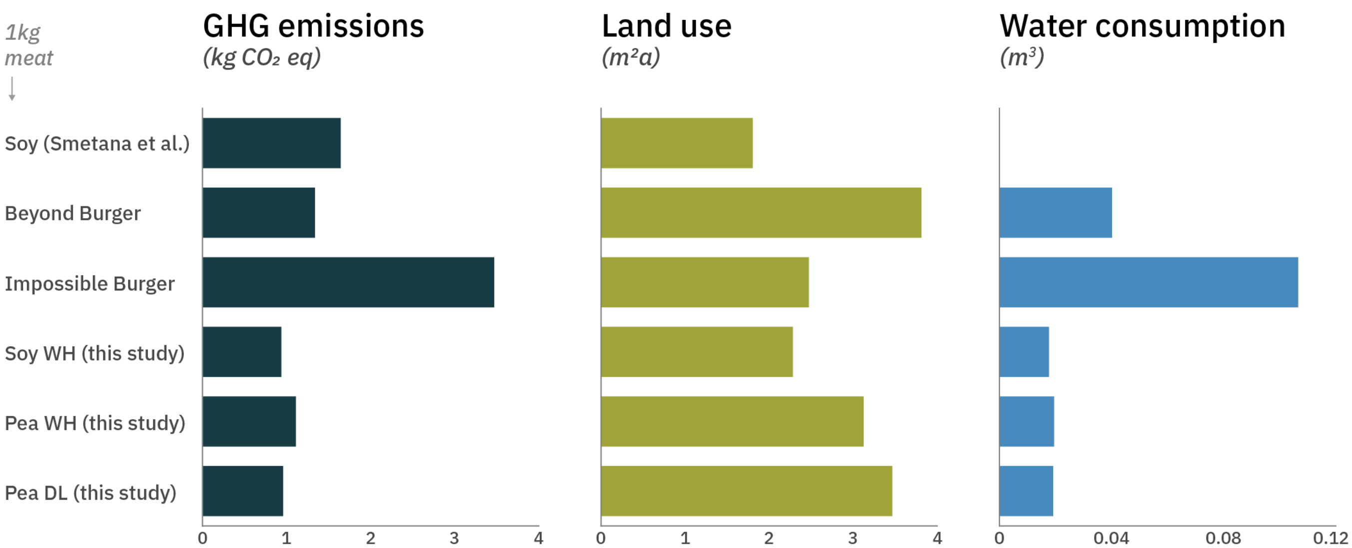


Figure 8. Study parameters and environmental impacts of plant-based meat production as reported in the ISO-certified LCA study compared to other plant-based meat LCAs. Water consumption is not reported for Smetana et al. (2021).

The Impossible Burger's slightly higher carbon footprint and water consumption are mostly attributed to the recipe containing leghemoglobin (fermentation-derived) and potato proteins, which both have slightly higher carbon and water footprints than other plant-based meat ingredients. Still, Impossible Burger provides one kilogram of meat with 89% less global warming potential and 87% less water consumption compared to a beef burger (Khan et al. 2019).

Carbon footprint, land use, and water consumption impact categories were chosen to compare to other studies because the impact assessment methodology was most available and similar for these parameters. Economic allocation from this study was used as a comparison because all compared studies used economic allocation for their LCA methodology.

**Because the boundaries between studies varied, cradle-to-manufacturing gate contributions were calculated for Beyond Burger 3.0 and Impossible Burger, using the contributions provided for each step in production and excluding packaging and cold storage transport.*

Despite global variability, plant-based meat consistently has lower environmental impacts than animal-based meat

Following ISO standards, uncertainty analyses were conducted to quantify the degree of uncertainty in the impact reduction of plant-based meat systems compared to animal-based meat systems due to uncertainty and variability of the input data. As mentioned previously, uncertainty analyses are critical to test LCA assumptions and reduce methodology bias (see: "Life cycle assessments are critical to understanding the environmental impact of foods" box).

Life cycle inventory data uncertainty arises from a number of variables, such as sources and methods for collecting data, variability across geography, and other specifications (e.g., energy and material consumption, agricultural practices, material composition). Uncertainty analyses for LCAs evaluate the combined influence of life cycle inventory data uncertainties by varying inputs based on an uncertainty distribution for each input variable to generate a range of potential results.

Without uncertainty analyses, LCAs run the risk of producing biased outcomes if non-representative or poor data quality life cycle inventory inputs are chosen. The LCA applied Monte Carlo simulations in SimaPro using 1,000 paired simulations comparing one animal-based meat system and one plant-based meat system. For each iteration, randomized inputs were selected and the differences between the impacts of the two systems were compared. From this, the distribution of the difference between each plant-based meat system and animal-based meat system for each impact category was determined within defined confidence intervals.

As shown in Table 8, plant-based meat has lower environmental impacts than animal-based meat in 12 of 18 impact categories with >95% confidence. In three categories, namely land use, freshwater ecotoxicity, and marine ecotoxicity, this certainty threshold is cleared for some plant-based systems versus pork and chicken only. In the remaining three categories, human carcinogenic and non-carcinogenic toxicity and water consumption, the data distributions are too broad, leading to higher uncertainty. Data uncertainty in this study is primarily attributed to the agricultural cultivation and animal husbandry datasets, which are taken directly from the ecoinvent database and World Food LCA Database.

Though more high-quality data is needed to draw comparisons with higher confidence intervals for certain impact categories, the environmental impacts of plant-based meat are lower overall than animal-based meat regardless of global input data variability, which are primarily driven by the feed, emissions, and operations associated with raising animals (see: "Animal husbandry drives the high global warming impacts of meat production" box). Reduction of the environmental impacts of raising animals is possible, albeit limited by technological innovation, animal physiology, and feed conversion ratio (Shepon et al. 2016).

A transition to alternative proteins, such as the plant-based meat systems presented here, is a tractable and impactful way to significantly reduce the environmental impacts of meat production. Additionally, as the plant-based meat industry grows, there is ample opportunity to further lower its environmental impacts (per kilogram produced) and increase resource efficiency.

Table 8. Data from uncertainty analysis for LCA demonstrating confidence intervals for each meat system and impact category.

Plant-based meat has a lower impact in...	*compared to* Beef	*compared to* Pork	*compared to* Chicken
Global warming	✓ >95%	✓ >95%	✓ >95%
Stratospheric ozone depletion	✓ >95%	✓ >95%	✓ >95%
Ionizing radiation	✓ >95%	✓ >95%	✓ >95%
Ozone formation, Human health	✓ >95%	✓ >95%	✓ >95%
Fine particulate matter formation	✓ >95%	✓ >95%	✓ >95%
Ozone formation, Terrestrial ecosystems	✓ >95%	✓ >95%	✓ >95%
Terrestrial acidification	✓ >95%	✓ >95%	✓ >95%
Freshwater eutrophication	✓ >95%	✓ >95%	✓ >95%
Marine eutrophication	✓ >95%	✓ >95%	✓ >95%
Terrestrial ecotoxicity	✓ >95%	✓ >95%	✓ >95%
Mineral resource scarcity	✓ >95%	✓ >95%	✓ >95%
Fossil resource scarcity	✓ >95%	✓ >95%	✓ >95%
Land use	✓ 50–95%	✓ >95%	<50%
Freshwater ecotoxicity	<50%	✓ >95%	✓ >95%
Marine ecotoxicity	<50%	✓ >95% Pea DL, Pea WH; 0% Soy WH	✓ >95%
Human carcinogenic toxicity	<50%	<50%	<50%
Human non-carcinogenic toxicity	<50%	<50%	<50%
Water consumption	<50%	<50%	<50%

Confidence interval: ✓ >95%   ✓ >95% Pea DL, Pea WH; 0% Soy WH   ✓ 50–95%   <50%

Animal husbandry drives the high global warming impacts of meat production

The environmental impacts of the animal meat systems modeled in this study are driven primarily by animal husbandry, specifically the associated feed production, emissions, manure management, and housing operations. The global warming impacts of each process associated with animal meat production, including animal husbandry, slaughtering, grinding, and transport, are presented in Figure 9 with further granularity provided for animal husbandry.

Animal husbandry alone is responsible for 92% of the global warming impacts of beef, compared to 90% for pork and 66% for chicken. The impacts of beef cattle production are driven by raising weaned calves, which was modeled as a market mix consisting of 77% intensive cattle production and 23% mixed and extensive production systems on pasture based on U.S. statistics.

In both scenarios, calves are primarily grazed on pastures, which are continuously fertilized. As such, the majority of the global warming impact from weaned calf production is the result of direct field emissions related to pasture fertilizer application, enteric fermentation, and manure management. Pork production's global warming impacts are driven by direct emissions of ammonia, particulates, and methane during housing and manure storage, followed by manure management activities, feed production, and housing. Finally, chicken production's global warming impacts are primarily driven by feed production, particularly maize cultivation, and direct emissions, namely emissions of ammonia and dinitrogen monoxide to air. Maize cultivation is also a primary driver of water consumption across all three animal-based meat systems.

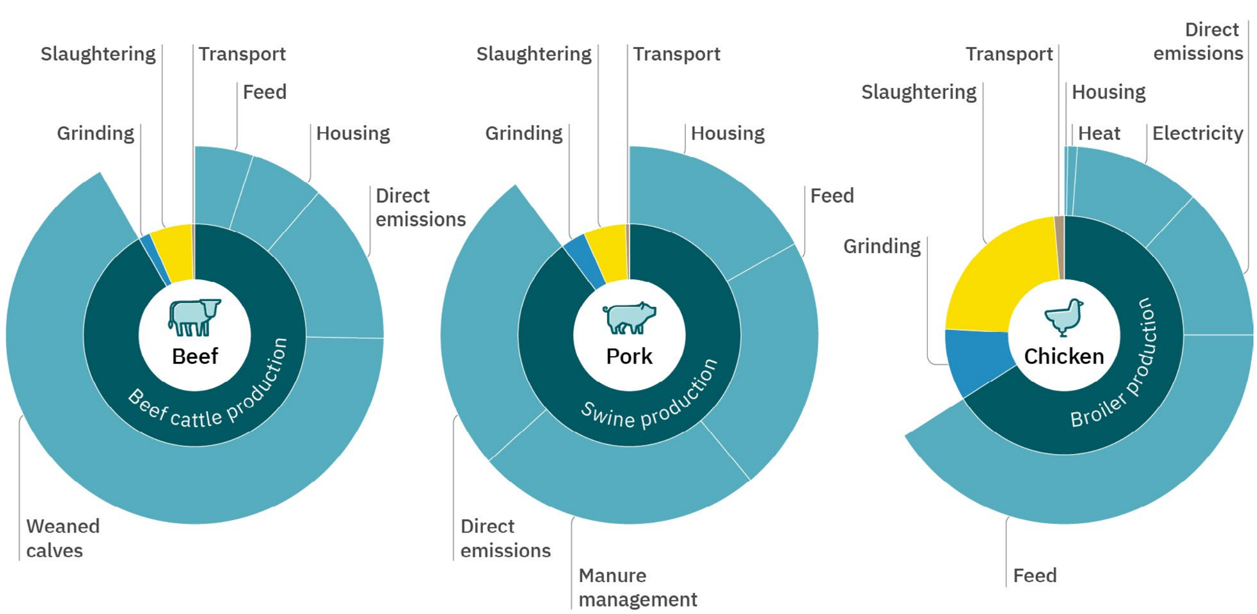


Figure 9. Breakdown of process contributions to global warming in animal-based systems: beef, pork, and chicken.

Animal husbandry in intensive farming systems, like the one modeled in this study, is highly optimized for resource utilization and further incremental improvements will likely not be enough to meet climate change mitigation goals. The Environmental Defense Fund's "Ambitious Climate Mitigation Pathways for U.S. Agriculture and Forestry: Vision for 2030" demonstrates that in the United States, where animal agriculture is already highly optimized, further agriculture optimizations would not be enough to reach 2030 agriculture sector goals for GHG emission reduction. Specifically, the report estimates the reduction potential of various crop and livestock agriculture strategies (e.g., improved manure management, reduced enteric methane emissions from livestock, and improved nitrogen management) and found that these ambitious strategies alone could not reduce GHG emissions in the U.S. agriculture and forestry sectors by the targeted 33%, 247 million metric tons (MMT) CO_2e, decrease.

Comparison of environmental impacts of plant-based meat production using different inputs and production methods

The ISO-certified LCA provides a uniquely granular view of the environmental impacts of plant-based meat, comparing dominant inputs and processing methods and using real-world, commercial-scale data. Despite variations in ingredients and production methods, plant-based meat consistently offers substantial environmental benefits compared to animal-based meat.

Plant-based meats offer substantial environmental benefits across different inputs and production methods.

Ingredient choices affect environmental impacts

The plant-based meat systems included in this analysis are composed of varying levels of texturized, extruded plant protein and water, along with equivalent amounts (by mass) of coconut oil, canola oil, wheat gluten, spices, and potato starch (see Table 3).

Extrudate is the primary ingredient in this study's plant-based meat recipes and the largest contributor to plant-based meat's impact in nine of 18 impact categories. However, other ingredients are also major contributors and sometimes exceed extrudate impacts in certain categories even though they are present at lower levels.

Coconut and canola oil contribute disproportionately to the plant-based meat impact given each only constituting 4% of the recipe. Coconut oil contributes as much impact as extrudate for global warming and land use and significantly to a number of other impact categories (Figure 10). Canola oil contributes disproportionately to marine eutrophication, fine particulate matter formation, and other categories primarily due to emissions related to cultivation. Potato starch and wheat gluten also show disproportionately large contributions to certain impact categories, especially water consumption.

Photo courtesy of Julee Ho and Doaa Jamal

Crop yield improvements, less reliance on fertilizers and pesticides, reduced irrigation requirements, and alternative oil ingredients could help further reduce the impacts of plant-based meat by reducing impact contributions from oil ingredients. Across the plant-based systems, differences in the total environmental impacts are driven by the protein extrudate as the other ingredients are held constant in all three recipes.

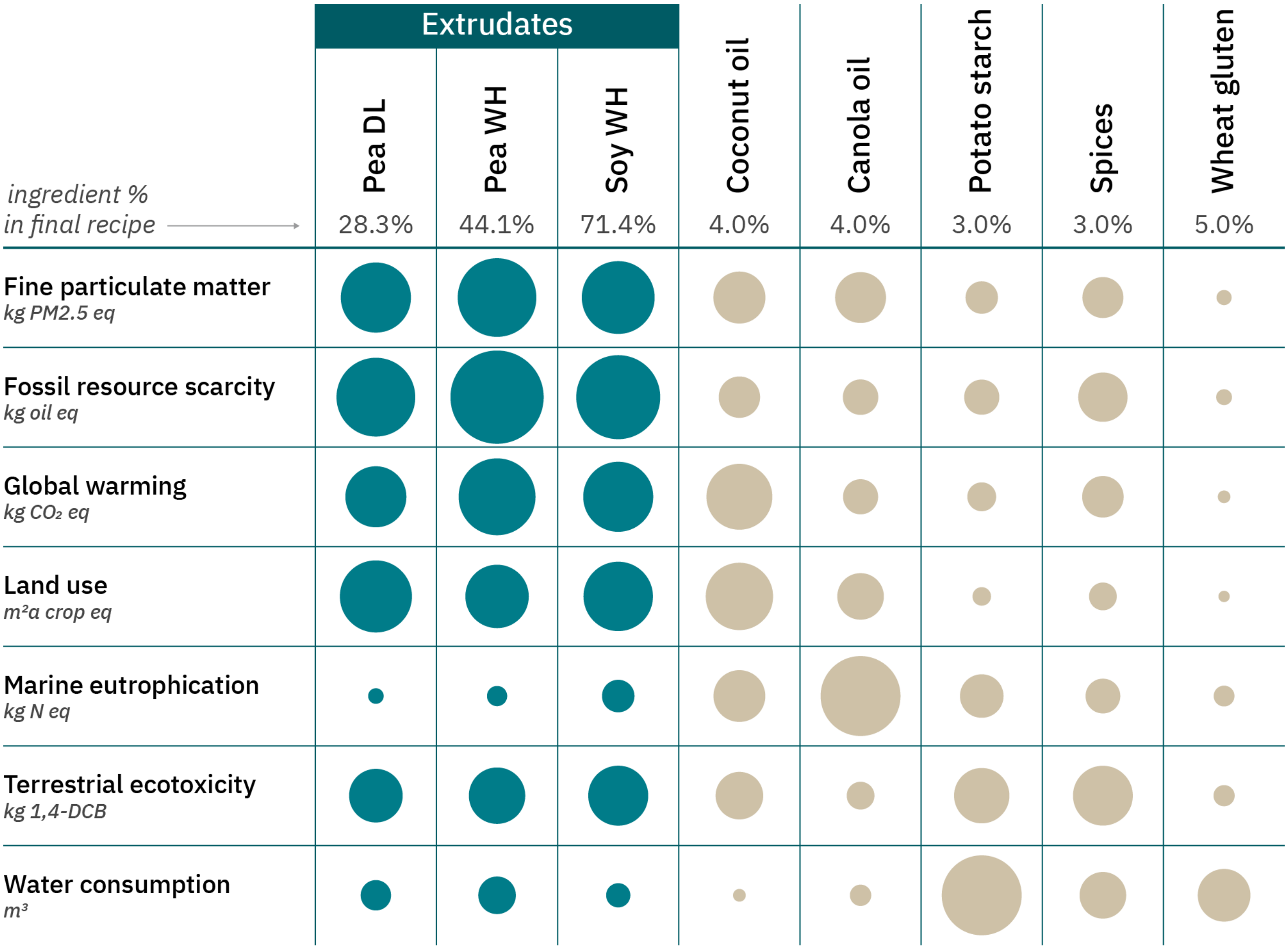


Figure 10. The relative impacts of ingredients in plant-based meat, where one of the extrudates (Pea DL, Pea WH, or Soy WH) is combined with all of the secondary ingredients (coconut oil, canola oil, potato starch, spices, and wheat gluten) to form the total impacts of a plant-based meat in any given category. The remaining ingredient % in each final recipe is additional water.

Extrusion and fractionation are key opportunities for optimization

This study examined the environmental impacts of three plant-protein extrudate variations and compared the contributions of the three production stages:

Stage 1: Cultivation of primary protein crop (pea/soy),

Stage 2: Fractionation, and

Stage 3: Extrusion

Each stage can be further differentiated into individual processes, utilities, and chemicals. The global warming impact of each plant-based meat system in the various stages of extrudate production are deconstructed in Figure 11. See Section 5.7.2 in the LCA report for a detailed comparison of the plant-based meat recipes across the 18 impact categories.

Of the extrudates, Pea WH has the largest impact overall, followed by Soy WH and Pea DL (Figure 11A). As shown in Figure 11B, the contribution of cultivation, fractionation, and extrusion to the impact of the extrudate varies across the plant-based recipes. This is because varying amounts of crop feedstock, protein isolate/concentrate, and extrudate are needed in each recipe to achieve 15 grams of protein in the final product (Table 9). Additionally, tradeoffs exist throughout the cultivation, fractionation, and extrusion stages, driven by varying processes and practices, yields, feedstock consumption, protein content, and more.

Table 9. Raw material feedstocks, protein ingredients, and final extrudates by weight and final extrudate protein content per 100 g in the plant-based meat LCAs.

System	Feedstock	Protein ingredient	Extrudate weight	Protein content *per 100g extrudate*
Pea DL	1.75 kg (peas)	0.29 kg PPC	0.28 kg	15 g
Pea WH	1.42 kg (peas)	0.19 kg PPI	0.44 kg	15 g
Soy WH	0.42 kg (soybeans)	0.22 kg SPC	0.71 kg	15 g

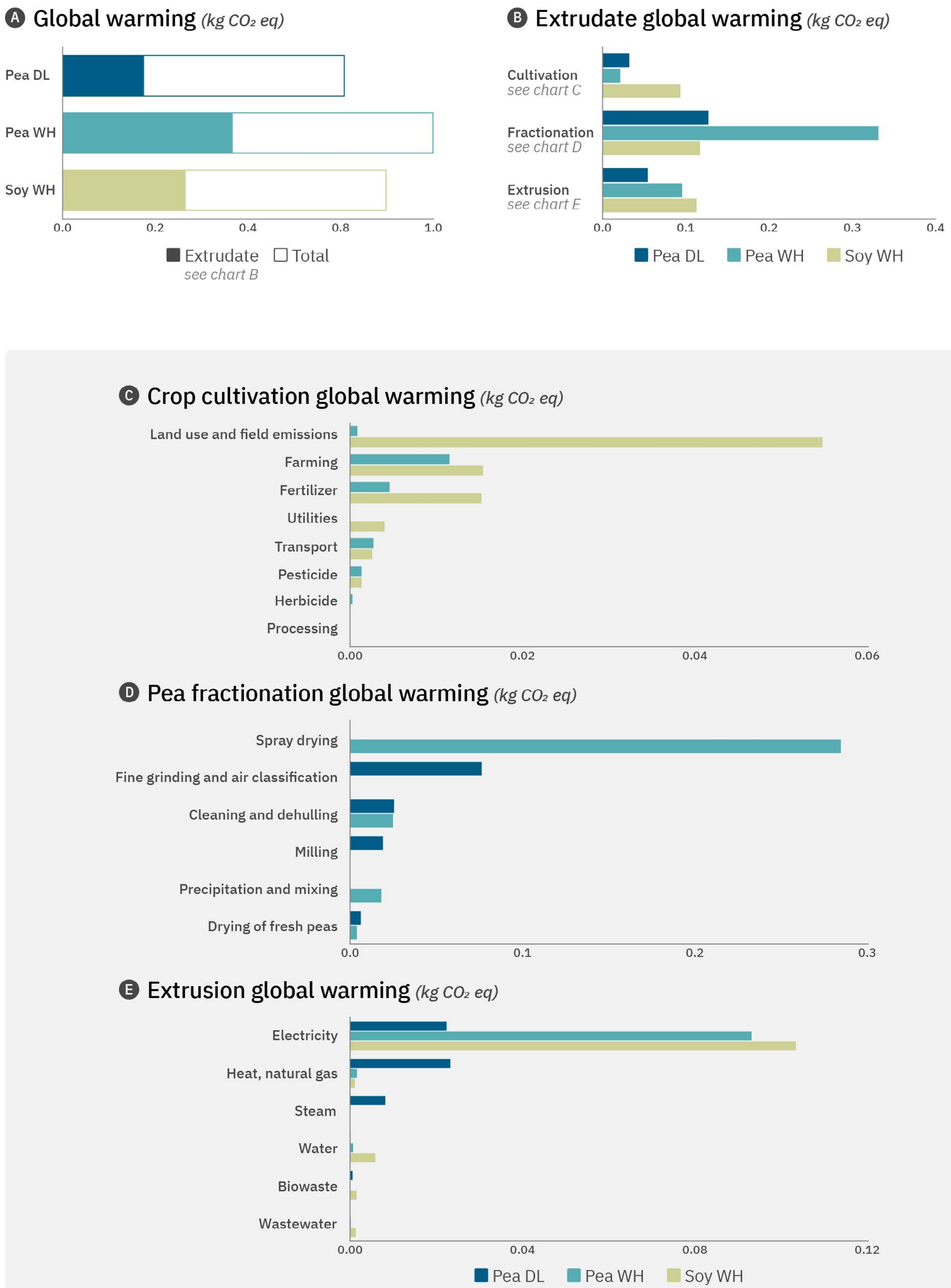


Figure 11. Global warming impact of (A) plant-based meat systems overall; (B) Pea DL, Pea WH, and Soy WH cultivation, fractionation, and extrusion; (C) Pea WH and Soy WH crop cultivation; (D) Pea DL and Pea WH fractionation process steps; (E) Pea DL, Pea WH, and Soy WH extrusion utilities.

Soy cultivation drives higher global warming impacts than pea cultivation due to direct land use, field emissions, and resource-intensive harvesting, despite using less feedstock (Figure 11C). At the fractionation stage, Pea WH has the highest global warming impacts, mainly due to the energy-intensive spray drying process, while Pea DL shows lower impacts as it avoids spray drying. Interestingly, Soy WH global warming impact is similar to that of Pea DL, but this is attributed to the lower starting mass of the crop input (0.42 kg soybeans vs. 1.7 kg peas). High moisture extrusion processes for both soy and pea have higher global warming impacts than low moisture extrusion due to greater electricity and heat requirements. Importantly, these individual impacts are still significantly lower than those associated with animal meat production.

Both dry and wet fractionation as well as high and low moisture extrusion are important processes for achieving the necessary texture and protein content for plant-based meats. This data does not promote the use of one process over another, but rather, highlights the opportunities to increase the energy efficiency of extrusion and fractionation, which is explored in more detail below.

Extrudate production impacts are sensitive to energy source and crop geography

Electricity consumption drives impacts in the fractionation and extrusion stages, and sensitivity analyses reveal that a transition to renewable energy is more impactful than incremental energy efficiency improvements. The effect of consuming 10% less electricity from the Midwest Reliability Organization (MRO) power grid leads to less than 2% impact reduction on average, while a transition to solar energy reduces the impacts of plant-based systems by 10–58% in the nine impact categories associated with fossil fuel consumption, as the MRO grid uses 52% fossil fuels from coal and natural gas. For example, ionizing radiation impacts show the greatest reduction potential when plant-based systems transition to renewable energy as it is associated with fossil fuel consumption (Figure 12). Baseline plant-based meat ionizing radiation impacts are on average 86% lower than animal meat, compared to 94% lower impacts for plant-based meat produced using solar energy.

Therefore, while plant-based meat is already significantly more sustainable than animal-based meat and highly resource efficient, using renewable solar energy can provide further environmental benefits compared to animal meats, especially in categories associated with fossil fuel consumption.

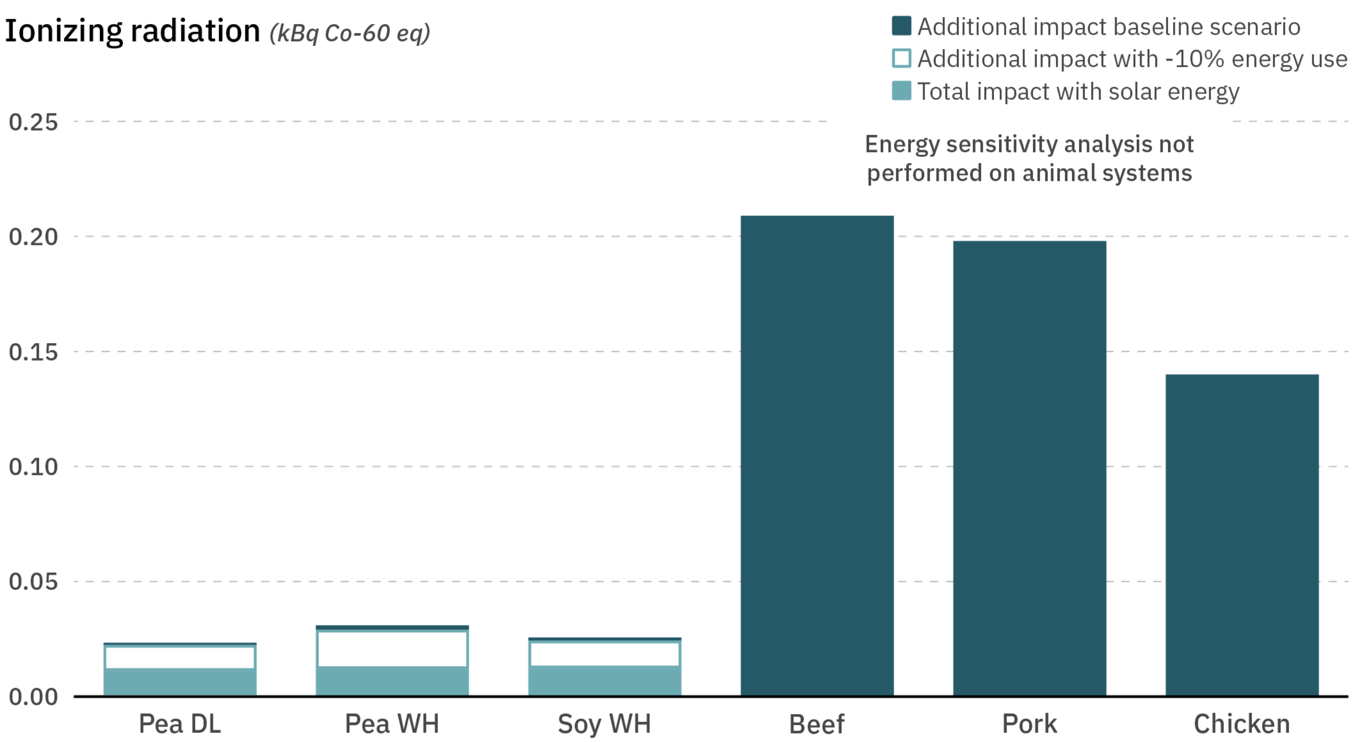


Figure 12. Ionizing radiation (kBq Co-60 eq) impact of meat production using solar energy or 10% less energy compared to the baseline assessed in the LCA.

Crop cultivation can serve as a main contributor to some of the environmental impacts associated with extrudate production for plant-based meats. The main causes for these contributions are dependent on the crop type and their associated cultivation activities, but optimizing direct land use and combine harvesting tend to be ubiquitous opportunities to reduce the environmental footprint of crop cultivation. Additional potential environmental optimization strategies for crop cultivation include diesel consumption reduction during tillage and improved fertilizer and pesticide production and application. Sensitivity analyses were conducted to understand the effects of crop geography and therefore cultivation practices, agricultural yields, soil conditions, and more.

The baseline scenario of Canada-grown peas was compared with France- and Germany-grown peas, whereas baseline U.S.-grown soy was compared with Canada- and Brazil-grown soy (Figure 13). Marine eutrophication and water consumption show the largest increases with alternate crop geographies for both pea and soy. This is due to higher consumption of fertilizer and pesticides in these geographies, which require more water for dilution prior to field application. Even when using a higher impact crop geography, plant-based meat still causes 84% less marine eutrophication and consumes 82% less water than animal-based meat on average, compared to 93% and 95% less in the baseline scenario.

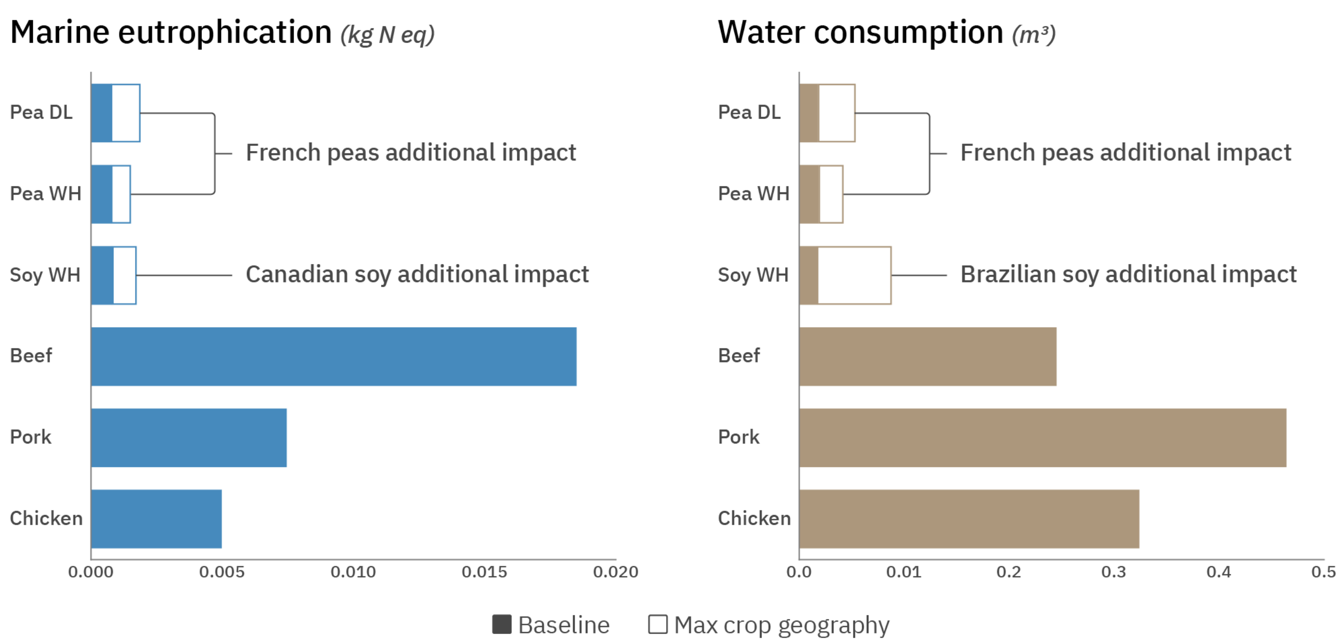


Figure 13. Environmental impacts for plant-based meat made with either Canadian peas (baseline, Pea DL and Pea WH) or French peas, U.S. soy (baseline, Soy WH) or Canadian soy.

Technical optimization and scaling to maximize the environmental benefits of plant-based meat

For researchers and manufacturers across the value chain motivated to maximize the environmental benefits of plant-based meat production, crop cultivation optimization, alternative fat inclusion, and upcycling byproducts are great opportunities to further improve plant-based meat sustainability.

The cultivation of soy and peas could be improved by avoiding the emissions related to land-use change and reducing the consumption of pesticides and water, especially in certain geographic regions. These results also show an opportunity to optimize pea protein content and isolation efficiency, as more peas are required than soy. The land use of pea and soy systems are similar (3.87 ton/ha and 2.76 ton/ha, respectively) and land use can be further reduced by improving cultivation yields. Overall, however, cultivating both pea and soy for human consumption is more efficient than producing crops for livestock.

Ingredient selection should also be considered when scaling plant-based meat production. As shown in Figure 10, certain ingredients have disproportionately large impacts even when included in small amounts, such as coconut oil. Coconut oil is widely used for plant-based meat due to its high saturated fat content and semi-solid consistency at room temperature that somewhat mimics the functional properties of animal fats.

However, as shown in GFI's plant-based meat production volume modeling analysis, the plant-based meat industry would require 16% of the global supply of coconut oil to produce 25 MMT of plant-based meat. If coconut oil maintains its dominance in plant-based meat formulations, supply chain bottlenecks may stifle its ability to scale with the industry. Cultivators, producers, and manufacturers should seek to rapidly diversify into alternative fats, such as gels, emulsions, fermentation-derived, or cultivated fats, that exceed coconut oil functionally and have lower environmental impacts.

Table 10. Mass and economic allocation factors of coproducts in evaluated plant-based meat systems.

System and process		Main products and coproducts	Mass allocation factor (%)	Economic allocation factor (%)
Pea DL	Dehulling	Dehulled peas	82.80	89.06
		Hulls	17.20	10.94
	Air classification	Protein concentrate	23.38	52.90
		Starch	76.62	47.10
Pea WH	Dehulling	Dehulled peas	73.14	89.06
		Hulls	26.86	10.94
	Precipitation	Pea protein isolate	21.73	54.97
		Starch	34.33	37.07
		Wet globulin slurry	43.94	7.96
Soy WH	Soybean oil extraction	Soybean meal	19.49	35.87
		Soybean oil	80.51	64.13
	Wet fractionation	Soy protein concentrate	62.54	97.41
		Soy fines	7.24	1.76
		Soy molasses	30.22	0.82

Finally, valorizing byproducts or sidestreams of plant-based meat production has the potential to allocate environmental impacts across more high-value products and further reduce the impacts allocated to meat production. The mass and economic allocation factors of animal-based and plant-based meat coproducts are shown in Table 10. Opportunities for valorization exist for plant protein coproducts with high mass allocation and low economic allocation, such as pea wet globulin slurry and soy molasses. In addition, soy and pea sidestreams can be leveraged for other alternative protein technologies, for example as feedstocks or growth media ingredients for fermentation-derived and cultivated meat, respectively, as detailed in GFI's recent analysis on cultivating alternative proteins from commodity crop sidestreams.

Scaling plant-based meat production will maximize environmental benefits

This report demonstrates that scaling plant-based meat has the potential to bring large, beneficial environmental changes to the global food system.

For example, this report demonstrates that the global warming impact of plant-based meat studied here is 15 to 20 times lower than beef. If a linear correlation between global warming impact and production scale is assumed,[2] producing 5 MMT (approximately 40% of current annual U.S. beef production, 11% of current annual U.S. meat production, and 1.4% of current global meat production[3]) of plant-based meat instead of beef would offset approximately 68 MMT CO_2e emissions annually,[4] more than the annual CO_2 emissions from all of California's approximately 14 million passenger vehicles.[5] These benefits are even greater when considering the volumes that could be produced globally to meet increasing meat demand while significantly improving the sustainability of the world's protein supply.

Fast, large, and sustainable shifts in food cultivation, production, and distribution are worth pursuing and possible but require multistakeholder buy-in, especially from governments. For these environmental benefits to be realized globally, the current demand and production scale of plant-based meat must increase immensely, while maintaining a low environmental footprint. For more details on how policy can support rapid alternative protein production scale-up, see GFI's 2023 The State of Global Policy on Alternative Proteins report and this analysis's accompanying policy summary report.

The global warming impact of plant-based meat studied here is 15 to 20 times lower than beef.

[2] Linearly correlating LCA results with scale should be evaluated carefully before making production decisions. Here, this is done as a thought experiment to extrapolate broad scalability implications and should not be interpreted as a concrete and rigorous evaluation.

[3] The U.S. produced approximately 122 billion lbs (55.3 MMT) of meat in 2022 with a breakdown of 59.3 billion pounds of broilers, 6.66 billion pounds of turkey, 168 million pounds of other chickens, 27.0 billion pounds of pork, 28.4 billion pounds beef, 136.2 million pounds of lamb and mutton, and 58.7 million pounds of veal (data for poultry and livestock). Global meat production is approximately 350 MMT per year).

[4] The estimated offset of CO_2e by substituting 5 MMT beef with plant-based meat is estimated by assuming 14.5 kg CO_2e per kg beef production and 0.75-0.98 kg CO_2e per kg plant-based meat production. The difference is 13.52-13.75 kg CO_2e per kg of meat or approximately 68-69 MMT CO_2e savings per 5 MMT of meat.

[5] The annual CO_2 emissions from all California passenger vehicles in 2021 is equal to 65.3 MMT CO_2 and calculated by multiplying 14.2 million registered vehicles in CA by 4.6 metric tons CO_2 emitted per passenger vehicle.

Conclusions

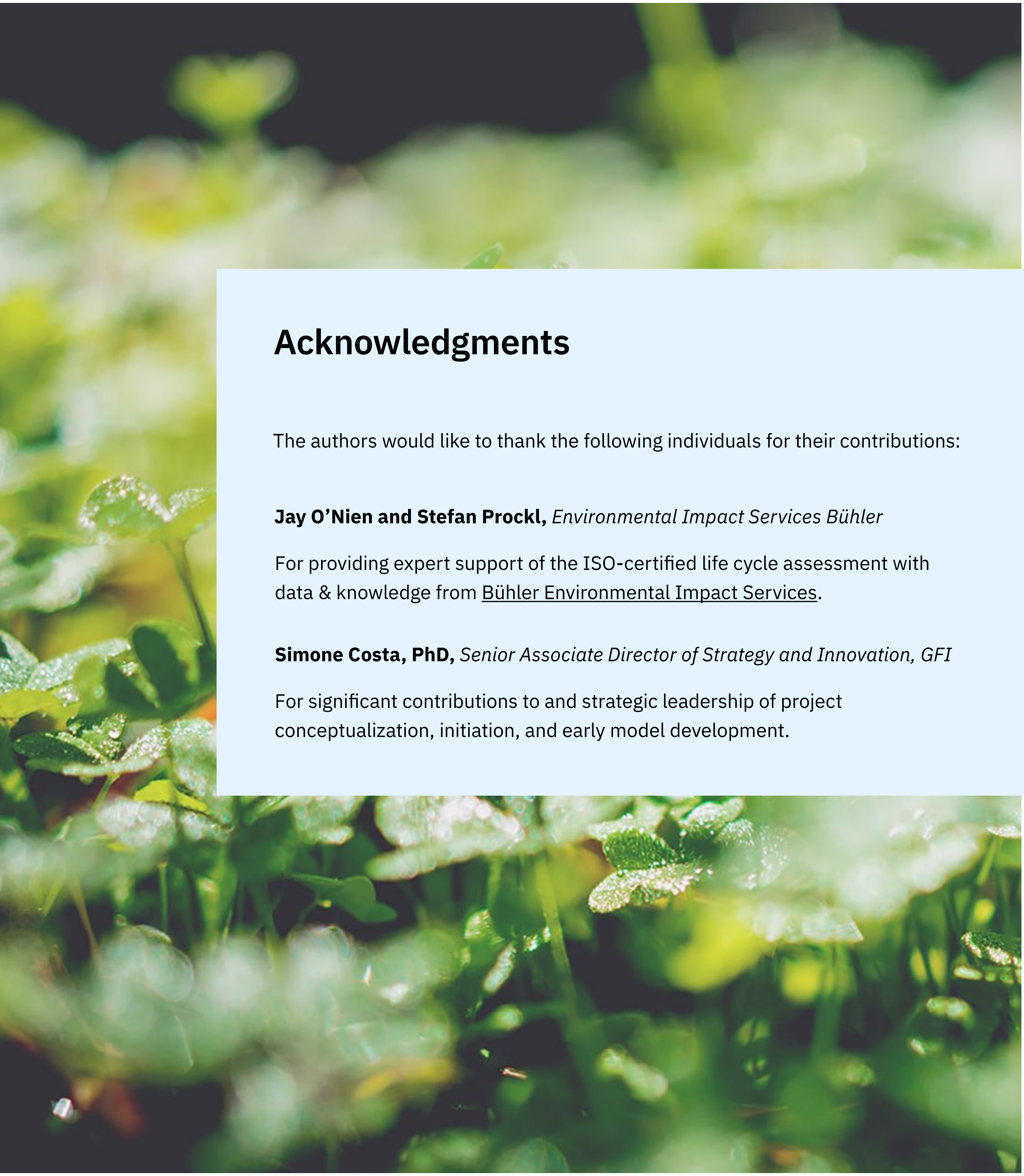
The ISO-certified LCA report demonstrates that a shift toward plant-based meat production would reduce the environmental impacts of meat production in every category by 79–99.8% on average. Plant-based meat impacts are 81–99.9% lower than beef, 60–97% lower than pork, and 10–94% lower than chicken; excluding land use, the average plant-based meat impacts are 64–94% lower than chicken.

The animal-based meat systems modeled here represent highly optimized and intensive operations that already have lower impacts than the average global operations with the majority of high impacts resulting from the cultivation requirements, emissions, manure management, and housing operations associated with animal husbandry. While incremental improvements to animal-based systems are possible, these improvements do not provide the impact reduction required to sustainably meet a growing meat demand.

Plant-based meats provide a practical solution to enable sustainable agriculture and food systems, but to realize their maximal environmental benefits, they must be consumed at a volume many times greater than the current consumption of approximately 1.0 MMT plant-based meat per year globally. As the production scale, taste, and cost of plant-based meats are improved with technologies such as high-protein crop cultivars, alternative fat ingredient production, emerging ingredient processes (e.g., cold pressing oils or using membrane filtration for protein purification), and innovative texturization methods (e.g., shear cell texturization or spinning proteins), maintaining the positive environmental benefits of plant-based meat production will be crucial for the industry. The industry should continue to evaluate the environmental benefits of plant-based meat production with additional LCAs as development advances.

For manufacturers interested in maximizing the environmental benefits of plant-based meat, there are many opportunities with technological advances, novel formulations, coproduct valorization, and efficiencies of scale. Other opportunities such as exploring new raw materials, upcycling processing sidestreams, and using less energy-intensive processes can reinforce the resilience and sustainability of plant-based supply chains.

Overall, the LCA provides the environmental case for plant-based meat with detailed insights into the environmental impact drivers of both plant-based and animal-based meat. LCAs are impartial analyses that help people and businesses better understand how their choices in goods or services impact their environmental footprint. Studies such as these should be utilized as a tool for policymakers, investors, companies, and consumers to build and support sustainable and secure agriculture and food supply chains. The summary presented here is based on a comprehensive, ISO-certified LCA which is available at gfi.org. Data summaries are available for download and on an interactive dashboard at gfi.org.



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