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Supplementary Material

Appendix A: Methods

A.1 Literature review

To identify published scientific research relevant to the public health, environmental, animal welfare, economic, and policy implications of meat alternatives, we designed a search approach using compound search terms. Specifically, we searched for articles that covered a type of meat alternative (e.g., plant-based substitute or cell-based meat) and either an impact concept or a production process concept (Table S1). We ran each compound search in the journal databases PubMed, SCOPUS, and Web of Science.

The search yielded over 7289 articles, which we narrowed down through two rounds of screening for relevance. We excluded articles about plant-based diets or whole food plant protein alternatives (e.g., soybeans, legumes, mushrooms) that did not discuss processed meat alternatives specifically; articles that discussed only farmed meat or blended meat (e.g., adding mushrooms to farmed meat); articles that looked at protein consumption or use in animals rather than humans; and articles that explored protein function within human bodies. For the first round of screening, we reviewed the article title and abstract. For the second round, we reviewed the full text. The full text screening required two researchers to review each article. Any conflicts between the reviewers were subject to an additional screening for final decision.

The screening process identified 110 articles relevant to plant-based substitutes (PBS) and 77 relevant to cell-based meat (CBM). The studies were reviewed and tagged with the implications discussed within their results sections: public health (PBS: 44, CBM: 8), environmental (PBS: 8, CBM: 17), animal welfare (PBS: 4, CBM: 13), economic (PBS: 2, CBM: 8), political/legal (PBS: 2, CBM:15), consumer perceptions (PBS: 14, CBM: 28), other sociocultural concerns (PBS: 0, CBM: 14) and technical production processes/food science (PBS: 56, CBM: 31). Many articles discussed more than one implication, so articles were tagged with as many implications as relevant. Authors then read all articles and synthesized relevant information for the different implication sections of the manuscript. Information about “other sociocultural concerns” was ultimately incorporated into the manuscript’s economic section. The consumer perceptions and technical production processes/food science were excluded from the analysis in the manuscript, due to being outside of the scope of this review.

The authors learned of three additional research articles (Bohrer, 2019; Curtain & Grafenauer, 2019; Hu et al., 2019) published about plant-based substitutes’ nutrition impacts after the initial literature search was completed in September 2019. We opted to include the studies as part of the literature review despite being obtained outside of the search strategy. Additional peer-reviewed research and selected gray literature was also consulted to address specific points made about certain topics in the paper.

Table S1: Search terms for identifying research on meat alternatives

Concept	Compound search terms
Type of meat alternative	"cellular meat*" OR "cellular agriculture*" OR "clean meat*" OR "cultured meat*" OR "in vitro meat*" OR "cell based meat*" OR "slaughter free meat*" OR "vat grown meat*" OR "synthetic meat*" OR "fake meat*" OR "lab grown meat*" OR "meat alternative*" OR "meat substitute*" OR "plant-based meat*" OR "artificial meat*" OR "vegan meat*" OR "plant meat*" OR "meat analog*"
Impact	climate OR greenhouse* OR GHG OR "carbon dioxide" OR regulate* OR policy* OR politics* OR legislation OR label* or FDA OR heath* OR nutrition* OR nutrient* OR calorie* OR sodium* OR digestion* OR heme* OR iron* OR dietary protein* OR meat protein* OR plant protein* OR "environmental assessment" OR LCA OR LCIA OR "life cycle analysis*" OR "life cycle assessment*" OR "life cycle inventory*" OR "life cycle impact assessment*"
Production process	"production process*" OR "tissue engineering" OR scaffold* OR bioreactor

A.2 Environmental impact calculations

A.2.1 Meat alternatives

Using data reported in the relevant literature, we calculated the mean, median, and range of greenhouse gas (GHG) footprints, land use, and blue water footprints associated with plant-based substitutes and cell-based meats. There was not enough research available, or the research that was available was reported in inconsistent units, to calculate average eutrophication potential, pesticide use, or biodiversity implications of meat alternatives, but we did cite available research on those topics in the manuscript text.

When reviews were identified in our search, we looked to the original studies cited in the reviews to identify potential additional data for inclusion. In many cases, cited data were from reports and other gray literature. Since our database searches identified only six peer-reviewed studies that provided primary environmental impact data for plant-based substitutes and three for cell-based meat, we expanded our inclusion criteria to allow for gray literature gleaned from published reviews. We also performed an additional search in Google Scholar to identify peer-reviewed and gray literature and research published up to March 2020. An additional six references were added to inform the environmental impact calculations for plant-based substitutes, bringing the total number of individual products reflected in the GHG footprints from 65 products (from 5 studies) to 95 products (from 11

studies); blue water footprints: 1 product (from 1 study[1]) to 7 products (from 4 studies); and land use: 9 products (from 4 studies) to 17 products (from 9 studies). We also included data from one unpublished conference presentation that presented updated data on the environmental implications of cell-based meat.

A limitation of our expanded criteria was that four of the included reports were published or commissioned by companies selling plant-based substitutes (see "study details" tab of Supplementary Data), along with the fact that one of the peer-reviewed studies identified was co-authored by an employee of Impossible Foods. Additionally, two of the four cell-based meat production articles were written by an author who reported being funded by New Harvest, a non-profit organization that promotes cell-based meat production. See Supplementary Data for a list of all studies included.

To maximize consistency and comparability across all studies and with the data reported from studies of other protein foods (see Supplementary Materials Section A.2.2), we extracted cradle-to-processing gate footprints wherever possible. We note the scope of supply chain activities in reported data from each study in the "study details" tab of the Supplementary Data.

We then standardized footprints to kg CO2e, L blue water footprint, or m^2/year of land use per kg of product and per 100 g protein. A few studies only reported the mean of multiple products rather than individual item footprints and are noted accordingly in the "product footprints" tab in the Supplementary Data. Additionally, some studies only reported a range of potential impacts – in those instances, we averaged the minimum and maximum to create an average for a single product. When available, we also noted reported ranges from sensitivity analyses or confidence intervals.

Some studies did not report the protein content of the products assessed. If the product's protein content was available on a nutrition label online, we used that to calculate the footprint per 100 g protein. For some mycoprotein-based products, the protein content was not available, and was estimated using average protein content for mycoprotein-based meat analogs, as reported in Smetana et al. (2015). These deviations are described in the notes column of the "product footprints" tab.

We then calculated the mean and median GHG footprint, land use, and blue water footprint for both plant-based substitutes and cell-based meat using the mean value from each individual study (in contrast to calculating the mean and median of individual product footprints, which would over-represent results from studies that included more products than other studies). We also determined ranges, which were based on the highest and lowest values among individual product footprints.

A.2.2 Comparison with other protein foods

We selected the most comprehensive literature reviews available to compare the environmental implications of meat alternatives with other protein foods. Specifically, GHG footprint and land use data for farmed animal products, farmed fish and crustaceans, and plant protein foods are reported from Poore & Nemecek (2018), an article that compiled environmental impact data for 40 major food products representing data from over 38,000 farms in 119 countries.

Due to the fact that Poore & Nemecek (2018) report the water indicators in terms of freshwater withdrawals rather than water consumption (the latter of which is almost universally used in the literature on meat alternative impacts), blue water footprint data for all other foods are from Kim et

[1] An additional study on the blue water footprint of plant-based substitutes that we identified in the literature search (Fresán et al., 2019) was ultimately excluded from calculations of the mean, median, and range of plant-based substitutes because of methodological concerns reported in Santo et al. (2020).

al. (2019). Kim et al. (2019) report water footprint data for 74 food items adapted from literature quantifying the blue and green WFs of plant foods (Mekonnen and Hoekstra, 2010a) and terrestrial animal products (Mekonnen and Hoekstra, 2010b). This data set aggregated 12,923 unique data points specific to over 200 countries, weighed by the tonnage of items produced in each country.

We also included two other protein foods for comparison with the environmental impacts of meat alternatives: insects, due to their potential as a more sustainable alternative to other farmed meats, and wild tuna, to represent one type of wild seafood. For these items, we performed targeted searches of academic databases and Google Scholar and expanded our inclusion criteria to allow for gray literature. Specifically, we searched for articles that included terms related to either insects or tuna, together with an impact concept (Table S2).

Table S2: Search terms for identifying environmental impact research on insects and wild tuna

Concept	**Compound search terms**
Insects	insect OR “alternative protein” OR cricket OR grasshopper OR locus OR weevil OR *worm
Tuna	tuna
Impact	"environmental assessment" OR lca OR lcia OR "life cycle analysis" OR "life cycle assessment" OR "life cycle inventory" OR "life cycle impact assessment" OR "climate impact" OR "greenhouse gas emissions”

Table S3: Ingredients in plant-based burgers from top plant-based substitute retail brands

Company name	"Burger" product	Primary protein source(s) (>2% by weight)	Other ingredients relevant to discussion
Amy's Kitchen	All American Veggie Burger	• Textured soy protein	None
Beyond Meat	Beyond Burger	• Pea protein • Rice protein • Mung bean protein	Coconut oil
Boca	All American Veggie Burger (XL)	• Soy protein concentrate	None
Dr. Praeger's	Perfect Burger	• Hydrated pea protein	None
Field Roast	Field Burger	• Vital wheat gluten	Palm fruit oil, carrageenan
Gardein	Ultimate Beefless Burger	• Textured wheat protein • Vital wheat gluten • Soy protein concentrate • Soy protein isolate • Pea protein	None
Impossible Foods	Impossible Burger	• Soy protein concentrate	Soy leghemoglobin (heme protein), coconut oil
Lightlife	Plant-Based Burger	• Pea protein	Coconut oil
Morningstar Farms	Meat Lovers Vegan Burgers	• Wheat gluten • Soy protein isolate • Soy flour	None
Quorn	Meatless Gourmet Burgers	• Mycoprotein • Egg whites • Milk protein concentrate	Palm oil
Tofurky	Plant Based Burgers	• Soy protein concentrate • Soy protein isolate • Wheat gluten	Coconut oil

Includes plant-based burgers available from the top 10 plant-based substitute retail brands identified by the Good Food Institute (GFI) (Cameron et al., 2019), along with the Impossible Burger, which entered the consumer retail market in September 2019, three months after the GFI report was published. Ingredients were extracted from ingredient labels published on company websites.

Table S4: Ingredients in a sample of commercially available plant-based seafood substitutes

Company name	Product name	Primary protein source(s) (>2% by weight)	Other ingredients relevant to discussion
Gardein	Mini Crispy Crabless Cakes	• Textured wheat protein • Soy protein isolate • Vital wheat gluten • Chickpea flour	None
Gardein	Golden Fishless Filet	• Soy protein concentrate • Soy protein isolate • Vital wheat gluten • Pea protein	None
Good Catch	Fish-Free Tuna	• Good Catch™ Protein Blend (Pea Protein Isolate, Soy Protein Concentrate, Chickpea Flour, Lentil Protein, Faba Protein, Navy Bean Flour)	None
Heritage Health Food	Vege- Scallops	• Wheat gluten • Soy protein isolate	None
Loma Linda	TUNO	• Non-GMO textured soy protein	No
Quorn	Fishless Sticks	• Mycoprotein	Palm oil, Coconut oil
Sophie's Kitchen	Breaded Vegan Fish Fillets	• Textured vegetable protein (non-GMO isolated soy protein, pea protein)	No
Sophie's Kitchen	Black Pepper Vegan Toona	• Pea protein	No
Vbites	Fish-free smoked salmon slices	• Soy protein	Carrageenan
Vbites	Fish-free fish fingers	• Soy protein	Carrageenan
Vegetarian Butcher	Vegetarian NoTuna	• Soy protein • Wheat protein • Whey protein	None

Vegetarian Plus	Vegan Fish Fillets	• Soybean protein • Wheat protein	None

Includes a sample of plant-based seafood substitutes available in English-speaking countries using Google searches. We excluded products on the market that are not designed to mimic seafood exactly but can be used in similar ways (e.g., products made from carrots, eggplant, or tomatoes). Ingredients were extracted from ingredient labels published on company websites.

Appendix B: Research needs for plant-based substitutes and cell-based meat

- Public health
    - Epidemiological studies examining how consuming plant-based substitutes and (once available) cell-based meats, in various consumption patterns, impacts diet quality, chronic disease biomarkers and the gut microbiome, in comparison with farmed meats and minimally processed legumes
    - How hexane use and emissions in the production of soy and pea protein isolates contribute to worker and community exposures
    - Whether and how the nutrient profiles (including macro and micronutrients, fatty acid profiles, inflammatory compounds, etc.) of cell-based meat products differ from those of farmed meats
    - The scale of antibiotics used in cell-based meat production, and level of contribution to antibiotic selection pressure, especially as compared to industrial food animal production
    - Quantitative analysis of how cell-based meat production could affect the number and incidence of food-borne illnesses attributed to meat consumption

- Environmental
    - Comprehensive, multi-product life-cycle assessments comparing different plant-based substitutes (including a variety from different companies and primary ingredients), farmed meats, and other protein alternatives (including pulses, tofu, insects) to reduce cross-study methodological inconsistencies
        - A framework for data presentation to allow cross-study and cross-product comparisons is also needed
        - Include detailed breakdowns of the specific greenhouse gases (e.g., carbon dioxide, methane, nitrous oxide) associated with the production of different products, in addition to the singular footprint reported in carbon dioxide equivalents
    - More environmental impact data specifically exploring the water use, eutrophication, pesticide use, and biodiversity implications of plant-based substitutes and cell-based meats
    - Life-cycle assessments evaluating actual—not just hypothetical—cell-based meat production, with specific attention to how environmental impacts differ depending on inputs used
    - How deforestation for ingredients in plant-based substitutes compares to deforestation for pasture expansion and feed crop production
    - Ongoing environmental analyses to assess the impact of technological developments and the scaling of operations in the production of plant-based substitutes and cell-based meats

- Animal welfare
    - Comparative life cycle assessments of farmed and cell-based meat production that integrate animal welfare considerations into their scope, as suggested by Llonch et al. (2015) and Scherer et al. (2018)

- Analyses examining the number and welfare of animals involved in producing cell-based meat, given existing animal-based inputs and various potential developments
- Further research to advance cell-based meat production methods that do not rely on animal-based inputs including fetal bovine serum, tissue scaffolds, and animal-derived hydrogels

- Economic
  - Assessment of the role of plant-based substitutes and cell-based meats as drivers of any observed shifts in meat consumption and animal product production, and factors that affect rate and permanency of change
  - How different market prices, tariffs, and trade dynamics affect livestock and feed crop farmers' production levels and practices
  - The implications of a significant decrease in industrial livestock production on other industries depending on by-products (e.g., biomedical, cosmetic, pet food, clothing)
  - Exploration of ways in which small and mid-sized producers could participate in cell-based meat production
  - Economic analysis of the cost of plant-based substitutes and cell-based meats and how they may change over time due to scaling of operations, ingredient availability, and other variables
  - Analysis of the economic externalities associated with the production of plant-based substitutes and cell-based meats
  - Geographic tracking of the production and processing locations for plant-based substitutes and cell-based meat, including international distribution
  - A sociological and economic analysis of how various shifts in the agricultural market might impact jobs in the livestock and animal processing sectors and rural communities

- Sociocultural
  - An analysis of key drivers of consumption, and common consumption patterns among psychographic and other subgroups, related to plant-based substitutes and (eventually) cell-based meats
  - Research exploring whether increased consumption of plant-based substitutes corresponds with a reduction in farmed meat intake (i.e., substitutive effect) or simply additional overall "meat" intake (i.e., additive effect), as described by Stephens et al. (2018)
    - Potential licensing effects: as consumers believe they are taking a beneficial action in one meal or domain, to what extent do they compensate in others, and with what impacts?
  - Analysis of the use of plant-based substitute products as "transitional" foods (i.e., encouraging meat eaters who try them to try other alternatives to meat protein)
  - Research into whether processed plant-based substitutes are replacing less processed plant-based proteins that vegetarians would otherwise eat
  - Further exploration of the gap between consumers' willingness to try plant-based substitutes and cell-based meats and actually adopting them as a regular part of their diets
  - Consumer perceptions of and knowledge of plant-based substitutes and cell-based meats and their attributes, and reactions to marketing and counter-marketing messages

- Policy
    - Tracking and evaluation of the development and implementation of policies related to plant-based substitutes and cell-based meat internationally
    - In light of changing market dynamics, research exploring how lessons learned from previous agricultural transitions (e.g., from horse to livestock feed, from tobacco to other industries) could be used to inform the development of policies that support farmers and ranchers in transitioning to other methods (e.g., agroecological) or products (e.g., legumes)
    - Research on policies that could encourage land spared from feed crop production or industrial livestock production to be re-forested or to preserve pasture-based livestock production systems
    - Examination of industry political contributions and other markers of influence and political impact, across both meat and meat alternative industries
    - Analysis of how different GHG reduction policies (e.g., carbon tax) could impact the consumption of farmed meats and their alternatives
    - An assessment of the GRAS self-certification process and its appropriateness

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