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Original Research Article

Is cell-based meat a climate solution for Canada? Interpreting lifecycle footprints within the domestic agri-food context

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Abstract

Interest and technological know-how in cell-based meat production has grown tremendously in recent years. The appeal is wide ranging, but two main drivers include: i) the possibility of producing edible meat without requiring the slaughter of sentient animals; and ii) the potential to significantly reduce the environmental impact of animal agriculture. Owing to these potential benefits, proponents have called for major government investments in cell-based meat to further develop the technology and help launch the industry. This article critically examines the environmental promise of cell-based meat, focussing specifically on its potential role in climate change mitigation, and specifically within the context of Canada's agri-food sector. The analysis is founded upon a comparison of available life cycle greenhouse gas assessments of cell-based and conventional meat, supplemented with contextual data about the Canadian agri-food sector. Cell-based meat in Canada is found to have a likely carbon footprint similar in scale to poultry meat, pork, and beef from dairy cattle, though considerably lower than meat from beef cattle. Alongside these findings and additional contextual factors pertaining to Canada's agri-food sector, the paper argues that cell-based meat is best understood as one tool among many which could potentially support greenhouse gas emissions reductions in domestic food production if supporting conditions are met, not a silver bullet climate solution obtained by fully replacing conventional meat.

Keywords: Cell-based meat; animal agriculture; climate change; Canada; agri-food policy

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Résumé

L'intérêt et le savoir-faire technologique quant à la culture de viande en laboratoire se sont considérablement accrus ces dernières années. L'attrait que cette production exerce est vaste, mais les deux principaux facteurs qui la motivent sont : 1) la possibilité de produire de la viande comestible sans l'abattage d'animaux sensibles ; et 2) le potentiel de réduction considérable de l'impact environnemental de l'élevage. S'appuyant sur ces avantages potentiels, les partisans de la viande cellulaire ont demandé aux pouvoirs publics d'investir massivement dans ce secteur afin de poursuivre le développement de la technologie et de contribuer au lancement de l'industrie. Cet article examine de manière critique les promesses environnementales liées à la viande cellulaire, en s'attardant plus particulièrement à son rôle possible dans l'atténuation des changements climatiques, et ce, dans le contexte du secteur agroalimentaire canadien. L'analyse est fondée sur une comparaison des évaluations disponibles des gaz à effet de serre liés aux cycles de vie de la viande cellulaire et de la viande conventionnelle ; s'y ajoutent des données contextuelles sur le secteur agroalimentaire canadien. La viande d'origine cellulaire au Canada présente une empreinte carbone probable similaire à celle de la viande de volaille, de porc et des vaches laitières, mais nettement inférieure à celle de la viande de bœuf. Outre ces résultats et d'autres facteurs contextuels relatifs au secteur agroalimentaire canadien, cet article affirme que la viande cellulaire doit être considérée comme un outil parmi d'autres qui seraient susceptibles de favoriser la réduction des émissions de gaz à effet de serre dans la production alimentaire nationale si les conditions requises sont remplies, et non comme une solution miracle au problème du climat, qu'on appliquerait en substituant totalement la viande cellulaire à la viande conventionnelle.

Introduction

Interest and technological know-how in cell-based meat production has grown tremendously in recent years. More than $4 billion have been invested in its development in recent years, with some conventional meat giants (including Canada's *Maple Leaf Foods*) also turning to this nascent food technology (Kucharsky, 2022). In 2020, a restaurant in Singapore made headlines for serving the world's first cell-based chicken nuggets (Gilchrist, 2021). While demonstration projects and cell-based meat companies have been founded around the world (including here in Canada), there is presently no commercial-scale production of cell-based meat. Accordingly, some have called for major government investments in cell-based meat to further develop the technology and help launch the industry. For instance, the Good Food Institute (GFI) calls for a US$2 billion public investment into the industry in the United States as part of the country's Building Back Better initiative (Almy, 2021). Acclaimed *New York Times* columnist Ezra Klein echoed this call, asking Congress to "dream a bit bigger" in its funding of the technology, as part of what he called a national "moonshot project" to tackle climate change, among other problems associated with livestock production (Klein, 2021). In Canada, it is expected that some cell-based meat will be commercially available within the next decade, although some regulatory hurdles are expected to slow the novel protein's commercial availability (Kucharsky, 2022).

The appeal of cell-based meat is wide ranging amongst proponents, but two main drivers of interest in the technology include, first, producing meat tissues without requiring the raising or slaughtering of sentient animals,[1] and second, the potential to significantly reduce the environmental impact of agriculture (Post et al., 2020). This article focusses on the latter environmental motivation, and specifically on the question of cell-based meat's potential as a climate change solution. To inform the analysis I conducted a straightforward comparison of the carbon footprint and land use impact of commonly consumed (terrestrial) meats in Canada with the *likely* carbon footprint and land use impact of cell-based meats if the latter were to be developed commercially in Canada. While the results show that cell-based meat would likely have a lower carbon footprint and land use impact than conventional beef from beef supply chains, I argue that a wholesale replacement of conventional with cell-based meat is an ill-advised policy objective in Canada if the intention is to reduce the agri-food sector's contribution to global warming while providing complete protein foods for human consumption. This is largely because i) there already exist other protein rich foods with even lower carbon footprints than cell-based meat (including some forms of conventional meat, plant-based meat alternatives, and protein rich plants); ii) there are a number of potential climate feedbacks associated with the removal of animals from the Canadian agricultural landscape; and iii) there are obstacles involved in commercially scaling up the technology of cell-based meat in the time required to achieve Canada's Net Zero objectives (as well as significant energy implications involved in doing so). Nevertheless, if greater cultural acceptance of cell-based meat could help to reduce demand for conventional beef in Canada, and potentially help relieve pressure on agricultural land use, it could play a role amongst a broader suite of sustainable protein food transition solutions. Ultimately, the development and introduction of cell-based meat should be seen as one tool to reduce the climatic footprint of the domestic agri-food sector provided certain conditions are met – not a silver bullet solution which will be able to address the problem of anthropogenic climate change in the Canadian agri-food system on its own by eliminating animal agriculture.

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Situating the research problem

The world faces an urgent climate change crisis, and as the eleventh largest emitter of greenhouse gases (GHGs), Canada has a key role to play in supporting mitigation, both domestically through emissions

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[1] Presently cell-based meat production does involve some slaughter of animals as animal stem cells are required as starter cells. All the cell-based meat products referenced in the datasets used for this study used animal stem cells or animal products as a cellular origin (Scharf et al. 2019).

reductions, and internationally through supporting mitigation projects in low-income countries (Crippa et al., 2021). Domestically, Canada aims to reduce its CO_2 emissions to "Net Zero" by 2050, with a current near-term emissions reduction target of 45 percent below 2005 levels by 2030. Currently, agriculture is responsible for about 10 percent of Canadian emissions, and animal production (including animal housing and direct emissions from livestock and manure) accounts for about 5 percent of domestic emissions (Environment and Climate Change Canada, 2021). Not all animal production is intended to supply *meat* (with eggs and dairy being prime examples), and so direct *meat*-related production emissions from livestock in Canada would likely only make up a few percentage points of total domestic GHG emissions. However, the full GHG profile associated with conventional meat supply chains in Canada is likely significantly larger than this, for a few reasons. First, a considerable portion of domestic crop production is used as animal feed, so emissions associated with such crops should be counted towards livestock emissions. Second, additional energy from fertilizer production and other farm inputs contributes to Canadian food production (and feed crop production) even though their emissions are not conventionally labelled as *agricultural* emissions (Qualman, 2022). Third, emissions associated with post-farm gate meat supply chains (such as energy used in operating slaughterhouses, packaging and retail, post-farm gate transport, etc.) are also not included within most tallies of Canadian agricultural emissions (Qualman, 2022). Thus, if one assumes that about half of domestic crop production goes towards the livestock sector (Dyer & Desjardins, 2021), half of fertilizer production is used for animal feed crops, and three quarters of other farm energy use in the country is either for animal *feed* or animal agriculture directly, then this would mean that all animal agriculture production is responsible for about 8.5 percent of Canada's total emissions—or about 57 megatons of CO_2 equivalents (Mt CO_2e)—with *meat-related* emissions likely serving as a sizable share of that.[2]

Global estimates show that when the entire life-cycle of food supply chains are incorporated (including pre- and post-production, packaging, retail, and waste, and land use changes associated with food production), the world's food system accounts for up to *a third* of all anthropogenic emissions (Tubiello et al., 2021). Growing awareness about the climate footprint of food systems has, in turn, helped cast greater attention towards meat and animal sourced foods specifically, in particular ruminant-based foods (like beef, lamb, and dairy). Following the publication of one of the most comprehensive assessments of the environmental impacts associated with global food production (Poore & Nemecek, 2018), one of the lead authors made headlines in claiming that avoiding the consumption of meat and dairy was "the single biggest way" for individuals to reduce their environmental footprint (Carrington, 2018). Growing awareness about the climate footprint of meat has contributed to reduced meat consumption in many nations, albeit on a relatively small scale here in Canada (Angus Reid Institute, 2019). Subsequent studies examining the "carbon opportunity costs" associated with animal food production have argued that global shifts to plant-based diets could also support climate change mitigation by facilitating the sequestration of large quantities of carbon—equivalent to about the last ten years of anthropogenic fossil fuel emissions (Hayek et al., 2020), or even more (Eisen & Brown, 2022)—thanks to the

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[2] Based on back-of-envelope calculations drawing from Canada's National Inventory Report (Environment and Climate Change Canada, 2021) and the National Farmer's Union recent analysis (Qualman, 2022).

restoration of agricultural lands made possible by switching to proteins requiring less land overall for production.

Of course, any plan to entirely switch out meat for plant-based protein faces significant obstacles. First, meat plays an important role in food cultures globally and, generally speaking, a majority of consumers prefer meat to plant-based protein alternatives (Clark & Bogdan, 2019; Van Loo et al., 2019). Second, the global agri-food system is dominated by large corporate firms, from those involved in fertilizer production to container shipping to agricultural inputs and machinery, and large meat packers—many of which have vested interests in maintaining high and continued volumes of meat production and consumption (Zaraska, 2016). Third, the inclusion of animals in agri-food systems can support food security and poverty reduction, help tackle food loss, and provide other non-food benefits like fertilizers, draught power, and renewable textiles (Adesogan et al., 2020; Dou et al., 2018; Mottet et al., 2017; Ryschawy et al., 2017; Upton, 2004), calling to question what benefits might be *lost* if farm animals were entirely removed from the agri-food landscape. Fourth, there are some potential nutritional implications of a dietary transition away from animal proteins (if plant-based dietary transition is not sustained with close attention to nutrient and amino acid adequacy; Leroy et al., 2022; White & Hall, 2017).

In response to some of these obstacles, the idea of cell-based meat has gained greater attention to continue to have protein-rich meat, just without the animals. One key challenge for cell-based meat producers, however, is that conventional meat is biochemically dissimilar to living muscle tissue, the implication being that animal muscle tissue produced in a laboratory environment will not have the same texture, taste, or nutritional composition as conventional meat (Fraeye et al., 2020). Unlike plant-based meat alternatives, cell-based meat (sometimes called "cultured meat" or "*in vitro* meat")[3] uses tissue engineering and culturing of animal stem cells to produce biomass made of animal muscle tissues (Tuomisto, 2019). This is not to be confused with acellular agriculture which seeks to synthesize edible protein biomass (not "meat") through the fermentation of recombinant microorganisms (so-called "precision fermentation")—a process already commonly used to produce enzymes, proteins, and fats (such as casein, gelatin, ovalbumin, etc.; Tuomisto, 2019).

As documented below, a small but growing literature examining cell-based meat's potential environmental impact has emerged over the last decade, largely consisting of lifecycle assessments (LCAs), institutional and privately commissioned reports, and feasibility studies. Environmental LCAs seek to quantify the impact of production of different foods at different stages of the supply chain. The LCA literature on cell-based meat has been speculative by necessity since production has not yet thoroughly scaled commercially. LCAs have thus primarily been based on theoretical production models, or extrapolations of smaller scale prototypes. As one critique of the commercial viability of cell-based meat notes, "in the absence of a clear view of a production process, any calculations comparing environmental impact [of cell-based and conventional meat] are theoretical estimates based on assumptions and oversimplifications" (Thorrez & Vandenburgh, 2019, p. 216). This has resulted in high levels of uncertainty over the real outcomes of scaling-up cell-based food products (Rodríguez Escobar et al., 2021). The LCA literature

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[3] This paper uses the term "cell-based meat" in line with recent guidance from the FAO (Food and Agriculture Organization of the United Nations [FAO] & World Health Organization [WHO], 2023).

on cell-based meat has tended to exclude second-order impacts and upstream supply chain inputs from its system boundaries (i.e. impacts associated with the production of laboratory equipment, pharmaceutical-grade materials and endotoxin removal of the growth media; Hadi & Brightwell, 2021; Risner et al., 2023); as such, should the industry scale-up it is possible that the total environmental impact could be larger than that resulting from an extrapolation of its inferred footprint from LCAs.

With these caveats aside, some comparative assessments have sought to determine whether a substitution of conventional meat with cell-based meat would result in a reduced climatic impact within the food system (Santo et al., 2020; Smetana et al., 2015). One early LCA found that cell-based meat production would involve 7 to 45 percent *less* energy, 78 to 96 percent *lower* GHG emissions, 99 percent *lower* land use, and 82 to 96 percent *lower* water use than conventional meat produced in a European context, though it did caution that the results were subject to "high uncertainty" (Tuomisto & Teixeira de Mattos, 2011). A follow up study in 2015 found that while cell-based meat would require smaller amounts of inputs and require less land, these benefits "could come at the expense of more energy intensive energy use" overall (Mattick et al., 2015, p. 11941), hinting at potential trade-offs involved in the scaling up of cell-based meat. This energy trade-off for cell-based meat was confirmed in a follow up comparative LCA of a range of different meat alternative proteins by Smetana et al. (2015), who found that when compared by energy equivalent portion sizes, cell-based meat performed *worse* that other high-protein meat alternatives (including chicken and dairy-based proteins) on a range of environmental and health impacts, including greenhouse gas emissions. Meanwhile, a more recent analysis of the energy required for purifying the growth medium used in cell-based meat production has found that existing LCAs significantly underestimate energy requirements, such that environmental impacts of cell-based meat in the near future could in fact be "orders of magnitude" higher than even conventional beef—the highest impact meat in terms of its carbon footprint (Risner et al., 2023).

Because of its relatively high energy requirements, Lynch and Pierrehumbert (2019) found that the potential for cell-based meat to serve as a climate benefit vis-à-vis conventional beef fundamentally comes down to *how the energy used for cell-based meat would be generated*: If energy systems remain dominated by fossil fuel sources, they found, then the long term climatic impact of a switch from conventional to cell-based beef would result in *more* warming than a world featuring beef from cattle instead. This is owing to the different warming influences that carbon dioxide (CO_2) from fossil fuel burning has on long term global warming compared to the shorter-term warming pulse caused by direct emissions from livestock—namely methane (CH_4) and nitrous oxide (N_20).[4]

More recent LCAs comparing a range of different types of conventional meat with cell-based meats have arrived at mixed results in terms of its climatic potential, depending on the specific meats compared and other parameters of comparison (e.g., using global average values vs. national values; assuming a renewable energy source or not; incorporating land use or not). For instance, one recent comprehensive LCA examining the future environmental footprint of cell-based meat found that in a world with a *conventional energy mix* (based on 2030 stated policy goals according to the IEA's World Economic Outlook), its GHG impact

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[4] See "Discussion" for further explanation.

would be *higher* than pork and chicken, but if the world instead aggressively adopts sustainable energy, its GHG impact would be *smaller* than chicken and pork (Sinke & Odegard, 2021). Similarly, Santo et al. (2020) found the mean GHG footprint of cell-based meat (measured in kg CO_2e/ 100g protein) is about on par with the mean global GHG footprint for pork, but *higher* than that of poultry (and in turn, orders of magnitude *lower* than beef). Similar findings were also obtained in a recent analysis by the Breakthrough Institute—in the analysis, Shah (2022) found that cell-based meat (on average) would have a *greater* GHG production footprint than poultry or pork, but significantly less of a footprint than conventional beef. However, when the potential emissions associated with their so-called "carbon opportunity cost" (the potential emissions from global land use changes associated with the production of each commodity which could be obtained if that land was not used as such) were added, cell-based meat was found to have a *smaller* GHG footprint than all three main types of conventional meat (Shah, 2022). According to these latter analyses, the main determinants of cell-based meat's climate benefit mainly come down to: a) the source from which energy used in production is derived, and b) its potential to reduce total agricultural land use, which could enable significant carbon drawdown from land restoration.

One challenge from the aforementioned studies is they focus on the global scale, incorporating global average values for the environmental footprints of conventional meat production. Additionally, the literature suggests that the underlying agri-food and domestic energy and land use contexts are just as important as each food's average carbon footprints as derived from LCAs. There is thus a need for a study in a specifically Canadian context to examine the climatic potential of cell-based meat in the Canadian agri-food system.

Methods

A straightforward comparison was conducted examining the GHG footprint of conventional (terrestrial) meats typically consumed in Canada (beef, pork, and poultry—including chicken and turkey), as well as the likely GHG footprint of cell-based meat, using available LCA data and supplemented with additional Canadian-specific data. First, Canadian-specific footprint values were determined using three lifecycle meta-analyses—two of which examine existing LCAs of cell-based meat (totaling n=5) and one including comprehensive data of LCAs for conventional meats (with Canadian-specific values for beef from beef herds, n=11; beef from dairy herds, n=2; pork, n=2; and poultry meat, n=3). Second, system boundaries of the available LCAs were leveled based on anticipated values for both types of meat production in a Canadian context (ensuring that all stages of the production chain for cell-based meat were included through to retail, then leveling for protein content, and incorporating known values from carbon sequestration in typical Canadian beef production).

For the base GHG LCA studies of conventional meat and country specific commodity chain stages, Poore & Nemecek's (2018) full scale model dataset was used, as the data is broken down by country and study. While Poore & Nemecek's main findings represent average LCA values for foods *globally*, there is a noticeable difference when country-level data are extracted from the full-scale model. For instance, Table 1 shows how Canada-wide average GHG footprints for conventional meat from the dataset are substantially lower (between -21.21 percent and -68.51 percent lower) than global average values for the same types of meat (there are no datasets for Canadian lamb or mutton in Poore & Nemecek's (2018) full scale model, so lamb and mutton are excluded from the analysis). It is important to use Canadian-specific carbon footprint values (if available) if the objective is to inform domestic agri-food policy.

Table 1: Canadian vs. Global average carbon footprints of Conventional Meats in Poore & Nemecek's (2018) Full Scale Model Dataset

	Global Avg (kg CO2eq per kg of food, retail weight)	**Canada Avg (kg CO2eq per kg of food, retail weight)**	**% Difference**
Beef from Beef Cattle	94.55	64.19	-32.11%
Beef from Dairy Cattle	32.17	10.13	-68.51%
Pork	11.41	8.99	-21.21%
Poultry	11.00	5.40	-50.91%

One area that is excluded from Poore & Nemecek's (2018) LCA dataset is soil carbon sequestration in pasture-based systems, and so a process was determined to apply a carbon sequestration deduction value for the GHG footprint of Canadian beef from beef cattle. Most beef cattle in Canada are grain *finished* but spend a considerable amount of their lives grazing in cow-calf operations. Studies have found that soil carbon sequestration during grazing can offset some of the aboveground emissions, particularly in adaptive or holistic planned grazing operations (Rowntree et al., 2020; Stanley et al., 2018; Teague et al., 2016). Others, however, have found that the grazing management strategy does not make a difference to rates of soil carbon sequestration (Briske et al., 2014), and moreover that the potential for carbon sequestration in grazing operations globally is greatly exaggerated (Garnett et al., 2017). Since most Canadian pasture and rangeland is found in native grasslands, some argue that well-managed grazing could mimic the role bison played before industrialization, which helped to sequester (and continually build) carbon-rich topsoil (Brown, 2022; Kelliher & Clark, 2010). Wang et al. (2014) for instance, found that existing grazing management systems used in Canadian grasslands over the last few decades have supported a net removal of CO_2 from the atmosphere. In another detailed assessment, Alemu et al. (2017) found that carbon sequestration in beef production is prevalent, but only reduces farm-stage GHG emissions by 12 to 25 percent. Based on these latter findings, a mean carbon sequestration deduction of 18.5 percent was applied to farm-stage emissions for beef cattle GHG emissions only[5] (see Supplementary Data Sheet).

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[5] Most *dairy* cattle in Canada are not grazed in pastures the way most *beef* cattle are, so the carbon sequestration premium is only applied to beef from beef herds (Medrano-Galarza et al., 2017). Similarly, most chicken and pork are grain fed in Canada.

Once GHG footprint values were derived for Canadian conventional meats (for beef from beef herds; beef from dairy herds; pork; and poultry meat), average GHG footprint values were determined for hypothetical cell-based meat in Canada. As the technology is still very much in its infancy, there are only a handful of LCAs for cell-based meat. Scharf et al. (2019) was used for the base GHG LCA dataset, as it provides an analysis of all pre-existing full LCAs of cell-based meat. Additionally, Sinke and Odegard (2021) and, later (during review stage edits), an updated peer-reviewed version of the same study (Sinke et al., 2023) were used to fill in gaps in the system boundaries. For instance, the Scharf et al. 2019 study highlights three main hypothetical LCAs of cell-based meat—one by Mattick et al. (2015), another by Tuomisto and de Mattos (2011) and then a revised study by Tuomisto et al. (2014). The Mattick et al. (2015) study includes energy used in cleaning the bioreactor and production facility energy requirements, but does not include energy in reactor production, whereas the opposite is true of the two studies led by Tuomisto. This added a 2.29 kg CO_2e premium to the footprint for 1 kg of *in vitro* biomass in the Mattick et al. (2015) study (0.62 kg CO_2e for facility energy, and 1.67 for bioreactor cleaning), and a 0.108 kg CO_2e premium to the footprint for 1 kg of *in vitro* biomass in the Tuomisto et al. study (see Table 2). Meanwhile, the LCAs prepared by Sinke and Odegard (2021) and Sinke et al. (2023) appear to have considered the exclusions highlighted by Scharf et al. (2019), so no additional GHGs were allocated to their production stage emissions.

Table 2: Carbon footprint values for cell-based meat by production stage, cradle to factory gate in existing LCAs (kg CO_2e per kg of food product)

	Assumed Production Location	**Bioreactor materials**	**Main production**	**Facility Energy**	**Bioreactor cleaning**	**Waste**	**Study totals**	**Totals with exclusions derived from opposing studies**
Mattick et al. 2015	United States	excl.	5.13	0.62	1.67	0.08	**7.5**	**7.608**
Tuomisto et al. 2014 best case (with cyanobacteria)	Spain, Thailand, California	0.108	2.16	excl.	excl.	excl.	**2.27**	**4.64**
Tuomisto et al. 2014 worst case (with wheat)	Spain	0.108	4.27	excl.	excl.	excl.	**4.38**	**6.75**

Sinke et al. 2023 Conventional energy scenario	Unspecified (average of 15 firms internationally)	14.34	**14.34**	**14.34**
Sinke et al. 2023 Renewable energy scenario	Unspecified (average of 15 firms internationally	2.82	**2.82**	**2.82**

The carbon footprint values for cell-based meat were then leveled with the five-stage parameters used in Poore & Nemecek's comprehensive LCA. To clarify, the cell-based meat LCAs all use cradle-to-factory gate system boundaries, whereas Poore & Nemecek (2018) break down the LCA into emissions from land use changes, feed production, farm stage production, processing, transport and storage, retailing, and loss. As such, a premium of "retail stage" emissions (0.27 kg CO_2e per kg) as well as "packaging" (0.41 kg CO_2e per kg) was added to the cell-based meat products to match the LCA stages used in Poore & Nemecek (2018) as closely as possible. These values were derived from Canadian-specific values for retailing and packaging emissions of Canadian conventional meats (as it is assumed that the retail and packaging footprints would be similar for the final meat product, regardless of where the meat was derived). The analysis here additionally assumes that other stages noted in Poore & Nemecek (2018) are incorporated in the cell-based meat LCAs, at least in part, based on the system boundaries analysis provided by Scharf et al. (2019) and Sinke et al. (2023). The main caveat here is that the comparison between the conventional and cell-based meat values is limited by discrepancies in interpretation and measurement of the various system boundaries and supply chain categories.

The final step of the carbon footprint LCA comparison involved levelling the conventional and cell-based meats for protein content. This was important in order to contextualize cell-based meat's proposed replacement value over conventional protein, thanks to its animal tissue content (Moughan, 2021; Smetana et al., 2015). For instance, the Mattick et al. (2015) study's final food product was a "Chinese hamster ovary cell biomass" at 7 percent protein content, whereas the Tuomisto studies' final assumed food product was a "cultured minced meat product" at 19 percent protein content. Meanwhile, the two scenarios in Sinke et al. (2023) assumed an average protein content of 21.5 percent. Using the online public database made available for the *Canada Nutrient File*, the average protein content was determined for raw, ground beef, pork, and chicken and turkey (see Supplementary Data Sheet). By determining an average protein conversion factor for these meats, it was then possible to calculate the likely carbon footprint for each type of meat in a Canadian production context to obtain 100 grams of protein.

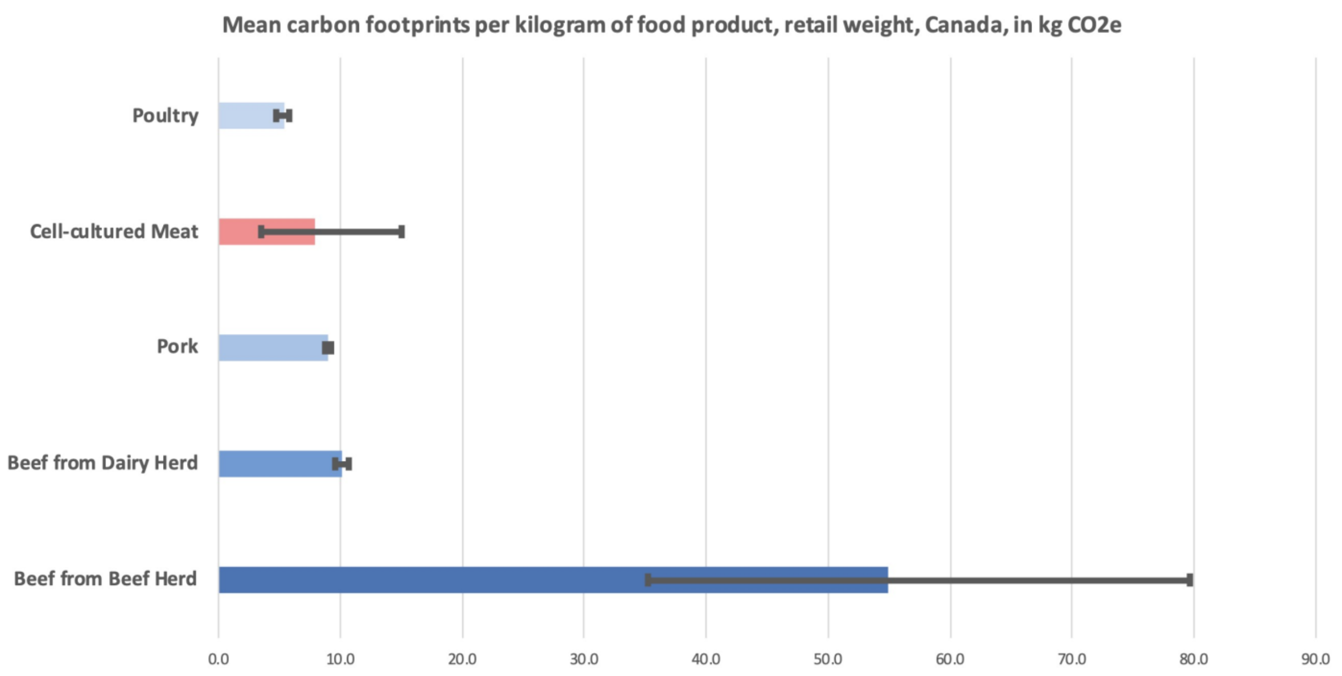
Following a similar process as above, *land use* footprints (in square meters per year; m^{2}a) were calculated for cell-based meat and conventional meats in Canada. However, as the main cell-based meat LCAs did not use the same system boundaries as Poore & Nemecek (2018) for determining land use, Sinke & Odegard's (2021) land use values were used instead, as they calculate mean land use values for beef, pork and chicken using the same feedstock-based system boundaries as they do in their analysis of cell-based meat. To clarify, Sinke and Odegard (2021) report land use values which are significantly lower for conventional meats than the average land use values identified in Poore & Nemecek's (2018) full scale model, even though the former derive their figures from the latter analysis. It was thus necessary to use Sinke and Odegard's (2021) revised values for conventional meat land use footprints to ensure that all values were derived using similar system boundaries. First, the *ratio* of Canadian average land use values relative to global average values in Poore & Nemecek's (2018) database (for each type of meat) was determined; this value was then used as a multiplier to convert the global expected land uses in Sinke & Odegard (2021) to Canadian specific values (see Supplementary Data sheet).

While efforts were made to level out system boundaries and assumptions across the three main data sources, it is important to note *considerable uncertainty underlying these estimates*, and they should thus be interpreted with caution. The assessment is merely hypothetical and intended to help inform the ensuing discussion. One final set of methodological caveats worth mentioning is that the analysis did not consider any potential nutritional differences between conventional and cell-based meat, nor additional ecological indicators (such as freshwater use, biodiversity impacts, air and water pollutants), which can offer a greater picture of a food's overall sustainability potential; nor sociocultural or economic factors which may limit the potential for cell-based meat to displace conventional meat in Canada (though these factors are briefly discussed below).

Results

The results of this analysis show that when compared with Canadian GHG footprint values, cell-based meat is likely to have a mean carbon footprint (7.9 kg CO_2e) between that of poultry meat (5.4 kg CO_2e) and pork (9.0 kg CO_2e), somewhat smaller than beef from dairy cattle (10.1 kg CO_2e), and substantially lower than typical Canadian beef (which mostly comes from beef specific herds; at 54.9 kg CO_2e), when measured in kilograms of meat product (see Figure 1). These findings are consistent with other comparative analyses of the climate footprint of cell-based meat (Santo et al., 2020; Shah, 2022; Smetana et al., 2015) in terms of the relative climate weightings of different types of meat. The carbon footprint of beef from dairy herds is substantially closer to cell-based meat than beef from beef herds, even though the latter supports some level of carbon sequestration in Canadian production systems. Given the preponderance of methane emissions from enteric fermentation as the main contributing factor to beef emissions (with a Global Warming Potential about twenty-seven times greater than CO_2 over a period of 100 years), it is perhaps unsurprising that when measured in CO_2 equivalents, beef performs relatively poorly. However, given that Canadian CH_4 emissions from enteric fermentation have been declining in recent years, a "combined" GHG footprint measured in CO_2 equivalents should be interpreted with caution (see further discussion below).

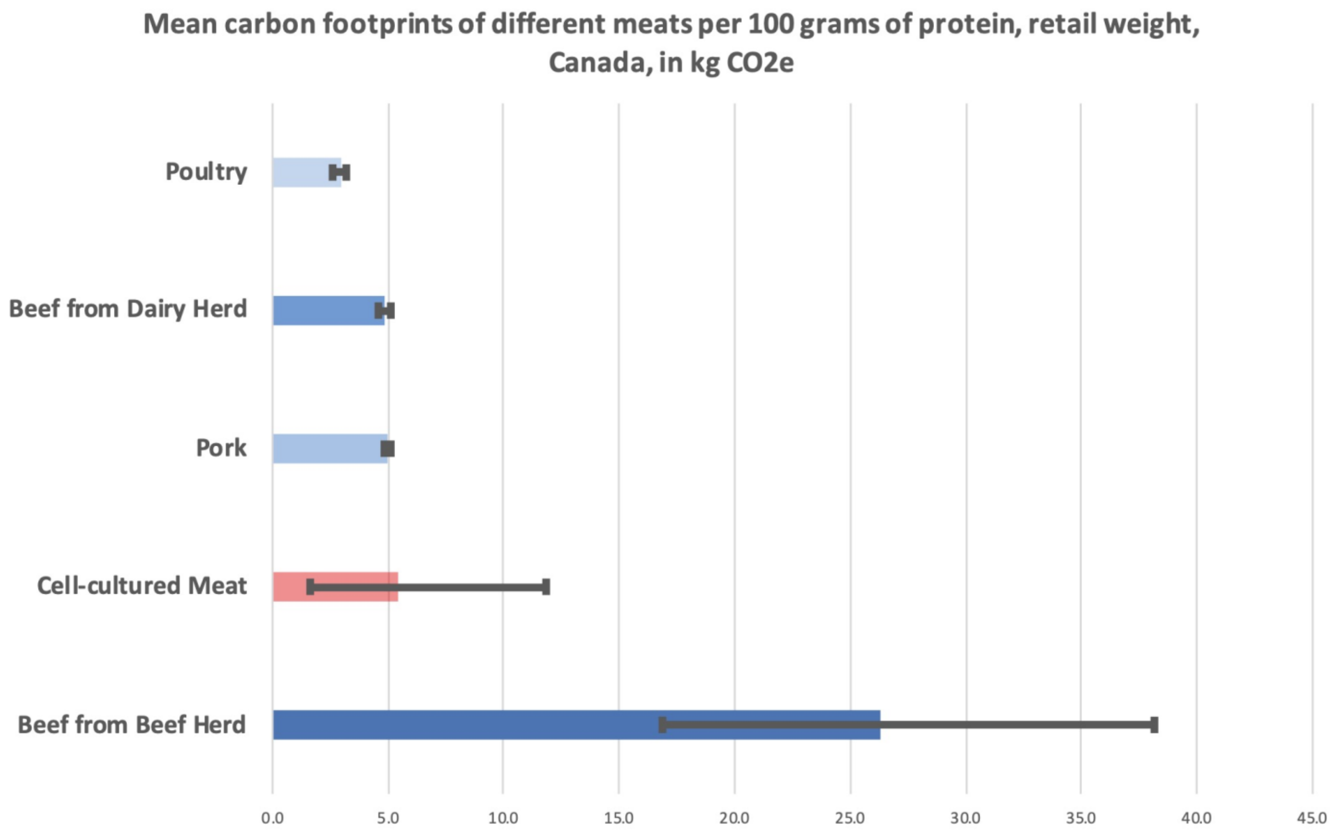
Fig.1 Mean carbon footprints per kilogram of food product, retail weight, Canada, measured in kg CO_2e. Error bars show the range between lowest and highest values in the available sample.



The discrepancy between the carbon footprint of beef from dairy herds as compared to beef from beef herds is notable. This lower footprint is a result of dairy cattle emissions being shared across different food commodities (Ritchie & Roser, 2020), the use of high quality dairy feed and methane-abatement supplements, and emerging emissions capture technologies in the dairy sector through improved manure management, yield improvements, and the adoption of methane biodigesters (Jayasundara et al., 2016). The existence of lower footprint beef from dairy cattle is striking when considering the wide range of carbon footprints seen between lowest and highest cell-based meats (denoted through the error bars in Figure 1), as the mean carbon footprint for beef from dairy cattle is on par with the *median* footprint of cell-based meat. This means that replacing conventional beef with cell-based meat is not guaranteed to reduce a consumer's climate footprint. Similarly, the replacement of poultry meat or pork with cell-based meat may or may not reduce a consumer's dietary carbon footprint—it ultimately depends on how the two types of meat compare with other meats of that same type in terms of their GHG intensity.

When levelled for protein content, beef from dairy herds and cell-based meat exchanged spots in terms of their average carbon footprint rankings (see Figure 2). While these findings are useful for highlighting the need to adequately incorporate protein content in comparisons of protein-rich foods, it is expected that cell-based meats produced for market will achieve protein levels which are commensurate (if not higher) than typical ground, raw, conventional meats, and that they will be able to do so without incurring higher energy costs (Scharf et al., 2019; Sinke et al., 2023). While the mean carbon footprint for cell-based meat placed it between poultry meat and pork, its lowest value from the sample—representing cell-based meat produced in a “renewable energy” context where all energy in production was sourced from renewables (solar, wind, and geothermal heat), and in which the soy used as feedstock was “Land Use Change Free” (Sinke et al., 2023). This matched existing findings within the literature—that the underlying energy and land use contexts will have a significant bearing on whether cell-based meat will be more or less carbon-intensive than conventional forms of poultry meat, pork, and beef from dairy cattle—also applies in a Canadian context.

Fig.2: Mean carbon footprints of different meats per 100 grams of protein, retail weight, Canada, measured in kg CO_2e. Error bars show the range between lowest and highest values in the available sample.



Finally, cell-based meat was found to have a mean land use footprint (2.8 m^2a) comparable to beef from dairy herds (2.6 m^2a), when compared in terms of retail weight (see Figure 3), and between that of pork and poultry when leveled for protein content (Figure 4). This again suggests that cell-based meat is not guaranteed to have a lower climate footprint than conventional beef in Canada—*even when considering carbon opportunity costs* arising from land use. It is nevertheless *likely* to incur a smaller land use footprint than conventional beef from beef herds (which accounts for the majority of beef consumed in Canada), and—if the right production conditions are met (in particular using renewable energy)—it could have a substantially smaller carbon footprint than all conventional meats. We now turn to a discussion of potential caveats and implications arising from this assessment.

Fig.3 : Mean Land Use per kilogram of food product, Canada, measured in m²a. Error bars show the range between lowest and highest values in the available sample

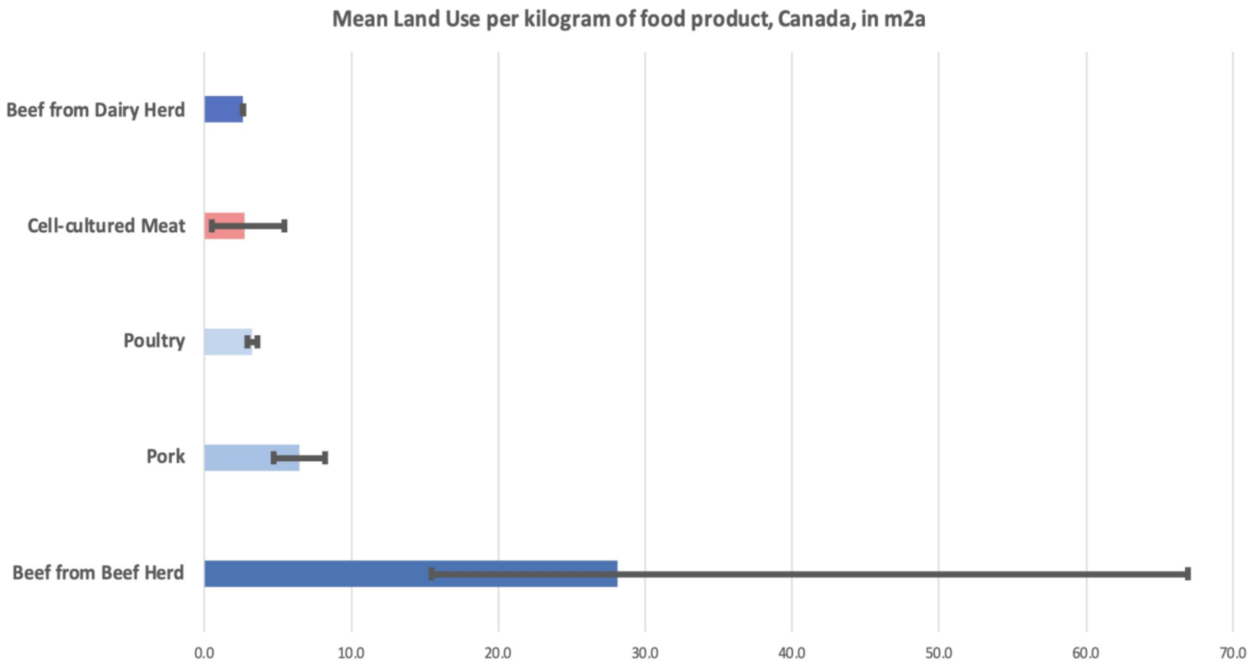
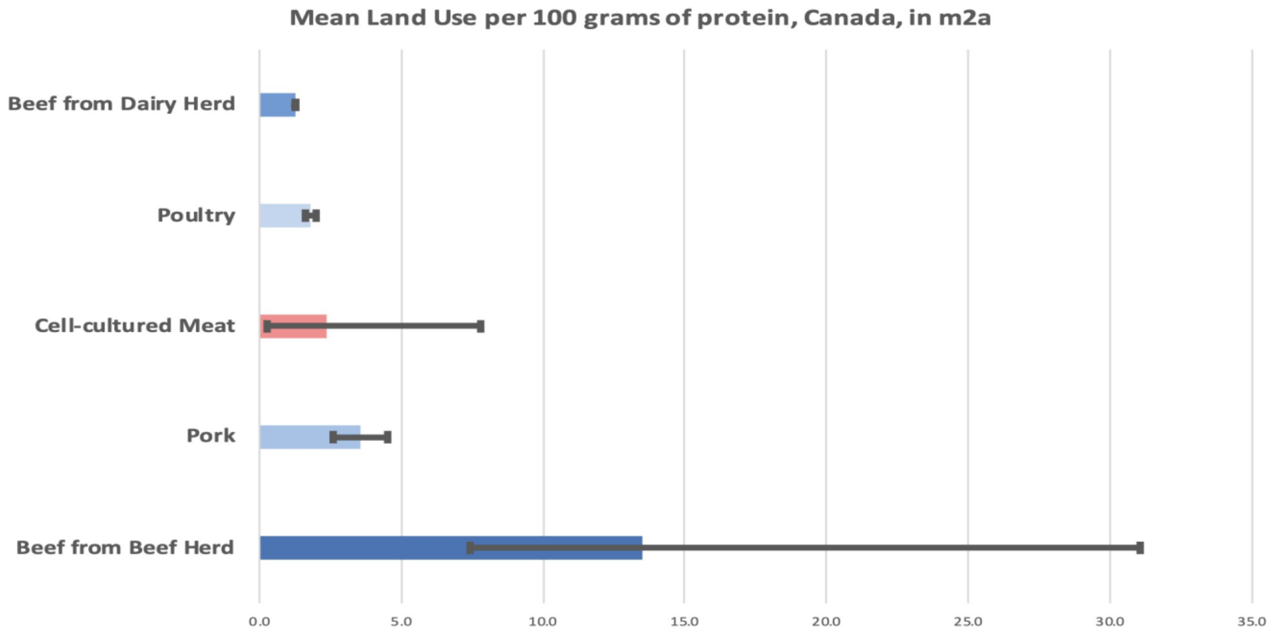


Fig.4 : Mean Land Use per 100 grams of protein, Canada, measured in m²a. Error bars show the range between lowest and highest values in the available sample



Discussion

The findings above show that cell-based meat could potentially be produced in a way which generates a smaller carbon footprint than conventional meats, and possibly even free up agricultural land for additional carbon sequestration, so long as the energy used in its production is derived from carbon neutral sources, and so long as agricultural lands no longer required for conventional meat production are reforested (and remain that way). But how likely is that in Canada over the next few decades (the period of time during which Canada aims to reach "Net Zero")? What are some of the climate feedbacks outside of the LCA parameters, and how are they likely to impact attempts to minimize cell-based meat's climatic footprint? Can cell-based meat serve as a climate-friendly animal protein replacement for meat derived from livestock? In this discussion I elaborate some important factors which contextualize the results of the LCAs above to help inform the policy context.

Energy tradeoffs and feedbacks

One of the most important determinants of cell-based meat's climatic potential is the source of the energy used in its production. Cell-based meat is energy intensive in terms of both cooling and heating (during proliferation), purification of the growth medium, and electricity required for the production facility (Risner et al., 2023; Swartz, 2021). In Canada, a majority (82 percent) of electricity is derived from low and non-emitting sources as of 2021, and this is expected to grow to 95 percent in 2050 under an "Evolving Policy Scenario" (one which is somewhat more ambitious than the "Current Policies Scenarios"; Canada Energy Regulator, 2021). In this sense, the *electricity* portion of cell-based meat production in Canada is most likely to be low carbon, particularly in provinces with mostly non-emitting grids (for instance, Quebec, British Columbia, Manitoba, Newfoundland & Labrador), in contrast to provinces which have larger shares of fossil fuel sourced electricity (for instance, Alberta, Saskatchewan, and Nova Scotia; Canada Energy Regulator, 2021). However, industrial cooling and heating is responsible for three quarters of the energy used in cell-based meat production, and for cost reasons the energy source most likely to be used for this today (in a Canadian context) would be natural gas (Alleckna, 2019). The use of passive cooling and on-site heat infrastructure *could* provide such energy with a much smaller carbon footprint, and the latter would provide green energy in a way which does not take away from the decarbonization efforts in other sectors of the Canadian economy (as the use of electricity above might). This is why the Sustainable Energy scenario envisioned by Sinke & Odegard (2021) assumed that energy for heat would be provided by a geothermal source. In short, if cell-based meat producers in Canada seek to minimize the carbon footprint associated with industrial cooling and heating of the cell proliferation process, they may need to pay more to install on-site non-emitting energy such as that provided by geothermal or rooftop solar, in addition to passive cooling systems (to benefit from Canada's relatively colder climate).

Perhaps a more important energy feedback limiting the climate mitigating potential of cell-based meat relates to scaling up the infrastructure in the first place. As noted above, cell-based meat technology is still very nascent. Even the data from LCAs used in this analysis for cell-based meat are "based on hypothetical production processes and simulation models as *currently no large-scale production facility…exists*"

(Scharf et al., 2019, p. 6 emphasis added). This means that an entire infrastructure for producing cell-based meat in Canada would have to be built, essentially from scratch, if it were to displace a significant portion of conventional meat. Scharf et al. (2019) assume that the typical facility size of a cell-based meat factory is about the size of a brewery (with the same energy, lighting, and HVAC requirements of a warehouse). In a techno-economic assessment of cell-based meat, the GFI envisioned a "large-scale" production facility which could produce 10,000 metric tons of meat per year, and would cost around US$450 million to build (Swartz, 2021). As Fassler (2021) points out, such a facility would require the bioreactor capacity equivalent to *one third of the entire global biopharmaceutical industry used today*. Moreover, such a large facility would only produce *a fraction* of the nation's meat supply. For instance, Agriculture and Agri-Food Canada reports that in 2021 there were nearly 1.3 million tonnes of *beef* produced in Canada (Agriculture and Agri-Food Canada, 2022). It would thus take nearly 130 large-scale facilities of the type envisioned by GFI to replace Canada's annual beef supply. It is impossible to tell what the carbon footprint would be for building and sourcing construction materials (concrete, lumber, metals and petrochemicals for wiring, the bioreactor and lab equipment, etc.) for this many large-scale facilities across the country, but such energy requirements arguably should be considered in the broader picture of the carbon costs of scaling up cell-based meat. Here it is worth noting that Canada's conventional meat production industry and infrastructure *already exists*, which gives it a slight advantage in terms of having already expended the bulk of energy required to build it in the first place. To maximize its climatic potential, cell-based meat producers would have to make use of best practices in using reclaimed construction materials, low-carbon building, and passive energy systems.

Lower carbon alternatives

As estimated above, all animal agriculture supply chains in Canada account for approximately 8.5 percent of domestic emissions. Already, this suggests that cell-based meat's climate mitigation potential must not be interpreted as a silver bullet solution to climate change writ large, because even if *all* Canadian animal production was halted immediately and *all animal products* (not just meat, but dairy, eggs, wool, fertilizers, etc.) were replaced with cell-based or synthetic alternatives, and even if the cell-based meat industry and all synthetic replacements for animal products were 100 percent carbon neutral, there would be only be a maximum GHG emissions reduction of around 57 Mt of CO_2 eq from Canada's annual emissions. Of course, as noted above, the GHG footprint of cell-based meat is not carbon neutral, and the development of a commercial industry to provide all the substituted materials would be significant. Moreover, in some cases—for instance substituting poultry meat, pork, or even some beef—for cell-based meat, would either result in very little emissions reductions or possibly even an increase in emissions (in terms of full protein substitution). Moreover, in terms of land use in a Canadian context, cell-based meat would likely be in the range of poultry, beef from dairy herds, and marginally better than pork. All of this suggests there are existing low carbon alternatives to the most GHG-intensive conventional meat in Canada (beef from beef herds), which are just as climate-friendly—if not more so—than cell-based meat. In particular, protein-rich plant-based foods (legumes, pulses, nuts, etc.), and even plant-based meat alternatives (which seek to mimic the texture and flavour of conventional meat but use plant proteins as a foundation), have a much lower GHG footprint than conventional meats (Poore & Nemecek, 2018; Santo et al., 2020). It stands to reason that a more effective climate-focussed protein transition for the national diet would be one seeking to replace a portion of conventional meat with existing available plant-based proteins. This already appears to be a trend in Canadian dietary consumption of protein foods over recent decades, with the ratio of animal proteins to plant proteins in the Canadian diet shifting from 64:36 in the 1960s to about 50:50 by 2017 (Roser & Ritchie, 2022). Similarly, over the last two decades per capita meat consumption has declined in Canada, from a peak of 168 pounds in 2001 to 147.3 pounds in 2020; and the shares of beef and pork in *per capita* meat consumption have declined during this period too (from about 31 percent and 29 percent, respectively, down to 27 percent and 21 percent), as the share of chicken has grown (from 40 percent up to about 52 percent; Statista, 2021). These general trends are commensurate with climate-friendly dietary transition. One exception is that the total protein supply in Canada has grown over the last seven decades (from just over 90 grams per day in the early 1960s, to just under 110 grams in 2019), which suggests there may be more protein consumption than necessary in Canada. A second exception is that declines in beef consumption have been relatively slow in this country. To this end, if the introduction of cell-based meat could help quicken the pace of reduced beef consumption, it could potentially play a role in the broader climate-positive dietary shifts already occurring in Canada, particularly by helping to swiften declines in CH_4 emissions from enteric fermentation.

Flow and stock GHGs

Nearly all direct agricultural GHG emissions in Canada come in the form of biogenic CH_4 and N_2O (Environment and Climate Change Canada, 2021), both of which are very powerful GHGs (about 28 and 273 times more powerful than CO_2 over a period of 100 years, respectively). Ruminant emissions of enteric fermentation account for 44 percent of Canadian agriculture emissions, and when combined with emissions of CH_4 and N_2O from livestock manure management, this total rises to 58 percent of Canadian agriculture emissions (Environment and Climate Change Canada, 2021). However, the relatively short lifespans of CH_4 and N_2O (in comparison to CO_2) present a bit of a conceptual problem from the point of view of climate change mitigation in the agri-food sector: In a condition where annual CH_4 or N_2O emissions are constant for the length of time it takes for these gases to naturally break down in the atmosphere (12 years in the case of CH_4, and 109 years in the case of N_2O; Smith et al., 2021), these emissions would make a negligible contribution to global warming, because each year natural sinks would be breaking down the same quantity of gases as that being emitted (effectively rendering a "Net Zero" condition for these gases). This contrasts with anthropogenic CO_2 emissions, a portion of which will remain in the atmosphere for thousands of years. Thus, even constant emissions of CO_2 would contribute to global warming on human timescales. Whereas climate mitigation policy seeks to completely cease anthropogenic CO_2 emissions (in net terms), what really matters in terms of CH_4 and N_2O emissions is their *rate of change*: If emissions of CH_4 and N_2O are *growing*, they have a pronounced warming impact; and conversely, if their emissions are *declining*, the result would be *atmospheric cooling* (Allen et al., 2018; Cain, Lynch, et al., 2019; Lynch et al., 2020). In this sense, the nature of direct livestock emissions presents an opportunity for climate-friendly food production, since meat from animals could still be produced without contributing to global warming (so long as CH_4 and

N_2O emissions are declining at a rate if about -0.3 percent reduction per year, or greater, in the case of CH_4; Cain, Allen, et al., 2019).

Interestingly, over the last fifteen years, emissions of CH_4 and N_2O from enteric fermentation and manure management have declined in Canada, though only minimally (Environment and Climate Change Canada, 2021). And this, in turn, means that direct livestock emissions in Canada—even direct methane emissions from enteric fermentation and manure from beef cattle, which receive inordinate amounts of attention as a cause of climate change—are not presently a significant contributor to global warming, especially if their present emissions trends continue (Katz-Rosene, 2020). However, this does not mean that livestock *supply chains* are not contributing to climate change: Emissions growth in N_2O from agricultural soils—a result of fertilizer and crop residue decomposition—have served as the predominant driver of emissions growth in the agriculture sector more broadly. Ironically, it is the animal meats *with lower relative GHG intensities*—poultry meat, pork, and grain fed beef—which are contributing more today to the Canadian agriculture sector's global warming footprint (through their substantial use of domestic crop production and fertilizer use).

What does this all mean for cell-based meat's climatic potential? On one hand, it suggests that cell-based meat's role as a climatically superior protein food option to Canadian beef from beef supply chains may not be as significant as originally appears through a comparison using CO_2e as a measure for CH_4 and N_2O. On the other hand, if we recognize the pronounced role that reductions in the domestic beef cattle herd have played in driving CH_4 and N_2O emissions reductions, it hints at additional (near term) climatic benefits to be had from further reducing the size of the beef herd and the scale of domestic livestock feed production. Here again cell-based meat could play a climate-friendly role merely by supporting a small reduction in the national beef herd, and by lessening domestic demand for agricultural cropland use. This climatically beneficial situation could be achieved without having to completely remove animals from the agri-food system.

Land use feedbacks

Proponents of cell-based meat suggest it could generate a major climate benefit from a reduction in land use. In theory, this is because a reduction in total acreage required for feed production and pasture enables land to be restored to its native habitat, thus resulting in carbon uptake from the restoration of vegetation (this is the aforementioned carbon opportunity cost benefit noted above; Hayek et al., 2020; Searchinger et al., 2019). But there are at least three main obstacles to fully realizing this opportunity cost when evaluated in a Canadian context. First, in Canada, over 85 percent of arable land is situated in the prairies, and thus a considerable portion of food production (including production of animal feed crops) takes place in that region (Campbell et al., 2002). Over 80 percent of the Canadian beef herd is raised in the prairies, from lands predominantly made up of native grasslands (Pogue et al., 2018). This means that land restoration in much of this area arising from phasing out meat production would be returned to native grassland, an ecosystem reliant upon large grazing herbivores (Anderson, 2006). True ecosystem restoration in Canada's prairie grasslands would thus require the return of bison and elk, or other large ruminant species (or perhaps allowing cattle to graze freely as a proxy for bison), and these wild ruminants would still produce a considerable amount of methane (Hristov, 2012). If restored grasslands thus result in continued emissions of CH_4 and N_2O from wild ruminants and their manure, then these emissions would negate emissions reductions achieved through the phasing out of livestock production (Cromsigt et al., 2018; Scoones, 2022).

Second, in order for carbon opportunity cost benefits to accrue, one has to ensure that agricultural lands previously used to support meat production actually result in less land used for agriculture. That is, one would need to ensure that such agricultural lands are not merely switched to *other* forms of agricultural production. Yet, without very strong policy intervention and financial compensation, the latter is arguably unlikely, as the drive to derive profit from agricultural land would be a strong motivator to continue its use in agriculture (particularly given expected high growth in demand for Canadian agricultural exports this century). Moreover, taking agricultural land out of livestock production, or converting it to cropland, could have unintended consequences for the climate and domestic food security. In prairie ecosystems, a conversion from rangeland with ruminants to cropland would release carbon stored in their perennial soils (Gage et al., 2016). And in non-grassland settings, (such as in eastern and western Canada) removing ruminants from pasture may not in fact yield net land use savings. This is because ruminant foods can be produced on marginal lands where crop production is not feasible. For instance, in a study examining the carrying capacity of U.S. land for food production under a range of different dietary scenarios (Gage et al., 2016), "less meat" and lacto-vegetarian diets outperformed vegan diets due to the trade off from land use savings from systems which seek to remove ruminants from marginal lands.

A third issue, related to the above, pertains to ecosystem restoration from restored pasturelands in eastern and western Canada (outside of the prairies). While successful forest remediation in these non-prairie regions could indeed lead to carbon sequestration (and produce biodiversity benefits), there are also limiting factors in terms of the net long term climate impact: First, the darkening of land cover from decreased albedo would counteract the cooling impact from CO_2 uptake, at least in part (Jiao et al., 2017). Second, the return of wild ruminant populations (deer, moose, etc.) and beaver habitats would increase non-anthropogenic methane, which again would counterbalance some of these CO_2 gains from increased sequestration in restored areas (Cromsigt et al., 2018; Whitfield et al., 2015). Finally, for such restored managed forestlands to contribute to climate mitigation, they would have to remain intact (protected from wildfire, pests, forestry, etc.), otherwise forest destruction would return CO_2 back to the atmosphere. Unfortunately, the long-term protection of restored forests is not guaranteed given the growing scourge of wildfires, tree pests, and demand for harvested wood products in Canada (Saxifrage, 2021). For all these reasons, claims about the potential climatic benefits from land use change resulting from the substitution of conventional meat (and even beef from beef supply chains) with cell-based meat need to be interpreted in the context of potential feedbacks which may negate some of the expected gains. Nevertheless, if careful attention were paid to the land use change context in Canada while cell-based meat is introduced to market, such that considerable thought goes into net gains/losses and potential land use feedbacks from albedo, forest damage, and the return of wild ruminants, its purported land use benefits *could* be obtained, particularly if used to replace a portion of conventional beef consumption. Once again, this hints at a role that cell-based meat *could* play in a climate-friendly dietary transition in Canada if other pieces of the agri-food puzzle also fall into place, and if the right conditions are met. Yet it is important to know that merely switching out conventional meat for cell-based meat does not guarantee a climate change mitigation benefit for Canada.

Conclusion

This paper has sought to examine whether cell-based meat can serve as a climate solution for Canada's agri-food sector. Based on three existing meta-data LCAs supplemented with Canadian-specific details, the likely mean carbon and land use footprints for cell-based meat were determined and compared to poultry meat, pork, and two different sources for beef (from dairy and beef herds). The analysis found—consistent with existing analyses—that the mean carbon footprint for cell-based meat was similar to that of poultry meat and pork, and lower than that of beef from beef cattle. However, this analysis found that the discrepancy between cell-based meat and beef was smaller than much of the existing literature has found, in part because Canadian-specific values were used for conventional meat (where average GHG footprints are lower than global averages), and in part because specific data for beef from dairy herds was obtained (which has a lower GHG intensity than beef from beef cattle), and finally because Canadian beef production is understood to help sequester carbon, which helps offset part of its above ground GHG footprint. Moreover, while much of the existing literature has found cell-based meat to have a lower land use footprint than conventional meats, this was surprisingly not found to be significant when compared with beef from Canadian dairy herds or poultry meat, which are both highly efficient agricultural industries with regards to land use relative to global dairy and poultry sectors.

The Canadian-specific LCA findings are useful in informing the discussion about climate change mitigation in the domestic agri-food sector. In Canada, just over a quarter of those surveyed said they would be willing to try cell-based meat—but amongst millennials and younger the portion willing to try it is closer to three quarters (Charlebois, 2022). Despite more than a dozen firms in Canada working on bringing cell-based meats to market, none has yet applied to Health Canada for regulatory approval.[6] While there appears to be a flurry of interest in cell-based meat, judging from the emergence of new advocacy groups—such as the Good Food Institute—industry events and more than US$2.8 billion in investment funding, most of this has taken place outside of Canada (with the U.S. and Israel accounting for the majority of capital funding; Mishler, 2023). Again, one of the main reasons for expressions of interest in cell-based meat involves its presumed lower carbon footprint. However, as hinted in the range of values from which mean LCA footprints are derived, LCAs are just part of the contextual story; they must be interpreted in light of the extraneous socio-political and ecological contexts of food production in which the data are situated. In the end, in order for cell-based meat to serve as a meaningful climate-friendly replacement for conventional meat in Canada, the following conditions would have to be met: First, its lifecycle carbon footprint must be lower than the specific conventional meat it is replacing (not merely lower than the global average footprint of said conventional meats); Second, the energy used to produce it would have to be generated from low-carbon sources, and in such a way that does not delay ongoing efforts to

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[6] In the United States, two firms have acquired permission from the USDA to sell their product commercially (Stober, 2023).

decarbonize Canada's energy system in other sectors; and third, its land use requirements must be lower than conventional meat land use requirements, and moreover, they must be leveraged to result in ecosystems restoration of agricultural lands where the carbon sequestration benefits are substantiated (and where they do not result in a reduction of the food supply). There are thus windows of opportunity for cell-based meat to play a role in Canada's agri-food context, particularly as a tool to support the demand reductions for conventional beef from beef herds—but insofar as serving as a comprehensive solution to the climatic impact of animal sourced foods in this country, cell-based meat is no silver bullet.

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Conflicting Interests Statement: RKR would like to declare that he lives and volunteers his time on a family farm which earns income from the sale of animal-source foods.

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