NUTRITIONAL AND ENVIRONMENTAL IMPACTS OF LIVESTOCK PRODUCTION SYSTEMS IN CANADA: A FOOD SYSTEMS PERSPECTIVE

By

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Abstract

Meeting the challenge of providing a consistent supply of nutritious food for a growing global population is a significant issue facing humanity in the 21st century. Animal-sourced foods (ASF) play a vital role in global food security and nutrition, but their production is often criticized for its high resource demand and greenhouse gas (GHG) emissions. This study examined the relationship between animal production and the environmental and nutritional impacts of land use and dietary choices in Canada. Data regarding animal feed demand and land base requirements, nutrient composition, prices and GHG emissions of crop and animal-based products, human nutritional requirements, and socio-demographic factors affecting food choices were collected from various sources, including Statistics Canada, USDA, industry reports, and published literature. The research employed a combination of mixed research methods, such as multilevel mixed-effects probit regression, inverse probability weighted with regression adjustment, mathematical diet optimization techniques, and spreadsheet models for data analysis. The analysis demonstrated that Canada's total annual dry matter (DM) feed demand in 2016 was approximately 63.9 million t, requiring approximately 17.9 million ha of land. Diet optimization indicated that nutrient intake requirements of Canadian population could generally be met from the domestic food supply, except for certain fatty acids and vitamins. Omnivore, lacto-ovo, and lacto-vegetarian diets required more food to meet Recommended Daily Allowance (RDA) requirements and produced more GHG emissions than vegan diets. However, completely removing animals from Canadian farming systems and transitioning to vegan diets led to increased diet costs. Based on our analysis, the exclusion of red meat from diets resulted in statistically significant differences in the intake of 14 -17 nutrients, depending on the analytical approach used. Further, the risk of calcium, energy, potassium, and vitamin D inadequacy was higher for people who did not consume red meat, while potential inadequacy for magnesium, fiber, and vitamin A was lower for those that did. Sex, education, family status, and cultural background are important determinants of dietary choice among Canadians. These findings can help scientists, policymakers, farmers, and other stakeholders make informed decisions about how to achieve food security and sustainability in a changing world.

FOREWORD

This thesis is prepared in a manuscript format and consists of eight chapters. The first chapter introduces the thesis, outlining the need for and relevance of food system sustainability. The second chapter highlights the current literature regarding the intersection between livestock production, human nutrition and the environment, and identifies gaps in knowledge that require additional research. The third chapter presents an approach for estimating the quantity of feed and land base required to feed the livestock species of commercial relevance in Canada, which was necessary for subsequent modeling efforts. The fourth chapter evaluates the capability of Canada's agri-food system to provide foods that meet nutritional requirements and environmental sustainability goals by considering food production and consumption scenarios in a comprehensive modeling framework. The fifth chapter examines the nutrient intake of Canadian consumers who eliminated red meat from their diet versus those who did not using dietary intake data from the 2015 Canadian Community Health Survey (CCHS) dataset. The sixth chapter characterizes demographic and socio-economic factors that are associated with Canadian consumers who include and exclude meat from their diets. Chapter 7 provides a synthesis of the research conducted and Chapter 8 highlights main conclusions and recommendations for future work in this area.

Status of Publications:

This thesis is written following a manuscript format and is composed of four manuscripts. All manuscripts in this thesis are formatted according to the guidelines of the Canadian Journal of Animal Science. The titles of these manuscripts and list of contributing authors are as follows:

Chapter 3: **"Feed and Land Requirements for Livestock Production in Canada"** is in preparation and will be submitted as a short communication to the Canadian Journal of Animal Science, with the following authors: E.G. Kebebe, R. White, G. Mengistu, M. Cordeiro, G. Legesse, T. McAllister, S. Jensen, K. Wittenberg and K. Ominski.

Contributions of Authors:

E.G. Kebebe: Conceptualization, methodology, writing of original draft and finalizing the papers by incorporating comments; R. White: Supervision, reviewing and editing; G. Mengistu: data validation; TM. Cordeiro: data validation and reviewing; G. Legesse: reviewing and editing; . McAllister: Interpretation, reviewing and editing, S. Jensen: data collection and curation; K. Wittenberg: Interpretation, reviewing and editing; K. Ominski: Supervision, reviewing and editing.

Chapter 4**: "Assessing Environmental Impacts and Nutritional Adequacy of Least Cost Diets Based On Different Dietary Patterns in Canada"** is in preparation to be submitted to Agricultural Systems with the following authors: E.G. Kebebe, K. Ominski, K. Wittenberg, H. Aukema, T. McAllister, G. Legesse, E. J. McGeough , N. Ibrahim and R. White.

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Chapter 5: **"Nutritional Impact of Excluding Red Meat from the Canadian Diet"** has been published in Meat Science. Authors in this manuscript are: E.G. Kebebe, N. Ibrahim, R. White, H. Aukema, T. McAllister, G. Legesse, N. Riediger, E. J. McGeough , K. Wittenberg, and K. Ominski.

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Chapter 6: "**Characterization of Consumer Behavior Associated with Red Meat Exclusion in Canada"**, is in preparation to be submitted to Food Security. Authors in this manuscript are: E.G. Kebebe, N. Ibrahim, R. White, K. Wittenberg, H. Aukema, T. McAllister, N. Riediger, G. Legesse, E. J. McGeough , and K. Ominski.

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DEDICATION

I dedicated this work to my mother Hello Abe, my wife Konjit Mussie, and to my kids Joseph, Lambie and Ayano (Amen).

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LIST OF ABBREVIATIONS

AI	Adequate Intake
AIC	Akaike's Information Criteria
AMPM	Automated Multiple-Pass Method
ANOVA	Analysis Of Variance
ASF	Animal-Sourced Foods
BCM	Bias-Corrected Matching
BIC	Bayesian Information Criteria
BMI	Body Mass Index
CCHS	Canadian Community Health Survey
CFIA	Canadian Food Inspection Agency
CH_4	Methane
CO_2-eq	Carbon Dioxide Equivalent
CRA	Complete Removal of Animals
DHA	Docosahexaenoic Acid
DM	Dry Matter
DPA	Docosapentaenoic Acid
DRI	Dietary Reference Intakes
EAR	Estimated Average Requirement
EPA	Eicosapentaenoic Acid
FCS	Farmers For Climate Solutions
GHG	Greenhouse Gas
GWP	Global Warming Potential
ha	Hectare
IPCC	Intergovernmental Panel on Climate Change
IPWRA	Inverse Probability Weighted Regression Adjustment
kg	Kilogram
LCA	Life Cycle Assessment
LP	Linear Programming
Mt	Metric Tonne
N_2O	Nitrous Oxide
NRC	National Research Council
PSM	Propensity Score Matching
PUFA	N-3 Polyunsaturated Fatty Acids
RAS	Recirculating Aquaculture Systems
RDA	Recommended Daily Allowance
RDC	Research Data Center
UL	Upper Intake Level
UNDESA	United Nations Department of Economic and Social Affairs
UNICEF	United Nations International Children's Emergency Fund
USDA	United States Department of Agriculture

CHAPTER I: GENERAL INTRODUCTION

Driven by world population growth, increases in disposable income, and urbanization, global food demand is poised to grow for the rest of the 21st century (UNDESA, 2019). There is a notable gap between the amount of food currently produced and the amount needed to feed the world's population in 2050 (Searchinger et al., 2019). Approximately one-third of future food demand increases may come from population growth, while the remaining two-thirds may come from increasing wealth and the desire for more diverse diets (Ranganathan et al., 2016; Springmann et al., 2018). Rising incomes have been shown to lead to dietary changes and increased spending on animal-sourced foods (ASF), including meat, milk, eggs, fish and other seafoods (Fukase and Martin, 2020; Rust et al., 2020). By 2050, global demand for dairy products and meat is projected to increase by 74% and 58%, respectively (FAO, 2012). In response to a growing demand from developing countries, global meat production is predicted to increase by 19% in 2030 compared to 2015-2017 (FAO, 2020; UNICEF, 2021). As one example of the expected impact of these trends, strong international demand for ASF will provide producers with an opportunity to increase export volumes to several middle-income countries seeking Canadian meat products, such as beef and pork.

With the increasing demand for food, there arises a pressing global challenge of producing a sufficient supply of nutritious food to sustain the growing human population while also ensuring environmental sustainability (Poore and Nemecek, 2018; Barrett et al., 2020). The challenge ahead is particularly arduous for ASF (Röös et al., 2017; Godfray et al., 2018). Livestock production has been described in some studies as extremely resource-intensive due to its high land and water requirements, as well as detrimental to the climate, biodiversity, and the environment at large (Godfray et al., 2018; Poore and Nemecek, 2018). More specifically, the livestock sector is heavily dependent on land resources, with feed production and grazing accounting for approximately half the world's agricultural land and 40% of all arable land (Mottet et al., 2017; Karlsson and Röös, 2019). Several previously published sources have reported that sheep meat, beef, dairy products, and pork are among the most resource-intensive food products when expressed on a land use per kilogram of product basis (Clark and Tilman, 2017; Poore and Nemecek, 2018). It has been estimated that approximately 100 times more land is required to produce a kilocalorie of beef and sheep meat versus plant-based alternatives (Karlsson and Röös, 2019). In Canada, approximately 62.7 million ha of the land base is dedicated to agriculture, with perennial forage land accounting for 19.3 million ha in 2016 (Statistics Canada, 2017).

In addition to land use, livestock production systems are often associated with high greenhouse gas (GHG) emissions per unit of product, and therefore, some researchers and policymakers are calling for the substitution of ASF with plant-based alternatives (Bonnet et al., 2020). Diets rich in meat, particularly those containing ruminant products, are associated with higher environmental costs, including higher GHG emissions (Karlsson and Röös, 2019). These emissions are associated with enteric fermentation, the production of animal feeds, manure management, and fossil fuel use on the farm (Grossi et al., 2018; Murphy et al., 2022). In Canada, agriculture accounted for 8.2% of total GHG emissions in 2020 (Environment and Climate Change Canada, 2022), with the beef cattle industry alone accounting for more than 53% of total agricultural emissions (Alemu et al., 2017; Liang et al., 2020). Globally, environmental impacts associated with livestock production may increase over the next several decades because of income-dependent dietary shifts toward more meat-based diets, particularly in populous and emerging middle-income countries in Asia (Clark and Tilman, 2017; Röös et al., 2017; Godfray et al., 2018). However, livestock have the capacity to convert inedible forage and surplus food to edible food. In doing so, they contribute to food security by providing a source of high-quality protein and essential micronutrients, including iron, zinc, and vitamins B-12 and A (Mottet et al., 2018). In addition, livestock production offers various advantages beyond fulfilling the demand for animal-derived foods. It serves as a crucial component of the Canadian economy within the current agri-food system. Ruminants, in particular, also contribute significantly to maintaining biodiversity, as well as providing essential services such as nutrient cycling and water filtration (McConkey et al., 2003; Pogue et al., 2018) and improving soil fertility when manure is utilized as a natural fertilizer (Mottet et al., 2018).

The dual burdens of meeting nutritional requirements for a growing global population and the need to alleviate adverse effects of livestock production and consumption on human and planetary health are shaping research priorities, influencing policy, and changing people's perceptions of food (Reisch, 2021). Appropriately, the 2021 U.N. Food Systems Summit has focused on healthier and more sustainable food systems worldwide (von Braun et al., 2021). Increasing agricultural productivity without expanding the area of land required to grow food (Van Eenennaam and Werth, 2021; Leroy et al., 2022) and shifting from meat and other animal products to plant-based diets (Willett et al., 2019; Bonnet et al., 2020) have been considered promising climate change mitigation strategies. However, debates regarding ASF production and consumption are complex, suggesting the need for changes in both for a sustainable food future (Röös et al., 2017; Barrett et al., 2020).

Achieving nutritional adequacy and agricultural GHG emissions reduction through increased agricultural production has focused on improving the efficiency of livestock and their resource use (Mottet et al., 2017; Chang et al., 2021). Increasing efficiency requires land use change and technological innovations in crop and livestock breeding/genetics, as well as health, management, and information technology to reduce environmental impacts (Van Eenennaam and Werth, 2021). The productivity and efficiency gains mentioned above have been proven to reduce feed requirements, land use, and GHG emissions per kilogram (kg) of meat or liter (l) of milk produced (Legesse et al., 2016). Although emergent genetic, agroecological, digital, and other innovations offer the promise of improving efficiency and addressing these serious challenges, projections show these solutions alone may not be enough to deliver the desired outcomes (Smith, 2015; Röös et al., 2017; Swinburn et al., 2022). In contrast, proponents of consumption-side solutions argue that the shift to plant-based diets is a preferable solution to ensuring nutritional adequacy and reducing the environmental impacts of food systems (Willett et al., 2019; Bonnet et al., 2020). Thus, a reduction in the consumption of ASF, including red meat, has been proposed as a strategy to protect the natural environment and promote human health (Godfray et al., 2018; Rose et al., 2019; Garvey et al., 2021), leading to decreased cropland and pasture areas, and reduced GHG emissions (Smith, 2015; Röös et al., 2017; Swinburn et al., 2022). The concept that dietary choices (including the types and amounts of foods that individuals consume) are major determinants of environmental impacts and human health has become the focus of considerable research in recent years (Poore and Nemecek, 2018; Clark et al., 2019; Willett et al., 2019). The EAT-Lancet Commission recently suggested that transformation to climate-friendly diets by 2050 will require a 50% reduction in the consumption of red meat and a doubling in the global consumption of plant-based foods (Willett et al., 2019). Several studies in North America and elsewhere have assessed the GHG emissions mitigation potential of land use change (Aleksandrowicz et al., 2016; White and Hall, 2017; Auclair and Burgos, 2021). A growing body of literature also exists in Canada on the environmental impacts of diet at the individual level (Veeramani et al., 2017; Chaudhary et al., 2018; Vergeer et al., 2020). However, there are recent indications that the complete elimination of animals from the U.S. food production system would reduce U.S. GHG emissions by only 2.6% (White and Hall, 2017). Moreover, achieving a substantial reduction of ASF is uncertain because food consumption decisions are driven by a myriad of factors, including age, sex, education, household income, cultural food customs, religious rituals, food nutrient profile, food knowledge and preparation skills, health consciousness, educational campaigns for healthy foods, weight control cognitions, and behaviors, product advertising, as well as the environmental footprint of food (Moser et al., 2011; Stok et al., 2017; Taufik et al., 2019).

Recommendations regarding shifting production and consumption of ASF to plant-based alternatives require a comprehensive analysis to consider the efficiency of the alternatives and fully account for the nutritional quality of ASF and other contributions such as CO_2 sequestration (Adesogan et al., 2020). Animal products contribute to global food security by supplying essential macro and micro-nutrients (Mottet et al., 2017) and are comprised of high-quality proteins, including nine essential amino acids needed by humans, some of which are limited in plant-based food sources (Enahoro et al., 2018). The decision to shift to exclusively plant-based diets might have health risks, including nutritional deficiencies in vitamins (A, riboflavin, B12, D), calcium, zinc, and iron (Cramer et al., 2017; Chungchunlam et al., 2020). Therefore, the elimination of ASF from diets could be risky if the nutritional impacts on various population categories are ignored. As such, the contribution of livestock production to human nutrition and food security, as well as critical CO_2 sequestration by grazing ruminants and the impact of livestock on the environment, have become highly polarized topics.

To achieve sustainability in our food systems, it is crucial to identify diets that meet nutritional requirements while also adhering to ecological limits, promote good health, are affordable, culturally appropriate, and accessible with a reliable supply chain (Seconda et al., 2021). Although there is a growing consensus regarding the need to meet nutritional requirements and address environmental sustainability challenges, there needs to be more agreement regarding the approaches necessary to achieve sustainable food systems. Studies exploring human dietary shifts in Canada have given little attention to a comprehensive understanding of the competition for land between humans and animals, the nutritional quality of the food, and the environmental impacts of our agri-food systems (Charlebois et al., 2020). Therefore, a clear understanding of the interdependence between agricultural production, health, nutrition, and the environment is central to achieving sustainable agri-food systems.

This thesis strives to address the question of how the dual objective of nutritional adequacy and reduction of agricultural GHG emissions could be achieved. Modeling research that examines the link between the food system, human nutrition, and the environment within the Canadian context could help find solutions to these complex questions. A systems-based approach was used to assess options for animal production systems that optimize food supply and human nutrition and reduce environmental impacts, with special emphasis to the growing body of knowledge regarding the role of red meat in sustainable food systems. Further, Canadian data was used to examine consumption patterns of consumers, with detailed characterization of the demographic and socio-economic factors that influence meat consumption. Beef cattle production served as the focus for this work, given that it represents an economically important industry within Canadian agriculture and is at the nexus of benefits and challenges associated with environmental sustainability including GHG emissions and nutritional adequacy of our food systems.

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CHAPTER II: LITERATURE REVIEW

Food systems are expected to provide sufficient, safe, and nutritious food for all, support the livelihoods of millions, and do so in an environmentally sustainable manner (Deconinck et al., 2021; Fanzo et al., 2021; Beal et al., 2023). Technological innovations in agri-food systems over the last century have led to significant improvements in various aspects of food production. Since 1961 alone, advancements in food production, among other factors, have contributed to an increase of more than 30% in the food supply per capita (Shukla et al., 2019). However, these innovations have also led to negative externalities, such as diet-related greenhouse gas (GHG) emissions, environmental degradation, and reduced biodiversity (Barrett et al., 2022). Meeting the food demands of a growing global population while preserving natural resources and avoiding harm to ecosystem services is one of the major challenges of the 21st century (Fanzo et al., 2021; Plowright et al., 2021). Transforming food systems to benefit human nutrition and health, protect ecological resources, support livelihoods, provide affordable food, and uphold social, cultural, and ethical values is a daunting challenge. As such, a comprehensive examination of current global food systems, including animal-sourced food consumption, on the above parameters is needed.

The literature review chapter examines the role of animal production in Canada's economy, as well as climate change and natural resource use. Further, it identifies knowledge gaps in the existing literature regarding the sustainability of both production-side and consumption-side options to meet nutritional health and GHG emission reduction objectives.

2.1. The Role of Livestock in Canada's Economy

The agriculture and agri-food sectors significantly contribute to the Canadian economy, and Canada is one of the world's largest producers and exporters of agricultural products (Halbe and Adamowski, 2019). In 2021, the agriculture and agri-food system in Canada employed 2.1 million people, provided one in nine jobs, and generated CA$ 134.9 billion (approximately 6.8%) of the national GDP (Agriculture and Agri-Food Canada, 2022). The Canadian beef and dairy sector specifically generated approximately 347,000 jobs directly or indirectly, with every job in the sector yielding another 3.9 jobs elsewhere in the economy (Canadian Cattlemen’s Association, 2022). The Canadian beef sector alone generated CA$ 9.7 billion (14% of total farm cash receipts), representing the second-largest source of farm cash receipts, and contributed CA$ 22 billion to the domestic GDP from 2019 to 2021 (Canadian Cattlemen’s Association, 2022). Canada is globally recognized as a major exporter of red meat and livestock. In 2021, Canada's export figures included 646,884 head of cattle and calves valued at CA$ 1.0 billion and 506,578 metric tonnes (Mt) of beef and veal with a total value of CA$ 4.45 billion (Canfax, 2022). The growing demand for animal products, particularly in middle-income Asian countries, presents international trade opportunities for major meat-exporting countries.

Livestock also contribute to the circular economy by recycling agro-processing by-products, food grains unfit for direct human consumption, and food waste estimated at 2.3 million t per yr. in Canada (National Zero Waste Council, 2017), streams that might may otherwise be directed to landfills (Ominski et al., 2021). With their unique ability to graze on perennial forage land and consume by-products unsuitable for human consumption, cattle convert high-fiber feed into high-quality protein and other micronutrients that contribute to satisfying global nutrient demand.

Chemical fertilizers are often used in conventional agriculture to provide essential nutrients to crops, but they are also responsible for significant GHG emissions due to their production, transport, and application (Liang et al., 2020). Livestock manure is a valuable source of nutrients that could be used to fertilize crops while also providing several environmental benefits. For example, use of livestock manure as a substitute for chemical fertilizers reduces GHG emissions and improves soil health (Guyader et al., 2017; Holly et al., 2017; Liang et al., 2020).

2.2. Livestock and climate change

Food systems, including livestock production systems, are complex social-ecological systems, with environmental impacts, including the use of natural resources, as well as the production of GHG and ammonia emissions (Pinstrup-Andersen, 2012; Barrett et al., 2020). The magnitude of agricultural GHG emissions differs from country to country, primarily based on production efficiency in both crop and livestock systems. In 2020, the energy sector (consisting of stationary combustion, transport, and fugitive sources) emitted 540 t or 80% of Canada's total GHG emissions. Of the remaining emissions (~20%), 8.2% of total emissions come from agriculture, 7.5% from industrial processes and product use, and 4.1% from the waste sector (Environment and Climate Change Canada, 2022).

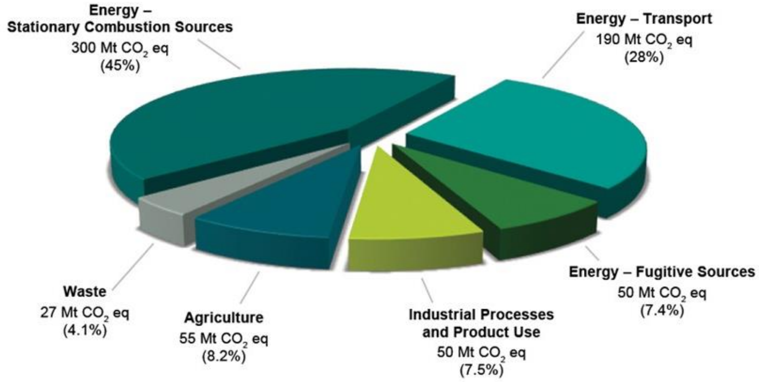

Figure 1: Breakdown of Canada’s greenhouse gas emissions by sector (Environment and Climate Change Canada, 2022)

Greenhouse gas emissions from the agricultural sector, including carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O), are attributed to crop (cereals and oilseeds) and animal production (beef, dairy, poultry, and swine) activities (Environment and Climate Change Canada, 2022). Carbon dioxide emissions from animal agriculture are associated primarily with feed production, including soil carbon dynamics (e.g., decomposing plant residues, mineralization of soil organic matter, land use change, etc.), the manufacturing of synthetic fertilizers and pesticides, and fossil fuel use in on-farm agricultural operations and the transport of feed and livestock to market (Goglio et al., 2018). In Canada, CO_2 from beef production, for example, accounts for only 5% of total emissions (Fouli et al., 2021).

Methane is a short-lived GHG with a global warming potential (GWP) of 28–34 times that of CO_2 over a 100-yr timespan (Rella et al., 2015). Recently, researchers in University of Oxford and Department of Animal Science at University of California have considered appropriate ways to evaluate the contributions of CH_4 to global warming, including the sources and types of emissions, and the timescale over which they occur (Mitloehner, 2018; Lynch et al., 2021). The term GWP* has been used to acknowledge that CH_4 is removed in approximately 12 yrs due to interactions with hydroxyl radicals in the atmosphere and therefore its impact on global temperatures has been overestimated in traditional fixed-time methods (Mitloehner, 2018). Globally, approximately 40% of CH_4 is emitted by natural sources (e.g., wetlands and termites), while the remaining 60% comes from anthropogenic sources, including ruminants, rice production, fossil fuel exploitation, landfills, and biomass burning (World Meteorological Organization, 2021). The oil and gas sector in Canada accounts for roughly half of the total CH_4 emissions in the national inventory (O'Connell et al., 2019). Ruminant emissions are primarily associated with enteric fermentation, a digestive process whereby bacteria, protozoa, and fungi in the forestomach (rumen) ferment plant biomass (Grossi et al., 2018). The CH_4 generated in the gastrointestinal tract of ruminants accounts for the majority of direct GHG produced by the livestock sector (Henderson et al., 2015; Herrero et al., 2016). Previous studies of GHG emissions from beef production in Canada have indicated that enteric CH_4 accounts for about 65% of total GHG emissions from beef (Legesse et al., 2016; Alemu et al., 2017; Chen et al., 2020).

Following CO_2, CH_4, and chlorofluorocarbon-12, N_2O is the fourth most important anthropogenic GHG, and has 273 times the global warming potential of CO_2 over a 100-yr timescale, and is also a reactant involved in the destruction of stratospheric ozone (Gerber et al., 2013; Nakazawa, 2020). Fertilizer and manure application are important sources of N_2O emissions from agricultural soils (Dennehy et al., 2017). Nitrogen use efficiency by ruminants is relatively low as only 5–30% of ingested nitrogen (N) is taken up by the animal, and the remaining 70–95% is excreted via feces and urine (Rivera and Chará, 2021). By comparing the ozone depletion potential of N_2O with that of other GHG emissions, N_2O is expected to remain the highest throughout the 21st century (Deng et al., 2020).

Although livestock contributes to global GHG emissions, climate change also affects livestock production in multiple ways (Squires and Gaur, 2020). Increased temperatures, longer growing seasons, shifting precipitation patterns, and an increase in the frequency and intensity of extreme weather events will bring both challenges and opportunities to Canada's livestock sector (Crane-Droesch, 2018). Impact on biomass yield and nutritive value of feed (Polley et al., 2013), water availability and livestock diseases, as well as livestock and crop pests, are anticipated to impact the production, processing, transport, and marketing of ASFs (Webb et al., 2020). In Canada, northern regions and the southern and central prairies are expected to realize more warming than other regions (He et al., 2018). Reduced forage yield due to climate change can lead to a shortage and increased cost of animal feed. Further, high temperatures may increase the lignin content of forages, which reduces digestibility and degradation rates (Polley et al., 2013). Insufficient feed to meet livestock feed requirements can limit animal productivity and disease resistance and exacerbate environmental degradation due to increased days on feed (Jégo et al., 2015; Thivierge et al., 2016; Rojas-Downing et al., 2017). Further, a larger number of animals may be needed to achieve the same quantity of marketable products, leading to increased natural resource use and lifetime GHG emissions (Grossi et al., 2019). Climate change also has the potential to benefit Canadian animal agriculture in several ways. Warmer temperatures can lead to longer growing seasons and increased crop yields, as well as the potential to grow new crop varieties (Gomez-Zavaglia et al., 2020). Moreover, warmer temperatures in colder regions could reduce heating costs for barns and other livestock facilities (Henry et al., 2018).

2.3. Strategies to meet human nutritional health requirements and GHG emission reduction objectives

Several options have been proposed to meet the challenges of feeding 9 billion people by 2050 and include the following: i) reducing the amount of arable land used for animal feed production (Henchion et al., 2017); ii) increasing the production potential of crops and animals through investment in research and use of new technologies (Röös et al., 2017; Fróna et al., 2019): iii) utilization of food waste in livestock diets (Searchinger et al., 2019): and iv) changing human diets through reduced consumption of animal products (Lamb et al., 2016; Godfray et al., 2018; Legesse et al., 2018).

2.3.1. Shifting land use from animal production to crops

Growing consumer demand for high-quality animal products in middle-income countries, including China, may influence land use decisions in major agricultural product exporting countries, including Canada (García-Martín et al., 2021). In the future, livestock production will increasingly be affected by competition for natural resources, particularly land, and water, for food vs. feed and by the need to operate in a carbon-constrained economy (Smith et al., 2020). Globally, livestock production currently uses about 70% of total agricultural land (primarily for feed production) and about 40% of arable land (Van Zanten et al., 2018). Land use change from animal production to crops for human consumption has been suggested as one of the production-side options to reduce GHG emissions through a reduction in the number of animals. Shifting land use from animal production to crops can increase the efficiency of the food system by reducing resource use and decreasing GHG emissions associated with animal agriculture. Furthermore, crops have higher yields per unit of land, potentially reducing the need for converting natural habitats to agriculture (Searchinger et al., 2019). Therefore, converting land used for animal grazing or feed crops to other uses has been suggested as a strategy to free up land for other purposes (Mason-D'Croz et al., 2022) and increase the overall resource use efficiency of the food system since more food could be produced with fewer resources.

In 2016, approximately 62.7 million ha of Canada’s land base was dedicated to agriculture, with perennial forage land accounting for 19.3 million ha (consisting of 3.25 million ha of alfalfa and legume grass mix, 4.69 million ha of improved pasture, 9.63 million ha of unimproved pasture, and 1.73 million ha of land designated as other hay and fodder (Statistics Canada, 2017a). A 6.9% increase in cropland (used for growing crops, such as grains, fruits, and vegetables) from 2011 to 2016 (Statistics Canada, 2017b) may be attributed to changes associated with decreased use of summer fallow and conversion of perennial forage land into cropland for human and animal feed (Statistics Canada, 2017a), as well as urban encroachment, potentially threatening feed security for ruminant production systems (Modongo and Kulshreshtha, 2018). Changes in land use can lead to adverse effects such as soil carbon and biodiversity losses (Kulshreshtha et al., 2015), which should be considered when implementing land conversion practices.

Although there have been widespread calls to shift land that is used for feed production to grow crops for direct human consumption (Searchinger et al., 2019; Williams et al., 2021), there are several inherent challenges in doing so. Most importantly, the conversion of perennial forage land into annual crop production ignores the economic and environmental challenges associated with the expansion of cropping into marginal land, including the reality that agricultural lands differ in quality and, therefore, not all land classifications are suitable for annual crop production (Leroy et al., 2022), without incurring decreased yield or severe degradation through erosion and other processes. As described above, White and Hall (2017) examined the impacts of changing land use by examining the potential nutritional adequacy and GHG reduction by eliminating animals from the U.S. food production system. These authors found GHG emissions would be reduced by 2.6% if this policy were adopted. A similar Canadian study that considers both the production and consumption aspects of changing diets from both a nutritional and environmental perspective has not yet been conducted.

2.3.2. Adoption of sustainable farming practices to improve production efficiency and reduce GHG emissions

Numerous production-side technological innovations, including improvements in plant and animal genetics, feeding and animal management, animal health, and manure management (Van Eenennaam and Werth, 2021), have been suggested to reduce the emissions of enteric CH_4 and N_2O from ruminant production systems. Dietary manipulation is one of the approaches that can improve animal productivity as well as reduce CH_4 emissions. Feeding strategies to reduce CH_4 emissions from livestock have included the use of high-quality forages, modification of the forage-to-concentrate ratio of diets, and the use of feed additives/supplements (Makkar, 2016). Feed additives such as nitrate and sulfate, fats and oils, organic acids, essential oils, condensed tannins, seaweed, saponins, ionophores (e.g., monensin), probiotics, secondary plant metabolites, and exogenous enzymes have been shown to reduce CH_4 emissions compared to control diets (Eckard et al., 2010; Haque, 2018). For example, 3-nitrooxypropanol (3NOP) has been shown to reduce CH_4 emissions by 30% in lactating Holstein cows without affecting feed intake, milk production, or composition while also increasing body weight gain (Hristov et al., 2015). The addition of 3-NOP to feedlot diets decreased CH_4 yield by 21.7% and tended to improve feed efficiency with no negative impacts on animal health. Further, a growing body of literature indicates that seaweed could be used to mitigate GHG emissions from ruminants (Maia et al., 2016; Nilsson and Martin, 2022). Supplementation with seaweed (*Asparagopsis taxiformis*) at levels ranging from 0.25% to 0.5% of the diet reduced enteric CH_4 emissions in beef steers by 70% to 80%, respectively.(Roque et al., 2021).

In addition to dietary manipulation, animal management practices, such as culling low-producing animals, increasing animal productivity (increased longevity of breeding stock and increased fertility rates), and selecting breeding animals with lower CH_4 emissions, have been suggested for CH_4 mitigation (Haque, 2018). It has been estimated that broader adoption of existing beneficial management practices and technologies in feeding, health, and husbandry, could help the global livestock sector reduce GHG emissions by as much as 30% (Gerber et al., 2013), while at the same time providing more food and higher incomes to enhance food security and alleviate poverty (Adesogan et al., 2020). Improved livestock productivity can reduce land use demands by increasing the amount of meat produced per unit of land, thereby reducing emissions intensity. This results in an improvement in food production efficiency and a reduction in the carbon footprint per unit of meat produced (Legesse et al., 2016).

Indeed, it is evident that there is a strong link between livestock resource use efficiency and the intensity of GHG emissions (Steinfeld, 2018). For example, Legesse et al. (2016) reported that advances in plant and animal genetics, nutrition, and improved herd management practices resulted in a 14% reduction in GHG emissions in Canada between 1981 and 2011, while at the same time resulting in 22 to 24% less land and 20% less water use (Legesse et al., 2018). As a result, Canada's beef industry has one of the lowest GHG intensities per unit of production globally at 12.0 kg CO_2 equivalent per kilogram of live weight (Legesse et al., 2016). Therefore, adopting best management practices is a promising solution for reducing GHG emissions.

2.3.3. The impact of consumer food choices on nutritional adequacy and reduction of GHG emissions

Recently, shifting diets to plant-based foods has been suggested as a strategy to meet future food needs and reduce the environmental impact associated with ASF (Mason-D'Croz et al., 2019; Willett et al., 2019; Bonnet et al., 2020). For example, highly visible and influential publications from the EAT-Lancet Commission (Willett et al., 2019), the IPCC (IPCC, 2019), the World Resources Institute (Searchinger et al., 2019), and Global Panel on Food Systems and Nutrition (Global Panel on Agriculture and Food Systems for Nutrition, 2020) have focused on dietary shifts. Notably, the EAT-Lancet Commission has suggested that a diet high in plant-based foods with limited ASF confers health and environmental benefits (Willett et al., 2019). In Canada, the 2019 Canada Food Guide emphasized that consuming plant-based foods will promote health and improve the long-term sustainability of the Canadian food supply (Health Canada, 2021). Other authors argue that vegan and vegetarian diets can reduce agricultural GHG emissions, reduce land clearing, and help prevent diet-related, chronic non-communicable diseases (Scarborough et al., 2014; Dagnelie and Mariotti, 2017; Satija and Hu, 2018; Bianchi et al., 2019). A study in North America has suggested that limiting ruminant meat consumption to 52 calories/person/d by 2050 would reduce GHG emissions by half. This would require reducing current beef and sheep consumption by nearly half (Ranganathan et al., 2018). Consumers in developed countries tend to be concerned with unhealthy, unsustainable, and unethical attributes that have been amplified by animal rights activists, vested interests of food corporations, and mass media. Indeed, a recent study in Canada reported that 9.4 % of Canadian consumers are willing to shift to vegetarian diets (Charlebois et al., 2020).

Although options on the consumption side, including dietary shifts, have been proposed, studies focusing on these strategies have not fully considered the consequences on nutritional adequacy, including deficiencies in vitamins and trace minerals essential for human health (Emami et al., 2017; Höller et al., 2018). At present, approximately three billion people cannot afford a healthy diet and suffer from one or more manifestations of poor nutrition (Webb et al., 2020). Deficiencies of vitamin A, iron, iodine, zinc, B12, and folic acid – the most deficient micro-nutrients globally and particularly in diets of children and pregnant women – contribute to poor growth, intellectual impairment, perinatal complications, and increased risk of morbidity and mortality (Adesogan et al., 2020; Rubio et al., 2020). Compared to plant-sourced foods, ASF supplies significant quantities of higher-quality protein and more bioavailable vitamin A, vitamin D3, iron, iodine, zinc, calcium, folic acid, and essential fatty acids (Williams, 2007; Mottet et al., 2018; Adesogan et al., 2020). Meat and milk from domesticated herbivores provide 16% of global protein consumption and 8% of global energy consumption (Mottet et al., 2018). For example, beef contributes to an array of nutritional requirements as it is rich in dietary energy, protein, essential amino acids, essential fatty acids, riboflavin, vitamin B6, vitamin B12, vitamin D, phosphorus, magnesium, potassium, selenium, iron, and zinc (Williams, 2007; Pereira and Vicente, 2013; Pretorius et al., 2016).

It is important to consider that dietary changes are shaped by food systems, which are made up of the people, environments, institutions, infrastructure and activities related to the production, processing, distribution, marketing, sale, preparation and consumption of food (Fanzo et al., 2020). Human diet and nutritional status are influenced by a wide range of factors such as income, demographics, and culture (Mathijs, 2015). Often non-market attributes and intrinsic values, including established production methods and systems, cultural attachment to ASF, concerns about the preservation of ecosystems, animal welfare, and health concerns (e.g., preventable zoonosis) play an important role in ASF production and consumption (Moran and Blair, 2021). Thus, transforming food systems requires a holistic approach that characterizes the behavior of producers, consumers, and agribusiness actors that incentivize or hinder the adoption of healthy diets as well as inform public decision-makers (Barrett et al., 2022). It is critical to quantitatively assess the sustainability of production and consumption options to achieve nutritional health and GHG emission reduction goals while considering consumer demographics impacting food choices.

2.4. System-based modeling approaches

The urgency to reduce GHG emissions while meeting the nutrient requirements of a growing global population requires metrics that could be used by the government, producers, consumers, and scientists to design appropriate GHG mitigation strategies (Liu et al., 2012). To fully assess the net abatement potential, these strategies must be examined using whole systems approaches to ensure that a reduction in emissions in one part of the system does not stimulate higher emissions elsewhere in the production system. Methods used to estimate emissions range from simple empirical factors to complex process-based models (Fouli et al., 2021), such as life cycle assessments (LCA) developed following the Intergovernmental Panel on Climate Change (IPCC) guidelines for calculating national GHG inventories (Lee et al., 2018), as well as linear programming (Dantzig and Thapa, 1997; Maillot et al., 2008; Gazan et al., 2018).

The LCA method accounts for the environmentally relevant inputs and outputs associated with the life cycle of a product and has become one of the most widespread environmental assessment tools over the last two decades (Liptow et al., 2018). The LCA approach typically uses emissions factors developed through original research or established through the IPCC or governmental bodies (IPCC, 2006), and it has been widely used to quantify livestock-related GHG emissions (Nijdam et al., 2012; McClelland et al., 2018).

Linear programming (LP) models have been used previously to identify diets that meet nutritional requirements and other additional constraints, such as the cost and environmental impacts of alternative diets (White and Hall, 2017; Gazan et al., 2018; Chungchunlam et al., 2020). Optimization is an analytical approach that could be described as identifying the scenario(s) of the lowest cost or highest benefit. An optimization problem strives to find the best solution among all feasible solutions. Diet optimization models have been used to simulate, quantify and compare the effects of the consumption of food groups and associated GHG emissions resulting from different scenarios. For example, using linear programming, Chungchunlam et al. (2020) examined least-cost dietary patterns and the constituent amounts of ASF in the United States. White and Hall (2017) used linear programming to analyze the most cost-effective diet combinations that met nutritional adequacy targets based on the consumption of domestically produced food in the United States. However, in order to fully understand the relationship between agricultural production, nutrition, and the environment in Canada, it is crucial to conduct similar quantitative studies that consider both production and consumption.

In summary, the review of existing literature indicates that research on sustainability of livestock production systems has targeted either the production- or the consumption-side perspective of the food system. Production centric strategies focus on improving livestock production efficiency to meet the rising demands for ASFs and minimize livestock-associated environmental impacts. Improving production efficiency and reducing GHG emissions focuses on breeding, feeding, animal management, as well as soil, crop and fertilizer management. Consumption-centric studies focus on dietary changes from ASF to plant-sourced foods. Generally, these studies conclude that shifting from a meat-based diet to a vegetarian or vegan diet reduces environmental impacts **(**Mason-D'Croz et al., 2019**;** Willett et al., 2019**;** Bonnet et al., 2020**)**. Although considerable progress has been made in understanding the relevant issues affecting agricultural GHG emissions, food security, and nutrition, an examination of both production-side and consumption-side scenarios of the food system has not been quantified under a comprehensive framework in Canada.

This disconnect could be resolved through interdisciplinary research which addresses the impact of food production and consumption choices on environment and economic outcomes.

2.5. Hypotheses

Numerous studies regarding sustainable food systems have been published in the past decade (Allen and Prosperi, 2016; Willett et al., 2019). However, most studies predominantly focus on the environmental impact associated with GHG emissions and conclude that environmental benefits from food production are generally proportional to reductions in ASF. Although the research to date has addressed the issues of food production, mitigation of agricultural GHG emissions, food, and nutrition security separately, the net impact of a combination of strategies has not been adequately determined. With a few exceptions, the nutritional implications of sustainable dietary scenarios have not been explicitly analyzed. Achieving sustainability targets for livestock production requires a comprehensive understanding of factors that govern the food system from farm to fork and the food production and consumption value chain (Moran and Blair, 2021). This thesis aims to explore the potential for Canada to meet the annual feed requirements for all types of livestock through domestic feed production on available land, which may be impacted by the effects of climate change on forage productivity and shifts in land use practices and policies. In addition, modeling changes in land use and dietary choices, such as eliminating the consumption of red meat, provides an opportunity to understand the associated reduction in GHG emissions more fully, but also consider the potential costs and nutritional impacts. Finally, it is also necessary to understand the demographic and socio-economic factors associated with proposed changes in consumer dietary choices and the potential impacts on nutrient intake. Through a comprehensive modeling framework that combines research on livestock production, human nutrition, and environmental sciences, this thesis addresses the issue of sustainable livestock production in Canada from a holistic perspective.

The specific research hypotheses include the following:

Hypotheses 1: Canadian livestock production systems have a high resource demand, including feed and land use, at current animal population and productivity levels.

Hypotheses 2: Shifting land use from animal feed production to crop production and removal of red meat from the diet can reduce GHG emissions but will have higher diet costs and adverse nutritional impacts.
Hypotheses 3: Excluding red meat from the Canadian diet will have a significant impact on nutrient intake and adequacy.
Hypotheses 4: Consumer dietary choices, such as reducing consumption of red meat, are influenced by demographic and socioeconomic factors.

2.6. Objectives

The overall objective of this thesis was to analyze the impact of changes in land use and dietary choices in Canada, as well as nutritional and environmental outcomes associated with current and alternative food systems.

The specific research objectives were:

I. To determine the amount of feed and land necessary to sustainably feed eleven commercially relevant livestock species in Canada, in order to ensure feed security for the livestock sector at 2016 animal population and productivity levels.

II. To investigate the impact of shifting consumption from standard omnivore diets to vegetarian diets and complete removal of animals from the Canadian production system on nutritional adequacy, cost, and GHG emissions.

III. To identify patterns of nutrient intake and nutrient adequacy among Canadian consumers who have eliminated red meat from their diet compared to those who have not.

IV. To explore the personal attributes and socio-demographic factors that influence the decision of Canadian consumers to exclude red meat from their diet.

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CHAPTER III: FEED AND LAND REQUIREMENTS FOR LIVESTOCK PRODUCTION IN CANADA

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Abstract

The ability to meet the growing global demand for livestock products depends heavily on the availability of animal feed. Quantifying aggregate feed demand and corresponding land base requirements is central to assessing feed security, characterizing competing priorities of food versus feed production, and addressing the impact of livestock on the environment. However, the national aggregate feed demand for livestock production has not been estimated in Canada since 2001. The objective of this study was to estimate the quantity of feed and land base needed to support commercial livestock production in Canada. Based on 2016 livestock inventory data, we found that the annual dry matter feed demand was approximately 63.9 million t, which equated to roughly 17.9 million ha of land. Feed consumed by livestock was composed of forages (65.4%), grains (28.0%), and agro-processing co-products and by-products (6.6%). The majority of feed demand (76.0%) came from ruminant livestock (i.e., beef, dairy, goats, and sheep), followed by pigs (12.8%) and poultry (5.5%). The information obtained from this study could be used to assess the current and future feed and land needs, and to examine the potential consequences of shifting land previously used for livestock feed production to grow food crops for direct human consumption.

1. Introduction

Driven by world population growth, as well as increasing disposable income and urbanization, global food demand by 2050 is projected to increase by 60% compared to 2005 (FAO, 2020). The projected increases in disposable income and urbanization, particularly in middle-income countries such as China (Searchinger et al., 2019), are expected to result in a significant portion of the global population transitioning to animal-sourced foods (ASF). Therefore, global demand for animal products is projected to increase by 60% to 70% by 2050 (Makkar, 2018). On the supply-side, global meat production is predicted to increase by 19% by 2030 compared to 2015-2017 (FAO, 2020; UNICEF, 2021).

Given that Canada is one of the largest global producers and exporters of agricultural products (Halbe and Adamowski, 2019), it is well-positioned to capitalize on the income-driven dietary shift to red meat and other ASF (Röös et al., 2017; Godfray et al., 2018). In 2021, Canada produced approximately 1.35 million t of beef (Statistics Canada, 2022a), 9.8 million t of milk (Statistics Canada, 2022c), 2.3 million t of pork (Statistics Canada, 2022b) and 1.3 million t of poultry (Agriculture and Agri-Food Canada, 2022). These tonnages equate to 2%, 1.7%, 2%, and 1.4% of global supplies, respectively. As a significant player in the global market, Canada is recognized as one of the largest red meat exporters worldwide. In 2020, Canada exported approximately 0.51 million t of beef, with a value of $4.4 billion (Canfax, 2022), and 1.44 million t of pork, valued at $4.96 billion in 2021(Statistics Canada, 2022b).

The potential to increase Canadian livestock exports in response to the rising global demand for ASF will depend on several factors, including access to the resources needed to produce adequate feed to sustain growth in the livestock sector. However, feed production can compete with food production as both activities require large land areas and sufficient quantities of water and nutrients (Makkar, 2018). In 2016, approximately 62.6 million ha of Canada's land base were dedicated to agriculture, with perennial forages accounting for 19.3 million ha of this total (Statistics Canada, 2017c). Agricultural census data indicates a 4.4% decline in perennial forage land in Canada between 2011 and 2016 (Statistics Canada, 2017c), driven by several factors, including increased land prices that catalyze the conversion of perennial forages to annual crops, as well as urban encroachment (Modongo and Kulshreshtha, 2018). The reduction in the area of perennial forages is posing a significant threat to feed security, for ruminants (Modongo and Kulshreshtha, 2018). For example, perennial forages in Ontario occupied 1.01 million ha in 1996 and decreased to 0.5 million ha in 2011, a 47% decline over 15 yrs (Corry, 2018). The availability of perennial forages in Canada may decline further. For example, simulation models predict 1.05 million ha of forage land could be converted to cultivated crops by 2030 (Zabel et al., 2019).

In addition to the conversion of perennial forage land to annual crops and urbanization, climate change is a significant factor that affects the availability and quality of feed for livestock(Polley et al., 2013). Increases in temperature, elevated atmospheric carbon dioxide, and water availability affect the productivity and quality of feed crops and forages (Thivierge et al., 2016). The future climate is expected to be warmer with more extreme weather events, which are projected to result in increased within-season and year-to-year variability in forage supply and feed quality (King et al., 2018). Reductions in forage yield could negatively impact animal growth, milk production, reproductive performance, and increase the incidence of diseases in livestock (Thivierge et al., 2016; Rojas-Downing et al., 2017; Deroche et al., 2020; Joy et al., 2020). However, climate change may also have some positive impacts on forage production (Wang et al., 2015; Environment and Climate Change Canada, 2020). Therefore, the need to increase animal production in response to the growing demand for ASF in resource-limited systems and the consequences of climate change and changes in land use requires a better understanding of the demand and supply of the feed needed for livestock production. However, current data regarding the feed demand of all commercially relevant livestock species in Canada is not available in the published literature. It is imperative to address this knowledge gap, as changes in animal inventories, land and animal management strategies, and production efficiency affect land requirements for feed production.

The objective of the current study was to estimate the quantity of feed and land base required to feed 11 livestock species of commercial relevance to ensure feed security for the Canadian livestock sector based on livestock inventories in 2016. Future farm scenarios with reduced feed availability due to land use change or climate change were also assessed. This study also examined temporal changes in the quantity of feed required between 2001 and 2016 as 2001 is the last time feed demand for livestock was estimated at national level (Mark Elward et al., 2001).

2. Materials and methods

2.1. Livestock inventories

Inventory data for all eleven commercially relevant livestock in Canada, including fish (aquaculture), beef, bison, dairy, goats, horses, other poultry, pigs, poultry, sheep and lambs, and turkey were garnered from the 2016 Census of Agriculture (Statistics Canada, 2017c). Livestock and poultry kept in the hobby and recreational farms were included in the Agricultural Census if they reported revenues or expenses to the Canada Revenue Agency (Statistics Canada, 2017c). The categories of some species were then divided into more detailed sub-categories based on age, sex, and stage of production using published literature (Peters et al., 2014) and expert advice. We assumed that no livestock was imported into or exported from Canada during the reference year (2016). This deliberate choice was made with the purpose of evaluating the sufficiency of domestically produced feed to meet the dietary needs of the animal population.

2.2. Characterization of livestock production cycles

The production cycle of each livestock species was represented as a system of stocks and flows and was estimated based on performance metrics, such as reproduction and mortality rates, as well as the nutrient intake required to achieve desired performance outcomes. Figure 1 depicts the stocks and flows associated with breeding, replacement, and finishing for market (Peters et al., 2014), using red meat production as an example. The systems were represented at a steady state with the number of replacement animals entering the breeding herd equaling those exiting due to culling, harvest/slaughter, or mortality. The number of breeding males was a function of the male-to-female ratio within the typical breeding group. Young animals not kept as replacements were assumed to be raised to finishing weight. The number of animals reaching market weight depended on the number finished and the expected mortality rate. For each livestock class (i), the stock of animals (N) in each life phase (j) was calculated as the average of the number of animals flowing in from the previous life phase (Ninflow) and the number of animals flowing out to the next life phase (Noutflow).

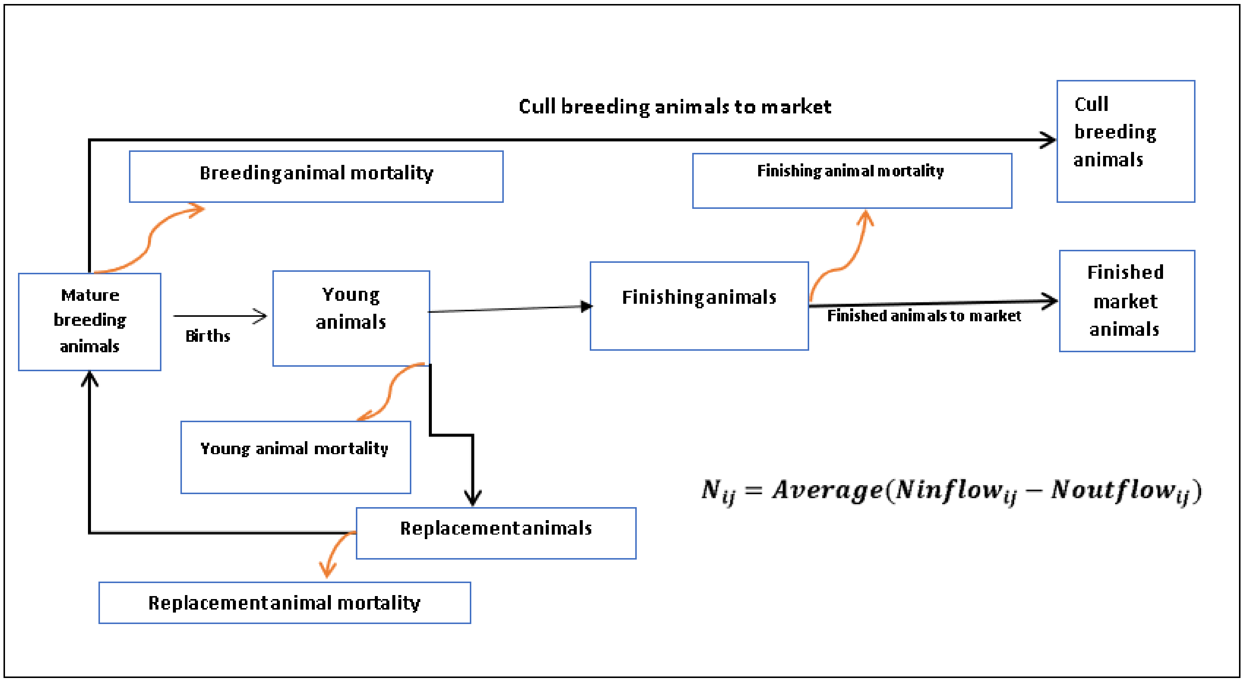

Figure 2: A generalized stock and flow diagram characterizing red meat production systems in Canada (adapted from Peters et al. (2014) with each box representing a pool of animals.

In total, 33 production phases were used to characterize the beef cattle production system in Canada (Legesse et al., 2016). Hence, the following strategies/assumptions were adopted for the current analysis:

- The number of calves on beef and dairy farms less than one year of age was estimated from the number of beef and dairy cows reported in the 2016 Census of Agriculture (Statistics Canada, 2017a);
- Half of the dairy calves (i.e., the heifer calves) were assumed to enter the dairy production supply chain with a 50:50 sex ratio of male-to-female calves at birth.
- Weaning rate for the dairy cow herd was 90% and all the calves in the census beyond the estimated weaning rates were assumed to be male calves from dairy farms (Legesse et al., 2016).
- The ratio of calf-fed; yearling-fed (backgrounded in confinement); yearling-grass fed (backgrounded in confinement and on pasture) cattle was assumed to be 58:25:16 of weaned calves not retained as replacements.

- Half (i.e., 50%) of the yearling-grass fed steers and heifers (backgrounded in confinement and on pasture) were transferred from other provinces for finishing.
- All bulls reported in the 2016 Cattle Inventory data (Statistics Canada, 2017a) were assumed to be from beef operations given the small number of dairy cows and the high dependence of dairy operations on artificial insemination; vii) weaning rate for the beef cow herd (i.e. number of calves weaned per 100 cows exposed) was assumed to be 85% (Beauchemin et al., 2011; Legesse et al., 2016).

To account for the variations in feed ingredients used in beef production systems across Canada, beef animals were disaggregated into two categories based on their geographical location - eastern and western Canada. In the eastern region, corn was the preferred grain and silage crop for beef cattle, while in western Canada, barley was the most commonly used grain and silage crop for feeding beef cattle (Sheppard et al., 2015; Legesse et al., 2016).

The dairy cattle herd was disaggregated into four categories: lactating cows, dry cows, replacement heifers, and dairy calves, with outputs that included milk, feeder calves, and culled cows (Supplementary Material-SA). Further disaggregation into eastern and western Canada was used to account for the differences in the feed ingredients used in dairy production systems in the two regions of Canada, with corn- and barley-based rations used predominantly in eastern and western Canada, respectively (Little et al., 2017).

Sheep were categorized as ewes, rams, and lambs disaggregated by age and sex with production and feed requirements estimated based on existing sheep farms in western Canada (Patrick Smith and Darryl Gibb, pers. comm.). Ewes were further divided into the following stages of production: early-mid-gestation, late gestation, and lactation, with annualized duration in each stage estimated based on published literature (Government of Ontario, 2016) and expert opinion (Pat Smith, pers. comm.). Similarly, lambs were classified into pre-weaning, replacement ewe lambs, ram lambs, and finishing lambs. The Canadian agricultural census reports the number of milk and meat goats as one category. Demographics of goats were further classified based on feeding and management and included dry does, late gestation does, flushing does, bucks, replacements, and feeders (Lunn, 2007).

Bison were categorized as mature cows/bulls, calves, and replacement heifers based on age and average weight (Canada Bison Association, 2019). Breeding was assumed to take place from late June to September, with calving occurring from mid-April through May (Berg, 2018; Berg 2022). Calves were assumed to be weaned at seven months of age (Manitoba Agriculture, 2017). Additional production data, including replacement rates of 5% for bulls and 10% for cows, were sourced from the Canada Bison Association (Canada Bison Association, 2019). Since there was limited baseline data to estimate the proportion of young male and female bison that transitioned to finishing, and the duration of the finishing phase, we assumed that these animals primarily relied on grass during this period.

Stages of production for pigs were categorized based on sex and age as boars, sows (gestation and lactation), gilts, nursing pigs, weaned pigs, growers, and finishers. As the 2016 Census of Agriculture did not discriminate between sows and gilts, the sow and gilt populations were calculated by assuming they account for 60% and 40% of the female swine population, respectively (Manitoba Agriculture, 2019). The average annual number of litters/sows was used to estimate annualized lactation and pregnancy days (Manitoba Agriculture, 2019). The 2016 Census of Agriculture reported the total number of horses as a single category and did not provide further detail regarding meat, work, or racing horses. Thus, a single category was used to determine the average feed requirements of horses.

For poultry, the 2016 Census of Agriculture livestock inventory categorized chickens into four categories (Statistics Canada, 2016): i) broilers, roasters, and Cornish hens; ii) pullets intended as layers under 19 wks; iii) layers 19 wks and older, and iv) layer and broiler breeders. Layer and broiler breeder chickens were subdivided into grower/starter, developer, pre-layer, layer, starter, grower, and finisher/broiler (Singh et al., 2009; Rattanawut et al., 2017). Although turkeys were reported as a single category in the inventory (Statistics Canada, 2017a), they were subdivided into starters, growers, developers, and finishers (Anna Rogiewicz, pers. comm.), for a more accurate assessment of feed requirements. A single category of other poultry was garnered from the livestock inventory (Statistics Canada, 2017a), which included quail, ostrich, emus, and pheasants.

Canadian Aquaculture Production Statistics (Government of Canada, 2017) were converted from annual fish catch data reported to live weight production at a rate of 1:1.1 (FAO, 1992). indicating that every 1 unit of reported fish caught is equivalent to 1.1 units of live weight production (FAO, 1992). As salmon and trout are the two most common species of commercial relevance in Canada, the average body weight data of these two fish species was used to convert the weight of fish production into the number of fish by dividing live weight by the average weight of live fish (5 kg/fish) based on fisheries expert opinion (Jeff Eastman, pers. comm.).

2.3. Diet composition, feedstuff nutrient profile, and feed intake

It was assumed that all feedstuffs (forages, grains, and agro-processing by-products), except for supplemental vitamins and, minerals, and feed additives, were domestically produced in Canada. Data regarding nutrient requirements and feed intake for various life stages of each species, considered age, size, and physiological status, were collected from the National Research Council (NRC) and published literature. Total daily DM intake of beef cattle (National Research Council, 2016), dairy cattle (National Research Council, 2001), small ruminants, including sheep and goats (National Research Council, 2007), horses (National Research Council, 2016), poultry (Daghir, 2008), and swine (National Research Council, 2012) were garnered from respective NRC reports.

Data regarding diet composition for beef (Legesse et al., 2016), dairy (McGeough et al., 2012; Little et al., 2017), goats (Lunn, 2007 ; Tarr, 2011), bison (Canada Bison Association, 2019; Huntington et al., 2019), poultry (Bennett et al., 2002; Salim et al., 2010), and aquaculture (Sun et al., 2016) were collected from Canadian publications or subject matter specialists in each of the industries. To calculate the average feed requirements for light and draft horses, we used the diet composition and dietary requirements data reported by the Government of Saskatchewan (Cymbaluk, 2015), the latter of which was based on the NRC requirement for horses (National Research Council, 2016)

Total DM intake, F_{ij}, for a group of animals from a given animal class at a given life stage was calculated as the product of the number of animals (N) in that life phase, the daily DM intake (i) for that animal type and life phase, the amount of time (t) spent within a given life phase (measured in days) and the feed ingredient included in the diet (j).

$$F_{ij} = \sum_{i=0}^{n} N_{ij} \times I_{ij} \times t_{ij}$$

To accurately assess the portion of agro-processing co-products and by-products utilized as animal feed from the total product biomass, we applied by-product recovery rates from published literature and various industries to apportion the amount of product biomass and the associated land base required. Our analysis included the following agro-processing co-products and by-products: barley screenings (Grimson et al., 1987), millrun pellets (Zinn, 1993), corn DDGS (Sutherland et al., 2020), corn gluten feed and meal (Zinn et al., 2002; Stein, 2005), dried beet pulp, molasses (United Molasses, 2019), canola meal (Canola Council of Canada, 2021), soybean hulls, soybean meal (Borucki Castro, 2007), and vegetable oil. By applying these recovery rates, we were able to estimate the amount of each type of agro-processing co-product and by-product that could be allocated as animal feed from the total product biomass. Calculations for the demand and land requirement of livestock feed only included straw that was used for feed and did not consider any straw used for bedding purposes.

In addition, the annual production of manure and its nutrient equivalent to chemical fertilizer were calculated for livestock species that produced manure of known chemical composition, using conversion factors established from the inventory data and manure nutrient profiles as described by the American Society of Agricultural and Biological Engineers (ASEBE) (American Society of Agricultural and Biological Engineers, 2005; Ogejo et al., 2010).

2.4. Crop and forage yield data

Data regarding the yield of field crops were garnered from official statistics (Statistics Canada, 2017a). National yield values for corn silage (Guyader et al., 2018), barley silage (Alberta Crop Report, 2019), and grass silage (Rotz and Muck, 1994), were garnered from published literature or official sources. Forage yields, including legume and grass yields and mixed legume-grass yields, were obtained from published literature in the ten provinces of Canada (Gill et al., 2013;

Bélanger et al., 2017; Rojas-Downing et al., 2017). A weighted average forage yield was calculated using land under forage production so as to account for variations in soil and climate conditions (Lark et al., 2020).

2.5. Quantifying land base required for feed production

The land area required for feed production was calculated by dividing the total feed required by the yield of the corresponding crops and forages. As the crop yield values reported by Statistics Canada were based on standing crops, a field loss of 3-5% (Cavalieri et al., 2016; Soltani et al., 2018) was used in the land area calculations. Field losses during harvest for hay and silages were estimated at 12% based on previous research (Rotz and Muck, 1994). A pasture utilization rate of 50% and 60% of the total above-ground biomass was used to calculate land area requirements for native and tame pastures, respectively (Legesse et al., 2018). Feeding losses were estimated at 5% for silage and 20% for hay (Rotz and Muck, 1994), 0% for grain ((Rotz and Muck, 1994), and 20% for stockpiled and swath grazed forages (Hutton et al., 2004). All crop yields were already in an as fed basis; however, all forage DM yields were converted to calculate the land base necessary to produce the feed required for specific livestock populations (Legesse et al., 2018). The total annual land required for feed production at a national level was calculated as the sum of the land needed for grains, oil crops, pulses, and native and tame forage production.

2.6 Future farm scenarios

With regards to perennial forage yield and quality, projected future climate scenarios for the period 2040 to 2069, described by Jing et al. (2013), indicate warmer conditions in all forage-producing areas of Canada. The historical period (1986–2014) was considered as the baseline, and 2040-2069 was the near-future period in climate change scenarios. Estimates of the future forage productivity change between baseline and projected future climate conditions for this period indicate that the annual yield of Timothy in 10 ecoregions of Canada would decrease by 72 kg DM ha^{-1} (7% reduction) over the coming decades (Jing et al., 2013; Qian et al., 2018). The predicted annual average DM yield would decrease by 11% for alfalfa–timothy mixtures (Thivierge et al., 2016), as compared to the reference yrs (1971–2000). Therefore, we considered a 7% yield reduction for pure perennial legume or grass pastures, hay and/or silage and an 11% yield reduction for grass-legume mixtures in the prediction of future forage and land base requirements. Furthermore, it must be acknowledged that in response to the effects of climate change on forage yield, producers might opt to grow warm-season grasses that are more suited to elevated temperatures.

3. Results

Changes in the total population of the 11 animal species between 2001 and 2016 (Statistics Canada, 2017a, 2021) are depicted in Table 1. With the exception of pigs, goats, chickens, and turkeys, the population of most animal species declined over this time period.

Table 1: Inventory of the commercially relevant livestock species in Canada in 2001 and 2016

Livestock type	Animal inventory (million head)		% Change in livestock inventory
	2001	2016	
Total cattle and calves	15.55	12.53	-19.42
Total pigs	13.96	14.09	0.93
Total sheep	1.26	1.05	-16.67
Goats	0.18	0.23	27.78
Bison	0.15	0.12	-20
Total hens and chickens	126.16	145.52	15.35
Turkeys	8.12	8.42	3.69
Other poultry	5.31	3.02	-43.13
Horses and ponies	0.46	0.29	-36.96

The total feed DM required in Canada was estimated at 63.9 million t (Table 2) for 2016. Forages accounted for 65.4% of the total estimated feed DM. Grains comprised primarily of barley, corn, wheat, and oats, accounted for 28.0%. Agro-processing co-products and by-products accounted for the remaining 6.6%. Approximately 17.9 million ha of land was required to meet the annual feed requirements of 11 animal species in Canada in 2016.

Table 2: Quantity of feed (DM basis) and land area required to meet the nutrient requirements of livestock and poultry in Canada

Feed type	2001	2016	
	Total feed DM (million t)	Total feed DM (million t)	Area (million ha)
Forages§	45.33	41.79	12.37
Grains¥	18.82	17.92	5.5
Agro-processing by-products*	3.81	4.24	
Total	**67.96**	**63.95**	**17.87**

§Forages include: alfalfa hay, alfalfa haylage, alfalfa pasture, alfalfa-grass hay, bale grazing, barley green feed, barley silage, barley straw, corn silage, fescue hay, grass hay, grass-legume hay, grass silage, meadow bromegrass, mixed alfalfa hay, native pasture, stockpiled forages, swath grazing, tame pasture, and wheat straw.

¥Grains include: Barley, corn, oats, and wheat

* By-products include: barley screenings, beet pulp, canola meal, corn DDGS (dried distillers grains with solubles), corn gluten feed, corn gluten meal, millrun pellets, molasses, soybean hulls, soybean meal, and vegetable oil.

The total DM required by each livestock species and the associated land base requirements are given in Table 3. Ruminants (beef, dairy, sheep, goats, and bison) accounted for the largest proportion (76.0%) of Feed DM required, with beef cattle accounting for 59.0%. Monogastric species (pigs and poultry) had the second-greatest demand for feed (19.3%) and land (19.1%). Among monogastrics, pigs (12.8%) and poultry (5.0%) required the highest proportion of feed. The feed demand and area required to produce feed for fish and horses were insignificant.

Table 3: The quantity of feed and land area required in Canada in 2016 for each animal type

Animal type	Total Feed DM required (million t)*	Area required for feedstuffs (million ha)
Ruminant	**48.43**	**13.34**
Beef	37.49	11.85
Bison	0.33	0.12
Dairy	9.77	1.14
Goats	0.23	0.11
Sheep	0.6	0.12
Monogastric	**12.36**	**3.42**
Other poultry	0.01	0.01
Pigs	8.21	2.41
Poultry	3.53	0.96

Turkey	0.61	0.05
Equine	**2.76**	**1.06**
Horses	2.76	1.06
Fish	**0.40**	**0.06**
Aquaculture	0.40	0.06
Total	**63.95**	**17.88**

[*] The numbers are rounded to two decimal places to prevent small values from being rounded to zero.

4. Discussion

The objective of this study was to estimate the amount of feed and land required to feed economically important farm animals (beef, dairy, pork, poultry, sheep, goats, bison, horse, other poultry, turkey, and aquaculture) with the assumption that all feedstuffs, except vitamins, minerals, and other feed additives, were produced and used in Canada. The findings demonstrate changes in the relative populations of different livestock species in Canada from 2001 to 2016, accompanied by changes in their feed requirements. Between 2001 and 2016, the population of horses, cattle, and sheep decreased by 37.0%, 19.0%, and 16.0%, respectively. Meanwhile, the population of goats, chickens, turkeys, and pigs increased by 27.8%, 15.0%, 3.7%, and 1%, respectively. Changes in animal inventory in Canada are impacted by both domestic as well as international factors. For example, Canada exported 51.5% of beef and 64.3% of pork production in 2016 (Statistics Canada, 2017b). Domestically, changes in animal inventory are associated with feed supply and cost, land prices, as well as health and disease outbreaks (Statistics Canada, 2017c).

Feed demand varied among the major livestock species, with ruminants accounting for approximately 76.0% of total feed DM required and 74.0% of the land area needed for feed production. Observed decreases in feed demand from 2001 to 2016 may be attributed to several factors, including changes in animal inventory, the relative proportion of sub-categories in each species, the length of feeding periods, as well as improvements in livestock production efficiency (Peters et al., 2014).

Ruminants, such as cattle and sheep, have traditionally been fed perennial forages such as hay and pasture, but there has been a shift towards the use of annual crops, such as corn and barley silage, as well as by-products from other industries, such as DDGS (Major et al., 2021). (Good et al., 2017; Pogue et al., 2018). Furthermore, improvement in corn breeding has resulted in the development of lower heat unit corn varieties that have a higher yield potential and can now be grown further north, including Canada, leading to an increase in the use of corn silage (Guyader et al., 2018). The reported increases in corn and barley yields in Canada demonstrate the tangible benefits of improving crop production efficiency, which in turn helps to reduce the land required for animal feed production, addressing issues related to land scarcity, deforestation, resource depletion, and environmental sustainability in agriculture. Furthermore, decreased feed demand from 2001 to 2016 can also be attributed to the improvements in livestock production efficiency (Darku et al., 2016). This includes genetic improvement, as well as advances in animal nutrition, including the use of feed additives (i.e., enzymes, pre, and probiotics) and improvements in animal husbandry practices (robotics) have led to an improvement in nutrient utilization, thereby reducing gross feed demand per unit of animal food product (Legesse et al., 2016; Terry et al., 2020). For example, Legesse et al. (2016) reported that only 71.0% of the breeding herd and 76.0% of the land in Canada were needed in 2011 to produce the same live weight of cattle destined for slaughter as in 1981. Similarly, the number of dairy cattle has been decreasing with increasing efficiency since 2001 (Crowe et al., 2021). In addition, increased corn and barley yields of 23% and 61% have been reported in Canada over a 30-yr. time frame (Legesse et al., 2016), leading to a decrease in land requirements to produce a comparable quantity of feed.

While forage and grain to feed the Canadian livestock population decreased in 2016 as compared to 2001, the amount of agro-processing co-products and by-products utilized in livestock diets increased by 11.3%, which is associated with increased use of soybean meal, canola meal, and DDGS (Maia de Souza et al., 2017; Terry et al., 2020). Based on the dietary inclusion rates and animal inventory in Canada in 2016, animals consumed approximately 4.24×10^6 t of agro-processing co-products and by-products (including 2.25×10^6 t of soybean meal, 1.02×10^6 t of canola meal, 0.30×10^6 t of soybean hulls and 0.22×10^6 t of corn gluten meal). The utilization of by-products (See Supplementary Material-SA1) is underestimated as their use is dependent on regional availability and cost. As a single diet was utilized for each sub-group of livestock, it was not feasible to consider the range of by-products arising from commodity processing. As Canada continues investment in primary and secondary processing of grains, pulses, and oilseeds, there will be increased opportunities to utilize by-products as feed.

The total available perennial forage land in Canada was 19.3 million ha in 2016 (Statistics Canada, 2017a), while the estimated land required for perennial forage production was 11.8 million ha (Supplementary Material-SA). National forage land areas (19.3 million ha) reported in 2016 were composed of 3.25 million ha of alfalfa and legume grass mixtures, 4.69 million ha of improved pasture, 9.63 million ha of unimproved pasture, and 1.73 million ha of land designated for the production of hay and fodder (Statistics Canada, 2017a). This implies a two-fold difference between the land available for the production of perennial forages and the land which is required in 2016. The discrepancy between the estimated and available land for perennial forage production is not surprising, given that the required perennial forage land was calculated based on the physiological feed requirements of livestock. The observed discrepancy between the available land area under native and perennial forage (19.3 million ha) and the land required for forage production (11.8 million ha) may be associated with the use of a single yield value for each crop/forage type to estimate land requirements, which inadequately reflects actual yield values due to differences in climate, agronomic factors, time of harvest, and other variables. Further, yield estimates also did not account for extreme weather events, such as drought, which can significantly reduce perennial crop yields. Studies in Canada have shown up to an 11% reduction in alfalfa–timothy mixture yields due to drought (Thivierge et al., 2016). Furthermore, the estimate did not consider feed stored on-farm for a 1–2-year period as a safeguard during periods of limited feed supply. These factors collectively could contribute to the observed differences between the available land area and the land required for forage production, highlighting the need for more nuanced estimates that account for these variables.

This observed difference between the available perennial forage land area (19.3 million ha) and the land required for forage production (11.8 million ha) suggests that some perennial forage land could potentially be converted to annual cropland to support grain and oilseed production for human consumption. However, much of the land under perennial forage production is not suitable for growing these types of crops due to land base constraints, such as steep slopes or rocky terrain, short growing season, or excess salinity (Government of Canada, 2021). Approximately 20% of

Canada's perennial forage land was cultivated on lower quality land categorized as Class 4, 5, or 6 (Environment and Climate Change Canada, 2021), suggesting that it is not suitable for annual crop production. In addition, Class 3 lands exhibit moderately severe limitations that restrict the spectrum of cultivatable crops and necessitate specialized conservation practices. Therefore, the implications of land use estimates can only be assessed in conjunction with information on the suitability of land for specific purposes (Peters et al., 2014).

The reduction in forage yield induced by climate change could potentially result in a 9.6% increase (11.8 vs. 12.9 million ha) in the total area of perennial forage land needed to produce forage in 2016. With current and anticipated frequent extreme weather conditions in many regions of the country, the need for adaptive strategies requires careful consideration. Young farmers in Canada face a unique set of challenges in establishing and sustaining their farm businesses, including the need for off-farm employment. Therefore, it will be important for the government to develop programs and policies that mitigate the negative impacts of climate change on forage yield and quality. Examples include " i) risk management strategies, including forage insurance, as well as access to alternative forage land (i.e., set aside land); ii) knowledge transfer programs regarding species selection, including new forage varieties, that tolerate extreme weather events, ii) design and establishment of grazing plans/strategies and start-up costs associated with fencing and waterers in multiple pasture grazing systems, iii) feed testing and ration formulation support for ruminant producers who use home-grown feedstuffs and do not traditionally work with feed companies/nutritionists, and iv) Canadian Food Inspection Agency (CFIA) support to conduct the feeding trials to provide data for approval of novel feed ingredients including hemp meal and screenings" (Farmers for Climate Solutions, 2022).

Furthermore, forage production could be negatively impacted by the continued conversion of perennial forage land to arable land for annual crop production. The trend is driven by factors such as high commodity prices, expansion of the biofuels industry, and lack of investment in land conservation programs (Lark et al., 2020). The impact of this conversion would be significant, affecting feed supply and cost, biodiversity, and other ecological goods and services (Pogue et al., 2018; Potapov et al., 2022). In addition, urban expansion, including the development of roads and recreation areas, which encroach on agricultural land, forests, and other natural areas, can also impact forage availability (Environment and Climate Change Canada, 2021). The conversion of cropland and forest into residential areas in Canada between 2010 and 2015 (1,215 km^2) indirectly increased pressure to convert natural areas, such as forests or wetlands, to cropland for increased agricultural production (Modongo and Kulshreshtha, 2018). The loss of these natural areas can disrupt ecosystem services, leading to a decline in air and water quality, increased air and water temperatures, and potential flooding (Legesse et al., 2016). It is also widely recognized that the conversion of perennial forage land to arable land can increase GHG emissions due to the loss of carbon-sequestering vegetation and emissions associated with the use of fossil fuels for more frequent tillage (Pogue et al., 2018).

Therefore, the conversion of perennial forage land to arable land for annual crop production, combined with urban expansion, poses significant risks to forage availability and the provision of ecological goods and services throughout Canada. Appropriate policies and programs are required to address these threats and promote sustainable land-use practices that prioritize the preservation of perennial forage land.

In light of the pressing need to address the rising demands for livestock feed while ensuring an adequate feed supply, it is imperative to explore strategies to improve resource utilization. These strategies encompass enhancing the efficacy of feed production and distribution, repurposing food waste for feed utilization, and advocating for sustainable land management practices. Furthermore, given Canada's role as a substantial exporter of animal food products, adapting to shifts in global economies, trade dynamics, potential disease outbreaks, and climate change underscores the necessity for region-specific resilience within the overarching framework of land management strategies that sustain animal agriculture.

Limitations of the study and suggestions for future considerations

Aggregate feed demand was estimated using average values for annual and perennial yield as well as average animal DMI. However, the use of average values in the model could be limiting. For example, the average daily DMI for each animal species (and subclass) is determined by a constant value without considering the heterogeneity of production systems, including variation in animal type and management, as well the environmental conditions, such as ambient temperature. In addition, forage yield is the average value weighted by the land area under tame or native forage in each province. Further, the use of average diets does not reflect the farm-to-farm and regional differences that exist, including the use of regionally available by-products. While climate change models may predict potential changes in annual and perennial crop yields, they do not consider changes in quality. Finally, this study focused on estimating the quantity of feed and land base requirements if Canada were to fulfill the feed demand of the livestock species of economic relevance using domestically produced feeds and did not consider imported or exported feed. In future work, it would be beneficial to expand the scope of the study to include imported and exported feeds, as these can have a significant impact on the quantity of feed and land base requirements for livestock production.

5. Conclusions

Canada's total annual feed DM demand was estimated at approximately 63.9 million t in 2016. Forages accounted for 65.4% of the total estimated feed DM, of which approximately 32% is accounted by perennial forages, with the remaining from annual forages. Grains comprised of barley, corn, wheat, and oats accounted for 28.0% while agro-processing co-products and by-products accounted for 6.6% of total feed DM. Ruminants (beef, dairy, sheep, goats, and bison) and monogastrics (pigs and poultry) consumed 76.0% and 19.3% of the feed biomass, respectively. The feed demand and area requirement of fish and horses were negligible. This information could be of use to researchers and policy makers for land use decisions. The findings of this study also suggest that meeting growing feed demand may be challenged due to the impact of climate change on the forage yield and quality, conversion of perennial land to annual cropland, and effects of urban encroachment. Shifting land use from perennial forages to annual crops could also lead to the loss of wildlife habitat and biodiversity and reduce the amount of carbon stored in the soil. To balance the need to meet increasing livestock feed requirements with feed supply, strategies such as improving the efficiency of feed production and distribution, using food waste as feed and promoting sustainable land use practices should be considered. Finally, as Canada is a major exporter of animal food products, changes in global economies, trade, exotic diseases, and climate will require regional-level resiliency concerning land management strategies supporting animal agriculture.

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Bridge to Chapter 4

The estimated land base data in Chapter 3 was necessary for subsequent modeling to assess the impact of shifting land from feed production to crops grown for human food and the potential reduction in livestock-related GHG emissions in Chapter 4. The objective of the next chapter of the thesis was to concurrently explore how land use shifts and dietary changes influence nutritional adequacy and GHG emissions of food produced from the Canadian agricultural system.

CHAPTER IV: ASSESSING ENVIRONMENTAL IMPACTS AND NUTRITIONAL ADEQUACY OF LEAST COST CONSUMER DIETS BASED ON DIFFERENT DIETARY PATTERNS IN CANADA

E.G. Kebebe, K. Ominski, K. Wittenberg, H. Aukema, T. McAllister, N. Riediger, G. Legesse,
E. J. McGeough , N. Ibrahim and R. White

Abstract

Many studies have assessed nutritional aspects and the environmental sustainability of different diets; however, few have explicitly evaluated the capability of the agri-food system to provide foods that meet nutritional requirements and environmental sustainability goals. The objective of this study was to explore how land use shifts and dietary changes concurrently influence nutritional adequacy and greenhouse gas (GHG) emissions of food produced in Canada. Linear programming was used to identify food commodities required to design diets that meet the nutritional requirements of the Canadian population at the lowest cost. Numerous optimization models were constructed to evaluate how optimal diets differ under alternative land use strategies or dietary preferences. Comparison among these scenarios suggested that Canada's nutritional adequacy and GHG reduction objectives are achievable with existing land use patterns across a variety of diets. Recommended Daily Allowance (RDA) of most nutrients, except fatty acids such as docosahexaenoic acid (DHA), eicosapentaenoic acid (EPA), and vitamins (choline, A, B12, C, D, and E), could be attained from domestic sources in most scenarios. Although modeled omnivorous, lacto-ovo-vegetarian, and lacto-vegetarian diets required higher amounts of food to meet RDA requirements with higher GHG emissions than vegan and complete removal of animal diets; the latter had a higher average diet cost. However, GHG emissions of diets increased with increasing consumption of foods of animal origin, suggesting a tradeoff between diet cost and a reduction in GHG emissions. The study also revealed that diets low in animal-sourced foods (ASF) had reduced nutritional value, indicating a tradeoff between achieving nutritional adequacy and reducing greenhouse gas (GHG) emissions. Further exploration of dietary patterns that deviate from the current patterns may identify alternative optima to concurrently address environmental and nutritional adequacy objectives.

1. Introduction

Meeting the demand for nutritious food for the growing world population from sustainable food systems is one of humanity's greatest challenges in the 21st century (Lindgren et al., 2018; Poore and Nemecek, 2018). Although livestock production contributes to global food security by supplying essential macro- and micro-nutrients (Mottet et al., 2017), some estimates suggest that livestock account for nearly two-thirds of global agricultural GHG emissions (IPCC, 2019). Many of the global environmental challenges associated with livestock production are also pertinent to Canada, where agricultural emissions account for 8.2% of total GHG emissions (Environment and Climate Change Canada, 2021), of which livestock represent about 60%. Emissions from livestock primarily consist of methane and nitrous oxide, with the beef industry alone accounting for 32% of Canada's total agricultural emissions in 2019 (Environment and Climate Change Canada, 2020). Global and Canadian GHG emissions associated with meat and milk production are likely to increase over the coming decades as increases in global population growth heighten the demand for meat and milk (Clark and Tilman, 2017; Röös et al., 2017; Herrero et al., 2020).

Although GHG emissions have received considerable attention, our food systems must also meet nutritional requirements while providing livelihoods for farmers and other actors in the food value chain (Béné, 2020). Some analysts argue that increasing the efficiency of animal production and resource use will better meet nutritional and environmental objectives (Mottet et al., 2017; Chang et al., 2021; White and Gleason, 2022). Improving production efficiency from animal-sourced foods (ASF) is a production-side solution that will require land use change and technological innovations in feeding, breeding, genetics, animal health, management, and information technology (Legesse et al., 2016; Van Eenennaam and Werth, 2021). Some of these approaches have already reduced the intensity of GHG emissions from beef production by 14% in Canada (Legesse et al., 2016). From the production side, it could be argued that land used for animal feed production should be repurposed for crop production to lower environmental impacts (Rounsevell et al., 2012; Lamb et al., 2016). In contrast, advocates of consumer-based solutions have argued that dietary choices are the major drivers of food production decisions and their associated environmental impact (Poore and Nemecek, 2018; Clark et al., 2019; Willett et al., 2019). The advocates of consumption-side solutions argue that the shift to plant-based diets is a preferable option for ensuring nutritional adequacy and ensuring the environmental sustainability of food systems (Mason-D'Croz et al., 2019; Willett et al., 2019; Bonnet et al., 2020). The consumption-side narrative is already influencing national food policies in industrialized countries. For example, the recent Canada Food Guide implied that shifting towards plant-based diets would promote health and improve the long-term sustainability of agri-food systems (Webster, 2019; Health Canada, 2021). However, such broad conclusions are often based on comparisons of GHG emissions between plant-based foods versus ASF, with consideration for mass rather than nutrient density, or the broader role of animal agriculture in food systems. Animal agriculture contributes to nutritional adequacy by converting low-quality, fibrous feeds into nutrient-dense meat and milk that are rich in essential nutrients, including high quality protein, vitamin A, riboflavin, vitamin B12, calcium, iron, and zinc (Williamson et al., 2005; Wolk, 2017; Rubio et al., 2020). Furthermore, the complete elimination of animals from the U.S. food production system was estimated to reduce U.S. GHG emissions by only 2.6% (White and Hall, 2017). Although production-focused assessments differ in their conclusions from the consumption-focused literature, neither option provides a complete assessment of the impact of alterations in food production or dietary preferences on nutrient intake or GHG emissions. Although the nutritional, environmental, and economic components of food systems are interdependent, previous studies have incompletely considered the interactions among these parameters. Similarly, the exploration of linkages between the food choices of Canadian households and the types of crops and animal products that are needed to sustain those food choices has also been limited. Many candidates for sustainable diets have been proposed for the Canadian population, however, a joint analysis of nutritional and environmental aspects of diets from both the production and consumption perspectives has not been conducted for Canada. A better understanding of these drivers and how they interact to influence the activities and outcomes of the food system requires a systems approach and integrated assessment tools to inform public policies (Allen and Prosperi, 2016; García-Martín et al., 2021). System-based models are useful for quantitatively assessing the sustainability of production-side and consumption-side options to meet nutritional adequacy and GHG emission reduction targets.

The objective of this study was to concurrently explore how land use shifts and dietary changes influence nutritional adequacy and GHG emissions of food produced in Canada. The present study considered most food commodities produced and consumed in Canada (70 plant-based and nine animal-based food commodities, including domestically farmed fish) and a comprehensive set of nutrients listed in the Canadian Dietary Reference Intakes (DRI).

2. Materials and methods

2.1. Conceptual framework

An agri-food systems approach is an interdisciplinary conceptual framework for research and policy aimed at sustainable solutions for the sufficient supply of nutritious and healthy food (Van Berkum et al., 2018). Through this framework, research questions are generated to drive insights into the interlinkages between different system levels and identify valuable leverage points for improving agri-food system outcomes and possible strategies for overcoming tradeoffs in healthy, sustainable, and inclusive diets (Ruben et al., 2018). Furthermore, this approach is beneficial to distinguish various opportunities for reconciling dilemmas between dietary transition and climate change, either through adjusting diets to target sustainability objectives (consumption-side solutions) or by adapting food production practices to address environmental goals (production-side solutions). Following the innovative approaches recently applied in comparable settings (White and Hall, 2017; Lachat et al., 2018; Van Zanten et al., 2018), we used systems modeling principles and tools to integrate land use for crop and animal feed production, the nutritional quality of diets and food systems environmental impacts (White and Hall, 2017; Nicholson et al., 2020). By using data and computational tools, these models can provide valuable insights into the potential impacts of different courses of action, helping to identify the most effective strategies for achieving long-term food security and sustainability.

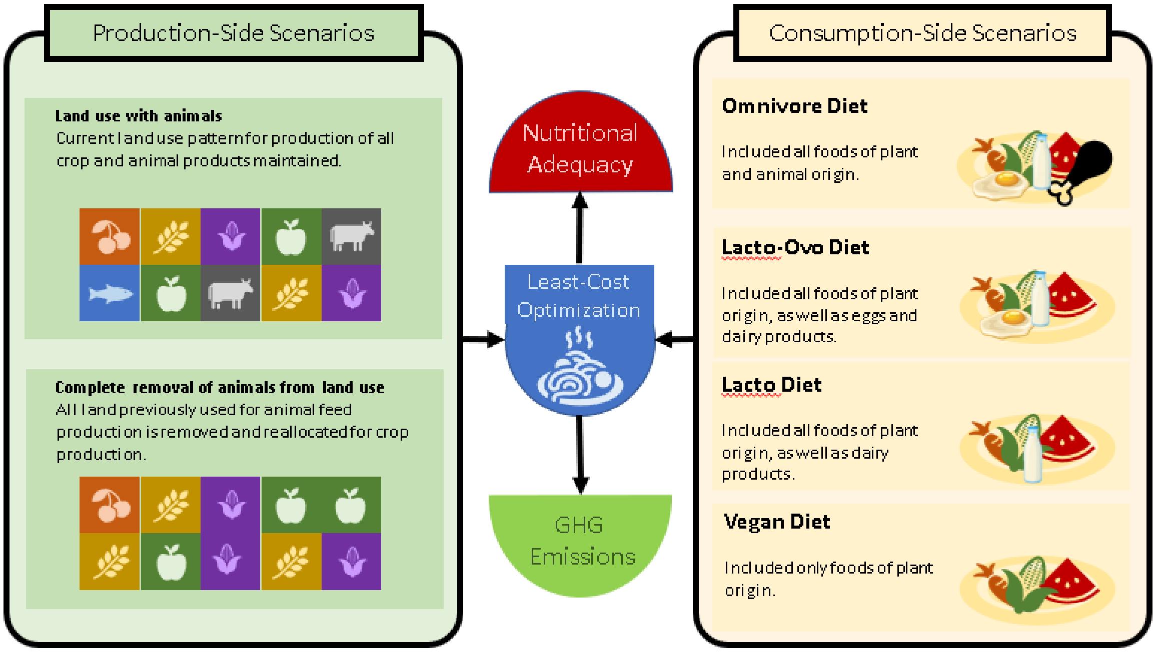

Figure 3: Conceptual framework for production-side and consumption-side scenario analysis
Note: We evaluate the impact of production change on nutrient intake and other indicators by comparing land use with animals to the complete removal of animals (CRA). To assess the impact of changes in consumption patterns, various dietary patterns that use food products produced under land use with animals were compared. These patterns included omnivorous, lacto-ovo vegetarian, lacto-vegetarian, and vegan diets.

2.2. Dietary scenarios

2.2.1. Consumption-side assumptions

Recent studies show that diet choice can have widely varying consequences on the sustainability of agricultural systems (Springmann et al., 2018). Therefore, it is crucial to explore a range of dietary scenarios using multiple sustainability indicators to identify potential tradeoffs and consequences of dietary change. To that end, we considered an omnivorous diet and three variants of vegetarian diets, including strictly vegan, lacto-ovo-vegetarian, and lacto-vegetarian scenarios (Fig. 3). We used data from the Canadian Community Health Survey (CCHS), which consisted of self-reported information provided by participants about their dietary habits (Health Canada, 2017).

Omnivorous diet

The omnivorous diet included all foods of plant and animal origin, including fish. Omnivorous diets meet nutrient requirements through a combination of both plant and animal-sourced foods. The omnivorous diet was considered to be the standard, as it is a diet that is most commonly consumed by Canadians (van Vliet et al., 2020).

Lacto-ovo-vegetarian diet

The lacto-ovo-vegetarian diet was characterized by a regular intake of milk, dairy products, eggs and egg products in addition to plant-based foods such as grains, legumes, oil seeds, vegetables, fruits, and plant extracted proteins, and related products (Chen et al., 2021). The lacto-ovo-vegetarian diets excluded all meat, including poultry and fish.

Lacto-vegetarian diet

The lacto-vegetarian diet included milk and dairy products in addition to plant-based foods but excluded eggs as well as all meat.

Vegan diet

The strictly vegan diet contained only plant-based foods. All foods of animal origin, such as meat, dairy, eggs, fish, and all their by-products, were excluded (Piccoli et al., 2015).

2.2.2. Production-side assumptions

The two production-side scenarios included in the analysis considered land use with animals or with complete removal of animals (CRA) from the production system (Fig. 3). Testing for potential benefits and adverse effects of the CRA scenario was complicated by the accuracy, number, and complexity of assumptions required to model changes in food production systems (White and Hall, 2017). Complete removal of animals from the farming system represents the most extreme scenario compared to other intermediate measures, such as partial livestock removal as a result of reduced red meat consumption. The CRA scenario assumed that all potentially tillable land previously used for annual feed crops, forage land (comprised of native pasture, alfalfa pasture, tame pasture, bale grazing, and stockpiled forages, alfalfa hay, grass-legume hay, grass hay, alfalfa haylage, and grass silage) was repurposed for plant-based human food production. The land base required for feed production was calculated using estimates of the quantity of feed required for feeding 11 livestock species of commercial relevance in Canada, as described in Chapter 3. The CRA diet included plant-based foods and wild-caught fish. However, foods of animal origin, such as meat, dairy, eggs, fish from aquaculture, and their by-products were not produced under the CRA scenario. It is important to note that the CRA diet was distinctly different from the vegan diet as the former was based on land use change (a production-driven decision) and the resulting foodstuff availability, while the latter was based on consumer-driven choice to eliminate all ASF. The CRA and vegan diets were similar food compositions, with the only difference being that the CRA diet includes fish sourced from natural waters. Although a vegan diet excludes all animal products, the CRA scenario involves the complete elimination of animals from the farming system with broader implications for food production.

2.2.3. Nutritional constraints

Each of the four dietary scenarios and the CRA scenario were examined using two nutrient requirement targets, resulting in ten scenarios. These targets were based on: i) weighted average RDA nutrient intake requirements defined in Canada's Dietary Reference Intakes Tables (Health Canada, 2005) and ii) the 2015 CCHS dataset, a comprehensive, nationwide survey conducted by Statistics Canada to gather information about the health status, health behaviors, and healthcare utilization of Canadians. By definition, RDA is set at a level that meets the nutrient needs of 97 to 98% of healthy individuals in a population at a particular life stage and gender group (Institute of Medicine, 2003). For those nutrients for which RDA could not be determined (such as choline, linoleic acid, manganese, pantothenic acid, potassium, and sodium), Adequate Intake (A.I.) was used as a substitute estimate (Health Canada, 2005). Because RDA requirements differ by age and sex, a single RDA value for all demographic groups within the 2015 Canadian population was determined using a weighted average that accounted for differences in nutrient requirements by age and sex, an approach similar to that used in previous studies (Broadley and White, 2010; Brink et al., 2019; Marushka et al., 2019).

The second nutrient intake target was developed based on current consumption patterns for omnivore, vegan, lacto-ovo-vegetarian, and lacto-vegetarian diets as reported in the 2015 CCHS database, conducted by Health Canada in partnership with Statistics Canada (Health Canada, 2017). This dataset was generated using the 24-hr. dietary recall questionnaire designed to collect information regarding consumption of food and corresponding nutrients for 12 age-sex groups: 1 to 3 yrs (genders combined), 4 to 8 yrs (genders combined), and males and females separated for ages 9 to 13 yrs, 14 to 18 yrs, 19 to 50 yrs, 51 to 70 yrs, and ≥71 yrs (Health Canada, 2017). These age groups correspond to the age ranges for which Dietary Reference Intakes (DRIs) have been established. Therefore, this nutrient target served as a benchmark for the nutrient intake of Canadians in each of the four diet scenarios.

2.3. Description of the linear programming model and integration of production-side and consumption-side interventions

Linear programming (LP) was employed to determine, for each scenario, the least-cost combination of food products that would satisfy the nutritional targets scaled assuming the entire Canadian population followed the consumption pattern outlined in that scenario (Dantzig and Thapa, 1997; Maillot et al., 2008). The model inputs consisted of nutrient content, nutrient intake targets (RDA and CCHS), cost, and GHG emission values of agricultural products that are produced domestically in Canada. To impose constraints, two primary factors were considered: 1) the total population-scale consumption of each food item had to be equal to or less than the modeled domestic supply of the food product, and 2) optimized consumption of each nutrient had to be greater than or equal to the target intake of the nutrient based on RDA or CCHS nutrient targets. for different nutrients. In order to prevent the creation of modeled diets that surpassed the human digestive system limits, the daily food intake upper limit was restricted to 2.5 kilograms/person/d (White and Hall, 2017; Health Canada, 2021). The objective function in the linear program was to minimize dietary costs (Dantzig and Thapa, 1997; Maillot et al., 2008). Following the development of the linear program with decision variables representing quantities of various food items and subject to constraints related to nutrient and food intake, a mathematical optimization algorithm was utilized to determine the optimal diet. The algorithm functioned by tuning the decision variables in such a way as to furnish the crucial nutrients in the most cost-effective manner possible. Finally, all least cost optimizations were constructed to evaluate the GHG footprint of the diet under each consumption scenario.

The formulation for the linear program used was as follows:

$\text{Minimize:}\, z = \sum c_j x_j$

$\text{Subject to:}\, \sum a_{ij} x_j \geq b_i$

$\text{and}\ x_j \geq 0,$

where z represents the cost of food items, the quantity of food commodities, j is represented as x_j;a_{ij} denoted the number of nutrients, i is a unit of food commodity, j; c_j is the unit cost of a food commodity j; b_i denoted minimum acceptable quantity of nutrient intake i.

To contrast the economic, GHG, and nutritional ramifications of diet change within the Canadian food system, daily food intake was optimized for each diet scenario using General Algebraic Modeling System (GAMS) version 31.1.0 (GAMS Development Corp, 2020). In certain scenarios, adjustments in production or consumption assumptions resulted in changes to the available nutrient profile, thereby making it impossible to simultaneously fulfill the two primary constraints (i.e., food intake being within domestic production, and nutrients consumed meeting nutrient requirements). When this was not possible, the constraints on dietary nutrient levels that could not be met from domestic supplies were omitted, leaving the model to include only nutrient constraints for those nutrients produced in sufficient supplies domestically to meet population targets. As a result, nutritional sufficiency was achieved only for a portion of the nutrients in each scenario (Table 4). It should also be noted that the models used crude protein as opposed to individual essential amino acids.

Table 4: Nutrients provided in insufficient supplies by Canada's domestic food production to satisfy optimization constraints

Nutrient intake requirement	**Nutrient name**	**OMN**	**LACTOVO**	**LACTO**	**VEG**	**CRA**
RDA	Calcium				x	
	Copper	x	x	x	x	x
	Docosahexaenoic acid		x	x	x	x
	Eicosapentaenoic acid		x	x	x	x
	Sodium	x	x	x	x	x
	Vitamin A				x	
	Vitamin B12				x	x
	Vitamin D	x	x	x	x	x
	Vitamin E				x	
CCHS	Copper		x	x	x	x
	DHA	x	x		x	x
	EPA		x	x	x	x
	Sodium	x	x	x	x	x
	Vitamin A				x	
	Vitamin B12				x	x
	Vitamin C	x	x	x	x	
	Vitamin D	x	x	x	x	x

It should be noted that the linear programming modeling approach is an illustrative tool and does not provide a comprehensive analysis of the nutritional value of foods. The food patterns generated by the model represent the least cost options and may not reflect the overall dietary needs and preferences of individuals in Canada.

2.4. Data sources

2.4.1. Land use data

Data regarding the seeded area, yield, and production of principal field crops (Statistics Canada, 2017b), vegetables (Statistics Canada, 2017a), and fruits (Statistics Canada, 2017c) were sourced from Statistics Canada. We considered land suitable for arable crops, where machinery use is feasible and is typically used for producing animal feeds, as potentially available for repurposing into crop production. All potentially tillable land previously used for animal feed production was reallocated to crop production in the same proportion as the seeded area of principal field crops, vegetables, and fruits, as reported by Statistics Canada. The total reclaimed land was calculated, and the total crop production for each crop was then determined by multiplying the originally seeded area plus the reclaimed land by the yield of each respective crop. Food produced in excess of that required by the Canadian population was assumed to be exported.

2.4.2. Food production data

Total domestic food production, including 79 (70 crops and nine animal) commodities produced in 2015/16 were used to calculate the quantity of nutrients available in Canada. More specifically, production weights (kilogram) of principal field crops (Statistics Canada, 2017b), vegetables (Statistics Canada, 2017a), fruits (Statistics Canada, 2017c), beef (Statistics Canada, 2016a), pork, sheep meat production (Statistics Canada, 2016b), dairy (Agriculture and Agri-Food Canada, 2016), poultry (Statistics Canada, 2016c), eggs (Statistics Canada, 2016d), and finfish (Fisheries and Oceans Statistical Services, 2016) were collected from Government of Canada documents. Goat and horse meat were not included in this study because the volume of production and consumption in Canada was insignificant (Dhanda et al., 2003; Lu and Miller, 2019).

2.4.3. Edible portion of foods

Reference amounts in Canada's Food Guide refer only to the edible portion of the food and exclude any components (e.g., peels) that are not usually consumed (Health Canada, 2021). Therefore, available food and nutrients derived from food commodities were calculated based on the proportion of unprocessed human-edible food commodities (Statistics Canada, 2018). Food available for human consumption was derived by subtracting proportions of the crop that were used for seed, livestock feed, export, crushing, or biofuel production from total crop production and ending stocks (i.e., inventory) from the total supply (Statistics Canada, 2018). Further, food losses can occur at retail, in restaurants, and in the household and would include food that is served but not consumed (i.e., plate loss). To better estimate the true edible/consumed proportion of food, available food supply data were multiplied by food-specific human-edible food conversion factors.

The edible portion of most food commodities was taken from the Economic Research Service of the United States Department of Agriculture (USDA, 2019), published literature (Franco et al., 2014; Bench et al., 2016; Whaley et al., 2019), and reported conversion factors in Canada (Agriculture and Agri-Food Canada, 2013; Canola Council of Canada, 2021).

2.4.4. Nutrient composition of food commodities

Estimating nutrient intake from food consumption requires reliable data regarding food composition. Therefore, the nutrient composition of 70 crops and nine animal commodities was sourced from USDA Food Composition Database (USDA, 2018). These data were used to calculate the total available nutrients by multiplying the amount of food produced in 2015/16 by the nutrient composition of each food product.

2.4.5. Greenhouse gas emission data

Data regarding GHG emissions from the production of food commodities were used to determine the environmental impact of the different diet scenarios. The GHG emissions (CO_2-eq/kg), including carbon dioxide, methane, and nitrous oxide for each food commodity, were derived using a systemic life cycle assessment (Clune et al., 2017). Packaging and transport median values were added to studies where the system boundary was the farm gate (Clune et al., 2017). To facilitate accurate comparisons of GWP across carbon dioxide, methane, and nitrous oxide, Clune et al. (2017) employed GWP values that were adapted to the system boundary of the regional distribution center (larger market centers). This approach ensured that the GWP calculations were consistent and scientifically sound, enabling reliable analysis and interpretation of the data. The total GHG emissions from each individual food commodity available for consumption were estimated based on food available at retail ,after correction for any food losses that may have occurred to this point in the food chain. When GHG values for individual food commodities were not available, median GHG values (kg CO_2-eq/kg) of food groups such as field-grown vegetables, field-grown fruit, cereals, legumes, fish, chicken, pork, dairy products, and beef were used (Clune et al., 2017).

2.4.6. Average retail price data

Average retail prices of some food commodities for 2015 were taken directly from Statistics Canada (Statistics Canada, 2022). For food commodities whose prices were not given in Statistics Canada, retail prices of food commodities were collected from several major retail stores at national level in 2020/21 and deflated by multiplying by the consumer price index to obtain the 2015 price.

3. Results and discussion

3.1. Food production with and without animals in Canada

3.1.1 Role of Livestock in Canadian Agriculture

In 2021, the agriculture and agri-food system employed 2.1 million people, providing 1 in 9 jobs in Canada, and generated $134.9 billion (approximately 6.8%) of Canada's GDP (Agriculture and Agri-Food Canada, 2022). Of these jobs, approximately 347,000 were in the livestock sector, either directly or indirectly, with each generating another 3.9 jobs elsewhere in the economy (Canadian Cattlemen's Association, 2022). Livestock also contributes to the circular economy by recycling agro-processing by-products, food grains unfit for human consumption, and food waste that would otherwise likely be directed to landfill (Ominski et al., 2021). Livestock recycled approximately 4.24 x 10^6 t of by-products (including 2.25 x 10^6 t of soybean meal, 1.02 x 10^6 t of canola meal, 0.30 x 10^6 t of soybean hulls and 0.22 x 10^6 t of corn gluten meal), as described in Chapter 3. In addition, livestock manure is a valuable organic fertilizer that can reduce the need for chemical fertilizers whose production in themselves generates significant GHG emissions (Legesse et al., 2018). In Canada, livestock generated 0.56 x 10^6 t of N, 0.11 x 10^6 t of P, and 0.28 x 10^6 t of K in the form of manure (Supplementary Material- SB9). Although carbon sequestration was not explicitly included in our GHG analysis due to data limitations, it is worth noting that cattle are capable of grazing on non-arable perennial forage lands, which can help conserve soil carbon stocks and promote carbon sequestration (Legesse et al., 2018; Pogue et al., 2018). Collectively, these data suggest that within the present agri-food system, animal agriculture is an important part of the Canadian economy, and helps to maintain biodiversity, provides nutrient cycling and water filtration services (McConkey et al., 2003; Pogue et al., 2018), and supports the conversion of inedible forages and surplus food to edible food.

3.1.2 Removal of Livestock from Canadian Agriculture

If all farm livestock in Canada were eliminated and the land formerly used for animal feed production reallocated to food crop production, 29.0% (18.15 million ha) of the land used for feed production would be liberated for food production. In comparison to the existing 44.44 million hectares, the total land designated for feed production in this scenario is estimated to be around 62.59 million hectares following the reclamation of 18.15 million hectares. To determine the per capita arable land in Canada, the total land designated for food production, amounting to 62.59 million hectares, is divided by the country's population of 36 million in 2016, resulting in a per capita arable land value of approximately 1.74 hectares. Although this scenario is hypothetical, it offers a unique opportunity to examine the impact of shifts in land use. It also highlights the significant implications of land use change for the agricultural industry, including farmers and agribusinesses who depend on livestock for their livelihood, and contribute to the food supply. Further, speculation regarding the fate of perennial forage land that is not used for grazing cattle is challenging because large parts of this land are not suitable for the production of cultivated crops (Terry et al., 2020). With grazing, the capacity of these land to produce human consumable nutrients would be greatly improved.

The land use change identified in this study (29% increase) was greater than reported in White and Hall (2017), where a 19% increase in available land was identified if livestock were removed from the landscape in the United States. Although similar, both values are far less than the estimated 75% gain in agricultural land anticipated with a global shift to a plant-based diet cited elsewhere (Ritchie, 2021). Nevertheless, 19 to 29% of agricultural land represents a significant shift in land area that could be converted to annual food crop production if North America shifted away from livestock production. The differences between Canadian and global estimates are likely due to the more efficient utilization of forage land by implementing better management practices such as rotational grazing and the use of improved varieties of forages (Legesse et al., 2016; Terry et al., 2020; Ritchie, 2021).

If livestock were removed from Canadian agricultural production systems and the land previously used for animal feed production used to grow human food crops, there would be a 23.5% increase in the amount of food available for consumption. Grains (16%), vegetables (4%), and oilseeds (4%) would experience the largest proportional increase Shifting land from livestock feed production to the production of crops for human consumption could result in increased the quantity of food leading to surplus production in Canada. It is important to carefully consider the potential uses of this surplus food, which could include exporting it to international markets or using it as raw material for industrial processes. However, the economic viability of these options requires further exploration.

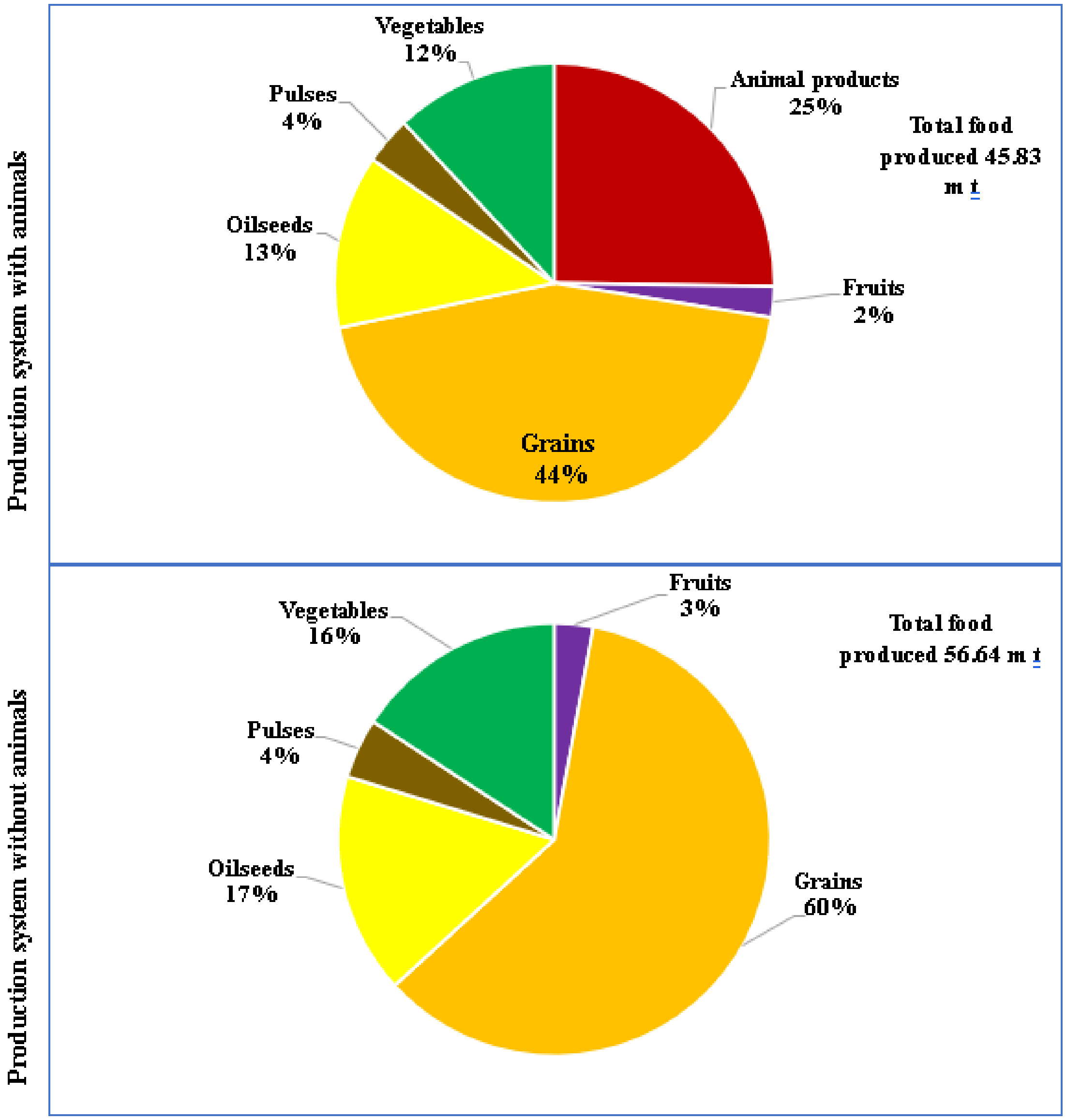

Figure 4: Total quantity (million tonnes) and proportions (%) of food produced in systems with animals and with complete removal of animals (CRA) (plants-only), based on from production data in 2016 (Statistics Canada, 2017a).

Although it is important to assess the changes in food production in systems with and without animals, the quantity of nutrients derived from these two production systems is more relevant in determining their ability to provide sufficient nutrient supply. Therefore, we also compared the two production scenarios in terms of nutrient supply. Canadian agriculture would increase the quantity of nutrients supplied, particularly macro-nutrients like protein (37.1%) and total fiber (67.4%), with shift away from animal agriculture. Dietary available energy was also predicted to increase by 50.3%. However, this shift away from animal agriculture would also reduce the supply of vitamin A (-16.6%), vitamin B12 (-99.6%), vitamin C (-56.2%), vitamin D (-96.6%), vitamin E (-58.5%), and vitamin K (-59.8%). It would also reduce the supply of some fatty acids, including DHA (-92.5%) and EPA (-88.5%), as well as calcium (-12.4%), magnesium (-59.2%), potassium (-44.5%), sodium (-51.2%), and selenium (-54.8%). An increase in dietary energy associated with removing animal protein from the diet may seem counterintuitive, given the concerns about the positive relationship between animal product consumption and obesity (Rogers et al., 2016). However, animal products, such as meat, dairy, and eggs, are typically more nutrient-dense than plant-based foods (Mottet et al., 2017), containing higher levels of essential nutrients, including amino acids, vitamins, and minerals (Bohrer, 2017). Eliminating animal products from the production system can pose a challenge in supplying the same amount of essential nutrients only from plant-based sources (Aschemann-Witzel et al., 2021). Therefore, consumers may need to eat more food overall to meet their nutritional needs, resulting in a higher energy intake (Alcorta et al., 2021).

Although shifting land use from animal feed production to crops may increase the supply of certain nutrients, it also decreased the supply of other essential nutrients. This is because different crops have different nutrient profiles, and relying solely on crops for food production can lead to inadequacy in certain nutrients, such as vitamin B12 and vitamin D. In order to ensure adequate nutrient intake and prevent deficiencies, it is important to maintain a balanced and diverse diet that includes a variety of both plant-based and animal-based foods. This can help support overall health and well-being while also considering the impacts of eliminating livestock from the agricultural system. To better understand the societal implications of livestock production, these changes in nutrient supply should be viewed within the context of human requirements.

Changes in nutrient supply are consistent with the findings of a comparative study in the United States that modeled the impacts of removing farmed animals from agricultural systems. These researchers found that diets formulated in a simulated production system without animal products resulted in excess dietary energy and increased deficiencies of essential nutrients (White and Hall, 2017). These results are also comparable to the findings of previous studies, which have observed that energy-dense foods are often supplied in excessive amounts in many parts of the world, while nutrients such as vitamin A, vitamin C, vitamin B2, vitamin B12, vitamin B6, niacin, iron, magnesium, niacin, zinc, iron, and magnesium are often deficient in plant-based diets (Williamson et al., 2005; Wolk, 2017; Rubio et al., 2020). Relying solely on plant-based diets can make it more difficult to meet the nutritional requirements of the population. Many of these micro-nutrients are provided in high concentrations in ASF, suggesting that the removal of livestock from agriculture would exacerbate deficiencies in these nutrients.

In order to meet the nutritional needs of the population, a balanced diet should include a variety of foods from both plant and animal sources, including fruits and vegetables, whole grains, legumes, nuts, and seeds, as well as lean meats, poultry, fish, eggs, and dairy products. Although it could be argued that alternative agricultural enterprises could use the land liberated from livestock production to produce more nutrients for human consumption, contemporary climate, and biodiversity threats require dedicating more land to sequestering carbon in grasslands, trees, and soils (Pogue et al., 2018; Barrett et al., 2020). As such, leveraging land used for forages for alternative agricultural activities may not present a concomitant advancement toward achieving the sustainability goals of agricultural systems.

3.2. Optimized dietary scenarios

The study's findings demonstrate that omnivorous, lacto-ovo-vegetarian, and lacto-vegetarian diets require a higher quantity of food to meet RDA intake targets (Fig. 5). Although the dietary profiles of these three diets were identical in terms of RDA-nutrient intake targets, the compositions of these diets differed to achieve CCHS targets. Omnivorous diets, based on CCHS intake requirements, required the largest quantity of total food intake. Lacto-ovo and lacto vegetarian diets differed in the amount of vegetables and grains to satisfy CCHS nutrient targets. Overall, the quantity of food consumed, nutrient intake, and GHG emissions exhibited similarities between omnivorous, lacto-ovo vegetarian, and lacto-vegetarian diets.

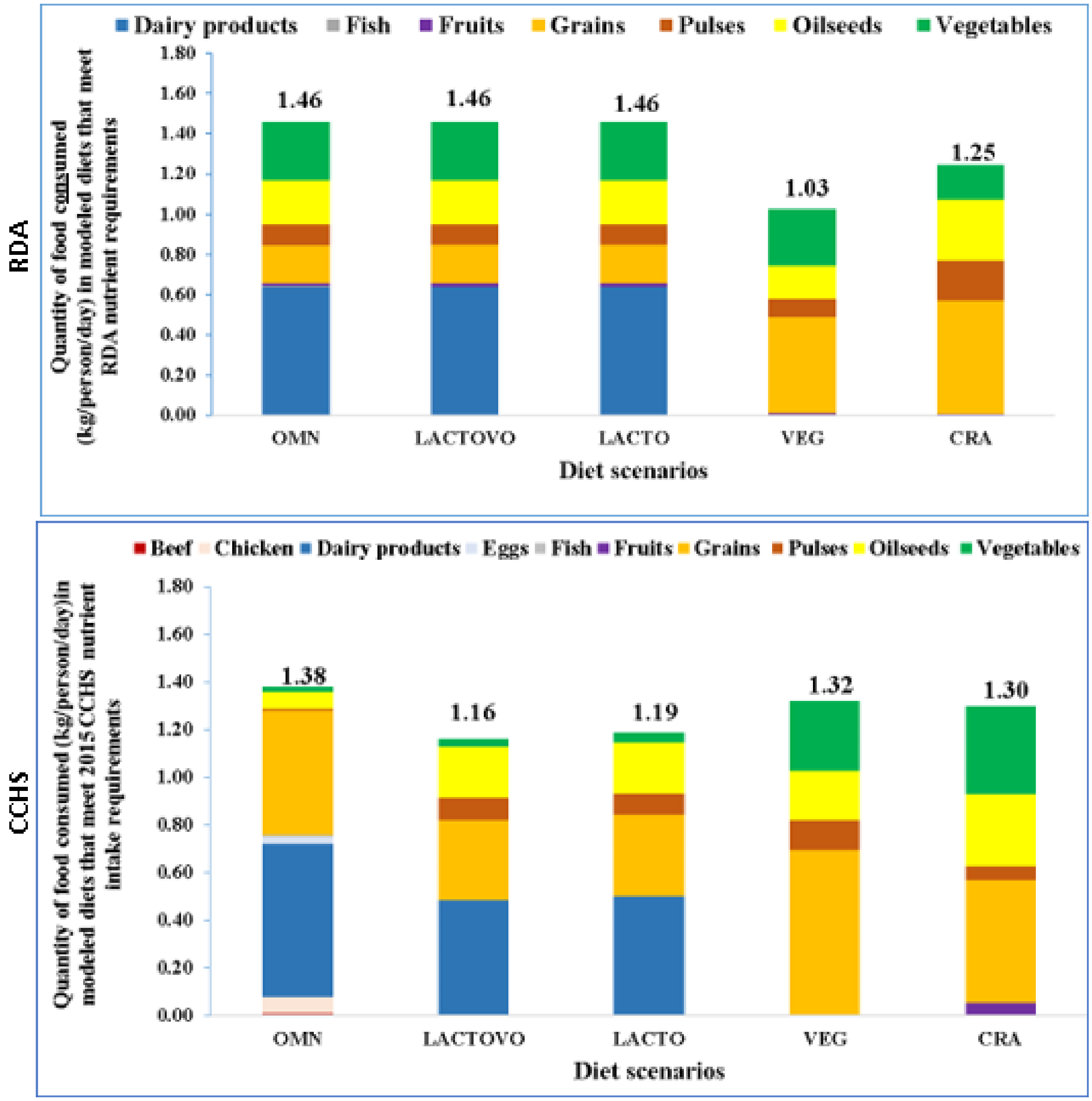

Figure 5: Quantity of foods (kg/person/d) required in least cost modeled diets that meet Recommended Daily Allowance (RDA) and 2015 Canadian Human Health Survey (CCHS) nutrient intake targets by diet type and complete removal of animals (CRA)
Note: OMN=Omnivorous, LACTOVO=lacto-ovo-vegetarian and LACTO=lacto-vegetarian, VEG=vegan

Our study found that the average optimized least-cost food intake for Canadians was 1.33 kilograms/person/d (Fig. 5), which is considerably lower than previous estimates of actual daily intakes. Auclair and Burgos (2021) estimated that Canadians consume 3.6 kg (range 3.3 kg to 3.9 kg) of food per day based on data from the CCHS. The discrepancy in estimates of the current study and Auclair and Burgos (2021) could be attributed to differences in methodology employed in the two studies. While Auclair and Burgos (2021) estimated total food intake by extrapolating from energy intake based on food intake ad libitum, the current analysis calculated food intake directly by optimizing all nutrients using a linear programming. The marked difference between Auclair and Burgos (2021) and modeled food intake in the current study highlights an opportunity for responsible bodies such as Health Canada to devise nutrient-dense, and affordable diets that align with Canadians' actual food consumption patterns. In other words, creating nutrient-dense diets that fit with Canadians' actual food consumption patterns could bridge the gap between recommended and actual nutrient intake, leading to better health outcomes and reduced risk of chronic diseases. This approach could have potential environmental and cost benefits. Nonetheless, practical, and behavioral hurdles may impede success in implementing such diets. Relying solely on satiety mechanisms may not be a reliable way to control food intake (Horgan et al., 2016; de Gavelle et al., 2019; Hosseini et al., 2021). Practical and behavioral challenges, including the limited availability and affordability of recommended foods and emotional or psychological factors such as stress or social pressures, can hinder the restriction of intake limitations based on satiety mechanisms. Combining satiety-based intake approaches with other strategies, such as portion control and portion size education, may be necessary to address this challenge. The dietary intake literature suggests advantages to using omnivorous eating patterns for nutritionally adequate, health-conscious, and environmentally sustainable diets (Bye et al., 2021). In addition to the amount of food consumed, assessment of the cost of different dietary scenarios is an important factor that can influence dietary choices.

When we evaluated the diet costs of the modeled omnivore and CRA diets in, CRA diets were more expensive (4.15 vs. 3.50 CA$/person/d). The Agri-Food Analytics Lab at Dalhousie University estimated an average national food expenditure of 8.53 CA$/person/d in 2022, or 7.10 CA$/person/d in 2016 when adjusted for inflation (Charlebois et al., 2020; Agri-Food Analytics Lab, 2022). Statistics Canada reported that the average Canadian household spent CA$ 217/person/month on food, which is approximately 7.11 CA$/person/d (Statistics Canada, 2021). As would be expected, with the modeled reduction in food intake, food costs in the present work were estimated to be 37 to 50% of the estimated average food expenditure/person/d of Canadian consumers. Costs were quite similar in the RDA-) and CCHS-based scenarios (<1% difference). The observed disparity between modeled and actual daily food costs could be attributed to multiple factors, most notably the methods (actual behavior vs optimized behavior), but also assumptions including food price, nutrient content of food products, and consumption patterns influenced by dietary choice, food availability, and cultural preferences.

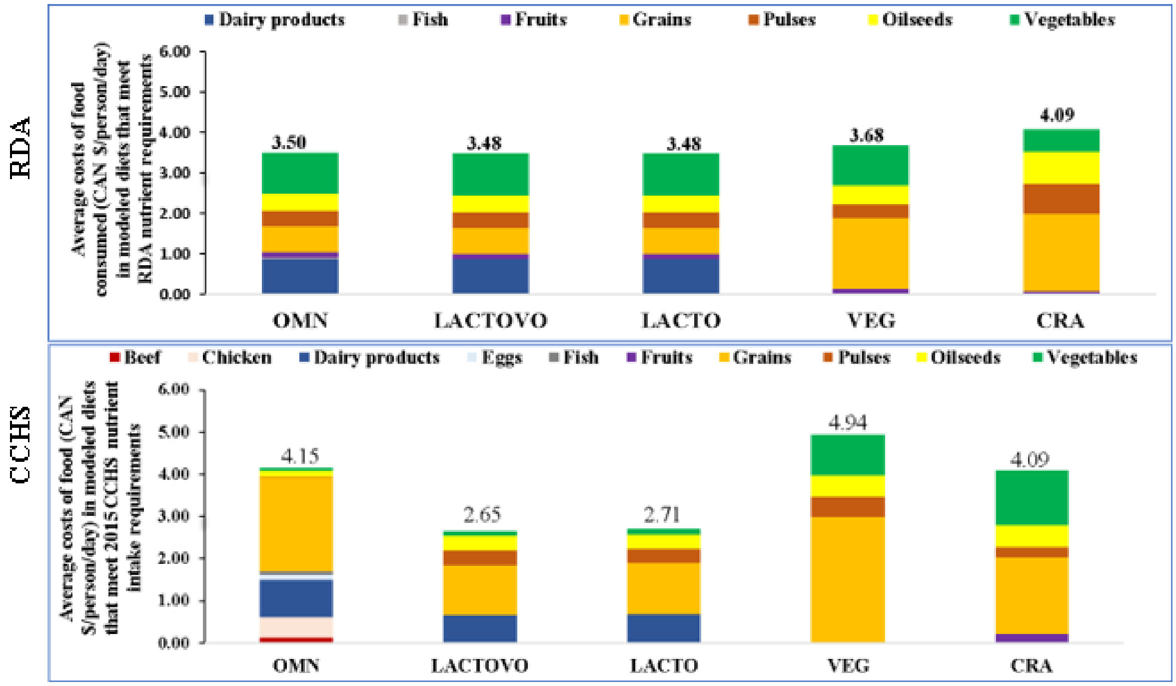

Figure 6: Averaged daily costs (CA$/person/d) of least cost modeled diets that meet Recommended Daily Allowance (RDA) and 2015 Canadian Human Health Survey (CCHS) nutrient intake requirements by diet type and with complete removal of animals (CRA)
Note: OMN=Omnivorous, LACTOVO=lacto-ovo-vegetarian and LACTO=lacto-vegetarian, VEG=vegan

To fully comprehend the nutritional adequacy of diets optimized in various scenarios, it is crucial to explore the potential of meeting RDA and CCHS nutrient targets. Specifically, our study revealed that least-cost diets derived based on CRA scenario could not meet the RDA intake requirements of vitamins (A, B12, D, E). from the Canadian food supply (Fig. 7). Although the CRA system had lower levels of DHA and EPA compared to the animal-based production system, it was infeasible to determine the implications of these differences in nutrient intake as there is no RDA requirement for DHA and EPA (Supplementary Material- SB5 and SB6). This finding serves as an important counterpoint to the broad-spectrum claims of some researchers and plant-based food advocates who argue that eliminating animal products from the production system in high-income countries would reduce GHG emissions, without negatively impacting consumers' ability to meet their nutrient requirements(Henchion and Zimmermann, 2021).

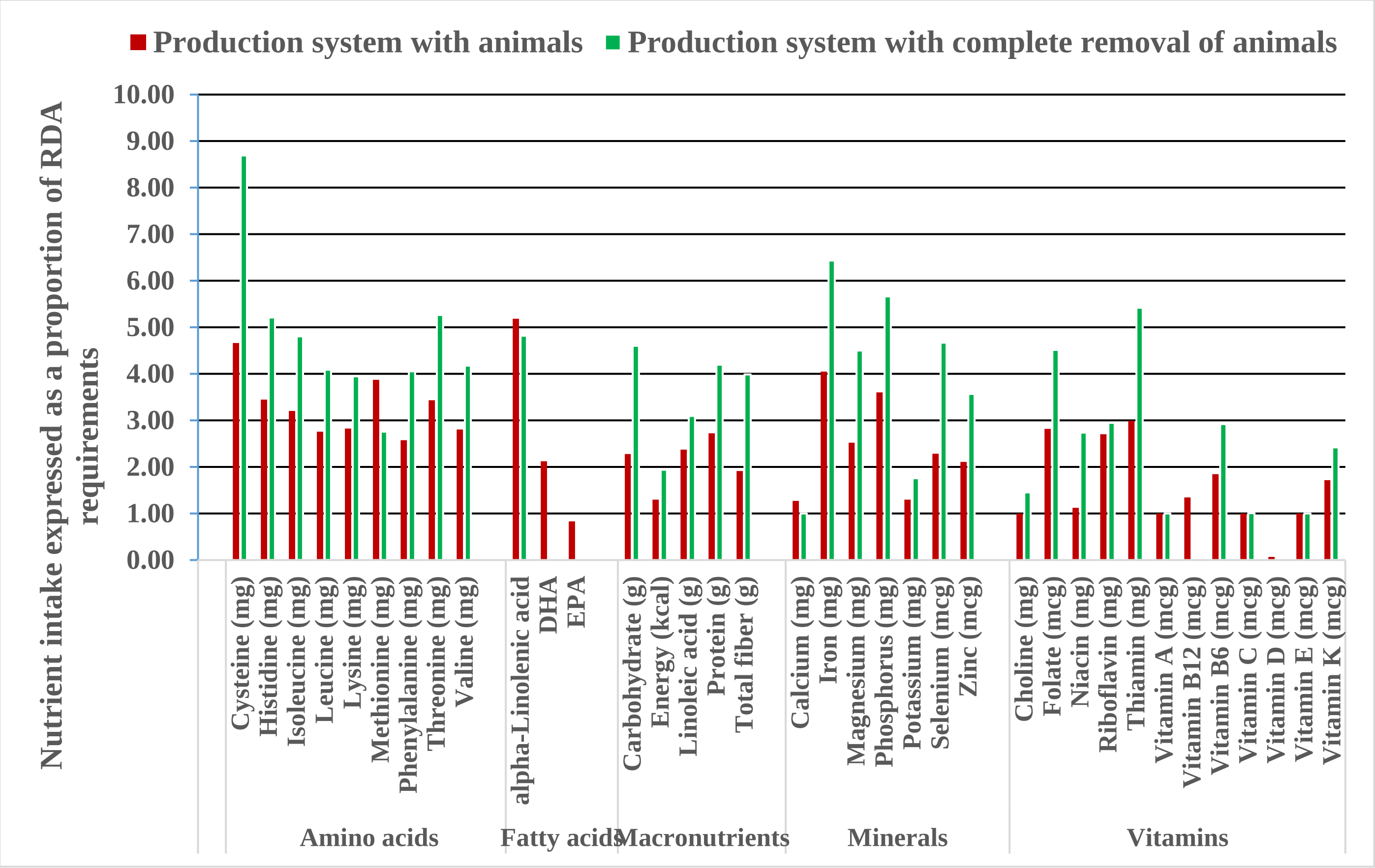

Figure 7: Daily nutrient intake of modeled least-cost optimized diets derived from food commodities produced in food production systems with animals and with complete removal of animals expressed as a fraction of RDA requirements

Comparing food with animals versus without animals, our study found that the least-cost diet relied solely on low-cost grains, oilseeds, pulses, and dairy products. However, the CCHS nutrient target required that animal products such as beef, chicken, fish, and eggs were included in least-cost diets. Of particular interest was the inclusion of beef in the omnivore scenario, despite it being considerably more expensive than pork (CA$ 20.0 vs. CA$ 7.4/kg). This suggests that the unique nutrient profile of beef, relative to pork, was a driving factor for its inclusion in the diet. Specifically, beef has higher vitamin B12, iron, zinc, and omega-3 fatty acids than either chicken or pork (Williams, 2007; Ahmed et al., 2021). On average, grass-fed beef might contain around 20-50 milligrams of EPA (eicosapentaenoic acid) and DHA (docosahexaenoic acid) combined per 100 grams of meat (De Cicco et al., 2019). However, the quantitative contribution of beef to total food consumption was 0.64 g/person/d. According to data from the 2015 CCHS, the average consumption of fresh red meat for all Canadians was 52 g/person/d and the total consumption of red meat (including processed red meat) was 74 g/person/d. Canadian dietary guidelines suggest 50 - 75 g/person/d of cooked fresh meat in the form of beef, pork, sheep, or veal per day (Cashman and Hayes, 2017). The cost of beef could be a factor resulting in the low inclusion rate in the modeled diets as compared to actual beef consumption by Canadians. The difference in inclusion rates of meat is likely a reflection that in omnivorous diets it often consumed at levels higher than required. In other words, the model prioritizes the selection of foods that provide the nutrients at the lowest cost, rather than aiming to match actual food consumption patterns. Hence, the shadow price optimization approach provides valuable insights into the potential trade-offs between nutrition, cost, and social factors that influence food choices and consumption habits (Shepon et al., 2018).

As indicated in Table 4, a number of essential nutrients were excluded from the model when either RDA or CCHS nutrient targets could not be satisfied from domestic production. By removing these nutrient constraints, it could be inferred that neither the CRA nor vegan diets result in sufficient nutrients to meet the CCHS nutrient intake targets. Hence, the comparison between vegan and CRA diets with omnivorous or vegetarian diets is infeasible within the scope of this study due to the limited convergence in nutrients that are regarded as constraints during the optimization process. More specifically, our analysis based on the CCHS dataset revealed that certain nutrients, such as DHA, EPA, calcium, and various vitamins, could not be adequately supplied through domestic food production. Moreover, copper, sodium, and vitamin D were eliminated from all scenarios due to insufficient supply from domestically produced commodities. In the CCHS scenarios, only the lacto-vegetarian diet satisfied the DHA target, while the omnivore and lacto-ovo vegetarian diets fell short. It is plausible that DHA and EPA could be obtained from other dietary sources, including fatty fish and algae-based supplements (Kutzner et al., 2017).

Our results confirm that meeting micro-nutrient requirements is a critical challenge for plant-only diets, which is consistent with previous studies (Adesogan et al., 2019; Adesogan et al., 2020; Salmon et al., 2020). Previous research has found that plant-based diets were associated with higher deficiencies in calcium, protein, vitamin A, vitamin D, omega-3 fatty acids, riboflavin, niacin, pantothenic acid, vitamin B12, iron, selenium, zinc, and thiamin as compared to diets that contain ASFs (Williamson et al., 2005; Wolk, 2017; Rubio et al., 2020). Further, meat and eggs are the major sources of long-chain n-3 polyunsaturated fatty acids (PUFA), and red meat is the main dietary source of DPA (Abedi and Sahari, 2014). These findings are also consistent with findings in the U.S. (White and Hall, 2017), which reported that essential micro-nutrients are a critical challenge in scaling diets from individuals to the population.

Our study estimated that eliminating animals from agricultural systems in Canada and relying solely on plant-based food ingredients for diets would lead to approximately 17.10 million metric tons of CO_2-equivalent emissions. These findings are consistent with the observed patterns of GHG emission reduction in a comparable study conducted in the United States, where the system without animals had lower emissions (White and Hall, 2017). The GHG emissions from the animal production systems that adhere to the RDA target accounted for 64.5% of modeled dietary emissions, which aligns with the Canadian national inventory value of 60% of agricultural emissions attributed to livestock in 2019 (Environment and Climate Change Canada, 2020). Optimal diets meeting RDA requirements had an average of 0.64 kg CO_2-eq/person/d, and those meeting 2015 CCHS nutrient intake targets had an average of 0.55 kg CO_2-eq/person/d under the CRA scenario (Fig. 8). In contrast, current Canadian diet emissions of 3.98 kg CO_2-eq/person/d have been estimated elsewhere (Auclair and Burgos, 2021), which is 1.43 times greater than the highest emissions estimated for an omnivore diet under CCHS nutrient intake targets. The observed disparities between Auclair and Burgos (2021) and the present study could be attributed to methodological differences, as the former study used life cycle analysis to estimate GHG, while the latter study employed Linear Programming to assess nutrient targets derived from CCHS, weighted average RDA, as well as nutrient composition data from USDA, a full suite of GHG values from Clune et al. (2017), and food prices collected from Canadian retail stores.

The estimated GHG emissions for a modeled omnivore diet with the CCHS nutrient intake target (1.64 kg CO_2-eq/person/d) in Canada was lower than the estimated GHG emissions for a modeled diet with animals (3.29 kg CO_2-eq/person/d) in the United States (White and Hall, 2017). Furthermore, the GHG emissions for a modeled diet without animals with 2015 CCHS nutrient intake target (0.55 kg CO_2-eq/person/d) was much lower than the estimated GHG emissions (1.43 kg CO_2-eq/person/d) for a system without animals in the United States (White and Hall, 2017). This could be associated with the difference in the quantity of food consumed in the modeled least cost diets in the two studies. It is important to note that these estimates may vary depending on the specific assumptions and data used in the studies, including the most recent USDA nutrient composition data, a comprehensive set of GHG values obtained from Clune et al. (2017) and food prices collected in Canadian retail stores. The potential for reducing GHG emissions through changes in diet composition within an omnivorous dietary scenario could be substantial, despite variations across studies. A critical method to achieve such reductions is through optimal diet planning, which involves boosting the intake of plant-based foods such as fruits, vegetables, and whole grains, while cutting back on meat and processed foods (Cashman and Hayes, 2017). By adopting this approach, significant GHG emission reductions could be achieved, resulting in notable environmental benefits. It is critical to note, however, this reduction only occurs if shifts in demand translate to shifts in supply. In high income countries, supply of livestock is highly inelastic to demand.

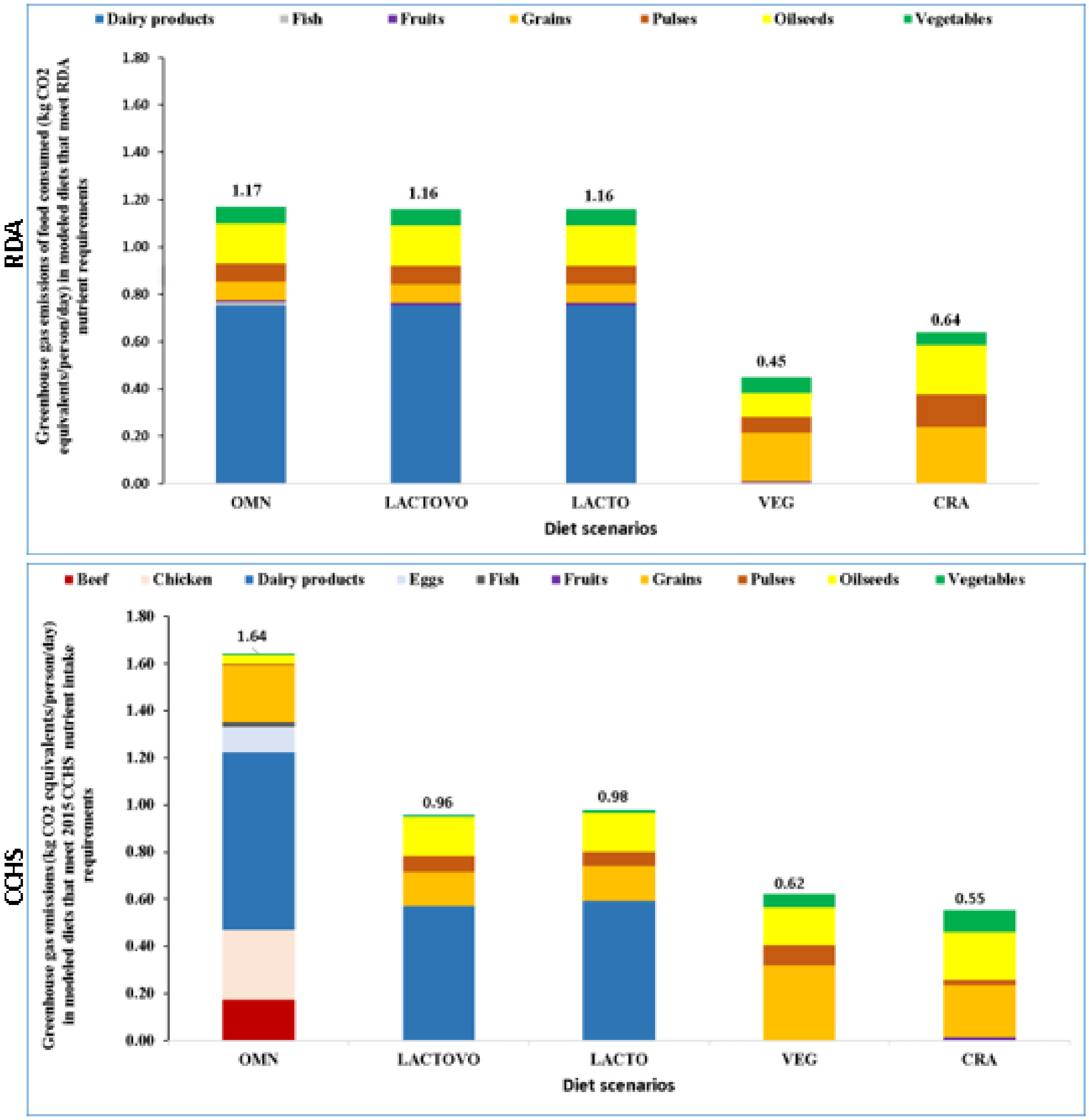

Figure 8: Greenhouse gas emissions (kg CO_2 eq/person/d) of least cost modeled diets that meet RDA and 2015 Canadian Human Health Survey (CCHS) nutrient intake targets by diet type and complete removal of animals (CRA).
Note: OMN=Omnivorous, LACTOVO=lacto-ovo-vegetarian and LACTO=lacto-vegetarian, VEG=vegan

The vegan and CRA scenarios resulted in lower GHG emissions than omnivorous or lacto-ovo- and lacto-vegetarian diets when compared on an RDA- or a CCHS-basis (Fig. 8). There are several reasons why vegan and CRA scenarios resulted in lower GHG emissions compared to omnivorous and vegetarian diets. The lower GHG emissions associated with vegan and CRA diets could be explained by the reduced consumption of animal products which generally have a higher environmental impacts (Mottet et al., 2017; Godfray et al., 2018). The reduction in GHG emissions is consistent with the lower GHG emissions intensity of plant-source foods as compared with ASF (Saxe et al., 2013; Horgan et al., 2016; Clark and Tilman, 2017). Interestingly, these scenarios resulted in higher diet costs, raising concerns about the affordability of plant-based diets when scaled to a population level. The highest food cost of CAD $ 4.94/person/d was recorded in modeled vegan diets based on the CCHS nutrient requirement target. The differences in target nutrient consumption levels among scenarios also conferred differences in diet costs and GHG emissions. The relative cost of nutrients in vegan and CRA diets may be higher than in omnivorous diets due to the lower nutrient density of plant-based foods. This potentially results in a higher cost of nutrients per unit for plant-based foods, leading to higher costs for consumers.

Limitations and suggestions for future work

Although least-cost diet optimization for humans based on nutrient targets derived from CCHS data or RDA is valuable because it provides a consistent basis for comparison among food consumption patterns, there are key limitations to this approach that should be highlighted. First, LP modeling was intended to illustrate potential impacts of land use shifts and dietary changes on selected outcomes of interest, and the study did not intend to formulate a balanced recommended diet for use in public nutrition and health. The least-cost modeled food patterns selected by the LP approach are not constrained to consider or replicate holistic properties of foods in actual diets and do not generate realistic diets that people would be willing to consume. Several factors may hinder consumers from adopting the food patterns selected by LP, including taste, cost, cultural preferences, convenience, and other important dietary considerations. As such, the modeled food patterns are not intended to reflect actual food consumption patterns of omnivores, vegetarians, vegans, or other food-consuming groups. As an additional limitation, the results of this study were based on nutrient intake and food prices from 2015/16, and future research accounting for changes in nutrient intake and food prices over time is necessary. In addition, the analysis was conducted on a snapshot of the Canadian population during a single time period, which may not reflect the nutritional needs of specific groups, such as the elderly, pregnant or lactating women, and growing children. Specific exploration of the needs of these nutritionally sensitive groups should be the subject of future work.

As with all simulation and model-based studies, it is also possible to explore additional variables or scenarios in future work. Future studies may focus on additional production- and consumption-side scenarios related to land use, which can lead to better management practices and consumption patterns. For example, this may include exploring the potential impacts of partially replacing land used for animal feed production with the production of food crops and other alternative uses. Alternatively, further ex-post impact evaluation could be conducted to further explore joint analysis of production-side and consumption-side options. Such an analysis can help identify appropriate scenarios for achieving both nutritional adequacy and environmental sustainability goals.

4. Conclusions

This work aimed to explore how dietary changes influence nutritional adequacy and reduction of GHG emissions of diets produced from the Canadian agricultural system while accounting for land use shifts associated with the omission of ASF. The land use-based production-side scenarios and a variety of consumption-side scenarios show that RDA requirements of most nutrients could be obtained from Canadian food supply in most production and consumption scenarios. Limiting nutrients were DHA, EPA, potassium, and vitamins (A, B12, C, D, and E). Dietary changes on the consumption side have highlighted opportunities for all food consumption patterns to alter dietary intake in terms of the amount and types of foods used to achieve nutritional adequacy requirements , while enhancing diet affordability compared with current average consumption patterns. The results suggest that the removal of animals has advantages and disadvantages in terms of nutrient supply and environmental impacts and tradeoffs among these diverse objectives are often inevitable. Comparing dietary patterns further supported previously identified tradeoffs between diet cost, environmental impact, and nutritional adequacy. The GHG emissions are greatest for omnivore, lacto-ovo-vegetarian and lacto-vegetarian dietary scenarios, while the complete removal of animals from the Canadian farming system and the shift to vegan diets resulted in a marginal reduction of GHG emissions with an increase in the cost of diets and risks of micronutrient deficiencies. Our results contribute to the discussion of the roles of ASF in national dietary recommendations aimed at enhancing public health and agricultural sustainability.

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Bridge to Chapter 5

Chapter 4 examined the nutritional adequacy and GHG emissions resulting from the elimination of ASF from consumer diets, utilizing both production and consumption scenarios. With this knowledge in hand, the logical progression was to assess the actual impact of excluding ASF on nutrient intake, using real food intake data from Canadians. Chapter 5 explores the post-exclusion analysis of the complete removal of red meat from diets as an example, utilizing data from the 2015 Canadian Community Health Survey to examine the impact on nutrient intake and overall nutritional adequacy.

CHAPTER V: NUTRITIONAL IMPACT OF EXCLUDING RED MEAT FROM THE CANADIAN DIET

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Abstract

The objective of the study was to examine differences in nutrient intake between consumers and non-consumers of red meat and to assess the nutritional adequacy of consumers relative to Recommended Daily Allowance (RDA) in Canada. Matching estimators were used to identify differences in nutrient intake between the two groups. Statistically significant differences were observed in nutrient intake between red meat consumers and non-consumers, including lower daily intake of protein, riboflavin, niacin, vitamin D, and zinc and a higher daily intake of dietary fiber, folate, and magnesium among Canadians who did not consume red meat. Further, red meat consumers and non-consumers had nutrient intakes below RDA for dietary energy, fiber, calcium, vitamins A and D, potassium and magnesium. However, individuals who chose not to consume red meat had a heightened risk of inadequacy for calcium, vitamin D, energy, and potassium, while those who included red meat in their diets were more susceptible to experiencing inadequacy in dietary fiber, vitamin A, and magnesium.

Keywords: Red meat consumption; nutrient intake; matching estimators; Recommended Daily Allowance; Canadian Community Health Survey

1. Introduction

Meeting the increasing demand for nutritious food in the face of a growing world population while reducing the environmental impacts of anthropogenic greenhouse gas emissions (GHGs), land-use change, water use, and avoiding biodiversity loss is one of the grand challenges facing humanity in the 21st century (Crist et al., 2017). Researchers predict that increased income in developing countries will hitherto lead to dietary changes towards animal-sourced foods (ASF) in the coming decades (Fukase and Martin, 2020; Rust et al., 2020). A recent scenario-based modeling study showed that the average global demand for red meat (i.e., beef, sheep, goats, and pork), poultry, dairy milk, and eggs would increase by 14% per person and 38% in total between 2020 and 2050, if trends in income and population continue along a mid-range trajectory (Fukase and Martin, 2020).

In recent years, the health impacts of consuming high quantities of red meat and processed red meat in high-income countries has attracted attention in academic and policy debates. Several studies have linked red meat intake to an increased risk of certain health conditions, such as cardiovascular disease, type 2 diabetes, and certain types of cancer (Battaglia Richi et al., 2015; Lescinsky et al., 2022). In contrast, an international team of researchers conducted five systematic reviews that examined the effects of red meat and processed meat on multiple health conditions such as heart disease, cancer, diabetes, and premature death and concluded that the evidence linking red meat to these health conditions is "weak" (Johnston et al., 2019). Moreover, some studies recommending the elimination of red meat from diets have not considered its value in supplying micro-nutrients (i.e., vitamins and trace minerals) that are essential to human health (De Smet and Vossen, 2016). It has been established that animal products contribute to global food security by supplying essential macro- and micro-nutrients (Tilman and Clark, 2014). Specifically, ASF including red meat provides high-quality protein and a variety of nutrients, including vitamin A, vitamin B12, riboflavin, vitamin D, calcium, iron, and zinc, which could be challenging to obtain in adequate quantities in bioavailable forms from plant-based diets (Dietary Guidelines Advisory Committee, 2020; Rubio et al., 2020). The conflicting results of these studies suggest that further research is necessary to better understand the relationship between red meat intake and human health.

Nonetheless, there have been calls to shift food choices towards more plant-based foods, with a reduction in ASF, including red meat, to protect the natural environment and promote human health (Bianchi et al., 2018). The EAT-Lancet Commission recently suggested that transformation to climate-friendly diets by 2050 will require a 50% reduction in the consumption of red meat and a doubling in the global consumption of plant-based diets (Willett et al., 2019). In Canada, the 2019 Canada Food Guide emphasized that consuming plant-based diets will promote health and improve the long-term sustainability of Canada's agri-food sector (Health Canada, 2021). Such policy initiatives could further reduce red meat consumption in Canada, which has already seen a 21% and 26% decrease in per capita beef and pork consumption between 1998 and 2017, respectively (Ruan et al., 2019). It has been reported that 42% of the Canadian population surveyed reported consuming red and processed meat (Vatanparast et al., 2020). It is evident that Canadians have started to display a preference for plant-based diets, with 3 million Canadians (9.4% of the total population) expressing their willingness to shift towards vegetarian diets in a survey administered in April 2017 (Charlebois et al., 2020).

Therefore, it is important to examine the impact of shifts in diet on consumption patterns and the potential to exacerbate existing inadequacies. For example, most recommendations to eliminate red meat from diets have failed to consider the nutrient requirements of diverse population categories such as growing children, adolescent girls, pregnant women, aging adults, and the malnourished and impoverished (Adesogan et al., 2020). Recommendations for healthy diets may be perilous, if the nutritional impacts associated with the elimination of meat from the diets of diverse population categories are ignored (Cliceri et al., 2018). Hence, building scientific evidence regarding the nutritional impacts of excluding red meat from diets is critical for informing national dietary policies and consumer food choices.

A 2015 Canadian Community Health Survey (CCHS) dataset (Health Canada, 2017) containing information regarding the intake of nutrients and socio-demographic characteristics of a sample of Canadian consumers provided an opportunity to examine the nutritional impact of excluding red meat from the diet. The CCHS provides detailed information about the types of foods that are consumed in Canada, including fruits, vegetables, meats, grains, and other food items (Health Canada, 2017). Previously published data regarding the dietary patterns of Canadians using this data set has demonstrated that animal sources contribute two-thirds of the protein consumed by Canadian adults (Auclair and Burgos, 2021). More specifically, these authors have reported that protein consumption included red and processed meat (21.6 ± 0.55%), poultry and eggs (20.1 ± 0.81%), cereals, grains, and breads (19.5 ± 0.31%), and dairy (16.7 ± 0.38%).

Analysis of survey data such as that provided in the CCHS is complex as linear models, which are frequently utilized to evaluate mean differences between treatment groups in cross-sectional nutrition surveys, have significant limitations (Soret et al., 2014; Vatanparast et al., 2020). In recent decades, the use of matching methods to evaluate public interventions using observational data has gained popularity in various scientific fields, including economics, epidemiology, medicine, and political science. This approach involves comparing individuals or groups who were exposed to an intervention with those who were not, in order to assess the intervention's impact on outcomes of interest (Imbens, 2015). Propensity score matching (PSM) is a statistical technique used to compare the outcomes of a treatment group with a control group in the absence of experimental data. This technique is based on the concept that if the treatment and control groups are similar in terms of their observed characteristics, then any differences in outcomes between the groups could be attributed to the treatment (Rosenbaum and Rubin, 1983). There has been a recent increase in the use of PSM for assessing the nutritional impacts of public nutrition interventions using observational survey data (Klurfeld, 2015, 2022) due to the growing recognition of the importance of accurately evaluating the effectiveness of these interventions in order to inform policy and improve public health outcomes (Ali et al., 2016; Hosseini et al., 2019; Webster, 2019).

Therefore, the objective of the current study was to examine the nutrient intake of Canadian consumers who excluded red meat from their diet versus those that did not, using matching methods. Moreover, the nutritional adequacy of consumers was assessed by comparing nutrient intakes of both populations with the Recommended Daily Allowance (RDA), a national guideline developed by Health Canada (Health Canada, 2010).

2. Materials and Methods

2.1. Source of data

This study used data from the 2015 CCHS (Nutrition) conducted by Health Canada in partnership with Statistics Canada (Health Canada, 2017). The survey included a single 24-hr dietary recall questionnaire. The method for the 24-hr recall was based on the United States Department of Agriculture (USDA) Automated Multiple-Pass Method (AMPM). The AMPM is an automated questionnaire that guides the interviewer through a system designed to maximize respondents' opportunities for remembering and reporting foods eaten in the previous 24-hours (Health Canada, 2017). The questionnaire was designed to collect detailed information about food nutrients and supplement intake as well as data regarding consumer profile, including body weight, height, sex, socioeconomic status, and other information such as smoking, and quantity of alcohol consumed. Studies using the CCHS 24-hr recall methodology have been published elsewhere (Auclair et al., 2019; Hack et al., 2020; Ahmed et al., 2021).

In the 2015 CCHS (Nutrition), a three-stage sampling design was used to select the sample of respondents from all 10 Canadian provinces, representing the population in terms of age, sex, geography, and socioeconomic status (excluding those living on reserves, in institutions and on military bases). In the first stage, clusters were selected in each province. In the second stage, households were selected from each cluster. In the third stage, selected households were visited, and a list of household members was created. One household member was randomly selected to respond to the survey from eligible members of the household using selection probabilities that varied by age to achieve targeted sample sizes (Health Canada, 2017). A minimum number of individuals were sampled in each of the following 12 age-sex groups: 1 to 3 yrs (sex combined), 4 to 8 yrs (sex combined), and males and females separated for ages 9 to 13 yrs, 14 to 18 yrs, 19 to 50 yrs, 51 to 70 yrs and ≥ 71 yrs. These age groups correspond to the age ranges for which Dietary Reference Intakes (DRIs) have been established. The DRIs are a comprehensive set of nutrient reference values that could be used to assess the nutritional adequacy of diets, including the Recommended Dietary Allowance (RDA), Adequate Intake (AI), Tolerable Upper Intake Level (UL), and Estimated Average Requirement (EAR) (Health Canada, 2013). As described in the Reference Guide to Understanding and Using the Data (Health Canada, 2017), a minimum of 80 participants in each DRI age-sex group were allocated to each province, and the remainder were assigned among the provinces using a power allocation technique based on the population in each province. Within provinces, the sample size was proportionally allocated to rural and urban strata based on the number of dwellings in each stratum. No provinces or specific population groups were oversampled. The final sample size used in the analysis was 10,117 people, as a consequence of missing observations (Health Canada, 2017). A listwise deletion approach was used to address missing observations, as it is the most frequently used method with datasets such as the CCHS where sample size is large and therefore statistical power is not a concern (Kang, 2013). An analytic weight was assigned to each person included in the final analysis based on the number of people in the entire population that were represented by the respondent. This approach was used to ensure that the population was balanced for socio-demographic characteristics such as sex, age, education, and geography. The database contained dichotomous indicators about the exclusion of red meat, poultry, fish, eggs, dairy products, and gluten from the diet. 'Completely exclude' signified that the individual did not consume a foodstuff individually or as part of a prepared dish. The red meat exclusion dichotomous variable enabled disaggregated modeling analysis of nutrient intake of consumers preferentially consuming or excluding red meat.

The food consumption data garnered from the CCHS data were then converted to 36 nutrients, as well as alcohol and caffeine, as defined by Health Canada's Nutrient File (CNF) regarding reference standards for monitoring nutritional adequacy and diet quality of populations in Dietary Reference Intake Tables (Health Canada, 2010). Only those nutrients for which $\geq 85\%$ of foods had a reported value were included in the extracted database. For this reason, the 2015 CCHS-Nutrition dataset did not include vitamin E, copper, selenium, vitamin K, pantothenic acid, biotin, choline, manganese, individual amino acids, omega-3 fatty acids, omega-6 fatty acids, or trans-fatty acids (Statistics Canada, 2017). Supplement intake was included in the analysis as nutrient intake data was reported as a sum of nutrients derived from all food items and supplements consumed per person over 24 hours in the CCHS dataset.

Ethics disclosures

The 2015 CCHS–Nutrition was conducted following the guidelines established in the Declaration of Helsinki. The respondents were informed of the nature and purpose of the questionnaire to collect information regarding the nutrition of Canadian consumers, including information regarding eating habits, as well as other health and demographic information. Verbal informed consent was acquired and formally recorded for all participants. Thereafter, data were collected under the authority of Statistics Canada's Statistics Act, with confidentiality confirmed. As the current study involved secondary analysis of public data, approval was obtained from the Manitoba Research Data Centre (RDC). Analysis was conducted in a secure Statistics Canada office located on the University of Manitoba campus.

2.2. Statistical analysis

Propensity score matching (PSM) is most commonly used for causal analysis in observational studies (Rosenbaum and Rubin, 1983). Matching methods are appropriate for improving causal inference where the assignment of units to treatment and control groups (e.g., participants who excluded meat from their diets vs. those who did not) is not controlled and not necessarily random (Abadie and Cattaneo, 2018). However, the conventional PSM approach also has limitations with respect to possible differences between groups when at least one covariate is related to both potential outcomes and exposure to the treatment (King and Nielsen, 2019). This shortcoming warrants alternative methods, including re-weighting of observations to ensure observable characteristics of the treatment and control group are similar after weighting. Given these caveats associated with the use of PSM, we chose to use inverse probability weighting with regression adjustment (IPWRA) estimator (Wooldridge, 2007; Cattaneo, 2010) and Bias-corrected Matching (BCM) estimator (Abadie and Imbens, 2011) in our data analysis.

The choice of which method to use in a particular study depends on the characteristics of the data and the research question. The IPWRA may be more suitable for continuous confounding variables and the ability to adjust for multiple confounders simultaneously, but may be less robust to certain types of model misspecification (Wooldridge, 2007; Cattaneo, 2010). Alternatively, the BCM may be more robust to certain types of model misspecification but may be less efficient in cases where the treatment probability varies widely within the study population (Abadie and Cattaneo, 2018). For example, the BCM would be more efficient than IPWRA for a study in which the treatment probability varies widely among subgroups of the population, such as a nutrition intervention targeting only overweight individuals (Srour et al., 2019; Chiu et al., 2021). A recent study has provided a thorough analysis of the advantages and limitations associated with both methods and highlights the various factors that may influence the selection of a particular method for a given study (Veroniki et al., 2018). The authors present simulation studies to compare the performance of two methods and their application in real-world settings.

As a robustness check, IPWRA results were compared with BCM estimator results to evaluate the accuracy of the estimation and ensure that estimated differences in nutrient intake between the two groups of consumers were consistent across the two statistical approaches. More specifically, matching estimation and inference methods utilize as many covariates as possible to estimate the propensity score (Abadie and Imbens, 2016). When two or more continuous covariates are included for matching the distributional approximations, changes relative to a low-dimensional distributional approximation may occur due to the inclusion of many continuous covariates in the estimation (Abadie and Cattaneo, 2018), thereby rendering matching estimators inconsistent. The BCM estimator was used to reduce bias due to covariate imbalance between matched pairs using regression predictions. The BCM estimator adjusts the deviation within the matching pairs for the differences in their covariate values. Using bias adjustment slightly decreases the size of the estimated mean differences, thus reducing the significance level (Abadie and Imbens, 2011). For example, in our model, education level and BMI included in the selection equation were continuous variables that can induce bias. Hence, we used BCM to shield the matching estimators from the bias that arises from imperfect matches in the covariates. In total, the intakes of 36 nutrients, as well as alcohol and caffeine, were compared using IPWRA and BCM estimators. All models were estimated in STATA 15 (StataCorp, 2017).

Additional analysis was performed to examine the nutritional status of the CCHS survey participants by comparing nutrient intakes determined from the analysis of the 24-hr dietary recall to the reference RDA values (Institute of Medicine, 2003). By definition, RDA is set at a level that exceeds the nutrient needs of nearly all healthy individuals in a population in a particular life stage and sex group (Institute of Medicine, 2003). Adequate Intake (AI) was used for some nutrients when RDA could not be determined (Institute of Medicine, 2003). One of the challenges was determining a single RDA/AI value for each specific demographic group within the Canadian population that could be compared with the average nutrient intake of the CCHS survey participants. Following the methodology of similar studies (Brink et al., 2019; Marushka et al., 2019), a weighted average RDA and AI were calculated to estimate nutrient requirements across age and sex categories. The DRI Committee, which work collaboratively to identify DRI needs, recommended a total of 16 nutrients for assessment of nutritional adequacy in the United States and Canada (Dietary Guidelines Advisory Committee, 2015; McBurney et al., 2021). In the 2015 CCHS dataset, only nine nutrients (protein, EPA, dietary fiber, magnesium, potassium, sodium, zinc, niacin, and vitamin B6) of the 16 nutrients recommended by the DRI committee for accessing nutrient adequacy were reported. Therefore, we included eleven additional nutrients (energy, linolenic fatty acid, calcium, iron, folate, thiamin, riboflavin, vitamin B12, vitamin A, vitamin C, and vitamin D), which are frequently examined in nutritional studies (Bohrer, 2017; Melse-Boonstra, 2020; Ahmed et al., 2021). We estimated nutrient gaps (deficit or surplus) for consumers in our sample by computing the percentage change of reported actual nutrient intake in the 2015 CCHS dataset from the respondents' nutrient requirement described in the RDA.

3. Results

Estimated nutritional impact of excluding red meat

Differences in the intake of 36 nutrients, alcohol, and caffeine by Canadian consumers who removed red meat from their diet as compared to those who consumed red meat are shown in Table 5. The IPWRA estimator identified significant differences ($p<0.05$) in the intake of 17 nutrients and alcohol and caffeine with lower intake of protein, saturated fatty acids, octadecanoic acid, cholesterol, vitamin D, riboflavin, niacin, and sodium, and higher intake of carbohydrates, dietary fiber, naturally occurring folate, folate, folacin, vitamin C, thiamin, magnesium, and moisture from food sources for Canadians who did not consume red meat compared to those who consumed red meat. In addition, alcohol and caffeine were lower for consumers who excluded red meat. The

BCM estimator identified significant differences ($p<0.05$) in the intake of 14 nutrients and caffeine; with lower intake of protein, cholesterol, vitamin D, riboflavin, niacin, vitamins B6 and B12, zinc and caffeine, and higher intakes of dietary fiber, octadecanoic acid, naturally occurring folate, folate, folacin and magnesium for Canadians who did not consume red meat from their diet as compared to those who did.

Both IPWRA and BCM analysis resulted in significant differences between red meat consumers and those who did not consume red meat in the intake of 11 dietary nutrients and components. For example, as estimated via IPWRA and BCM analysis, red meat excluders consumed 10.87 and 11.32 g d^{-1} less protein than red meat consumers, respectively. Both methods generated similar results with lower daily intake of protein, cholesterol, riboflavin, niacin, vitamin D, and caffeine and higher daily intake of dietary fiber, folate and magnesium for Canadians who eliminated red meat as compared to those who consumed it. The two approaches had conflicting results for differences in the daily intake of octadecanoic acid. IPWRA suggested a significantly lower daily intake while BCM indicated a significantly higher daily intake for people excluding meat from their diets.

Table 5: Nutrient intake differences among Canadians based on red meat consumption: Inverse probability weighting with regression adjustment (IPWRA) and Bias-corrected Matching (BCM) Analysis

Dietary Nutrients and Components	IPWRA	BCM
Energy (kcal)	-31.08(34.758)	-52.58(45.795)
Carbohydrates (g)	16.68***(4.655)	6.23(5.605)
Sugar (g)	1.91(2.484)	-3.50(3.072)
Protein (g)	-10.87***(1.648)	-11.32***(2.095)
Dietary fiber (g)	5.11***(0.635)	4.60***(0.776)
Total fat (g)	-2.81(1.955)	-1.51(2.941)
Saturated fatty acids (g)	-2.04**(0.741)	-1.43(1.091)
Monounsaturated fatty acids (g)	-1.13(0.833)	-0.52(1.338)
Polyunsaturated fatty acids (g)	0.09(0.515)	0.39(0.686)
Linoleic acid (g)	0.16(0.459)	0.45(0.644)
Linolenic acid (g)	0.01(0.062)	0.01(0.070)
Octadecanoic acid (g)	-0.82***(0.157)	0.55**(0.264)
Docosahexaenoic acid (DHA) (g)	-0.02(0.022)	-0.02(0.019)
Docosapentaenoic acid (g)	-0.01(0.006)	-0.01(0.004)
Eicosapentaenoic acid (EPA) (g)	0.06(0.035)	0.00(0.019)
Cholesterol (mg)	-67.31***(10.181)	-60.08***(18.827)
Naturally occurring folate (mcg)	64.78***(8.890)	49.89***(10.670)
Folic acid (mcg)	-6.81(4.676)	-2.95(6.959)
Folate (mcg)	51.57***(13.149)	42.97**(16.720)
Folacin (mcg)	57.83***(10.189)	48.44***(12.550)
Vitamin A (mcg)	17.58(38.963)	22.88(38.197)
Vitamin D (mcg)	-0.54**(0.249)	-0.80**(0.292)
Vitamin C (mg)	15.86*** (5.105)	10.28(6.985)
Thiamin (mg)	0.10**(0.045)	0.07(0.057)
Riboflavin (mg)	-0.10**(0.041)	-0.13**(0.055)
Niacin (mg)	-5.36***(0.817)	-5.88***(1.069)
Vitamin B6 (mg)	-0.06(0.043)	-0.12**(0.053)
Vitamin B12 (mcg)	-0.73(0.356)	-0.72**(0.268)
Calcium (mg)	20.23(22.047)	7.45(28.030)
Iron (mg)	0.54 (0.293)	0.15(0.343)
Magnesium (mg)	29.02***(7.678)	21.58**(9.088)
Phosphorus (mg)	-33.15(28.152)	-48.34(33.533)
Potassium (mg)	65.42(57.058)	66.48(72.278)
Sodium (mg)	-252.65***(59.091)	-164.71(101.133)
Zinc (mg)	-0.82 (0.433)	-1.22***(0.319)
Alcohol (g)	-2.51***(0.742)	-1.29(1.462)
Caffeine (mg)	-29.57***(5.975)	-26.27***(8.255)

Moisture intake from food sources (g)	112.79**(54.510)	152.68(81.920)

§Data source: 2015 Canadian Community Health Survey- Nutrition
*** $p<0.001$ ** $p<0.05$
Note: Average age of survey participants was 48 yrs.

Nutritional adequacy of diets consumed by individuals excluding red meat from their diet

As indicated in Table 6, both groups of consumers met or exceeded daily nutrient requirements for the majority of the 20 nutrients recommended by the DRI committee for accessing nutrient adequacy (Dietary Guidelines Advisory Committee, 2015), including protein, eicosapentaenoic acid, linolenic acid, folate, niacin, thiamin, riboflavin, thiamin, vitamins B6, B12, and C, iron, sodium, and zinc. Both red meat consumers and those who did not consume red meat were unable to fulfill daily nutrient requirements (RDA or AI) for dietary fiber, vitamins A and D, calcium, magnesium, potassium and the total amount of energy provided by nutrients.

Table 6: Mean nutrient intake of 20 nutrients by respondents (n=10,117) participating in the Canadian Community Health Survey relative to Recommended Daily Allowance (RDA) or Adequate Intake (AI) requirements

Nutrients	Mean daily requirements (RDA/AI)*	Diets with red meat	Diets without red meat	% change from RDA	
				Diets with red meat	Diets without red meat
Dietary fiber (g)	27.91	16.78	20.62	-39.88	-26.12
Eicosapentaenoic acid (g)	0.02	0.07	0.09	250.00	350.00
Energy (kcal)	2105.34	1904.01	1798.13	-9.56	-14.59
Folate (mcg)	369.54	435.18	463.53	17.76	25.43
Niacin (mg)	13.93	39.16	33.06	181.12	137.33
Linolenic acid (g)	1.27	1.63	1.61	28.35	26.77
Protein (g)	45.95	79.33	67.40	72.64	46.68
Thiamin (mg)	1.07	1.60	1.60	49.53	49.53
Riboflavin (mg)	1.11	1.94	1.76	74.77	58.56
Vitamin A (mcg)	736.90	664.09	671.20	-9.88	-8.92
Vitamin C (mg)	72.61	96.04	109.75	32.27	51.15
Vitamin B6 (mg)	1.31	1.66	1.51	26.72	15.27
Vitamin B12	2.22	4.22	3.62	90.09	63.06
Vitamin D (mcg)	15.56	5.07	4.45	-67.42	-71.40
Calcium (mg)	1067.86	805.68	780.49	-24.55	-26.91
Iron (mg)	10.32	12.38	12.24	19.96	18.60
Magnesium (mg)	331.24	303.20	318.44	-8.47	-3.86
Potassium (mg)	4545.56	2677.44	2628.26	-41.10	-42.18
Sodium (mg)	1367.54	2777.12	2473.80	103.07	80.89
Zinc (mg)	8.80	10.47	9.26	18.98	5.23

* Weighted average RDA and AI were calculated to estimate nutrient requirements across age and sex categories

4. Discussion

As indicated in Table 5, differences in daily nutrient intake for both red meat consumers and non-consumers were generally consistent between the two estimators, except for octadecanoic acid intake. The IPWRA method was less stringent, resulting in significant differences in a greater number of dietary nutrient intakes than the BCM estimator (Table 5).

Excluding red meat from the diet significantly reduced the daily intake of eight nutrients, including protein, vitamin D, riboflavin, niacin, vitamins B6 and B12, zinc and cholesterol, and caffeine, and increased intake of carbohydrates, dietary fiber, naturally occuring folate, folate, folacin, vitamin C, thiamin, and magnesium using IPWRA. This observed pattern is consistent with the published literature, indicating that meat products are rich sources of high-quality protein, zinc, vitamins B6 and B12 (Biesalski, 2005; Klurfeld, 2015; Bohrer, 2017). Animal sourced-foods, such as dairy and meat products, are also major sources of octadecanoic acid for adults (Mapiye et al., 2015). Increased intake of carbohydrates, dietary fiber, folate, vitamin C, thiamin, and magnesium by individuals who did not consume red meat was expected, given that their diets typically consist of vegetables, fruits, legumes, grains, nuts, and seeds, which are important sources of these nutrients (Papier et al., 2019). The current study indicated no difference between meat consumers and non-consumers in their daily intake of iron, DHA, and EPA, when using either IPWRA or BCM-based analyses. Whereas the IPWRA suggested a lower alcohol and caffeine intake by people excluding red meat, the BCM estimator did not identify any differences in alcohol intake. The significant difference in caffeine and alcohol consumption by red meat consumers is plausible, given that meat, wine, and coffee are often consumed together in western dietary habits (Kasai and Kawai, 2021), which are often characterized by high fat and sugar intake (Yeomans, 2017). Earlier research has found that people who do not eat red meat tend to have a lower daily cholesterol intake (Wolk, 2017). The current study indicated that although both consumers and non-consumers of red meat are overconsuming sodium, those individuals who exclude red meat from their diets consumed less sodium than Canadians who consume red meat.

A potential explanation for the observed difference in IPWRA and BCM estimators could be related to differences in the adjustment algorithms used by each method to correct bias in the estimated means and variance (Guo et al., 2020). Fewer significant nutrients reported by the BCM estimator, as compared to IPWRA, were expected given that bias adjustment by the latter slightly decreases the size of the estimated mean differences, thus reducing the significance level (Abadie and Imbens, 2011).

Existing dietary recommendations to limit meat consumption have been made based on results derived from observational data analyzed using binary and linear logistic regression models with linkages to the risk of cardiovascular disease (Koch et al., 2019; Klurfeld, 2022). Klurfeld (2015) reviewed the current research that underpins existing dietary recommendations for meat consumption and established that most observational studies have limitations, including the inability to accurately estimate intake due to confounding factors such as age, body weight, race, cultural traditions, personal beliefs and taste preferences, as well as behavioral factors such as lifestyle and smoking. These factors can significantly confound the ability to adequately assess the effect of red meat exclusion on nutrient intake and subsequent health benefits or risks, limiting the reliability of the conclusions from the study. Moreover, consumers often deviate from the recommendations set by the Canada Food Guide when making dietary decisions.

As indicated in Table 6, an analysis of the 2015 CCHS data indicated that both red meat inclusion and exclusion from diets could result in nutrient intakes below RDA or AI requirements. Although the intake of calcium, energy, potassium, magnesium, fiber, and vitamins (A and D) were inadequate for both groups in the current study (Table 6), a numerically higher magnitude of inadequacy in calcium (-26.91%), energy (-14.6%), potassium (-42.18%) and vitamin D (-71.40%) was noted among consumers who did not consume red meat. Magnesium and potassium are involved in a variety of bodily processes, including muscle function, bone health, and the regulation of heart rhythm (Schwalfenberg and Genuis, 2017). There is some evidence to suggest that diets high in red meat may be associated with lower levels of magnesium and potassium in the body. This may be because red meat is relatively low in these minerals compared to fruits, vegetables, and whole grains as these plant-based sources are typically rich in these minerals (Schwalfenberg and Genuis, 2017). The observed deficiency in potassium and vitamin D in both diets is consistent with previous findings that these nutrients are frequently inadequate in consumer diets, despite the high content of these nutrients in red meat (Cashman and Hayes, 2017; Mota et al., 2021). This implies that diets of some Canadian consumers may require supplementation. Mota et al. (2021) also noted greater risks of calcium deficiency if red meat intake was below 375 grams per week for 25-44 yr-old women. Energy intake below the requirements for consumers who excluded red meat as well as those who consumed red meat was not expected. In contrast, Ahmed et al. (2021) used the same 2015 CCHS dataset to assess the adequacy of nutrient intakes and reported adequate energy intake for adults based on RDA requirements. The discrepancy in the intake of energy between Ahmed et al. (2021) and our study may reflect differences in demographic distribution considered in the analysis. While Ahmed et al. (2021) examined nutrient intake of the adult (> 19 yrs) sample population from the 2015 CCHS dataset, the current study considered weighted average nutrient intake for all age groups, including participants aged 1 to ≥70 yrs. The discrepancy in the intake of nutrients across demographic groups suggests the need for bias adjustment and weighting when assessing the dietary impact on nutrient intake for various categories of the Canadian population. That said, it should also be noted that underreporting of energy intake as compared to actual intake in dietary surveys has also been observed elsewhere (Rennie et al., 2007), including the 2015 CCHS dataset (Garriguet, 2018).

The values reported in our study refer to total consumption and do not reflect the increased bioavailability of calcium and other nutrients such as folate, iron, magnesium, zinc, and vitamins (B6, B12, and E) from animal-based products (Herrero-Barbudo et al., 2006). While several studies in low-income countries have reported inadequate nutrient intake of protein, heme iron, zinc, and vitamins (B6 and B12) among people who exclude red meat (Shubham et al., 2020), our data did not suggest inadequate intake of these nutrients among Canadian consumers. It may be that consumers in high-income countries, such as Canada and the US, have better access to non-meat food sources known as high-protein replacements for meat, including kale, lentils, broccoli, green peas, spinach, and soy-based tofu products. Although achieving protein adequacy in diets without red meat is possible, consuming adequate quantities of essential amino acids could be challenging. Efforts have been made to determine amino acid level and bioavailability for many plant-based foods (Beal et al., 2023). Although many high protein plant-based diets provide adequate amounts of EPA, iron, and zinc when compared with meat products (Bohrer, 2017), nutrient density and bioavailability may differ. Nutritional inadequacy of heme-iron, zinc, bioavailable B vitamins, and essential amino acids may be greater than for those including red meat in their diets (Bohrer, 2017). Further, deficiencies in calcium, iron, zinc, iodine and vitamin A have been associated with poor bioavailability of these nutrients from plant-based diets (Platel and Srinivasan, 2016) and are more pronounced among individuals who did not consume red meat (Biesalski, 2005). In addition, inadequate intake of vitamin B12 in low-income populations due to low consumption of animal-source foods can result in low serum vitamin B12 concentrations in young adults (Bohrer, 2017). The differences in bioavailability of vitamin D among food groups are also well documented (Melse-Boonstra, 2020). Several studies have also suggested that red meat provides a unique mixture of highly bioavailable micronutrients not readily available in plant-based diets essential to the cognitive development and function of children and adolescents (Anzani et al., 2020).

It is also interesting to note that Canadians, whether they are red meat consumers or non-consumers, are not consuming adequate amounts of dietary fiber. Although both groups did not meet RDA requirements for fiber, consumers who excluded red meat had a numerically lower dietary fiber inadequacy, which could be seen as a potentially positive aspect of excluding red meat from the diet. Similarly, although both consumer groups reported excessive sodium intake, it was numerically higher among red meat consumers than among individuals who did not consume red meat. This information is important for consumers to help make informed food choices.

The health implications of nutrient deficiencies have been well-documented worldwide. A review of the literature published between 2012 to 2018 (Watson et al., 2018) summarized the impact of vitamins (A, B12, and D), calcium, iron and folate deficiencies, which include megaloblastic anemia and demyelinating neurological symptoms, including irreversible nerve damage and neuropathy (B12); neurodegeneration vision and skin diseases (vitamin A); fracture risk bone loss and the resulting osteoporotic fractures, particularly for those over 70 years of age (vitamin D and calcium). These risks may be greater for some sex and age categories within a population even when average nutrient intakes of the general population appear to be adequate. For example, there is an increased risk of iron deficiency in post-menopausal women and older men because of chronic blood loss from disease, decreased absorption due to reduced acid secretion, use of medications such as antacids, or a diet low in iron (Watson et al., 2018). Some segments of the population, including growing children, adolescent girls, pregnant women, and aging adults, may be more likely to incur specific nutrient deficiencies by reducing red meat within their diet.

Limitations of the study

It is important to note that the present analysis relies on individual, self-reported consumer data from a single 24-hr dietary recall. The results of this study should be interpreted with caution. As noted earlier, by using a 24-hr recall, we are unable to account for seasonal variation in food and nutrient intake (Campbell et al., 2019). The 24-hr dietary recall is not necessarily representative of an individual's usual dietary intake, which varies from day-to-day. However, average individual daily intake is an appropriate estimate of the usual average intake of a population (Campbell et al., 2019). Further, the diet categories in the 2015 CCHS dataset, "diet with red meat" and "diet without red meat," are not defined with specific guidelines or recommendations and therefore, it is difficult to assess whether individuals who did not eat red meat, did not consume other types of meat or meat products.

Another limitation of this study, and indeed all survey-based studies, is the use of average nutrient profiles that may not account for the variation in nutrient content due to differences in variety of fruits and vegetables, as well as climate, soil type and a myriad of other factors. Further, fortification of food may not be fully accounted for in all food and therefore may impact study outcomes. For example, the addition of vitamin A and D to fluid milk is a legal requirement under Health Canada's Food and Drug Act (https://inspection.canada.ca/food-labels/labelling/industry/fortification-of-food/eng/1468504433692/1468504697186). As well, food composition tables may not account for the form of different nutrients including, for example, the 25(OH)D content of food which could alter estimates of vitamin D intake (Cashman and Hayes, 2017).

Finally, the use of average RDA values for some nutrients may not be suitable for specific groups of the population such as children, adolescents, pregnant women, and the elderly with higher nutritional requirements (Russell, 2007). It is well documented that pregnant women and young children are at increased risk of having compromised iron status. Ideally, all 36 nutrients, alcohol, and caffeine intakes should have been analyzed for red meat consumers and those excluded disaggregated by sex and age. However, the data show that the average difference in iron intake between red meat consumers and those who excluded red meat, as depicted in Table 5, did not differ between the two groups using either methodology. In addition, the literature shows that populations with a daily iron intake greater than 100 mg have demonstrated that iron deficiency in women is rare (Gupta and Gadipudi, 2018). However, this is an interesting question to consider in future work.

5. Conclusions

This study examined differences in nutrient intake, as well as the ability of Canadians who include or exclude red meat from their diet to fulfill RDA requirements. The impact of excluding red meat on nutrient intake was estimated by IPWRA and BCM methods, using data collected from the 2015 Canadian Community Health Survey. The IPWRA identified that excluding red meat from the diet significantly reduced the daily intake of several nutrients including protein, saturated fatty acids, octadecanoic acid, cholesterol, vitamin D, riboflavin, niacin, sodium, alcohol and caffeine. Contrary to the claims that a shift away from red meat in favor of plant-based diets may not alter nutrient intake, our study demonstrates that red meat exclusion resulted in statistically significant differences in the intake of 14 to 17 nutrients, depending on the estimation approach used. Further, both red meat consumers and those who did not consume red meat had nutrient intakes below the average daily requirements (RDA or AI) for calcium, dietary fiber, magnesium, potassium, vitamins A and D, and the total amount of energy provided by nutrients. Inadequate intake of these nutrients can have negative health consequences. Therefore, recommendations to eliminate red meat from the diet and replace it with meat substitutes should consider nutritional and health implications for the Canadian population, specifically young children, pregnant women, and the elderly. Given these results, further research is needed on the nutritional consequences of excluding red meat from diets across age and sex groups and the health conditions of individual consumers and various socioeconomic and cultural groups.

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Bridge to Chapter 6

Chapter 6 complements Chapters 4 and 5 by characterizing the factors associated with consumer food choices in more detail, including socio-demographic characteristics such as gender, education level, psychological, social, and cultural impacts. As such, a logical next-step in working to understand the role of ASF in sustainable diets is to explore what factors contribute to the decision to change from ASF-based diets to various dietary patterns with reduced ASF consumption.

CHAPTER VI: CHARACTERIZATION OF CONSUMER BEHAVIOR ASSOCIATED WITH RED MEAT EXCLUSION IN CANADA

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Abstract

Red meat provides a variety of macro- and micro-nutrients that are difficult to obtain in adequate quantities from plant-based foods. However, high consumption of red meat in upper-income countries has been associated with several chronic diseases and environmental degradation. Reducing red meat consumption in these countries has been suggested as a strategy to address health and environmental sustainability challenges. Characterizing Canadian consumer demographics and socio-economic factors associated with red meat inclusion or exclusion is an essential step in identifying strategies to translate food choices into national food policies and guidelines that support food systems consistent with consumer values and preferences. The objective of the study was to examine demographic and socio-economic characteristics that are associated with Canadian consumer food choices and preferences for red meat. Data from the 2015 Canadian Community Health Survey (CCHS; n=9,235) were analyzed using weighted probit and multilevel fixed effect probit models to identify factors associated with red meat preference. Results indicated that less than 5% of Canadian consumers who participated in the 2015 CCHS 24-hr recall survey excluded red meat from their diet. The likelihood of red meat exclusion was positively associated with sex (female), individuals possessing a Bachelor's degree, increased intake of nutritional supplements and African and Asian cultural backgrounds. In contrast, red meat exclusion was negatively associated with males, households living as common-law partners, smokers, higher body mass index (BMI), and households living with children aged 25 yrs and younger. Disparities in red meat consumption patterns by sex, education, family status, and cultural identity offer guidance for researchers and practitioners developing nutrition programs and government policies to improve public health impacts of consumer diets.

1. Introduction

Red meat is a rich source of a variety of macro- and micro-nutrients, including essential amino acids, vitamins, and minerals that could be difficult to obtain in adequate quantities from plant-based foods (Mottet et al., 2017). Global consumption of meat is projected to increase by 14% by 2030 compared to the base period average of 2018-2020, driven largely by income and population growth (OECD, 2020). A growing demand for red meat from Asia and other fast-growing markets, as well as a reputation for food quality and safety, present lucrative opportunities for red meat export from Canada (Greenwood, 2021). However, in high income countries changes in consumer preference and aging, as well as slower population growth will lead to a plateau in per person meat consumption and a shift towards higher valued meat cuts (Valli et al., 2019; OECD, 2020).

Nevertheless, the production and consumption of red meat has become a subject of intense debate in recent yrs due to potential health, environmental sustainability and animal welfare concerns (Cashman and Hayes, 2017; Bonnet et al., 2020). Some researchers and a growing number of plant-based food advocates contend that reducing red meat consumption in upper-income countries can improve human health, and curb environmental degradation, including greenhouse gas (GHG) emissions (Bonnet et al., 2020; Mathur et al., 2020). The 2019 EAT-Lancet Commission report argued that the global population must drastically reduce the consumption of red meat and other animal products to save the health of humans and the planet. Recent dietary guidelines in North America advocate for the consumption of diets characterized by reduced intake of red meat and minimally processed meats, alongside an increased incorporation of plant-based products. This dietary approach is proposed with the aim of mitigating the risk of chronic diseases while simultaneously enhancing the long-term sustainability of the agri-food system (Sanders et al., 2021). Food consumption decisions are driven by a myriad of factors related to food products, individual consumer preferences and socio-cultural circumstances (Charlebois et al., 2020a). More specifically, food choice decisions are impacted by age, sex, education, nationality, ethnicity, cultural food customs, religious rituals, household income, food nutrient profile, household food security, food knowledge, food preparation skills, health consciousness, educational campaigns for healthy foods, weight control cognitions, behaviors, product advertising, as well as the environmental footprint of food (Moser et al., 2011; Stok et al., 2017; Taufik et al., 2019). Although emerging research has focused on consumer preferences and demand for red meat versus plant-based alternatives (Van Loo et al., 2020; Martin et al., 2021), a systematic understanding of the demographic and socio-economic characteristics influencing food choice is lacking. A comprehensive understanding of Canadian consumer demographics associated with red meat consumption is essential for industries to meet the complex demands of a growing population. Furthermore, this information is essential in identifying strategies to translate consumer food choices into national food guidelines and policies that support food systems consistent with consumer values and preferences. Therefore, the objective of the present study was to examine consumption patterns of red meat and to characterize demographic and socio-economic factors associated with food choices and preferences for red meat in Canada.

2. Materials and methods

2.1. Source of data

A large nationally representative dataset based on a single 24-hr dietary recall from the 2015 Canadian Community Health Survey-Nutrition (CCHS), conducted by Health Canada in partnership with Statistics Canada was used to examine the factors which influence dietary choice (Health Canada, 2017). The 2015 CCHS-Nutrition questionnaire (Health Canada, 2017) was designed based on the United States Department of Agriculture (USDA) Automated Multiple-Pass Method (AMPM). The AMPM is an automated questionnaire that optimizes the respondents' ability to recall and report foods eaten in the past 24 h (Health Canada, 2017). The survey followed a three-stage stratified sampling design that selected a sample of respondents from all 10 provinces, thus representing the population in terms of age, sex, geography and socio-economic status. However, the 10 provinces were aggregated into four groups for the analysis based on their similarities in food habits and culture. While the survey aimed to cover a wide range of demographics, certain groups might have been excluded or underrepresented due to various reasons, including logistical challenges, sampling methods, and data collection limitations. Initially, clusters were selected in each province and thereafter, households were selected from within clusters. Finally, selected households were visited in person, and a list of household members was created. The dataset contained dichotomous (yes or no) indicators regarding the exclusion of red meat, poultry, fish, eggs, and dairy products from the diet (Health Canada, 2017). "Completely exclude" signified that the individual never consumed a food type individually or as part of a prepared dish. A total of 80 respondents were sampled from the following 12 age-sex groups: 1 to 3 yrs (sex combined), 4 to 8 yrs (sex combined), and males and females separated for ages 9 to 13 yrs, 14 to 18 yrs, 19 to 50 yrs, 51 to 70 yrs and ≥ 71 yrs. These age groups correspond to age ranges for which Dietary Reference Intakes (DRIs) were available (Health Canada, 2005).

The DRIs are a comprehensive set of nutrient reference values that could be used to assess the nutritional adequacy of diets, including the Recommended Dietary Allowance (RDA), Adequate Intake (AI), Tolerable Upper Intake Level (UL), and Estimated Average Requirement (EAR) (Health Canada, 2013). As described in the reference guide to understanding and using the data (Health Canada, 2017), a minimum of 80 respondents in each DRI age-sex group were allocated to each province and the remainder were assigned among provinces using a power allocation technique that considered the population in each province. Further information on sample size and allocation is available in Chapter 4 of Statistics Canada's 2015 CCHS-Nutrition User Guide (Health Canada, 2017). Within provinces, the sample size was proportionally allocated to rural and urban strata based on the number of dwellings in each stratum. No provinces or specific population groups were oversampled. Detailed descriptions of the type of information gathered in the survey, data collection instruments and methodology are described in the reference guide (Health Canada, 2017). When preparing the data for this study, a list wise deletion approach was used to address missing observations as per similar datasets (Kang, 2013). We grouped together several categories of explanatory variables whose observations were below the frequency threshold required to meet Statistics Canada's reporting requirements regarding the minimum sample size. After consideration for missing data, 9,235 individuals were included in the analysis. Analytic weight was assigned to each person included in the final analysis based on the number of persons in the entire population that the respondent represented. This approach was used to ensure that the population was balanced for demographic and socio-economic characteristics such as sex, age, education, geography and household income.

Ethics disclosure

The 2015 Canadian Community Health Survey - Nutrition (CCHS-Nutrition) was conducted in accordance with the guidelines established by the Declaration of Helsinki (Smith et al., 2021). Participants were informed about the nature and purpose of the questionnaire, which aimed to collect data on the nutrition of Canadian consumers, including their eating habits and other health and demographic information. Verbal informed consent was obtained from all participants and recorded formally. The data was collected under the authority of Statistics Canada's Statistics Act and confidentiality was ensured. As the study involved secondary analysis of public data, approval was obtained from the Manitoba Research Data Center (RDC) to conduct the research in a secure Statistics Canada office on the University of Manitoba campus. An RDC statistician verified the outputs from all analyses prior to release.

2.2. Statistical analysis

Descriptive statistics were analyzed using the analysis of variance (ANOVA) for continuous variables and a chi-square test to compare categorical variables (Wooldridge, 2010). The dichotomous response (yes or no) regarding red meat exclusion is a categorical dependent variable (Greene, 2004) and cannot be modeled by conventional linear regression models (Wooldridge, 2010). Therefore, probit regression was used to describe the relationship between consumer response regarding inclusion or exclusion of red meat in the diet and independent variables garnered from the CCHS dataset. Probit regression transforms the dependent variable and then uses maximum likelihood estimation, rather than least squares, to estimate parameters of interest (Aldrich et al., 1984; Greene, 2004). Several studies have used probit and logit models to study factors influencing dietary preference (Shimokawa, 2013; Cliceri et al., 2018; Iris et al., 2018).

As described above, the sampling design used “clusters” to select sample respondents from 10 Canadian provinces, representing the population in terms of age, sex, geography, and socio-economic economic status. Regional differences may exist in the CCHS dataset, including, increased consumption of beef in the Prairie and seafood in Atlantic regions of Canada. From a statistical standpoint, the grouped structure of the data implies a violation of the assumption of independence among observations within the second-level units, e.g., individuals living in the same region (Robins and Rotnitzky, 1995). Further, food preferences and eating habits could be influenced by race or religion (Ma, 2015), directly or indirectly impacting the decision to consume red meat (Abay et al., 2019). Given this, using probit regression alone may be inadequate as the standard errors of the regression coefficients could be underestimated (Alom et al., 2012; Demidenko, 2013). To overcome potential confounding arising from a clustered and hierarchical (individual and provincial level) data structure, we used a multilevel mixed-effects probit to analyze the influence of covariates at the individual and provincial level on red meat exclusion behavior (Demidenko, 2013). The random components were incorporated in the model to account for population intra-cluster correlation, heterogeneity, and over-dispersion (Smith et al., 2017). Using this approach, all clusters were assumed to be comparable once these additive stratum-specific components were accounted for.

A flexible binary mixed-effect model was generated by assuming

$$Y = X\beta + Zu + \varepsilon,$$

where X and Z are known matrices, $u \sim N(0, D)$, and $\varepsilon \sim N(0.1)$, are independent of u. Y represents an unobserved continuous variable, X is a vector of fixed covariate variables including age, sex, marital status, highest level of education, smoked 100 or more cigarettes during lifetime, BMI, household size, household type, country of birth, immigration status and total household income. Z is a vector of random effects and ε is a vector of disturbances. The error terms ε are distributed as standard normal with a mean 0 and a variance of 1 and are independent of u. Associations between multilevel (individual and provincial level) factors and dietary intake were assessed using weighted multilevel random-intercept regression models. A two-sided p-value of <0.05 was used to test statistical significance.

The two model specifications (probit regression and multilevel mixed-effects probit regression) were compared using Akaike's Information Criteria (AIC) and Bayesian Information Criteria (BIC) (Acquah, 2010). All data analysis was conducted at the University of Manitoba RDC using Stata version 15 (StataCorp, 2017).

3. Results

3.1. Summary statistics

Descriptive statistics of the variables used in the regression analyses are provided in Tables 7 and 8. In 2015, the percentage of individuals who chose to exclude red meat was 4.65% (Table 7). Respondents who did and did not exclude red meat differed ($P< 0.05$) in terms of sex, marital status, education level, smoking status, household type, use of nutritional supplements in the past month, immigration status, country of birth, location of residence (rural or urban), and the province of residence, as described in detail below.

Differences were observed between Canadians who consumed red meat and those that did not in terms of age (48.13 vs 48.67, respectively), as well as mean BMI (27.32 vs 26.00, respectively; Table 8). Although statistical difference in age is significant, it may not have practical significance in terms of policy making as the magnitude of the difference is small. However, there were no significant differences between the two groups for household size, moderate physical exercise in the past 7 d, or household income.

Table 7: Descriptive statistics for categorical variables associated with red meat exclusion as indicated by respondents who participated in the 2015 Canadian Community Health Survey

Variable	Response categories	Did not exclude red meat (n=8806) %	Excluded red meat (n=429) %	Prob >χ^2
Sex	Male	96.64	3.36	0.001
	Female	94.17	5.83	
Marital status	Married	94.81	5.19	0.022
	Living common-law	98.23	1.77	
	Widowed	93.63	6.37	
	Separated	88.64	11.36	
	Divorced	96.59	3.41	
	Single	96.04	3.96	
Highest education attained (compared to high school)	Less than high school diploma	96.48	3.52	0.001
	High school diploma	96.81	3.19	
	Certificate or diploma	96.55	3.45	
	College certificate	96.33	3.67	
	University certificate below BA level	96.48	3.52	
	Bachelor's degree	93.68	6.32	
	University certificate, diploma, degree above the BA level	93.79	6.21	
Smoked 100 or more cigarettes in life	No	94.08	5.92	0.001
	Yes	97.09	2.91	
Household type (compared to married)	Unattached individual	95.69	4.31	0.002
	Unattached individual living with others	95.89	4.11	
	Couple alone	96.31	3.69	
	Couple with children < 25	90.19	9.81	
	Couple with all children < 25	98.89	1.11	
	Couple with all children >25	92.07	7.93	
	Female lone parent with children < 25	95.44	4.56	
	Other household type	94.86	5.14	

(Continued on the next page)

Variables	Response categories	Did not exclude red meat (n=8806)	Exclude red meat (n=429)	Prob >χ^2
		%	**%**	
Nutritional supplements taken (past month)	Yes	95.02	4.98	0.001
	No	95.71	4.29	
Immigration status (landed immigrant in Canada)	Yes	91.81	8.19	0.001
	No	96.71	3.29	
Country of birth	Canada	97.05	2.95	0.001
	Other N. America	96.10	3.90	
	South, Central America and Caribbean	95.05	4.95	
	Europe	93.82	6.18	
	Africa	91.49	8.51	
	Asia	88.40	11.60	
Location of residence from population center (rural or urban)	Urban	95.02	4.98	0.001
	Rural	97.03	2.97	
High blood pressure	Yes	94.57	5.43	0.075
	No	95.57	4.43	
Household food security status	Food secure	95.29	4.71	0.840
	Moderately food insecure	96.06	3.94	
	Severely food insecure	97.49	2.51	
Self-perceived health	Excellent	95.47	4.53	0.971
	Very good	95.29	4.71	
	Good	95.85	4.15	
	Fair	94.58	5.42	
	Poor	91.11	8.89	
Participation in 150 min per week of physical activity	Yes	95.63	4.37	0.205
	No	95.18	4.82	
Province of residence	Ontario	94.57	5.43	0.001
	Quebec	95.99	4.01	
	Atlantic Canada	96.25	3.75	
	Prairie (Alberta, Manitoba and Saskatchewan)	96.26	3.74	
	British Columbia	94.35	5.65	

Table 8: Descriptive statistics for continuous explanatory variables associated with red meat exclusion as indicated by respondents participating in the 2015 Canadian Community Health Survey

Variable name	Did not exclude red meat	Excluded red meat	Prob > F
	Mean (SE)	Mean (SE)	
Age (yr)	48.13 (0.18)	48.67 (0.81)	0.050
Body mass index (kg/m^2)	27.32 (0.06)	26.00 (0.26)	0.001
Household size	2.72 (0.02)	3.08 (0.08)	1.000
Moderate/vigorous physical activity (hrs)	3.53 (0.05)	3.29 (0.19)	0.100
Total household income (CA$)	84,713.69 (928.52)	81,563.46 (6399.11)	0.650

3.2. Demographic and socio-economic determinants of red meat exclusion from diets

Demographic and socio-economic factors associated with red meat exclusion are presented in Table 9. The latter suggested that the explanatory variables included in the regression model jointly explain exclusion of red meat while the smaller estimates of AIC (3272.97 vs. 6027245.00) and BIC (3572.46 vs. 602757.00) suggest that multilevel mixed-effects probit model fit the data better than the weighted probit model (Table 9).

Both weighted probit and multilevel mixed-effect probit regression analysis showed that the likelihood of red meat exclusion was positively associated with sex (being female), having a Bachelor's degree, and being of African or Asian cultural background based on country of birth (relative to those born in Canada). The multilevel mixed-effect probit regression analysis also revealed that the likelihood of red meat exclusion was positively associated with having a university degree above a Bachelor's and being of South, Central America, or Caribbean origin.

The regression analysis also indicated that the likelihood of red meat exclusion was negatively associated with BMI. However, this analysis did not consider assessment of obesity based on BMI. The weighted probit regression analysis showed that the likelihood of red meat exclusion was negatively associated with individuals who smoked 100 or more cigarettes in their lifetime, households with children aged 25 yr and younger, households living as common-law partners, and individuals who took nutritional supplements. The multilevel mixed-effect probit regression analysis showed that the likelihood of red meat exclusion was negatively associated with couples with no children and single individuals. Age and total household income were not found to be associated with the exclusion of red meat.

Table 9: Demographic and socio-economic factors affecting red meat exclusion based on weighted probit and multilevel mixed-effect probit analysis

Variables	Weighted probit (SE)	Mixed-effect probit (SE)
Age (yrs)	0.00(0.003)	0.00(0.002)
Sex (female relative to male)	0.26***(0.087)	0.20***(0.052)
Body mass index	-0.01**(0.007)	-0.01***(0.005)
Smoked 100 or more cigarettes in lifetime (yes)	-0.12**(0.052)	-0.14(0.089)
Household size	0.06(0.061)	0.07(0.039)
Moderate/vigorous physical activity (hrs)	0.00(0.012)	0.00(0.008)
Total household income (CA$)	0.00(0.000)	0.00(0.000)
Marital status (relative to married)		
Living common-law	-0.31**(0.146)	-0.09(0.097)
Widowed	0.19(0.215)	-0.10(0.119)
Separated	0.70*(0.375)	-0.08(0.150)
Divorced	-0.01(0.202)	-0.07(0.121)
Single, never married	0.02(0.152)	0.01(0.092)
Highest level of education in household (relative to < high school diploma)		
High school diploma	-0.10(0.150)	-0.03(0.102)
Trade certificate or diploma	-0.07(0.128)	-0.13(0.082)
College certificate or diploma	0.00(0.200)	-0.08(0.109)
University certificate or diploma	-0.05(0.223)	-0.20(0.136)
Bachelor's degree	0.21**(0.105)	0.21***(0.070)
University degree above BA level	0.12(0.134)	0.25***(0.081)
Household type (relative to married)		
Unattached individual living with others	0.00(0.227)	-0.15(0.141)
Couple alone	0.03(0.216)	-0.17(0.103)
Couple, children < 25	0.06(0.375)	-0.22(0.214)
Couple, all children <= 25	-0.69**(0.292)	-0.0735
Couple, all children >=25	0.05(0.416)	-0.17(0.262)
Female lone parent, children < 25	-0.23(0.232)	-0.0377
Other household type	-0.05(0.285)	-0.37***(0.136)
Nutritional supplements taken- no	-0.15*** (0.049)	-0.04(0.079)

(Continued on next page)

Variables	Variable sub-categories	Weighted probit (SE)	Mixed-effect probit (SE)
Country of birth (relative to Canadians)			
	Other North America	0.32(0.358)	0.17(0.250)
	South, Central America and Caribbean	0.53(0.330)	0.54***(0.180)
	Europe	0.64(0.376)	0.13(0.170)
	Africa	0.91**(0.347)	0.68***(0.197)
	Asia	0.95***(0.293)	0.62***(0.155)
Immigration status (Are you now, or have you ever been a landed immigrant in Canada?) - Yes		-0.04(0.151)	-0.43(0.297)
Location of residence from population center being rural relative to urban		-0.05(0.139)	-0.06(0.068)
High blood pressure		-0.18(0.113)	0.04(0.067)
Household food security status relative to food secure			
	Moderately food insecure	-0.05(0.160)	0.06(0.100)
	Severely food insecure	-0.22(0.202)	0.20(0.141)
Self-perceived health relative to excellent			
	Very good	0.05(0.113)	0.06(0.066)
	Good	-0.07(0.119)	0.03(0.071)
	Fair	0.15(0.174)	0.06(0.101)
	Poor	0.54(0.385)	0.21(0.163)
150 minutes physical activity per week-Yes		0.05(0.068)	0.01(0.116)
Province of residence of respondent relative to Ontario			
	Quebec	0.06(0.115)	
	Atlantic Canada	0.07(0.128)	
	Prairie	-0.07(0.106)	
	British Columbia	0.04(0.112)	
Constant		-1.68***(0.364)	-1.65***(0.234)
Number of observations		9235	9235
Wald χ2 (45)		207.59	271.38
Prob >χ2 (23/41)		0.00	0.00
Log likelihood		-3013576.00	-1594.48
AIC		6027245.00	3272.97
BIC		6027573.00	3572.46

Note: ***, **, and *represent 1%, 5%, and 10% significance levels, respectively

4. Discussion

4.1. Descriptive statistics

The objective of the current study was to examine consumption patterns and characterize demographic and socio-economic factors associated with consumer food choices and preferences for red meat in Canada. Less than 5% of Canadians reported complete exclusion of red meat from their diets in the 2015 survey (the latest available CCHS data), despite a growing advocacy to do so (Schösler et al., 2015; De Oliveira Mota et al., 2019). Nonetheless, this 5% represents approximately 1,575,858 individuals within the total Canadian population of 36,991,981 in 2021 (Statistics Canada, 2021). The estimates regarding red meat exclusion were considerably lower than the recent finding of an opinion survey from Dalhousie University, which indicated that 9.4% of Canadians identify as vegetarians (Charlebois et al., 2020b). Observed differences may be attributed to the question posed as respondents of these studies were questioned regarding the "willingness of consumers to shift to a vegetarian diet" as opposed to the complete exclusion of red meat from the diet, as was the case for the CCHS. Therefore, exclusion of meat in the above studies could include red and white meat, whereas the question in 2015 CCHS data was focused specifically on red meat exclusion. Further, these studies (Charlebois et al., 2020b) employed an opinion survey to identify consumers' "stated preference" to reduce meat consumption, while the 2015 CCHS was based on a self-reported recall of the foods consumed within the last 24-hrs. The database contained dichotomous indicators about the exclusion of red meat, poultry, fish, eggs, dairy products, and gluten from the diet. 'Completely exclude' within the last 24-hr recall signified that the individual did not consume a foodstuff individually or as part of a prepared dish. Differences in the percentage of survey respondents who expressed a desire to exclude red meat, could also be due to the smaller sample size (n=1,019) in Charlebois et al. (2020a). In the current study, we used a nationally representative data from the 2015 CCHS collected from daily revealed food intake of 9,235 individual respondents living in both urban and rural settings in all 10 Canadian provinces. Finally, our results may not be directly comparable to previous results due to differences in survey year or study population.

The descriptive statistics for the continuous explanatory variable associated with red meat consumption revealed that age and BMI were significantly higher for participants who ate red meat than for those who did not. However, household size, physical activity and total income did not differ between the two groups. Results of the descriptive statistics indicated significant differences in most socio-demographic variables, including sex, age, education level, BMI, marital status, smoking, household size, total household income, immigration status, and country of birth between red meat consumers and excluders. However, the results of the stochastic weighted probit regression and multilevel mixed-effect probit regression indicated statistically significant association between red meat exclusion and a limited number of explanatory variables. Several variables which were significant in the chi-square test of independence and ANOVA (e.g., age) were non-significant in the probit regression. This is plausible as the association of a given explanatory variable with the dependent variable in regression analysis depends on the correlation between itself and the dependent variable, as well as other explanatory variables included in the model and the residuals of the model predicting the dependent variable in multivariate probit regression (Rohrer, 2018). Some variables improve the overall fit of the regression model, but they may not uniquely explain the dependent variable (Gefen et al., 2011). The presence of variables with high variance-covariance correlation could provide insight as to why the constant term is highly significant. Further examination of the data using variance-covariance correlation in the weighted probit regression revealed highly correlated variances between some variables. For example, the variances of immigration and marital status were strongly negatively correlated (-0.74), but we cannot be sure whether it is related to ethnic meat consumption. In contrast, the variances of household size and household economic status or household type (couple living alone, couple living with children < 25 yrs old, couple living with children over 25 yrs old, female lone parent, etc.) were strongly positively correlated (0.71). However, interpreting the constant term in the regression output is difficult because it is impossible to know the composition of residuals contributing to it.

4.2. Demographic and socio-economic factors associated with exclusion of red meat from diets

The consumption or avoidance of red meat is notably linked to factors such as gender, BMI, smoking habits, marital status, education level, household composition, usage of nutritional supplements, and cultural identification as African or Asian (determined by the respondent's country of birth).While the association between demographic and socio-economic variables is generally consistent in the weighted probit and the multilevel mixed-effect probit, variation in the regression coefficients and standard errors between the two models is apparent. For example, both methods identified a positive association between the likelihood of red meat exclusion and females, higher educational attainment, and Asian and African cultural backgrounds. Conversely, weighted probit and multilevel mixed-effects regression methods revealed negative association between red meat exclusion and BMI. A weighted probit regression analysis identified a negative association between red meat exclusion and smoking, households living with young children, and people taking nutritional supplements. However, some of the significant variables in the weighted probit regression analysis were found to be insignificant in the multilevel mixed-effects probit regression analysis. This is understandable given that the standard errors of the regression coefficients may be underestimated by weighted probit due to clustering of the dataset (Aldrich et al., 1984; Gibbons and Hedeker, 1994). The association of red meat inclusion or exclusion with demographic and socio-economic factors are supported by previous nutritional studies, which reported a significant association between consumer food choices and socio-demographic traits, including sex, education, ethnicity, nationality, and cultural food preferences (Stok et al., 2017; Taufik et al., 2019). Several studies in upper-income countries, including the United States (Sparkman and Walton, 2017; Neff et al., 2018), Canada (Charlebois et al., 2020b; Valdes et al., 2021), United Kingdom (O'Keefe et al., 2016), Belgium (De Groeve and Bleys, 2017),and Austria (Kwasny et al., 2022) have noted that women are more likely than men to reduce or completely exclude red meat from their diet. Exclusion of red meat by women could also be explained by various factors such as health issues, cultural norms, personal beliefs, and lifestyle choices (Hargreaves et al., 2021).

Excluding red meat consumption is also correlated with BMI. Canadians with higher BMI were less likely to exclude red meat, which has been reported previously in US and Canada (Kushi et al., 2012; Valdes et al., 2021). A body of literature shows that red and processed meat intake is directly associated with the risk of obesity and higher BMI (Wang and Beydoun, 2009; Zhang et al., 2021). Three prospective cohort studies evaluating U.S. men and women revealed a causal link between BMI and meat consumption (Pan et al., 2013). These studies suggest that people with obesity consume more red and processed meat and have a higher risk of cardiovascular diseases (Zhang et al., 2021). Nonetheless, an ongoing discussion is underway to comprehensively grasp the intricacies of this association (Papier et al., 2023).

The positive relationship between respondents who smoked a total of 100 or more cigarettes in their lifetime and exclusion of red meat is not surprising, as the association between red meat consumption and lifestyle factors such as smoking is well documented in the United Kingdom (Foster et al., 2018), Sweden (Kaluza et al., 2019), and the United States (Cramer et al., 2017; Zaccardelli et al., 2019). Therefore, the results in our analysis reinforce the positive association between smoking and meat consumption reported in previous studies.

The positive relationship between possession of a Bachelor's or higher degrees and red meat exclusion also corroborates previous findings in the literature that have consistently reported a positive association between higher education and a reduction or exclusion of red meat in Canada (Charlebois et al., 2020b; Valdes et al., 2021), the United States (Cramer et al., 2017), France (de Gavelle et al., 2019) and Australia (Turrell and Kavanagh, 2006). The rationale behind the significant interaction between higher educational attainment and food choice could be explained by diffusion theory which suggests that highly educated people are more willing to adopt practices that are outside of the society norm (Fard et al., 2021).

The significant relationship between red meat exclusion and cultural identity also confirms previous findings in the published literature in the United Kingdom (Çoker et al., 2021), Canada (Charlebois et al., 2020b; Valdes et al., 2021), the United States (Ruby et al., 2013; Cramer et al., 2017), and Australia (Reddy and Anitha, 2015; Kwasny et al., 2022). More specifically, Valdes et al. (2021) noted that South Asians in Canada had an increased likelihood of consuming vegetarian/vegan diets. In this regard, several studies reported that one of the significant challenges in reducing consumer preferences for red meat could be attributed to the role of red meat as an integral part of North American food culture (Charlebois et al., 2020b; Norris, 2020; Frank et al., 2021). These findings support the notion that traditional policy tools aimed at influencing dietary change through food guide recommendations, nutrition education, and policy regulations without considering cultural context, may fail (Tapsell et al., 2016). Consistent with the findings in Valdes et al. (2021), the association between red meat exclusion and age, household income, and marital status were insignificant. Interestingly, income did not significantly impact red meat exclusion. The average household annual income was CA$ 84,713.69 and CA$ 81,563 for red meat consumers and non-consumers, respectively, slightly lower than the total yearly income received by all household members from all sources before taxes and deductions (Health Canada, 2017). In comparison, the average before-tax household income in Canada was CA$ 92,764 in 2016. Although increased income is generally associated with higher demand for meat, a country-specific ‘peak meat consumption’ is reached at a certain income level, beyond which higher income is associated with a lower demand for meat (Moran and Blair, 2021). Recent studies in Canada also reported that consumers earning between CA $75,000 and CA $ 99,999 have expressed their willingness to reduce meat consumption over the next 6 months (Charlebois et al., 2020b). Hence, the non-significant relationship between household income and red meat exclusion among CCHS respondents seems plausible. However, we cannot conclude that income does not influence individual decisions to eat red meat-based on the insignificant association between total household annual income and red meat consumption. People with higher household incomes might choose to avoid meat due to cultural, health, and environmental reasons but this has not been conclusively determined. Further research is needed to understand the interplay of various factors, including income, in shaping red meat consumption habits.

Contrary to the results of this study, other researchers in Canada have reported that the association of red meat exclusion among regions of Canada and immigration status were insignificant (Valdes et al., 2021). This difference in outcomes between the two studies may be attributed to the analytical procedures employed. These authors used multinomial logistic regression to assess the relationship between red meat exclusion and socio-economic variables, in contrast to the multilevel mixed-effect probit used in our study. Estimates by multinomial logistic regression rely on the assumption that the effects of unobserved factors do not vary across regions (Kwak and Clayton-Matthews, 2002; Abay et al., 2019). Therefore, multinomial logistic regression can entail prediction bias due to clustering effects arising from unobserved factors across census regions and provinces in Canada. Hence, the standard errors of the regression coefficients may be underestimated. Our result goes beyond previous related studies by accounting for region-specific factors that could be correlated with impacts of household behaviors on red meat consumption.

Limitations of the study

It is important to note that the present analysis relies on individual self-reported consumer data from a single 24-hr dietary recall, and therefore we are unable to account for seasonal variation in food and nutrient intake (McLean et al., 2018; Campbell et al., 2019). The 24-hr dietary recall is not necessarily representative of an individual's usual dietary intake which varies from day-to-day. Therefore, the results of this study should be interpreted with caution.

Data from specific territories, like northern or indigenous populations, were not included due to challenges stemming from their relatively small populations and logistical issues in data collection, particularly in remote regions. While this exclusion impacts the study's comprehensiveness and introduces a potential information bias, it was a carefully considered decision driven by data quality and feasibility.

Moreover, assumptions made regarding food availability, cost, and environmental impact pertain specifically to the regions covered by the study and might not be applicable to areas beyond that scope. This underscores the intricate connection between data and context and emphasizes the importance of aligning assumptions with the characteristics of each region for a well-rounded understanding.

5. Conclusions

The objective of the study was to examine consumption patterns of red meat and to characterize factors associated with Canadian consumer food choices and preferences for red meat using nationally representative survey data based on actual consumption. Women, common-law couples, individuals with a Bachelor's degree or higher, consumption of nutritional supplements and African and Asian cultural identities had an increased likelihood of red meat exclusion. Men, people with higher smoking habits, higher BMI and couples living with children aged 25 or younger were less likely, compared to other demographics, to exclude red meat from their diets in 2015. Age and income were not significantly associated with the exclusion of red meat in probit regression, even after controlling for clustering by regions in Canada. It is evident that disparities in red meat consumption patterns are driven by sex, race/ethnicity, education, and family status. This information can help policy makers formulate recommendations and dietary interventions that improve consumer awareness and engagement in food choices that result in nutritional adequacy. The findings regarding value-driven preferences for red meat highlight the need for institutional and socio-cultural innovations that address cultural identity and demographic dynamics in policy decisions affecting both producers and consumers. Major fast-food chains are engaged in the mass-advertising of plant-based proteins using social influencers such as celebrity chefs, athletes, and entertainers to influence the dietary habits of young people. Regulating food companies that promote non-nutritive attributes, especially foods with potentially harmful attributes appears to be critical (Barrett, 2021). Since behavioral factors related to food and nutrition are embedded in cultural contexts, recommendations for dietary guidelines require explicit consideration of consumer values and preferences.

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CHAPTER VII: GENERAL DISCUSSION

Sustainable food systems in Canada

The global agri-food system faces the challenge of feeding a growing world population with minimum adverse effects on the environment in the decades to come. The central problem with the current food system is its inability to provide sufficient nutrients to all while also reducing its negative impact on the environment and natural resources (Barrett et al., 2020). The U.N. Food Systems Summit sought to alter food systems to be healthier, safer, more sustainable, efficient, and equitable (von Braun et al., 2021). Animal products contribute to global food and nutrition security by supplying essential macro-and micro-nutrients, including quality protein. vitamin A, vitamin B12, riboflavin, vitamin D, calcium, iron, and zinc, which could be challenging to obtain in adequate quantities in bioavailable forms from plant-based diets (Mottet et al., 2017). Ruminant agriculture also plays an important role in biodiversity maintenance and C-sequestration through the grasslands it utilizes; however, the research community has also long recognized the contribution of livestock production to GHG emissions, as well as air and water pollution. A recent report by the Intergovernmental Panel on Climate Change indicated that livestock contributes nearly two-thirds of global agricultural GHG emissions and 78.0% of agricultural methane emissions—with cattle representing a significant percentage of that contribution (IPCC, 2019). Further, high levels of red and processed meat consumption in upper-income countries have been associated with adverse health outcomes (Godfray et al., 2018; Vernooij et al., 2019). Therefore, the dual burdens of meeting nutritional requirements and the need to alleviate adverse effects of food production and consumption on human and planetary health are shaping research priorities, influencing policy, and changing people's perceptions of food (Reisch, 2021). Farmers around the globe, including Canada, are under pressure to produce nutritious, affordable, safe, and healthy food in sufficient quantities at an affordable price while taking care of the animals, the land, and the water on their farms. Resolving the quandary of providing an adequate supply of nutritious food while mitigating environmental degradation will be contingent upon the specific characteristics of each region or country. For instance, certain regions may find it more prudent to import rather than produce particular food types, primarily due to the environmental or economic costs associated with the latter approach.

Scientific understanding of the link between agricultural production, nutrition, and the environment is crucial for transforming the current agri-food system towards sustainability. Research has separately addressed food production, nutritional security, and agricultural GHG emissions but needs to investigate how these issues are interconnected adequately. Examining the agri-food system from only the production or consumption side has hindered understanding of the complex interactions among agricultural production, human nutrition, health, and the environment. A transdisciplinary approach incorporating agricultural and environmental sciences, human nutrition, consumer behavior, supply chain logistics, and stakeholder engagement is needed to analyze these complex factors. Using integrated assessment tools is important to identify food production and consumption scenarios that meet nutritional adequacy and GHG emission reduction goals. Governments need this information to make informed decisions regarding relevant policies and programs.

This thesis aimed to analyze the effects of changes in land use and dietary choices in Canada on nutritional and environmental outcomes associated with current and alternative food systems. The study evaluates Canada's ability to provide its growing population with nutrient-sufficient and affordable food, taking into account constraints such as land resources, food and nutrient availability, intake limits, and relative prices, using a combination of research methods. It is noteworthy to highlight that Canada possesses a favorable advantage compared to many other nations in terms of arable land per capita, a valuable resource for food production. The research also attempted to convert the principles of sustainable food systems and expert knowledge into algorithms and use computing power for decision-making. Mixed research methods including econometric approaches like multilevel mixed-effects probit regression, Inverse Probability Weighted Regression Adjustment, mathematical diet optimization techniques, and spreadsheet models, were employed. Mixed method designs, which involve a combination of quantitative and qualitative research methodologies, allow researchers to deepen their understanding of the interplay between food production, diet choice, nutritional adequacy, and emissions.

This chapter summarizes and integrates the findings from individual manuscripts, focusing on the impacts of changes in land use and dietary choices on land use, food cost, nutritional adequacy, and emissions. It also examines the nutritional impact of Canadian consumers who have eliminated red meat from their diets and the demographic and socio-economic factors associated with food choice. The synthesis of findings is intended to support the development of nutrition and land-use programs, encourage evidence-based policy-making, and inform consumers about the impact of their dietary choices.

Impact on land use and other environmental benefits

As indicated in Chapters 3 and 4, the land formerly used for animal feed production could hypothetically be liberated and reallocated to agricultural production if all livestock in Canada were eliminated. However, large parts of the grasslands in Canada, especially in Prairie regions, are only suitable for some agricultural uses (Terry et al., 2020). The elimination of livestock from the Canadian farming system could also have unintended negative consequences for the environment, such as loss of biodiversity, decreased soil fertility, and increased use of chemical fertilizers and pesticides. Strategies to mitigate climate change include dedicating more land to facilitate carbon sequestration in trees, grasslands, and soils and to conserve habitat to preserve wild species (Barrett et al., 2020). Moreover, as indicated in Chapter 3, the amount of agro-processing co-products and by-products used in livestock diets has increased by 11.3% from 2001 to 2016. In recent years, there has been an observed increase in the availability of agro-processing co-products and by-products for animal feed in Canada due to increased regional processing of commodities (Ominski et al., 2021). The increase in the amount of agricultural processing co-products and by-products used in livestock feed is consistent with land-sparing and emission reduction animal production strategies (Dou et al., 2018; Van Zanten et al., 2018). Further, this approach is aligned with Canada's commitment to supply healthy and nutritious food to meet the demands of a growing population while minimizing the impact on the environment through the implementation of circular economy principles (Xavier et al., 2021). Ruminants also play an integral role in grassland ecosystems as grazing facilitates carbon sequestration and improved soil nutrient concentrations using organic fertilizer sources such as manure, which has not only positive impacts on soil fertility but also soil organic matter and biodiversity (Cusack et al., 2021). Beef cattle, in particular, embody this advantage because they produce nutrient-dense meat from forages and other feedstuffs that are not suitable for other livestock species or human consumption (Mottet et al., 2018). Therefore, improving the efficiency of animal production (Mottet et al., 2017; Chang et al., 2021; White and Gleason, 2022) continues to be a sensible alternative to removing livestock from food production systems to achieve nutritional and environmental goals. These production-side changes include improvements in efficiency resulting from innovations in feed additives (i.e., use of enzymes, probiotics), feeding management (i.e., robotics), breeding, and genetics that have reduced the gross feed demand per unit of animal food product (Legesse et al., 2016). Over the last 30 yrs, the adoption of these management practices has already significantly reduced the intensity of GHG emissions from beef production by 14% in Canada and reduced land use by 24% (Legesse et al., 2016). It is important to note that the adoption of these management practices alone, which have been shown to reduce enteric CH_4 emissions by 10-15%, will not achieve the deep cuts in emissions that are needed to achieve the ambitious goals established by industry and government. The economic viability of several emerging technologies, including feed additives such as 3-nitrooxypropan (3-NOP) or seaweed (Eckard et al., 2010; Jayasundara et al., 2016) that can significantly reduce GHG emissions from livestock must be demonstrated in order to facilitate large scale adoption.

Impact on the composition of diets and quantity of food consumed

Providing a sufficient quantity of nutritious, safe, affordable, and culturally diverse food to all people is the stated objective of food policy in Canada (Agriculture and Agri-Food Canada, 2020). The results presented in Chapter 4 demonstrate that to meet the RDA for omnivorous diets, not only do the dietary compositions differ significantly from vegan diets, but they also require a higher quantity of food (1.46 kg/person/d) when compared to the vegan counterpart (1.08 kg/person/d). The observed differences in quantity between omnivorous and vegan diets can be attributed to factors such as the nutrient density and bioavailability of animal-based vs. plant-based foods, as well as cultural and psychological influences on dietary preferences and energy expenditure. The omnivorous diet modeled to meet RDA nutrient intake targets included food commodities such as grains, pulses, oilseeds, fruits, vegetables, dairy products, and fish. When the modeled diets were set to meet CCHS intake targets, the total dietary intake for the omnivorous diet was 1.38 kg/person/d, consisting of grains, pulses, oilseeds, fruits, vegetables, beef, chicken, dairy products, eggs, and fish. Based on the food commodities included in the least cost optimal omnivorous diet under the CCHS intake levels, the quantitative contribution of beef to total food consumption was 0.64 g/person/d. Given the constraints imposed, this result is plausible as the model was programmed to select food products from the Canadian food supply based not only on their nutrient profile but also on their relative cost (e.g., CA$ 20.01/ kg of beef vs. CA$ 5.63 / kg of wheat grain). To put the quantity of beef included in the least cost optimal diet in perspective, Canadian dietary guidelines suggest a daily portion of 50–75 g of cooked fresh meat, such as beef, pork, mutton, or veal (Cashman and Hayes, 2017). The data from 2015 CCHS indicate that the average consumption of fresh red meat for Canadians was 52 g/person/d, and the total consumption of red meat (including processed red meat) was 74 g/d Therefore, the intake of beef estimated in this study are substantially less than the 50-75 g recommended by the Canada Food Guide and the 2015 intake reported by Canadian consumers.

Although it is reported that consumers are willing to shift to meatless diets (Charlebois et al., 2020a), data presented in Chapter 6 demonstrated that this represented only 5% of Canadian consumers in 2016. This result is less than the percentage of people (9.4%) that indicated their willingness to exclude ASF in a recent survey (Charlebois et al., 2020b). These authors reported that consumers are willing to shift towards diets with fewer ASF products (meat, dairy, eggs, and seafood) and more plant-based alternatives (Charlebois et al., 2020b). Nonetheless, their work, coupled with our findings from the CCHS data set, indicate that omnivorous diets predominate in Canada. Our data also indicated that socio-demographic characteristics such as gender, education level, and psychological, social, and cultural factors were associated with the decision of Canadian consumers to remove red meat from their diet. Consumers who were more likely to exclude red meat were disproportionately females, highly educated, or of Asian and African descent. Gender preferences associated with the consumption of meat were recently reported in an opinion survey in which men placed more value on eating meat than women (Charlebois, 2020). Further, these authors also reported that younger and more educated respondents were less likely to enjoy meals with meat. It is evident that the decision to include or exclude meat is a personal choice that is driven by intrinsic factors including satisfaction, cultural preferences, and perceived health outcomes, as well as extrinsic factors, including cost (Mullee et al., 2017; Ripoll and Panea, 2019). Therefore, it is essential for both production-side and consumption-side stakeholders to recognize the drivers of individual food choices to design appropriate interventions and support food systems consistent with consumer characteristics, preferences, and values. Examples include the adoption of management practices and product development, as well as program and policy changes that reflect consumer values and help them make informed decisions regarding dietary choices.

Impact on cost of diets

As reported in Chapter 4, optimal diets that meet RDA nutrient intake requirements cost CA$ 3.5 to CA$ 4.1/person/d for the omnivore and complete animal removal scenarios, respectively. Least cost diets that meet nutrient intake levels in the 2015 CCHS had a wider range with an estimated cost of CA$ 2.7/person/d for the lacto-vegetarian scenario to CA$ 4.9/person/d for the vegan scenario. The transition from an omnivorous diet adhering to RDA guidelines to a diet that eliminates animal-based products led to a notable 16.7% escalation in food expenditures. This shift resulted in an increase in daily costs per capita from CA$ 3.5 to CA$ 4.1. However, shifting from an omnivorous diet that met current nutrient intake levels in the 2015 CCHS dataset to a diet that excluded animals from the production system decreased food cost by 1.5% (from CA$ 4.2 to 4.1 /person/d). The difference in cost between the two systems is likely due to the difference in nutrient requirement targets between RDA and CCHS. Nonetheless, food costs in all scenarios were much less than the average daily food budget of CA$ 7.10/person/d in Canada (Auclair and Burgos, 2021). This wide variation in the cost of modeled diets and average daily food expenditure could be explained by the fact that consumers are likely not to be eating at the least cost-optimal level. However, the complete removal of animals from the Canadian farming system and the shift to vegan diets increased the diet costs, suggesting that sometimes the primary determinant of food choice (Bai et al., 2022). It also suggests that marketing campaigns for unhealthy foods based on non-nutritional attributes and the demand for convenience and storability could explain unhealthy food choices by those who can afford a healthy diet (Barrett et al., 2020). Much would depend on the relative cost of the variety of foods eaten by vegetarians.

Impact on nutrient intake and adequacy

Several studies have also reached a similar conclusion that consumers who exclude ASF from their diets would struggle to meet the RDA for essential nutrients such as protein, omega-3 fatty acids, riboflavin, niacin, pantothenic acid, vitamin B12, iron, selenium, zinc, and thiamin from the plant-only food sources (Sheehy et al., 2015; Tian et al., 2016; Tapia, 2018). A recent comparative study in the U.S. also observed that domestic supplies of EPA, and DPA fatty acids; and vitamins A and B12 were insufficient to meet the requirements of the U.S. population without animal-derived foods (White and Hall, 2017). As described in Chapter 5, essential fatty acids such as omega-3 fatty acids may also have been limited for consumers who excluded red meat in Canada, but omega-fatty acids were not reported in the 2015 CCHS dataset. Finally, recommendations to eliminate ASF from the diet and replace it with plant alternatives should consider nutritional and health implications for the Canadian population, specifically young children, pregnant women, and the elderly. In optimizing the different dietary patterns, we strategically relaxed certain constraints to achieve optimal outcomes. This was done to balance real-world feasibility with nutritional adequacy, especially when conflicting demands arose between domestic production capacity and nutrient intake targets. This flexibility allowed us to prioritize key nutrients within the limitations of the food system. However, it's important to acknowledge that complete nutritional sufficiency for all nutrients simultaneously might have been compromised due to this approach.

Impact on greenhouse gas emissions

The result of modeled diets in Chapter 4 suggests that shifting to diets with fewer or no animal-sourced products could reduce GHG emissions but with the risk of inadequate essential fatty acids, vitamins, and minerals for the Canadian population. The GHG emissions of diets gradually decreased across scenarios (as a dietary pattern moved from omnivorous to consumption scenarios without animal products) from 0.83 to 45.3% under the RDA intake target and from 40 to 66.0% under CCHS intake target. This modeling study suggests shifting from omnivore to vegan diets can reduce GHG emissions but within a limited range (1.64 and 0.55 kg CO_2 eq/person/d for omnivore diets and for diets with complete removal of animals, respectively). Our GHG emissions results (kg CO_2 eq/person/d) generally align with the previous study in the United States that implemented diet optimization methods to determine the GHG emissions for optimal diets with and without animal products (White and Hall, 2017). The authors found that optimal diets derived from systems with animals, which meet nutritional requirements, had emissions of 3.29 kg CO_2 eq./person/d, while optimal diets derived from systems without animals had emissions of 1.43 kg CO_2 eq./person/d.

However, we found no evidence to support the claim that the removal of ASF could reduce GHG emissions with little consequences on nutritional adequacy (Willett et al., 2019). Our data show that setting GHG emissions reduction goals with no consideration for the nutritional adequacy of various food groups could lead to the deficiency of some essential nutrients. Policies that focus mainly on GHG emissions reduction goals, with no nutritional consideration, will result in land use patterns and diet combinations that are unable to meet requirements for essential nutrients.

The need for a transdisciplinary research approach

The debate surrounding the balance between animal and plant-based foods is centered on two primary objectives: meeting human nutritional requirements and reducing greenhouse gas (GHG) emissions from food systems. It recognized that ASFs are rich in protein and other essential nutrients, making them an important part of the diets of many Canadians. However, the production of animal-based foods, particularly red meat, is a significant source of GHG emissions.

Meeting nutritional requirements while reducing greenhouse gas (GHG) emissions is a challenge that requires careful consideration of multiple factors. The ASFs are resource-intensive, requiring large amounts of land, water, and energy, while plant-based diets may be challenging to meet nutritional requirements, particularly for individuals with specific dietary needs or preferences.

The importance of nutrient density is highlighted in Chapter 4, which uses a modeling approach to examine the impact of land use and dietary preferences on optimal diets. The modeled diets met nutritional requirements for most nutrients from domestic production, except for fatty acids such as DHA, EPA, and vitamins (choline, A, D, and E). Chapter 5 explores the risks associated with completely excluding red meat from the diet, including nutrient inadequacy for calcium, vitamin

D, energy, and potassium. However, consuming red meat also presents risks of dietary fiber, vitamin A, and magnesium inadequacy.

To find the right balance, a more diverse and balanced diet that includes both plant-based and animal-based foods may be necessary to ensure nutrient requirements are met to avoid inadequacies and associated health risk while also reducing the environmental impact of food systems. It is essential to consider the environmental impact of food systems and promote more sustainable production methods for animal-based foods to reduce GHG emissions. Finding the right balance between meeting nutritional needs and reducing environmental impact requires collaboration and innovation across the food system and signals the need for transdisciplinary research. This approach is paramount as agri-food systems span the breadth of agricultural production, processing, and distribution of food, with each step comprised of numerous processes, value chains, stakeholders, and their interactions. Given the complex nature of agri-food systems, the collective knowledge of diverse disciplines and models which consider constraints that reflect cost, nutritional and environmental metrics is necessary. However, the modeled diets for which we imposed these extrinsic constraints have limitations. For example, we are unable to impose intrinsic constraints, including cultural acceptability and other value-based criteria including willingness to pay more if the diet choice brings satisfaction. Therefore, understanding consumer behavior is crucial for developing strategies and educational interventions necessary to transition towards more sustainable diets at the individual and population levels. The results from Chapter 6 demonstrate that there are a number of drivers, including age, sex, education, nationality, and ethnicity, that impact food choices – which are difficult to include as constraints in optimization models.

A systems-based approach was used to better understand the dynamics of livestock production, the environment, and human food and nutritional security in Canada. The research included in this thesis examined sustainability through a wide range of indicators, including nutritional, environmental, and economic dimensions. We showed how data generated regarding the land base required for feed production could be used to model the potential impact of shifting the allocation of resources from feed production to crop production on food and nutrient supply and the potential reduction in livestock-related environmental impacts. Further, identifying the drivers of changes in consumer behavior is essential as these factors are not easily incorporated into modeling activities but are necessary to help policymakers improve consumer awareness regarding sustainable eating habits. This type of scholarship involves careful, time-consuming collaboration to integrate diverse knowledge from academic and non-academic stakeholders to develop viable solutions to complex issues while ensuring values and preferences are considered (Sellberg et al., 2021). In addition to knowledge, skills, and data, stakeholders must continue to use holistic approaches to identify, prioritize and manage trade-offs and diverging/competing priorities, to transform agri-food systems.

CHAPTER VIII: CONCLUSIONS. LIMITATIONS AND FUTURE CONSIDERATIONS

Achieving nutritional adequacy and livestock GHG emission reduction objectives requires a combination of production and consumption-based strategies and must recognize that trade-offs are inevitable. This thesis analyzed the links between animal production and the environmental and nutritional impacts of changes in land use and dietary choices in Canada by applying mixed research methods, including multilevel mixed-effects probit regression and inverse probability weighted regression adjustment, mathematical diet optimization techniques, spreadsheet models. The current debate regarding the exclusion of animal-sourced foods and the transition to plant-based diets raises concerns about potential nutrient inadequacies, including essential fatty acids, vitamins, and certain minerals. Chapter 4 of this research highlights the nutritional inadequacies among vegans and those who have completely removed ASF from their diets. Comparisons among these scenarios suggest that the RDA of most nutrients could be achieved with existing land use patterns across a variety of diets, except for fatty acids such as docosahexaenoic acid (DHA), eicosapentaenoic acid (EPA), and vitamins (A, B12, C, D, and E) in most consumption scenarios. Chapter 5 delves deeper into the impact of removing red meat from the diet on nutrient intake and adequacy, revealing that red meat excluders are at a higher risk of nutrient inadequacy. While most nutrients could be obtained from domestic sources, red meat excluders are at an increased risk of calcium, vitamin D, energy, and potassium inadequacy. Conversely, those who consume red meat are at increased risk of dietary fiber, vitamin A, and magnesium inadequacy. Therefore, careful consideration must be given to achieving a sustainable and nutritionally adequate diet to avoid inadequacies and associated health risks. Although the scenario modeling included production-side and consumption-side scenarios, other actors in the agri-food value chain also play an important role through distribution, processing, storage and packaging, trading, wholesale, and by retail.

The following conclusions could be drawn based on the research conducted::

Chapter 3:

- The ability of the Canadian livestock sector to respond to the growing demand for ASF will be dictated by feed availability.
- The estimated annual feed demand in Canada was approximately 63.9 million t, and land base requirements were 17.9 million ha in 2016.
- Feed DM consumed by livestock in Canada consisted of forages (65.4%), cereals (28.0%), and co-products and by-products of agricultural processing (6.6%).
- Ruminants (76.0%) had the highest feed demand in Canada, followed by monogastric animals (19.3%).
- Changes in feed availability associated with climate change and land use policy must be considered to realize the growth of the Canadian livestock sector to meet growing global demands for ASF.

Chapter 4:

- Nutrients that could not be met by food produced in Canadian were greatest in vegan diets.
- Diets excluding animal-sourced foods failed to meet RDA requirements for vital nutrients, including DHA, EPA, calcium, potassium, and vitamins A, D, E.
- Modeled diets excluding ASFs, like CRA and vegan diets, demonstrate lower GHG emissions but result in higher costs.

Chapter 5:

- Red meat exclusion resulted in statistically significant differences in the intake of 14 to 17 nutrients.
- Neither Canadians who included or excluded red meat from their diet met RDA requirements for calcium, energy, potassium, vitamins A and D, fiber, and magnesium. However,
- red meat excluders had increased risk of inadequacy for calcium, energy, potassium and vitamin D while reded meat consumers had an increased risk of inadequacy for fiber, magnesium, and vitamin A.

Chapter 6:

- Less than 5% of Canadians exclude red meat

- Demographic factors such as sex, education, family status, and cultural background influence dietary choices. Females, possession of a Bachelor’s degree or higher, and Asian and African cultural identities were positively associated with red meat exclusion.
- Males, households living with children aged 25 yrs or younger, higher BMI, and smoking were negatively associated with red meat exclusion.

The research findings underscore the need to optimize crop-livestock systems for nutrition and environmental stewardship. It supports adoption of balanced diets that integrate both plant and animal-sourced foods rather than eliminating ASFs. Tailoring dietary recommendations and policies to demographic and socio-economic factors could address the diverse challenges faced by society.

Limitations and Future Considerations

In our research endeavor, we embraced an inclusive methodology, drawing upon a mixed-method approach that harnessed a diverse array of analytical tools. This encompassed techniques such as multilevel mixed effect probit-regression models, inverse probability-weighted regression, and mathematical diet optimization. The ambition was clear – to untangle the intricate interplay between livestock production, shifts in land utilization, and individual dietary preferences within the unique context of Canada. This comprehensive perspective acknowledged both the supply and demand facets of the agri-food ecosystem, with a discerning recognition of the pivotal roles played by stakeholders across the value chain. Their influence extends beyond the immediate boundaries of food production, as we accentuate the need for a broader scope, encompassing domains like healthcare expenditure, quality of life, and life expectancy. It's this panoramic lens that serves as the bedrock for a comprehensive understanding of food system sustainability.

While our analysis examined the nutritional implications and GHG emissions inherent in diverse dietary choices, we do admit that our assessment might not fully address potential long-term health ramifications, such as the potential for osteoporosis. Rigorous model development calls for a multi-faceted approach that takes into account production dynamics, environmental stewardship, ecosystem services, and the intricate interplay of nutrition and health considerations. Collaborative interaction with programmatic and policy experts, and the holistic methodology exemplified by "one health," charts a course toward achieving this comprehensive vantage point.

The complexity of modeling intricate systems, as we've witnessed in Canada's agri-food sphere, demands a compilation of data from a spectrum of sources. In scenarios where data constraints loom, the formulation of assumptions emerges as a necessity, albeit one that introduces the potential for bias. It's of paramount importance to approach our model outputs with a discerning eye, reinforced by a robust validation protocol to fortify forthcoming investigations.

As we gear up for our subsequent modeling ventures, our focus rests on exploring the potential outcomes arising from alternative production strategies. An intriguing prospect is the assessment of reallocating portions of marginal lands designated for livestock production, steering them toward crops intended for direct human consumption. Additionally, unraveling the environmental consequences linked with the utilization of co-products and by-products from agricultural processes as livestock feed, compared to their disposal in landfills, and weighing the merits of employing animal manure as an agricultural input versus conventional fertilizers, holds the promise of invaluable insights. On the consumption frontier, scrutinizing the GHG emissions tied to the moderation of red meat intake or the juxtaposition of conventional beef consumption with lab-grown alternatives stands as a compelling avenue for deeper exploration.

While our study has unveiled the impact of shifting land use patterns and evolving dietary inclinations, we openly recognize the far-reaching influence of emerging technologies like lab-grown meat. These technological advancements call for seamless integration to holistically assess the nexus between nutritional adequacy and GHG emissions.

In our pursuit of integrating critical sustainability benchmarks spanning nutrition, costs, and GHG emissions, we duly acknowledge the absence of pivotal metrics such as eutrophication and biodiversity within our analytical framework. It's imperative to underscore that the very foundation of our study rested on the Comprehensive Canadian Health Survey (CCHS) database, compiled in 2015. This temporal context is a reminder of the imperative to assess potential temporal disparities in reflecting contemporary dietary trends, which may well have evolved over time.

As we strive to deepen our comprehension of the wider environmental implications entwined with dietary and production choices, a proactive stance beckons in future inquiries. This trajectory mandates a nuanced evaluation of alternative production strategies, encompassing the wise utilization of co-products, the recalibration of marginal lands, and a careful examination of diet choices for optimal human health. The confluence of these multifaceted dimensions promises a broader and more holistic understanding of sustainable practices. It's noteworthy that the potential benefits of lab-grown meat, including reduced environmental impact and enhanced animal welfare, should be weighed against technological, cultural, and regulatory challenges, alongside the potential disruption to conventional beef-related industries.

Moreover, for securing the longevity of our food systems, enhanced strategies are imperative to more accurately estimate environmental indices encompassing GHG and ammonia emissions, land and water use, carbon sequestration, and biodiversity. The crux lies in the continuation of interdisciplinary research that delves into the intricate interplay between food production, consumption, environmental sustainability, and nutritional health. The insights garnered from this ongoing research and future investigations hold the compass to steer stakeholders in the agri-food system and policymakers toward more informed decisions.

Ultimately, the essence of a more sustainable future for our food systems hinges on the active engagement of multiple stakeholders. This collaborative spirit is the driving force in reshaping our food systems, offering a trajectory toward a more sustainable tomorrow.

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Supplementary Material - (SA): Estimation of feed and land requirements in Canada

Supplementary Material - SA1: Contribution of by-products to livestock feed in Canada

Feed type	**Total Feed DM required including waste (t/yr)**
Barley screenings	43909.72
Beet pulp dried	129759.82
Canola meal	1019221.37
Corn DDGS	43397.81
Corn gluten feed	156272.49
Corn gluten meal	223015.37
Millrun pellets	10203.47
Molasses	1808.38
Soya	1119.80
Soybean hulls	302126.82
Soybean meal	2248644.88
Vegetable oil	58200.40
Total	4237680.34

Supplementary Material - SA2: Contribution of perennial forages to livestock feed in Canada

Perennial forages	Area required produce feed for animals (ha/yr)
Alfalfa (pasture)	16556.52
Alfalfa grass hay	286362.2
Alfalfa hay	68131.72
Alfalfa haylage	18925.01
Bale grazing	603178.1
Grass hay	1538755
Grass hay	49254.18
Grass pasture	2653963
Grass silage	11860.15
Grass-legume hay	1554751
Native pasture	4806924
Stockpiled forages	146266.5
Total forage required (ha/yr)	**11754927**
Total forage required (million ha/yr)	**11.75**

Supplementary Material - (SB): Estimation of modeled food, cost, nutrient intake and greenhouse gas emissions

Supplementary Material - SB1. Summary of dietary scenarios and assumptions

Scenarios	Assumptions and products included	Nutrient targets	Typology of interventions
1. Complete removal of animals	All land previously used for animal feed production is removed and reallocated for crop production	Recommended Daily Allowance (RDA)	Production-side
		Actual nutrient intake of Canadians based on Canadian Community Health Survey data (CCHS) representing omnivore diets	Consumption-side
2. Omnivore baseline	All plant-and animal-based foods are consumed	RDA	Production-side
		Actual nutrient intake of omnivore diets from 2015 CCHS	Consumption-side
3. Vegan	Edible portion of fruits, vegetables, legumes, and cereals included all foods of animal origin (dairy, eggs, fish, and meat) excluded	RDA	Consumption-side
		Actual nutrient intake of vegans from 2015 CCHS	Consumption-side
4. Lacto-ovo-vegetarian	Plant-based foods and dairy products (including cow and goat milk) and eggs included meat, poultry, and fish excluded	RDA	Consumption-side
		Actual nutrient intake of lacto-ovo-vegans from 2015 CCHS	Consumption-side
5. Lacto-vegetarian	Plant-based foods and dairy products, including cheese, milk, and yogurt included meat, poultry, fish, and eggs excluded	RDA	Consumption-side
		Actual nutrient intake of lacto-vegans from 2015 CCHS	Consumption-side

Supplementary Material - SB2: Frequency of food categories included in modeled omnivore (OMN), complete removal of animals (CRA), vegan (VEG), lacto-ovo (LACTOVO) and lactose inclusive (LACTO) diets that meet Recommended Daily Allowance (RDA) and nutrient intake requirements reported by the Canadian Community Health Survey (CCHS)

Nutrient intake requirement	Food category	OMN	CRA	VEG	LACTOVO	LACTO
	Dairy products	2			2	2
RDA	Fish	1				
	Fruits	3	2	3	3	3
	Grain & oilseeds	5	10	10	5	5
	Pulses	5	7	4	5	5
	Vegetables	22	20	18	22	22
		38	39	35	37	37
CCHS	Beef	1				
	Chicken	2				
	Dairy products	2			2	2
	Eggs	1				
	Fish	1				
	Fruits		3			
	Grain & oilseeds	4	3	11	3	4
	Pulses	1	2	7	4	4
	Vegetables	1	18	13	3	5
		13	26	31	12	15

Supplementary Material - SB3: Relative change in the quantity of foods consumed for each of the diet scenarios compared to omnivore diet based on RDA and CCHS requirements

Scenarios	Quantity of food consumed (kg/person/d)		% Change compared to omnivore baseline	
	RDA	2015 CCHS	RDA	2015 CCHS
Omnivore baseline	1.62	1.38		
Complete removal of animals	1.25	1.3	-14.38	-5.86
Vegans	1.03	1.32	-29.45	-4.34
Lacto-ovo-vegetarians	1.46	1.16	0.00	-15.91
Lacto-vegetarians	1.46	1.19	00.00	-14.06

Supplementary Material - SB4: Relative change in daily costs of foods consumed against omnivore baseline

Scenarios	Daily costs (CA$/person/d)		% Change against Omnivore baseline	
	RDA	2015 CCHS	RDA	2015 CCHS
Omnivore baseline	3.50	4.15		
Complete removal of animals	4.09	4.09	16.68	-1.53
Vegans	3.68	4.94	5.09	19.13
Lacto-ovo-vegetarians	3.48	2.65	-0.72	-36.13
Lacto-vegetarians	3.48	2.71	-0.72	-34.72

Supplementary Material - SB5. Nutrient intake of modeled omnivore (OMN), complete removal of animals (CRA), vegan (VEG), lacto-ovo (LACTOVO) and lactose inclusive (LACTO) diets that meet Recommended Daily Allowance (RDA) requirements

Nutrient category	Nutrients	OMN	CRA	VEG	LACTOVO	LACTO
Amino acids	Cysteine	1.77	3.29	2.34	1.77	1.77
	Histidine	3.25	4.91	3.36	3.24	3.24
	Isoleucine	5.49	8.22	5.53	5.48	5.48
	Leucine	9.51	14.09	9.65	9.49	9.49
	Lysine	7.85	10.98	7.18	7.81	7.81
	Methionine	3.73	2.66	4.02	3.72	3.72
	Phenylalanine	6.07	9.58	6.70	6.07	6.07
	Threonine	4.83	7.41	4.97	4.81	4.81
	Valine	6.22	9.26	6.35	6.21	6.21
Fatty acids	alpha-Linolenic acid (g)	6.58	6.12	1.90	6.60	6.60
	DHA	0.01	0.00	0.00	0.00	0.00
	EPA	0.02	0.00	0.00	0.00	0.00
Macronutrients	Carbohydrate (g)	296.48	598.08	473.55	299.61	299.61
	Energy (kcal)	2735.33	4078.75	2815.53	2746.80	2746.80
	Linoleic acid (g)	30.29	39.60	21.53	30.34	30.34
	Protein (g)	125.02	192.87	136.45	124.83	124.83
	Total fiber (g)	53.32	111.28	83.60	53.75	53.75
Minerals	Calcium (mg)	1356.70	1067.86	736.01	1357.28	1357.28
	Iron (mg)	41.82	66.37	50.49	41.90	41.90
	Magnesium (mg)	834.83	1490.85	1088.72	837.90	837.90
	Phosphorus (mg)	2654.55	4176.18	3008.50	2658.38	2658.38
	Potassium (mg)	5890.79	7984.03	5974.48	5893.72	5893.72
	Selenium (mcg)	116.02	237.62	208.00	116.92	116.92
	Zinc (mg)	18.55	31.43	22.48	18.61	18.61
Vitamins	Choline (mg)	450.11	653.88	450.11	450.11	450.11
	Folate (mcg)	1040.61	1667.98	1067.07	1040.65	1040.65
	Niacin (mg)	15.60	38.10	31.18	15.74	15.74

Riboflavin (mg)	2.99	3.26	2.23	2.99	2.99
Thiamin (mg)	3.19	5.78	4.08	3.20	3.20
Vitamin A (mcg RAE)	736.90	736.90	172.34	736.90	736.90
Vitamin B12	2.98	0.00	0.00	2.91	2.91
Vitamin B6 (mg)	2.42	3.83	3.34	2.43	2.43
Vitamin C (mg)	72.61	73.11	72.61	72.61	72.61
Vitamin D	1.05	0.00	0.00	0.72	0.72
Vitamin E (mg AT)	13.84	13.84	4.88	13.84	13.84
Vitamin K (mcg)	160.83	226.48	117.30	161.53	161.53

Supplementary Material - SB6. Nutrient intake of modeled omnivore (OMN), complete removal of animals (CRA), vegan (VEG), lacto-ovo (LACTOVO) and lactose inclusive (LACTO) diets that meet the 2015 Canadian Community Health Survey (CCHS) nutrient intake target

Nutrient category	**Nutrients**	**OMN**	**CRA**	**VEG**	**LACTOVO**	**LACTO**
Amino acids	Cysteine	2.14	2.91	3.01	2.1	2.1
	Histidine	3.47	4.1	4.26	3.41	3.4
	Isoleucine	5.4	7.05	6.68	5.77	5.75
	Leucine	9.72	12.23	11.89	10.06	10.04
	Lysine	7.13	9.14	8.2	7.84	7.8
	Methionine	2.49	4.59	4.79	2.04	2.06
	Phenylalanine	6.49	8.51	8.37	6.77	6.75
	Threonine	4.79	6.48	5.96	5.15	5.14
	Valine	6.5	7.97	7.77	6.66	6.65
Fatty acids	alpha-Linolenic acid (g)	1.53	6.12	5.78	6.84	6.72
	DHA	0.04	0	0	0	0
	EPA	0.04	0	0	0	0
Macronutrients	Carbohydrate (g)	440.66	514.95	648.82	366.49	367.75
	Energy (kcal)	2874.7	3681.31	4019.22	2978.17	2978.58
	Linoleic acid (g)	16.17	39.28	31.97	30.88	30.8
	Protein (g)	125.24	157.27	168.98	123.13	123.01
	Total fiber (g)	62.08	92.29	110.78	59.86	59.99
Minerals	Calcium (mg)	1105.12	958.64	839.83	1110.08	1134.25
	Iron (mg)	28.19	60.7	60.14	37.24	37.06
	Magnesium (mg)	859.31	1267.8	1412.09	843.05	851.03
	Phosphorus (mg)	2877.03	3469.28	3846.81	2690.99	2713.71
	Potassium (mg)	4121.8	7496.29	7016.49	5018.43	5035.57
	Selenium (mcg)	287.46	202.45	345.13	151.28	154.45
	Zinc (mg)	19.23	24.45	28.57	18.33	18.37
Vitamins	Choline (mg)	379.01	525.5	516.76	450.11	450.11
	Folate (mcg)	438.54	1134.19	1196.39	906.3	879.97
	Niacin (mg)	38.56	38.56	42.36	26.38	26.7
	Riboflavin (mg)	2.61	2.92	2.65	2.7	2.73
	Thiamin (mg)	3.37	4.4	5.25	3.38	3.37
	Vitamin A (mcg RAE)	643.12	643.12	413.14	633.59	652.73

Vitamin B12	4.12	0	0	2.19	2.28
Vitamin B6 (mg)	3.03	3.8	4.34	2.49	2.5
Vitamin C (mg)	7.19	99.93	62.15	21.97	23.54
Vitamin D	1.35	0	0	0.56	0.58
Vitamin E (mg AT)	3.71	13.84	13.84	13.84	13.84
Vitamin K (mcg)	51.98	226.53	154.37	140.34	143.26

Supplementary Material - SB7: Percentage changes in GHG emissions (kg CO_2 eq/person/d) associated with modeled omnivore (OMN), complete removal of animals (CRA), vegan (VEG), lacto-ovo-vegetarian (LACTOVO), and lacto-vegetarian (LACTO) diets that meet RDA and 2015 Canadian Community Health Survey (CCHS) nutritional intake targets

Scenarios	GHG emissions (kg CO_2 eq/person/d)		GHG emissions reduction relative to Omnivore baseline (%)	
	RDA	2015 CCHS	RDA	2015 CCHS
Omnivore baseline	1.17	1.64		
Complete removal of animals	0.64	0.55	-45.28	-66.29
Vegans	0.45	0.62	-61.67	-62.10
Lacto-ovo-vegetarians	1.16	0.96	-0.83	-41.67
Lacto-vegetarians	1.16	0.98	-0.83	-40.45

Supplementary Material - SB8: Percentage change in nutrient supply after removal of animals

Nutrients	Percentage change in nutrient supply after removal of animals
alpha-Linolenic acid (g)	55.40
Arachidonic acid (AA)	50.77
Calcium (mg)	-12.39
Carbohydrate (g)	63.01
Choline (mg)	42.49
Copper (mcg)	59.58
Cysteine	50.44
Docosahexaenoic acid (DHA)	-92.45
Docosahexaenoic acid (DHA) and eicosapentaenoic acid (EPA)	-88.49
Energy (kcal)	50.33
Folate (mcg)	55.35
Histidine	33.36
Iron (mg)	59.92
Isoleucine	31.16
Leucine	35.98
Linoleic acid (g)	53.84
Lysine	17.68
Magnesium (mg)	59.21
Methionine	38.19
Niacin (mg)	49.57
Phenylalanine or Tyrosine	40.20
Phosphorus (mg)	46.31
Potassium (mg)	44.54
Protein (g)	37.08

Riboflavin (mg)	15.38
Selenium (mcg)	54.78
Sodium (mg)	-51.23
Thiamin (mg)	54.50
Threonine	32.39
Total fiber (g)	67.39
Valine	33.02
Vitamin A (mcg)	-16.55
Vitamin B12	-99.62
Vitamin B6 (mg)	50.65
Vitamin C (mg)	56.15
Vitamin D (mcg)	-96.59
Vitamin E (mg)	58.53
Vitamin K (mcg)	59.78
Zinc (mg)	46.85

Supplementary Material - SB9: Nitrogen (N), phosphorus (P), potassium (K) content of of livestock manure

Nutrients	Total production of nutrients from manure (million t)		
	N	P	K
Annual total NPK production from manure	0.56	0.11	0.28