The role of animal and plant protein foods in Canadian sustainable diets

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Abstract

Background: Greenhouse gas emissions (GHGE) from the food system are projected to exceed global scientific targets for climate change. However, the impact of animal and plant protein foods on a combination of nutrition, health, and climate outcomes in the context of Canadian self-selected diets is not known. The objectives of this dissertation were four-fold: 1) to assess usual protein intake, inadequacy, and the contribution of animal and plant-based sources to nutrient intakes in Canadian diets; 2) to quantify the carbon footprint of Canadian diets and to compare intake of food groups, nutrients, and diet quality between low- and high-GHGE diets; 3) to conduct a systematic review of studies that modeled replacements of animal with plant protein foods in self-selected diets on diet-related GHGE, nutrition, and health outcomes; and 4) to model the impact of partial substitutions of red and processed meat or dairy with plant protein foods in Canadian diets on nutrient inadequacy, health, and diet-related GHGE.

Methodology: In Manuscripts 1, 2, and 4, we utilized the dietary data of non-pregnant and non-lactating adults ≥19 y with a 24-h recall from the 2015 Canadian Community Health Survey (CCHS) – Nutrition. In Manuscript 1, we estimated usual protein intakes and inadequacy among Canadian adults and used population ratios to determine the contribution of animal and plant-based foods to intakes of protein, nutrients, and energy. In Manuscript 2, we linked GHGE estimates for food commodities from the database of Food Impacts on the Environment for Linking to Diets and food loss estimates from Statistics Canada to foods and beverages reported in the CCHS to quantify the carbon footprint of Canadian self-selected diets. Low- and high-GHGE diet respondents were compared in terms of their consumption of animal and plant-based foods, intake of nutrients of concern (calcium, vitamin D, iron, potassium) and to limit (sodium, saturated fat, sugars), and diet quality (Alternative Healthy Eating Index-2010). In Manuscript 3,

we systematically searched PubMed, Scopus, and EMBASE for nutrition surveys or cohorts that modeled substitutions of animal with plant protein foods in self-selected diets and that reported data for diet-related GHGE and, optionally, the percentage of the population meeting nutrient recommendations or changes to life expectancy. In Manuscript 4, we used individuals' dietary intake from the CCHS to model graded replacements (25% and 50%) of either red and processed meat or dairy with plant protein foods. Health outcomes (i.e., changes to life expectancy and life years) were estimated using life table models. Changes to nutrient inadequacy, health outcomes, and diet-related GHGE were compared between observed and modeled diets.

Results: Most Canadian adults had adequate protein intakes (Manuscript 1). Red and processed meat contributed the most to total protein intakes (21.6±0.55%), followed by poultry and eggs (20.1±0.81%), cereals, grains, and breads (19.5±0.31%), and dairy (16.7±0.38%). Dairy contributed most to intakes of calcium (53.4±0.61%) and vitamin D (38.7±1.01%), but also saturated fat (40.6±0.69%). Animal-based foods contributed three-quarters of Canadians' total diet-related GHGE, with red and processed meat alone accounting for 47.05±0.82% (Manuscript 2). Respondents with high-GHGE diets consumed more animal-based foods. They had higher intakes of nutrients of concern, but also saturated fat and sodium, and a lower diet quality score compared to low-GHGE diet respondents (47.27±0.46 vs. 55.31±0.49 points). Six of the 1,188 studies retrieved were included in the systematic review (Manuscript 3), and whereas all reported on diet-related GHGE, two reported on nutrition outcomes and none on health outcomes. Replacing meat led to the greatest reductions in diet-related GHGE (3-55%), most of which was attributed to beef alone (10-40%), and increased the percentage of the population meeting requirements for fibre, calcium, potassium, and iron by 1-5%. Replacing meat and dairy also increased the percentage of the population meeting requirements for iron (5-15%) and vitamin D

(2-7%) and decreased the percentage above recommendations for saturated fat (10-76%), but increased the percentage below requirements for calcium (9-33%) and vitamin A (8-48%). Modeling partial substitutions of red and processed meat with plant protein foods in Canadian self-selected diets induced minor changes to nutrient inadequacy, while replacing dairy increased calcium inadequacy by up to 14% (Manuscript 4). Replacing red and processed meat or dairy increased life expectancy by up to 8.7 or 7.6 months, respectively, but gains in the dairy scenarios were attenuated due to reductions in life expectancy with lower milk intakes. Diet-related GHGE decreased by up to 25% when red and processed meat was substituted and by up to 5% when dairy was replaced. The magnitude of health and environmental impacts was greater for males than for females.

Conclusion: Despite the prominence of animal protein foods in Canadian self-selected diets, consuming more plant protein foods can lead to beneficial synergistic effects with diet-related GHGE, nutrient adequacy, and health outcomes, especially when partially replacing red and processed meat. These findings are relevant for future dietary guidance and food policy in facilitating the shift towards healthy and sustainable diets in Canada and other high-income countries.

Résumé

Contexte : Les émissions de gaz à effet de serre (GES) provenant de systèmes alimentaires, devraient dépasser les objectifs scientifiques mondiaux pour combattre le changement climatique. Cependant, dans le contexte des régimes alimentaires Canadiens, l'impact des aliments protéinés d'origine animale et végétale en tenant compte des facteurs de nutrition, de santé et climatiques est inconnu. Cette thèse a pour but d'exposer 4 objectifs : 1) Évaluer l'apport habituel en protéines, son adéquation et la contribution des sources animales et végétales aux apports nutritionnels dans l'alimentation des Canadiens; 2) quantifier l'empreinte carbone des régimes alimentaires canadiens et comparer la consommation de groupes d'aliments, les nutriments et la qualité de l'alimentation entre les régimes alimentaires faibles et riches en GES; 3) mener une revue systématique des études qui ont modélisé le remplacement des protéines d'origine animale par des protéines végétales au sein de l'alimentation Canadienne ainsi que leurs résultats liés aux GES, à la nutrition et à la santé; et 4) modéliser l'impact, dans les régimes alimentaires Canadiens, des substitutions partielles de viande rouge et transformée ou produits laitiers pour des aliments protéinés d'origine végétale et relever l'impact sur la santé, l'adéquation nutritionnelle et les GES liés à l'alimentation.

Méthodologie : Pour les études 1, 2, et 4, nous avons utilisé des données de consommation alimentaires spontanées (i.e. « auto-sélectionnées »), relevées dans l'Enquête sur la santé dans les collectivités Canadiennes (ESCC) – Nutrition 2015. Ces données furent prélevées auprès d'adultes masculins et féminins (non enceintes et n'allaitant pas) ≥19 ans avec un rappel alimentaire de 24 heures. Pour étude 1, nous avons estimé l'apport habituel en protéines et leur adéquation chez les adultes Canadiens. Nous avons également utilisé des ratios de population pour déterminer la contribution des aliments d'originale animale et végétale à l'apport en

protéines, en nutriments et en énergie. Pour étude 2, nous avons fait le lien entre les estimations de GES mondiales pour les commodités provenant de « database of Food Impacts on the Environment for Linking to Diets », les estimations de pertes alimentaires de Statistiques Canada, et les aliments et breuvages cités dans l'ESCC, afin de quantifier l'empreinte carbone de l'alimentation consommée au Canada. Les répondants ayant des régimes aux taux faibles et riches en GES ont été comparés en termes de leur consommation d'aliments d'origine animale et végétale, de leurs apports de nutriments suscitant une préoccupation d'ordre de santé publique (calcium, vitamine D, fer, potassium), de nutriments à limiter (sodium, graisses saturées, sucre ajouté) et la qualité de leur régime alimentaire (« Alternative Healthy Eating Index-2010 »). Pour étude 3, nous avons effectué une recherche systématique de PubMed, Scopus et EMBASE afin de trouver des enquêtes de nutrition ou des cohortes. Ces enquêtes avaient pour but d'étudier l'effet des substitutions modélisés d'aliments protéinés d'origine végétale effectuées au sein de régimes alimentaires auto-sélectionnés. Ces enquêtes devraient rapporter des données sur les GES liés à l'alimentation et, optionnellement, le pourcentage de la population ayant des apports en nutriments adhérant aux recommandations ou les changements d'espérance de vie. Pour étude 4, nous avons modélisé des remplacements (25% et 50%) de viande rouge et transformée ou de produits laitiers par des aliments protéinés d'origine végétale dans les régimes alimentaires Canadiens. Les bilans de santé (i.e. changements d'espérance de vie et d'années de vie) ont été estimé en utilisant des modèles de table de survie. Les changements de bilan de santé, l'adéquation nutritionnelle et les GES reliés à l'alimentation ont été comparés entre les régimes observés et modelés.

Résultats : La plupart des adultes Canadiens se sont avérés avoir un apport de protéines suffisant (étude 1). Les viandes rouges et transformées (21,6 ± 0,55%) ont contribué le plus à l'apport de protéines. La volaille et les œufs (20,1 ± 0,81%), les céréales, le pain et les graines (19,5 ± 0,31%) et les produits laitiers (16,7 ± 0,38%) sont également des éléments ayant contribué à l'apport total de protéines. Les produits laitiers ont notamment contribué le plus au taux de calcium (53,4 ± 0,61%), de vitamine D (38,7 ± 1,01%) et de graisses saturées (40,6 ± 0,69%) enregistrés. Les aliments d'origine animale ont engendré les trois quarts des GES reliés à l'alimentation totale des Canadiens, avec les viandes rouges et transformées représentant 47,5 ± 0,82% (étude 2) de ce total. Les répondants ayant un régime alimentaire riches en GES ont consommé d'avantage d'aliments d'origine animale et ont enregistré un apport plus élevé de nutriments préoccupants pour la santé, de sodium et de graisses saturées. Ces répondants ont également présenté des indices de qualité alimentaire inférieurs comparé aux répondants avec des régimes aux taux de GES plus bas (47,27 ± 0,46 vs 55,31 ± 0,49 points). Des 1188 études révisées, 6 ont été incluses dans la revue systématique (étude 3). Alors que toutes les études ont présenté des données de GES liés à l'alimentation, deux ont enregistré des résultats en matière de nutrition et aucune en matière de bilan de santé. Le remplacement de la viande a engendré les réductions les plus importantes de GES liés à l'alimentation (3% à 55%). Le remplacement du bœuf à lui seul a produit un résultat considérable (10% à 40%) et, a de plus, occasionné une augmentation (1% à 5%) du pourcentage de la population présentant des taux adéquats de fibres, calcium, potassium et fer. La substitution de la viande et des laitages a également augmenté le pourcentage de la population présentant des apports adéquats de fer (5% à 15%) et de vitamine D (2% à 7%). Ces substitutions ont également diminué le pourcentage de graisses saturées qui se situe au-dessus des taux recommandés (10% à 76%) mais a augmenté le pourcentage de besoins en calcium (9% à 33%) et en vitamine A (8% à 48%) qui se situe en-dessous des taux recommandés. Un modèle se basant sur des substitutions partielles de viandes rouges et transformées par des aliments d'origine végétale a démontré des changements mineurs quant à la l'adéquation nutritionnelle dans les régimes alimentaires Canadiens (étude 4). Par contre, les remplacements de produits laitiers ont augmenté l'inadéquation en calcium de 14%. Les substitutions de viandes rouges et transformées ainsi que de produits laitiers par des protéines d'origine végétale ont provoqué une augmentation de l'espérance de vie des sujets atteignant jusqu'à 8,7 et 7,6 mois respectivement. Pourtant, une diminution de consommation de laitages (sans substitution) a occasionné une réduction de l'espérance de vie des sujets. La substitution des viandes rouges et transformées a occasionné une diminution jusqu'à 25% des GES liés à l'alimentation. Parallèlement, une substitution des produits laitiers a occasionné une diminution allant jusqu'à 5%. L'ampleur des impacts sur la santé et sur l'environnement était plus élevée pour les hommes que pour les femmes.

Conclusion : Malgré la présence importante d'aliments contenant des protéines d'origine animale dans les régimes alimentaires des Canadiens, il est possible d'entraîner des effets synergiques bénéfiques des GES liés à l'alimentation, un taux adéquat de nutriments et un meilleur bilan de santé en consommant une plus grande quantité d'aliments à base de protéines d'origine végétale, particulièrement à place de viandes rouges et transformées. Ces résultats sont pertinents pour l'élaboration de futures orientations alimentaires diététiques et politiques. Cela aiderait à faciliter un virage vers une alimentation saine et durable au Canada ainsi que dans d'autres pays développés aux revenus élevés.

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Contribution to Original Knowledge

This dissertation utilized data from the 2015 CCHS – Nutrition, the most recent and comprehensive source of information pertaining to food and beverage intakes in the Canadian population, to characterize the role of animal and plant protein foods in Canadian sustainable diets. This research contributes to original knowledge by being the first to assess diet sustainability in the Canadian context, which is particularly timely given the publication of the new Canada's Food Guide (CFG), which specifically encourages the consumption of plant protein foods, and a growing body of literature linking population-level dietary data to their environmental impacts. This dissertation starts by estimating protein intake and inadequacy among Canadian adults, as well as the contribution of animal- and plant-based sources to total protein and nutrient intakes (Chapter 3). Despite assumptions of adequate protein intake in Canada based on data from the National Health and Nutrition Examination Survey (NHANES) in the United States, there were no studies that quantified protein inadequacy in the Canadian population. Therefore, we were the first to provide nationally representative estimates of usual protein intake and inadequacy using the National Cancer Institute (NCI) method, which reflects individuals' long-term rather than 1-d dietary intake. Moreover, we filled a knowledge gap by determining the contribution of animal- and plant-based sources to total intakes of protein, nutrients of concern, and nutrients to limit. We followed up by quantifying the carbon footprint of Canadian self-selected diets and the contribution of low- and high-greenhouse gas emissions (GHGE) diets to intakes of animal- and plant-based foods, nutrients, and diet quality (Chapter 4). As such, we were the first to estimate the diet-related carbon footprint of self-selected diets in Canada by linking estimates of greenhouse gas emissions for food commodities to foods reported in the CCHS 24-h recalls. Our systematic review captured similar studies that modeled replacements of animal with plant protein foods on diet-related GHGE in combination with nutrition or health outcomes (Chapter 5). While existing systematic reviews have focused more broadly on theorical optimized diets, we focused instead on self-selected dietary intake and simple food substitutions that are likely more feasible than the complete uphauling of dietary patterns. To assess the practical implications of CFG's protein recommendations, we modeled partial replacements of animal with plant protein foods in individuals' diets on nutrition, health, and climate outcomes (Chapter 6). While previous modeling studies have combined animal protein foods or used surrogate measures of diet healthfulness, our manuscript explored the impacts of substituting either red and processed meat or dairy with plant protein foods on a unique combination of diet sustainability dimensions. Taken together, the results of this dissertation provide a comprehensive overview of the role of animal and plant protein foods in regional self-selected diets as a baseline with which to gauge the changes necessary for addressing human and planetary health.

Published research articles in peer-reviewed journals

- **Auclair, O.** & Burgos, S.A. Protein consumption in Canadian habitual diets: Usual intake, inadequacy, and the contribution of animal- and plant-based foods to nutrient intakes. *Applied Physiology, Nutrition, and Metabolism* 2020; **46**(5): 501-10. DOI: https://doi.org/10.1139/apnm-2020-0760. (Chapter 3)
- **Auclair, O.** & Burgos, S.A. Carbon footprint of Canadian self-selected diets: Comparing intake of food groups, nutrients, and diet quality between low- and high-greenhouse gas emissions diets. *Journal of Cleaner Production* 2021; **316**: 128245. DOI: https://doi.org/10.1016/j.jclepro.2021.128245. (Chapter 4)

Research articles submitted to peer-reviewed journals

- **Auclair, O.,** Jin, Y. & Burgos, S.A. The impact of substituting animal with plant protein foods in adults' self-selected diets on diet-related greenhouse gas emissions and prevalence below or above nutrient recommendations: A systematic review of modeling studies. *Environmental Research: Food Systems.* ERFS-100017. In review (submitted 2023-09-26). (Chapter 5)
- **Auclair, O.,** Eustachio Colombo, P., Milner, J. & Burgos, S.A. Modeling the replacement of red and processed meat or dairy with plant protein foods in Canadian diets. *Nature Food*. NATFOOD-23010024. In review (revision 1 submitted 2023-09-04). (Chapter 6)

Published abstracts

- **Auclair, O.,** Jin, Y. & Burgos, S.A. The impact of substituting animal with plant protein foods in adults' self-selected diets on diet-related greenhouse gas emissions and prevalence below or above nutrient recommendations: A systematic review of modeling studies. *Current Developments in Nutrition*, 2023. DOI: https://doi.org/10.1016/j.cdnut.2023.100234.
- **Auclair, O.** & Burgos, S.A. Carbon Footprint of Canadian Self-Selected Diets: Trade-Offs with Nutrient Intakes and Diet Quality. *Current Developments in Nutrition*, 2021. DOI: https://doi.org/10.1093/cdn/nzab060_002.
- **Auclair, O.** & Burgos, S.A. Carbon footprint of Canadian self-selected diets: comparing intake of food groups, nutrients, and diet quality among low- and high-GHGE diets. *Applied Physiology, Nutrition, and Metabolism,* 2021. DOI: https://doi.org/10.1139/apnm-2021-0172.

- **Auclair, O.** & Burgos, S.A. Contribution of animal- and plant-based protein sources to nutrient intakes among Canadian adults. *Applied Physiology, Nutrition, and Metabolism,* 2020. DOI: https://doi.org/10.1139/apnm-2020-0129.

Conference presentations

- **Auclair, O.,** Eustachio Colombo, P., Milner, J., Burgos, S.A. Modeling the replacement of red and processed meat or dairy with plant protein foods in Canadian diets: Impact on nutrient inadequacy, health outcomes, and greenhouse gas emissions. International Symposium: Dietary Protein for Human Health, Utrecht, The Netherlands, September 2023. (Selected for oral presentation)
- **Auclair, O.,** Jin, Y. & Burgos, S.A. The impact of substituting animal with plant protein foods on diet-related greenhouse gas emissions, nutrition, and health outcomes: A systematic review of modeling studies. American Society for Nutrition, Boston, MA, July 2023 and Canadian Nutrition Society, Quebec City, QC, May 2023. (Poster)
- **Auclair, O.** & Burgos, S.A. The impact of substituting animal with plant protein foods on diet-related greenhouse gas emissions, nutrition, and health outcomes: A systematic review of modeling studies. American Society for Nutrition, Boston, MA, July 2023. (Poster)
- **Auclair, O.** & Burgos, S.A. The impact of substituting animal with plant protein foods on diet-related greenhouse gas emissions, nutrition, and health outcomes: A systematic review of modeling studies. Canadian Nutrition Society, Quebec City, QC, May 2023. (Poster)
- **Auclair, O.** & Burgos, S.A. Modeling the replacement of animal with plant protein foods in self-selected Canadian diets: Impact on greenhouse gas emissions and intakes of nutrients of concern and to limit. Canadian Nutrition Society, Gatineau, QC, May 2022. (Poster)

- **Auclair, O.** & Burgos, S.A. Carbon footprint of Canadian self-selected diets: comparing intake of food groups, nutrients, and diet quality among low- and high-GHGE diets. Centre Interuniversitaire de Recherche en Économie Quantitative Interdisciplinary PhD Student Symposium on Climate Change, online, June 2021. Available online: https://youtu.be/WtyVdCi_bVU?t=14654. (Oral presentation)
- **Auclair, O.** & Burgos, S.A. Carbon Footprint of Canadian Self-Selected Diets: Trade-Offs With Nutrient Intakes and Diet Quality. American Society for Nutrition, online, June 2021. Finalist for the Emerging Leaders in Nutrition Science Abstract Recognition Award Program in the topical area Climate/Environment, Agriculture and Food Supply. (Selected for oral presentation)
- **Auclair, O.** & Burgos, S.A. Carbon footprint of Canadian self-selected diets: Comparing intake of food groups, nutrients, and diet quality among low- and high-GHGE diets. Quebec Inter-University Centre for Social Statistics Emerging Excellence Conference, online, April 2021. Finalist for highest quality presentation. (Oral presentation)
- **Auclair, O.** & Burgos, S.A. Carbon footprint of Canadian self-selected diets: Comparing intake of food groups, nutrients, and diet quality among low- and high-GHGE diets. Canadian Nutrition Society, online, May 2021. (Poster)
- **Auclair, O.** & Burgos, S.A. Protein consumption in Canadian habitual diets: Usual intake, inadequacy, and the contribution of animal- and plant-based foods to nutrient intakes. Metabolic Disorders and Complications (MeDiC) Research Day, online, November 2020. (Poster)

Contribution of Authors

For manuscript 1, I was the primary author, designed and conducted the research, analyzed the data, performed the statistical analyses, and wrote the paper. Sergio A. Burgos designed the research, wrote the paper, and had primary responsibility for the final content.

For manuscript 2, I was the primary author and was responsible for data curation, formal analysis, investigation, visualization, and writing the original draft. Sergio A. Burgos was responsible for conceptualization, methodology, project administration, supervision, validation, and review and editing of the manuscript.

For manuscript 3, I was the primary author and was responsible for designing and conducting the research, analyzing the data, and writing the paper. Yi Jin was responsible for conducting the research and editing the paper. Sergio A. Burgos was responsible for designing the research, editing the paper, and had primary responsibility for the final content.

For manuscript 4, I was the primary author and was responsible for conceptualization, data curation, formal analysis, investigation, methodology, software, visualization, writing the original draft, and reviewing and editing the final manuscript. Patricia Eustachio Colombo and James Milner were responsible for methodology, resources, software, validation, and reviewing and editing the final manuscript. Sergio A. Burgos was responsible for conceptualization, methodology, project administration, supervision, validation, visualization, and reviewing and editing the final manuscript.

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List of abbreviations

AHEI	Alternative Healthy Eating Index
AI	Adequate Intake
AMDR	Acceptable Macronutrient Distribution Range
BMI	Body mass index
BNS	Bureau of Nutritional Sciences
CCHS	Canadian Community Health Survey
CFG	Canada’s Food Guide
CI	Confidence interval
CNF	Canadian Nutrient File
CO_2eq	Carbon dioxide equivalents
dataFIELD	Database of Food Impacts on the Environment for Linking to Diets
DIAAS	Digestible Indispensable Amino Acid Score
DRI	Dietary Reference Intake
EAR	Estimated Average Requirement
FBDG	Food-based dietary guidelines
FCID	Food Commodity Intake Database
FNDDS	Food and Nutrient Database for Dietary Studies
GHGE	Greenhouse gas emissions

GWP	Global Warming Potential
HEFI	Healthy Eating Food Index
IBW	Ideal body weight
LAFA	Loss-Adjusted Food Availability
LCA	Life Cycle Assessment
NCI	National Cancer Institute
NHANES	National Health and Nutrition Examination Survey
NSS	Nutrition Survey System
PDCAAS	Protein Digestibility Corrected Amino Acid Score
PER	Protein Efficiency Ratio
RDA	Recommended Daily Allowance
SE	Standard error
WWEIA	What We Eat in America

Chapter 1: Introduction

1.1 Background and rationale

Food systems contribute majorly to human health and climate change. Climate modeling studies have shown that GHGE from the food system alone are enough to surpass a global temperature rise of 1.5°C above pre-industrial levels and approach 2°C by the end of the century, even if all non-food fossil fuel emissions were suddenly halted (1). However, about half of these future projected emissions can be mitigated by a combination of improvements to food production practices, reductions to food loss and waste, and shifts to dietary patterns (1, 2). Diets rich in animal-source foods and poor in plant-based foods, particularly in high-income countries, are part of what is driving emissions (2), as well as the increasing incidence of non-communicable diseases (3). Therefore, leveraging the actions of food system actors across the entire supply chain, including consumers, is crucial for meeting global scientific targets for climate change.

Over the past decade, growing recognition of the significant impact of food production on the environment has prompted research on the relationship between consumer dietary patterns and environmental sustainability. Life cycle assessments (LCA) are an international standard by which to quantify the environmental impacts of a food commodity throughout its life span, from cradle to grave (4). Meta-analyses of global LCA have shown that the environmental impacts of animal-based foods generally exceed that of plants (5, 6). However, standalone LCA do not provide context for the role of animal and plant-based foods in population-wide self-selected diets based on actual dietary intake. To quantify the environmental impacts of "self-selected diets", studies have linked LCA data to foods and beverages reported in nationally representative surveys or cohort studies. Using this approach, studies have consistently found that diets containing greater quantities of plant-based foods have lower environmental impacts than those containing larger amounts of animal-source foods (7-9). Importantly, these methods have also been used to characterize synergies and trade-offs of observed diets among a combination of diet sustainability dimensions (e.g., nutrition, health), however, high heterogeneity among metrics used renders assessing their compatibility difficult. Studies have also used self-selected dietary data as a baseline with which to perform diet modeling to gauge the necessary changes for transitioning to diets that fulfill nutrient requirements, adhere to dietary guidelines, or minimize cost while remaining culturally acceptable to consumers. Yet, many such studies generate theoretical diets that would be challenging for individuals to adhere to in real-life settings. Whereas most of these analyses have been conducted in Europe and the US, differences in dietary intake among regions requires country-specific assessments of potential synergies and trade-offs among dimensions of diet sustainability. No studies have explored the role of animal and plant protein foods in the context of Canadian self-selected diets on a combination of diet sustainability dimensions.

With the primary goal of promoting nutritional adequacy and reducing the risk of chronic diseases, many countries emphasize consumption of plant-based foods in their FBDG (10), while several have also started to incorporate sustainability messaging (11). Indeed, the most recent iteration of CFG, released in 2019, moved away from the traditional concept of food groups and towards a more holistic approach to healthy eating that emphasizes the consumption of fruits and vegetables, whole grains, and protein foods (12). The guide specifically recommends trying to consume protein from plants every day, since compared to other protein foods, plant protein foods contain more fibre and less saturated fat which can promote heart health (13). Their protein foods group is the only part of the visual plate that contains both animal and plant protein foods, examples of which include lean meats and poultry, fish and shellfish, lower fat dairy products, and eggs, as well as nuts and seeds, beans, peas, and lentils, and fortified soy beverages, tofu, soybeans, and other soy products. However, animal and plant protein foods differ in their provision of nutrients, associations with health, and environmental impacts. Therefore, adopting CFG's protein food recommendations at a population-level could pose implications for human and planetary health. Yet, no studies quantified the impact of CFG's recommendations for protein foods on a combination of diet sustainability dimensions in Canadian self-selected diets.

1.2 Statement of purpose

The overarching aim of this dissertation was to characterize the role of animal and plant protein foods in Canadian self-selected diets on diet-related GHGE, nutrient inadequacy, and health outcomes.

1.3 Objectives

Manuscript 1 (Chapter 3):

The primary objective of this study was to assess usual protein intake and inadequacy among Canadian adults. The secondary objective was to determine the contribution of animal- and plant-based foods to intakes of protein, nutrients of public health concern, and nutrients to limit.

Manuscript 2 (Chapter 4):

The primary objective of this study was to estimate the carbon footprint of self-selected Canadian diets. The secondary objective was to compare intakes of food groups, nutrients, and diet quality between respondents with low- and high-GHGE diets.

Manuscript 3 (Chapter 5):

The objective of this study was to systematically review nutrition surveys and cohorts that modeled partial replacements of animal with plant protein foods in self-selected diets on diet-related GHGE in combination with nutrition or health outcomes.

Manuscript 4 (Chapter 6):

The objective of this study was to assess the implications of partial substitutions of red and processed meat or dairy with plant protein foods consistent with CFG recommendations in Canadian self-selected diets on nutrient inadequacy, health outcomes, and diet-related GHGE.

Chapter 2: Literature review

2.1 Environmental impact of global food systems

Global food systems are one of the largest drivers of environmental change (14). Food systems refer to the entire range of actors and activities involved in the production, processing, distribution, consumption, and disposal of food products (15). Food systems account for one-third of global anthropogenic GHGE, the majority of which stem from agriculture and land-use change activities at the farm stage (71%) and the rest from other points along the supply chain (e.g., retail, transport, consumption) (16). Food systems also account for 32% of terrestrial acidification, 78% of eutrophication, 43% of ice- and desert-free land use, 90 to 95% of scarcity-weighted water use, and contribute majorly to loss of biodiversity and ecological resilience (5).

2.1.1 Greenhouse gas emissions from the food system

The primary greenhouse gases from the food sector are carbon dioxide, methane, and nitrous oxide. Absolute quantities of GHGE are typically expressed as carbon dioxide equivalents (CO_2eq) to account for differences in their global warming potential (GWP). GWP refers to the amount of heat trapped by one ton of gas relative to that of carbon dioxide over a set period, typically 20 or 100 y (17). For methane and nitrous oxide, these are 27.9 and 273 over a 100 y horizon (18). GWP also accounts for the lifetime of greenhouse gases (i.e., how long they persist in the atmosphere). For instance, methane and nitrous oxide have a half-life of 11.9 and 109 y (18), respectively, whereas the lifetime for carbon dioxide cannot be accurately defined due to various rates of removal from the atmosphere. One of the main limitations of using CO_2eq is that despite providing a measure of the amount of heat trapped, it does not necessarily account for the change in temperature that may result (19, 20). This is problematic for a gas such as methane, which can cause short-term spikes in temperature relative to other greenhouse gases.

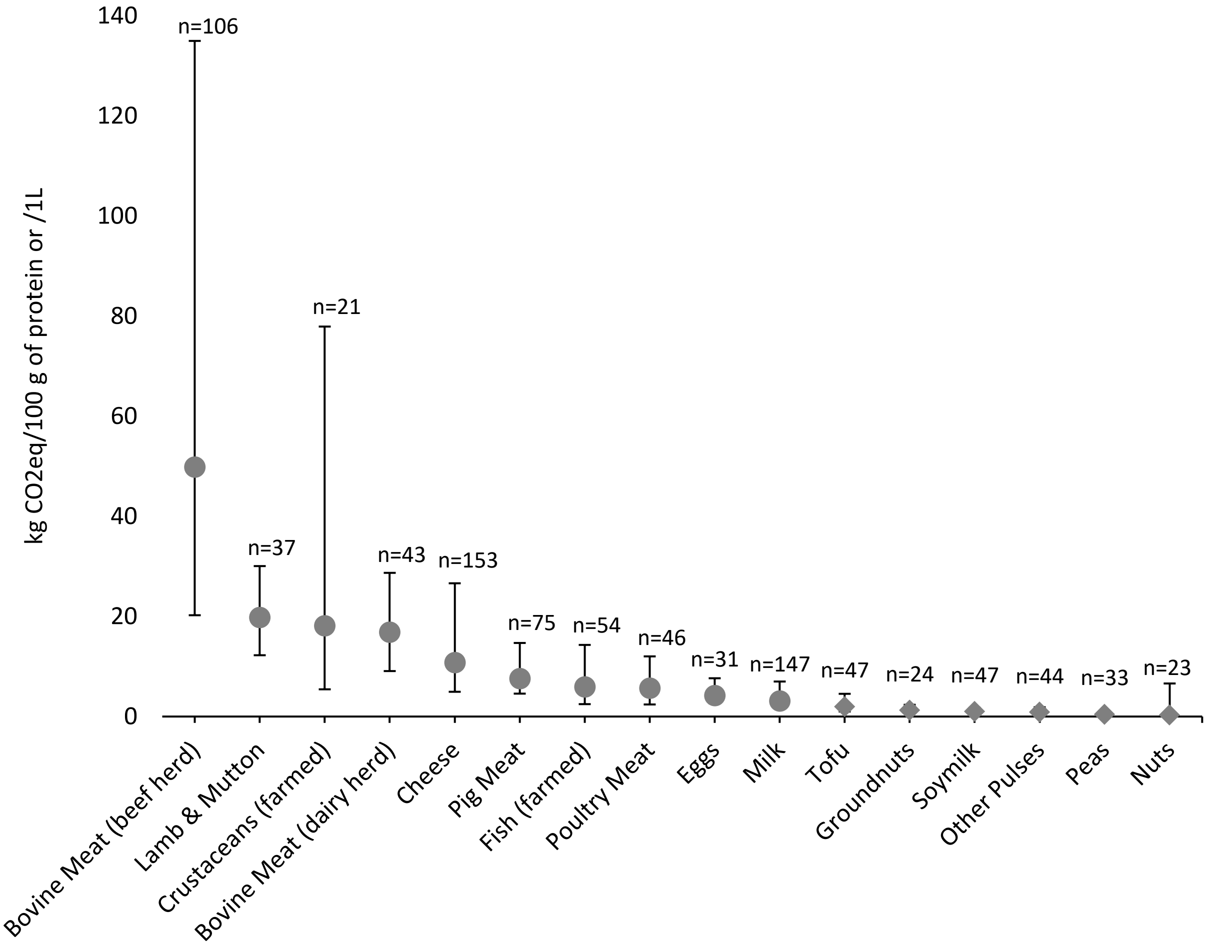
2.1.2 Life cycle assessment of food commodities

LCA studies are an international standard by which to estimate the environmental impact of a product (e.g., milk), technology (e.g., pasteurization), or function system (e.g., dairy farming) (4). Ideally, LCA studies will cover all life cycle stages, from cradle-to-grave, however most only account for impacts up to the farm gate. Even so, most impacts have been found to occur on the farm (5, 16). Environmental impacts are expressed on the basis of a functional unit, typically mass or volume; although potentially suitable for use in non-food LCA studies, these do not accurately reflect the main function of the food which is to provide nutrients (21). Importantly, results of food-based LCA studies can vary widely depending on the chosen functional unit. One study compared the environmental impacts of cow's milk, soy beverage, and almond beverage using a volumetric functional unit and found that cow's milk had the highest impact for eutrophication, whereas soy beverage had the highest impacts for GWP and acidification, and almond beverage had the highest impact for water use from irrigation (22). However, when compared using a protein-based functional unit, almond beverage had the highest impacts for all categories analyzed. Thus, the scope of LCA studies and choice of functional unit have implications on the interpretation of a food's environmental impact.

2.1.3 Environmental impact of animal- and plant-based foods

Animal- and plant-based foods have important implications for environmental sustainability. Using global LCA estimates for 40 foods representing 90% of global protein and calorie consumption, one meta-analysis showed that per 100 g of protein, the environmental impacts of animal protein foods generally exceed that of plants (**Figure 2.1**) (5). In fact, the lowest-impact animal products were found to exceed average impacts for most plant-based foods for GHGE, eutrophication, acidification, and in most cases, land-use. Importantly, however, the authors noted high variability both within and among similar protein-rich products. For example, 90th percentile GHGE for beef were found to be 12 times higher than that of 10th percentile GHGE for dairy beef, whereas 10th percentile GHGE for dairy beef were 36 times that of peas. However, one of the main drawbacks of food-based LCA studies is that since individuals do not consume single foods, their interpretation in the context of population-wide diets will vary according to their combinations and proportions consumed.

Figure 2.1 Greenhouse gas emissions of animal and plant protein foods from global life cycle assessment studies



Estimates are mean kg CO_2eq/100 g of protein or per 1L for milk and soy beverage from Poore & Nemecek (5). Error bars are 5th and 95th percentiles. n = number of observations (i.e., studies). Animal protein foods are depicted by circles and plant protein foods by diamonds.

2.2 Animal and plant protein foods

2.2.1 Protein composition and quality of animal- and plant-based sources

Dietary protein is a constituent of all foods but varies in terms of quantity and quality. Most of these differences stem from the origin of the food as either animal- or plant-based. Animal products generally contain more protein per unit than plant sources (**Table 2.1**). Animal sources with the highest protein contents, notably red and processed meat, poultry, fish and shellfish, cheese, and eggs, contain between 18 and 27 g of protein per 100 g of food. Plant-based sources with the highest protein contents include seeds (22 g protein/100 g food), nuts and nut butters (17 g protein/100 g food), cereal grains and flours (14 g protein/100 g food), and legumes (12 g protein/100 g food). Despite often being recommended as an alternative to cow's milk, the protein content of fortified soy beverage is one-third that of cow's milk (2.6 vs. 8.6 g protein/100 g food). Nevertheless, fortified soy beverage contains 8.7-fold the amount of protein than other plant-based beverages made from almond, cashew, coconut, or rice (2.6 vs. 0.3 g protein/100 g food).

Table 2.1 Mean protein content of selected animal- and plant-based foods in the Canadian Nutrient File

Food	n	Mean g protein/100 g food (95% CI)
Beef and veal	154	26.6 (25.7, 27.6)
Lamb	41	24.9 (23.4, 26.3)
Pork	123	24.7 (23.8, 25.6)
Poultry	219	24.4 (23.8, 25.1)
Seeds	17	22.4 (19.1, 25.7)
Fish	200	22.3 (21.0, 23.5)
Cheese	83	20.5 (19.0, 22.1)
Luncheon and other meats	312	20.5 (19.5, 21.4)
Eggs	17	20.0 (10.4, 29.6)
Shellfish	46	17.7 (15.4, 20.1)
Nuts and nut butters	70	16.6 (14.8, 18.4)
Cereal grains and flours	82	14.2 (11.3, 17.0)
Legumes	135	12.4 (10.6, 14.1)
Breads	174	9.4 (9.0, 9.8)
Milk	34	8.6 (5.0, 12.3)
Breakfast cereals	58	8.6 (7.2, 10.0)
Pasta	44	8.5 (7.0, 10.1)
Rice	21	5.2 (3.7, 6.8)
Yoghurt	54	4.6 (4.0, 5.1)
Frozen dairy	31	4.1 (3.8, 4.3)
Potatoes	12	3.8 (2.0, 5.6)
Cream	14	3.0 (2.2, 3.9)
Vegetables	406	2.8 (2.4, 3.2)
Fortified soy beverage	3	2.6 (1.8, 3.3)
Butter	6	1.6 (0.1, 3.0)
Oils and fats	94	1.3 (0.4, 2.1)
Fruit	245	0.9 (0.8, 1.0)
Plant-based beverages other than fortified soy (i.e., almond, cashew, coconut, rice)	6	0.3 (0.1, 0.5)

Data are from the 2015 Canadian Community Health Survey – Nutrition Public Use Microdata Files. n = number of individual food items in each food subgroup. Abbreviations: CI, confidence interval.

All protein in the human body is made up of 20 amino acids which are categorized as indispensable (i.e., essential), dispensable (i.e., non-essential), or conditionally essential (23). Indispensable amino acids are those that cannot be synthesized by the body and thus must be obtained from the diet. These are: histidine, isoleucine, leucine, lysine, methionine, phenylalanine, threonine, tryptophan, and valine. Protein derived from animal sources is considered high-quality because it contains all nine essential amino acids and is more digestible and bioavailable compared to protein from plant sources (24). Protein from plant sources is deemed low-quality since it typically lacks one or more essential amino acid in proportions required by the body – most often lysine in cereals, tryptophan in beans and peas, and sulfur-containing amino acids in legumes – and contains antinutrients that inhibit its digestibility (25, 26). One exception is soybeans and other soy products, which contain all indispensable amino acids and are deemed high-quality compared to other plant-based protein sources. The protein content of soybeans and other soy products in the Canadian Nutrient File (CNF) are in **Table 2.2**. While cooking appears to reduce the overall protein content of soybeans (soybeans, dry, raw: 36.5 g protein/100 g vs. soybeans, dry, boiled: 16.6 g protein/100 g), there is also evidence that certain forms of heat treatment, including boiling, improves their protein quality and digestibility by reducing the presence of antinutritional factors (27).

Table 2.2 Protein content of soybeans and other selected soy products in the Canadian Nutrient File

NSS food code	Food description	g protein/100 g food
3328	Soy protein isolate (prepared with sodium)	80.7
3400	Soybeans, dry, raw	36.5
4986	Soybean, fermented products, Tempeh (tempe), cooked	18.2
3401	Soybeans, dry, boiled	16.6
5968	Veggie / soy burger patty, unprepared	15.7
5572	Soybean, curd cheese	12.5
3404	Tofu, regular, firm or extra firm, raw (prepared with calcium sulphate and magnesium chloride)	8.2

Data are from the 2015 Canadian Community Health Survey – Nutrition Public Use Microdata Files. Abbreviations: NSS, Nutrition Survey System.

Several methods exist for determining protein quality, the earliest method being the Protein Efficiency Ratio (PER). The PER is determined by dividing the weight gain of weanling rats by the amount of a test protein consumed over 4 weeks and then comparing this measure to that of a control group fed the same amount of casein. In Canada, the PER is used to determine the protein rating, which is used as the basis for protein content claims. The protein rating is calculated by multiplying the PER by the amount of protein per Reasonable Daily Intake or Reference Amount, which are similar to the concept of a serving (28). A food is labeled a 'source of protein' if it has a protein rating of at least 20 and an 'excellent source' if it has a rating of at least 40 (29). For example, whole egg would be considered an excellent source since it has a protein rating of 40 (28). Comparatively, white bread has a protein rating of 13 and thus would not be considered a source of protein.

The Protein Digestibility Corrected Amino Acid Score (PDCAAS) is another more widely used measure of protein quality. The PDCAAS is determined by estimating the concentration of the first limiting amino acid of a test protein as a percentage of that of a reference amino acid pattern and then correcting for true fecal digestibility (30). Scores are truncated at 100% since they are deemed to provide no additional benefits to humans. More recently, however, the Digestible Indispensable Amino Acid Score (DIAAS) was developed as an improved method for determining protein quality. The DIAAS considers an updated amino acid reference pattern to that of the PDCAAS and ileal amino acid digestibility instead of true fecal nitrogen digestibility (26). The DIAAS is advantageous over the PDCAAS in that ileal digestibility is a more accurate measure of protein digestibility since it avoids potential overestimations from bacterial nitrogen captured in measures of human fecal nitrogen. Moreover, the DIAAS is more specific in that it considers individual amino acids as opposed to single proteins. Nevertheless, the DIAAS has yet to be widely adopted. PER, PDCAAS, and DIAAS values for various animal and plant-based foods are in **Table 2.3**.

Table 2.3 PER, PDCAAS, and DIAAS values for animal and plant-based foods

Foods	Adjusted PER	PDCAAS	DIAAS
Milk	2.5	1	114
Eggs	3.1	1	113
Chicken	2.7	1	108
Oatmeal	1.8	0.82	84
White bread	1	0.28	29
White rice	1.5	0.56	57
Tofu	2.3	0.56	52
Red kidney beans	1.55	0.55	51
Navy beans	1.51	0.67	65
Whole green lentils	1.3	0.63	58
Split red lentils	0.98	0.54	50
Split yellow peas	1.42	0.64	73
Split green peas	0.86	0.5	46
Black beans	1.61	0.53	49
Chickpeas	2.32	0.52	85
Pinto beans	1.64	0.59	60

Data are from Nosworthy et al. (26). Abbreviations: DIAAS, Digestible Indispensable Amino Acid Score; PDCAAS, Protein Digestibility Corrected Amino Acid Score; PER, Protein Efficiency Ratio.

2.2.2 Protein requirements

The Dietary Reference Intakes (DRI) for protein are based on the amount of protein that is required for growth and maintenance (31). The Recommended Daily Allowance (RDA) is the average daily intake that is sufficient to meet the needs of 97.5% of healthy individuals in a population. The RDA for protein is 0.8 g/kg of body weight/d for adults ≥19 y of age. The Estimated Average Requirement (EAR), which is defined as the median daily intake that is sufficient to meet the needs of half of healthy individuals in a population, is 0.66 g/kg of body weight/d for adults. The RDA is used as a target for individual intakes, whereas the EAR is used as a target for group intakes and to assess the prevalence of inadequacy in a population. The Acceptable Macronutrient Distribution Range (AMDR), which is the percentage of total energy from a macronutrient that is associated with a reduced risk of chronic disease while providing adequate intakes, is 10-35%. In the US and Canada, there are no separate requirements for vegetarians since consuming a variety of plant protein foods is said to provide complimentary amino acids of the same quality as those from animal sources (32). Requirements in countries such as the Netherlands, however, are 20% and 30% higher for vegetarians and vegans, respectively, to account for the lower quality protein obtained from plant sources (33). The DRI for protein are in **Table 2.4**.

Current protein requirements were established based on a meta-analysis of nitrogen balance studies (34). The nitrogen balance technique, which was long considered the 'gold standard' for determining protein requirements, measures net nitrogen intake from dietary sources (i.e., protein) and excretion to determine the minimum quantity of protein needed to achieve nitrogen balance. Yet, this technique has been scrutinized in part for its defining minimal but not optimal protein needs. Findings based on the Indicator Amino Acid Oxidation method, which determines the minimum requirement for deficient or limiting amino acids based on the rate of oxidation of other amino acids, have shown that protein requirements may be 40 to 50% higher than the current RDA (35). Moreover, recent research suggests benefits of higher protein consumption in the range of 1.2 to 1.6 g/kg of body weight/d for older adults (36) who are at risk of sarcopenia, a disease characterized by the progressive loss of muscle mass and strength (37).

Table 2.4 Dietary Reference Intakes for total protein

	Total protein			
	g/kg/d		g/d	
	EAR	**RDA/AI**	**RDA/AI**	**UL**
Infants				
0-6 months	ND	1.52*	9.1*	ND
7-12 months	1.0	1.2	11.0	ND
Children				
1-3 y	0.87	1.05	13	ND
4-8 y	0.76	0.95	19	ND
Males				
9-13 y	0.76	0.95	34	ND
14-18 y	0.73	0.85	52	ND
19-30 y	0.66	0.80	56	ND
31-50 y	0.66	0.80	56	ND
51-70 y	0.66	0.80	56	ND
≥71 y	0.66	0.80	56	ND
Females				
9-13 y	0.76	0.95	34	ND
14-18 y	0.71	0.85	46	ND
19-30 y	0.66	0.80	46	ND
31-50 y	0.66	0.80	46	ND
51-70 y	0.66	0.80	46	ND
≥71 y	0.66	0.80	46	ND
Pregnancy				
≤18 y	0.88	1.1	71	ND
19-30 y	0.88	1.1	71	ND
31-50 y	0.88	1.1	71	ND
Lactation				
≤18 y	1.05	1.3	71	ND
19-30 y	1.05	1.3	71	ND
31-50 y	1.05	1.3	71	ND

Data are from Health Canada (38). * signifies AI. Abbreviations: AI, Adequate Intake; EAR, Estimated Average Requirements; ND, not determinable; RDA, Recommended Dietary Allowance; UL, Upper Limit.

2.2.3 Protein foods in food-based dietary guidelines

A recent review found that three-quarters of national FBDG contained messaging geared towards the consumption of 'protein foods' (39). Half of FBDG with protein food messaging referred to both animal and plant sources, which typically included meat (53% of FBDG), poultry (29%), fish (58%), eggs (31%), legumes (41%), and nuts and seeds (8%). Some FBDG also included dairy as a protein food, but most referred to it as its own distinct group (64% of countries, mainly from North America and Europe). Twenty-three percent of FBDG, mostly from Europe, recommended limiting meat consumption, and one-third of countries with protein food messaging presented plant protein foods as substitutes for animal sources (e.g., "When there is no meat, fish or eggs in a given day, you can replace them with pulses, peanuts, soybeans, soya, cheese or peas" (Benin)). Five countries, all from Latin America and the Caribbean, regarded meat as non-substitutable. Non-dairy alternatives, including soy beverage and other calcium-rich foods, were included in 11% of FBDG with dairy messaging.

The most recent iteration of dietary guidance in Canada is depicted to consumers by the food guide snapshot, a plate containing half fruits and vegetables, one-quarter whole grains, and one-quarter protein foods (40). The guide specifically recommends choosing protein foods that come from plants every day, stating that plant protein foods contain more fibre and less saturated fat than other types which can promote heart health (13). In addition to lean meats and poultry, fish and shellfish, lower fat dairy products, and eggs, examples of plant protein foods in the guide include nuts and seeds, beans, peas, and lentils, and fortified soy beverages, tofu, soybeans, and other soy products. Unlike previous iterations, however, the current version does not contain age- or sex-specific recommendations.

2.2.4 Protein intake among adults in high-income countries

Adults in high-income countries generally exceed minimum protein recommendations. In the US, the percentage of adults ≥19 y of age from NHANES 2011-14 that were below the EAR for protein was between 0.6% and 5.9% for males and between 4.1% and 6.9% for females (41). Protein inadequacy was highest for females and older adults. Just over 60% of total protein intakes among US adults derived from animal sources, particularly beef, poultry, and dairy, but only 30% came from plant sources (42). Data from the 2015 CCHS – Nutrition, Canada's most recent and comprehensive source of nutrition and diet information in the population, showed that adults ≥19 y of age were within the AMDR for protein, making up between 16% and 18% of their total energy intake (43). Moreover, the percentage of Canadians that consumed protein foods on any given day was 94% for dairy products, 63% for meat, 56% for eggs, 44% for poultry, 34% for nuts and seeds, 17% for fish and shellfish, and 14% for legumes (44). However, data on protein inadequacy and the contribution of animal- and plant-based sources to total protein intakes in the Canadian population was not available prior to work undertaken in this dissertation.

2.2.5 Contribution of animal and plant protein foods to nutrient intakes and adequacy

In addition to protein, animal and plant protein foods provide an array of essential nutrients. Data from NHANES 2007-10 revealed that animal protein foods, and particularly lean beef and pork, led to greater intakes of protein, zinc, vitamin B12, phosphorus, and iron among adults ≥19 y of age compared to plant protein foods, yet the later contributed more fibre, vitamin E, and magnesium (45). In a nationally representative sample of adults from the 2015 CCHS – Nutrition, dairy products, namely milk and cheese, were found to contribute more than half of total calcium intakes, 39% of vitamin D, 28% of vitamin B12, 26% of vitamin A, 25% of phosphorus, 24% of riboflavin, and between 10 and 16% of protein, zinc, potassium, and magnesium (46). However, dairy products also contributed substantially to Canadians' total intakes of saturated fat (29%), and to a lesser extent sodium (12%). Despite generally being consumed in much smaller quantities than animal protein foods, studies have also shown that individuals that consumed tree nuts or beans had greater intakes of fibre, calcium, potassium, magnesium, and iron compared to non-consumers (47, 48).

In a sample of adults from the French Individual and National Consumption Survey (INCA2) (n = 1,912), Camilleri et al. (49) assessed the relationship between intake of animal and plant protein foods and the Probability of Adequate Nutrient Intake (PANDiet) index, a validated score based on the probability of adequacy for 24 favorable and unfavorable nutrients. For both sexes, plant protein foods were positively associated with the PANDiet score. Positive associations with PANDiet were also observed for fish, milk, and yoghurt, irrespective of sex. On the contrary, consumption of red meat and poultry was inversely associated with the PANDiet score for males but not females, whereas processed meat, offal, eggs, cheese, and other dairy products were inversely associated for both sexes. Therefore, while plant protein foods were found to be favorably associated with nutrient adequacy, associations with animal protein foods were not only sex-dependent, but differed based on the type of animal protein in question. However, nutrient profiling indices such as PANDiet have limited practical applications since they combine information into a single score as a proxy for overall diet quality. Hence, scores should be complemented with data for nutrient inadequacy, for example, which are more relevant to public health.

2.2.6 Association of animal and plant protein foods with nutrition-related chronic diseases

Animal and plant protein foods also have differing associations with non-communicable diseases. The Global Burden of Disease (GBD) is an ongoing global observational epidemiological study that has assessed 396 diseases and injuries and 87 risk factors across 204 countries since 1990 (50). Using the World Cancer Research Fund evidence grading criteria, they identified dietary factors for which there was convincing or probable evidence supporting a causal relationship with chronic disease from dose-response meta-analyses of prospective observational studies (51). The GBD 2017 identified red meat and processed meat as having convincing or probable evidence of a positive association with type 2 diabetes, colorectal cancer, and ischemic heart disease (processed meat only). Contrarily, milk was found to be inversely associated with colorectal cancer and legumes and nuts and seeds with ischemic heart disease and type 2 diabetes (nuts and seeds only). Despite providing updated relative risks (RR), the latest GBD from 2019 was scrutinized due to concerns about their systematic analysis of risk factors, particularly for unprocessed red meat whose estimates of death were 36-fold higher than estimates from 2017 (52). Moreover, their conclusion of sufficient evidence of an association between red meat intake and ischemic heart disease based on an update of their own systematic review was not in line with findings from other studies (53). RR for morbidity and mortality from non-communicable diseases per serving of dietary component for animal and plant protein foods from the GBD 2017 and 2019 are in **Table 2.5**.

Table 2.5 Relative risks for animal and plant protein foods with non-communicable disease morbidity and mortality from the Global Burden of Disease 2017 and 2019

	GBD 2017		GBD 2019	
Risk – Outcome	**Units**	**RR**	**Units**	**RR**
Diet low in legumes				
Ischemic heart disease	50 g/d	1.22	50 g/d	1.14
Diet low in nuts and seeds				
Ischemic heart disease	4.05 g/d	1.08	28 g/d	1.23
Type 2 diabetes		1.03		1.04
Diet low in milk				
Colorectal cancer	226.8 g/d	1.11	240 g/d	1.12
Diet high in red meat				
Ischemic heart disease		–		1.35
Type 2 diabetes	100 g/d	1.19	200 g/d	1.27
Colorectal cancer		1.67		1.27
Diet high in processed meat				
Ischemic heart disease		1.53		1.14
Type 2 diabetes	50 g/d	1.54	100 g/d	1.22
Colorectal cancer		1.18		1.1

RR are from the GBD 2017 (51) and GBD 2019 (3). RR were averaged for males and females ≥25 y of age. RR from the GBD 2019 for legumes, nuts and seeds, and milk were inverted to reflect risks associated with a decrease in consumption of these foods.

Meta-analyses have shown inverse associations between diets containing greater quantities of plant protein foods and all-cause and cause-specific mortality from cardiovascular disease, but not cancer, compared to diets with less (54). Moreover, substituting just 5% of energy from animal with plant protein foods was associated with a lower risk of mortality from all-causes (Hazard Ratio: 0.86; 95% confidence interval (CI): 0.81-0.91) and cardiovascular disease (Hazard Ratio: 0.78; 95% CI: 0.7-0.87) (55). However, associations with animal protein foods are more varied and depend largely on the source of animal protein in question. For example, Patterson et al. (56) modeled graded replacements of 25%, 50%, and 100% of red and processed meat with a combination of vegetables and legumes in self-selected Swedish diets and found step-wise increases of nearly 300,000 to just under 1 million years of life lost would be avoided over the course of 20 years. Yet, replacements of milk with soy beverage caused an additional 700 to 3,000 years of life to be lost (although the impacts of soy beverage were not accounted for since RR were not available). Despite consistent associations of plant protein foods with health outcomes, there is a need for more nuanced research into substitutions of animal with plant protein foods in combination with diet-related GHGE and other facets of sustainability to assess the population-level impacts of FBDG promoting greater consumption of plant-based foods.

2.3 Sustainable diet studies based on self-selected diets

Over the past decade, recognition of the significant impact of food production on the environment has prompted research into the relationships between diets and environmental sustainability. To quantify the environmental footprint of population-wide diets, LCA estimates for food commodities are linked to foods and beverages reported by individuals from national nutrition surveys or cohort studies. Nutrition surveys and cohorts use dietary assessment tools, most often 24-h recalls or food frequency questionnaires, to collect detailed information about the foods and beverages consumed by individuals in a population. These studies also provide nutritional information by linking reported items to their nutrient profiles from food composition databases. Unlike food availability or expenditure data that serve as proxies for food intake, self-selected diets reflect the actual dietary intake of individuals. Most studies assessing diet sustainability have been conducted in high-income European countries and more recently in the United States.

2.3.1 Low- versus high-greenhouse gas emission diets

There have been several approaches to characterizing sustainable diets at the population level. One such approach has been to divide the study sample into quantiles based on individuals' diet-related carbon footprint to compare low- and high-GHGE diets most commonly in terms of foods consumed, nutrient intakes, and measures of diet quality (7, 8, 57-59). Findings from these studies have estimated the diet-related carbon footprint of individuals as averaging 4.6 kg CO_2eq/person/d, with males tending towards a higher diet-related GHGE compared to females (20 to 34%). Furthermore, studies have consistently shown that high-GHGE diets are characterized by a higher consumption of animal protein foods, particularly meat and dairy, compared to low-GHGE diets. High-GHGE diets are also found to have higher total energy intakes than low-GHGE diets. In terms of nutrient assessments, high-GHGE diets generally have higher energy-adjusted intakes of total and saturated fats, vitamin D, calcium, vitamin A, and protein from animal sources. Conversely, low-GHGE diets tend to have higher intakes of fibre and carbohydrates, and in some instances, added sugars. Differences in iron intakes between low- and high-GHGE diets are typically small. While useful in getting a general sense of nutrients that are consumed in lesser or greater quantities among low- and high-GHGE diet groups, absolute intakes are not necessarily informative of whether they are consumed in adequate amounts. In other words, lower protein intakes in the low- compared to high-GHGE diet group, for example, is not a direct indication that low-GHGE diet respondents are failing to meet requirements.

Beyond nutrient assessments, studies will also typically explore comparisons between low- and high-GHGE diets with respect to diet quality. For example, Rose et al. (7) used the Healthy Eating Index-2010 to compare the overall healthfulness of low- and high-GHGE diets. The Healthy Eating Index-2010 consists of 12 components: 9 are components that should be encouraged (i.e., whole fruits, total fruits, greens and beans, total vegetables, whole grains, dairy, total protein foods, seafood and plant proteins, and fatty acids) and 3 are components that should be limited (e.g., refined grains, sodium, and empty calories). Maximum scores for each component sum up to a total possible diet score of 100 points, with higher scores indicative of a higher overall diet quality. Low-GHGE diets had higher overall Healthy Eating Index-2010 scores compared to high-GHGE diets (50.2 vs. 48.0) and received higher scores for the whole fruit, whole grains, seafood, plant protein, fatty acids, and sodium components. High-GHGE diets, on the other hand, scored higher for the total vegetables, dairy, total protein foods, and refined grains components. Again, while diet quality indices are helpful in providing an overall sense of the healthfulness of low- and high-GHGE diets, their abstract nature deem them somewhat unhelpful with regards to public health. Moreover, there are dozens of different diet quality indices being used in sustainable diet research that hinders comparisons among population samples.

2.3.2 Identifying 'more sustainable diets' through a combination of climate and nutrition metrics

Studies have also identified 'more sustainable' self-selected diets in population samples by combining climate and nutrition metrics (60-62). Using data from INCA2 (n = 1,918), Masset et al. (61) identified 'more sustainable' diets – having a diet-related carbon footprint lower than the median and a PANDiet score higher than the median – in 23% of males and 20% of females. The diet-related GHGE of 'more sustainable' diets were 19% and 17% lower for males and females consuming average diets, respectively, and a PANDiet score that was 10% higher. Intake of plant-based foods was higher for 'more sustainable' diets whereas intake of meat, particularly ruminant meat, was lower compared to average diets; no differences were detected for intake of dairy products. 'More sustainable' diets were also characterized by a lower total energy intake (8% for males and 10% for females) and a lower overall diet cost (10% for males and 7% for females) compared to average diets.

Similarly, Vieux et al. (9) identified 18% of self-selected diets from five European countries (Finland, France, Italy, Sweden, and the UK) as 'more sustainable', having a good compromise between nutritional quality and diet-related GHGE (21% lower compared to the average of all observed diets). Diets in the 'more sustainable' cluster were characterized by higher quantities of plant-based foods, particularly vegetables, fruit, and plant protein foods, but were still made up of various animal-based foods; while meat was consumed in lesser quantities compared to the rest of the sample, dairy was consumed in slightly higher quantities. Therefore, despite consumption of animal-based foods, and particularly ruminant meat, as having the strongest positive correlation with diet-related GHGE, findings from this study demonstrate that 'more sustainable' diets do not necessarily require complete exclusion of any single food group.

Interestingly, studies combining climate and nutrition metrics have found that higher-nutritional-quality diets are not necessarily more environmentally sustainable. Another French-based study identified respondents with high-nutritional-quality diets as those with the highest Mean Adequacy Ratio, an indicator of good nutritional quality, and the lowest Mean Excess Ratio and Energy Density, indicators of poor nutritional quality (60). Energy-adjusted high-nutritional-quality diets had diet-related GHGE that were 9% and 22% higher for males and females than low-nutritional-quality diets, respectively ($p<0.0001$). High-nutritional-quality diets were characterized by higher contents of plant-based foods, including fruits and vegetables, but intake of ruminant meat, pork, poultry, and eggs did not differ between nutritional-quality groups. However, the Mean Adequacy Ratio was positively associated with diet-related GHGE whereas the Mean Excess Ratio and Energy Density were negatively correlated. Consumption of animal products, particularly ruminant meat, but also fruits and vegetables when expressed on a caloric basis were associated with higher diet-related GHGE, whereas consumption of starches, sweets and salted snacks, and fats were associated with lower diet-related GHGE. Taken together, findings from studies combining climate and nutrition metrics contribute to the notion that there is more nuance to diet sustainability when considering whole diets as opposed to single foods, particularly when dichotomized as animal- or plant-based. Moreover, the best compromise between low-GHGE and nutritionally adequate diets appears to be somewhere between extremes of the lowest emitting diets and those with the highest nutritional quality.

2.4 Sustainable diet studies based on diet modeling

While self-selected diets provide insight into aspects of diet sustainability through assessment of their observed (i.e., unaltered) characteristics, they can also serve as the basis for which to model dietary interventions. Diet modeling can be useful for investigating changes to a combination of outcomes related to diet sustainability stemming from simple food substitutions, or for determining the necessary changes for achieving diets optimized to meet a specific set of constraints (e.g., nutritionally adequate, low-GHGE diets).

2.4.1 Dietary substitution scenarios

Using self-selected dietary data from national nutrition surveys or cohorts, studies have modeled dietary substitution scenarios of one food or food group for another on a combination of diet sustainability dimensions. Typically, high-GHGE foods, most often meat or beef, are replaced with plant-based foods or alternatives, and in some cases poultry products, with lower GHGE. Scenarios are often graded to showcase the range of effects stemming from partial to complete substitutions. In the US, graded replacements (25%, 50%, and 100%) of beef, pork, or poultry with plant protein foods in the self-selected diets of individuals from NHANES 2007-10 most receptive to making dietary changes given the inclusion of environmental messaging in the Dietary Guidelines for Americans reduced diet-related GHGE by 12.1 to 49.6%, increased diet quality based on the Healthy Eating Index by 2.2 to 8.7%, and decreased diet cost by 2.6 to 10.5% (63). Substituting beef with plant protein foods led to similar but slightly smaller changes, indicating that beef alone has the greatest impact on diet-related GHGE, diet quality, and diet cost than other meats. Comparatively, replacing beef with poultry attenuated changes to the outcomes assessed. These findings were mirrored in a subsequent study that modeled single-item substitutions in the self-selected diets of US adults that found that substituting beef with foods of similar culinary equivalence (i.e., poultry or pork) led to the greatest reductions in diet-related GHGE and water use of 48% and 30%, respectively, among individuals that consumed beef on their recall day (~20% of sample) than all other substitutions assessed (64). Other impactful substitutions were shrimp with cod and cow's milk with soy beverage for diet-related GHGE (−34.1% and −8.1%, respectively), and asparagus with peas for water footprint (−48.2%).

Substituting meat and dairy with plant-based alternatives in the self-selected diets of adults in the Dutch National Food Consumption Survey 2007-10 reduced diet-related GHGE and land use by 14% each when 30% was replaced and by 47% and 41%, respectively, when 100% was replaced (65). Replacing 30% of meat and dairy did not induce any major changes to the percentage of the population below the EAR for nutrients assessed, whereas substituting 100% led to higher habitual intakes of fibre (37%) and vitamin D (36%) and lower intakes of saturated fat (5%) and sodium (7%), but increased the percentage of the population (average for males and females) below the EAR for zinc (23%), thiamin (13%), vitamin B12 (26%), and vitamin A (44%) and decreased mean intakes for calcium (25%). The percentage of females below the EAR for iron decreased substantially by 31% for those 19 to 30 y of age and by 26% for those 31 to 50 y of age in the 'no meat and dairy scenario' due to replacement with a combination of iron-containing and iron-fortified plant-based alternatives. Therefore, the types of foods, but also the quantities in which they are substituted, are important determinants of changes to diet sustainability outcomes.

One of the main strengths of diet modeling is the simplicity of the designed scenarios, which typically substitute one food or food group for another rather than changing individuals' entire dietary patterns. However, one limitation is the categorization of distinct food groups. For example, grouping meat and dairy, or even a combination of meats, precludes the ability to parse changes to diet sustainability outcomes to specific foods. Moreover, while many studies provide a rationale for their choice of foods to substitute, typically high-GHGE animal-source foods with low-GHGE plant-based foods, many do not justify their reasoning for the types of foods included in the replacements. Therefore, there could be bias in the types of foods chosen and in turn, the conclusions that are derived from said scenarios.

2.4.2 Diet optimization

Another approach has been to use mathematical optimization techniques to model theoretical diets. The goal of diet optimization is to identify a combination of foods that fulfil a series of selected constraints while minimizing or maximizing an objective function. In sustainable diet research, optimization is often used to design diets with the lowest environmental impacts that meet nutrient requirements and stray as little as possible from observed diets. This technique allows for an objective assessment of the compatibility of diet sustainability dimensions, as well as any trade-offs among them. Using dietary data from French adults in INCA2, Perignon et al. (66) designed diets with step-wise reductions in diet-related GHGE that minimized the departure from observed diets and three nutritional scenarios of increasing stringency: i) no nutritional constraints, ii) macronutrients constrained to meet AMDR requirements, and iii) macronutrients and micronutrients (including fibre and fatty acids) constrained to meet RDA requirements. Regardless of the nutritional scenario, moderate reductions to diet-related GHGE up to 30% were found to be compatible with nutritional, cost, and acceptability constraints; however, reductions to diet-related GHGE beyond 30% induced trade-offs with nutrient adequacy and required large-scale dietary shifts. While all food groups were present in nutritionally adequate diets with moderate reductions in diet-related GHGE, albeit certain within food group substitutions (e.g., cheese for milk), higher reductions led to the exclusion of particular food groups, namely the meat, fish, and eggs and dairy groups.

Similarly, Seconda et al. (67) optimized the diets of French adults in the NutriNet-Santé cohort with lower environmental impacts (diet-related GHGE, land use, and cumulative energy demand) and higher content of organic foods while minimizing the departure from observed diets. Conservative to disruptive diets contained progressively more plant-based foods, including vegetables, fruit, and soy-based products, and progressively less animal-source foods. The percentage of total protein intake from animal products decreased by 12 to 70%. Therefore, achieving more environmentally sustainable, nutritionally adequate diets that are in line with cultural and personal preferences appear to include a diversity of animal- and plant-based foods, but tend toward higher quantities of the latter.

One of the main challenges to diet optimization is that despite many studies accounting for cultural and personal preferences by estimating the departure from observed diets, diet optimization reconfigures diets to such a degree that may not be feasible for consumers. Therefore, while they may be helpful in designing healthy and sustainable diets, it will be important to investigate the drivers and barriers to adopting such diets in populations where animal protein foods have a prominent role.

2.5 Global dietary assessments

In 2019, the EAT-Lancet Commission set out to define scientific targets for healthy eating and sustainable food production. Their Planetary Health Diet, in combination with several intervention strategies such as reducing food loss and improving production practices, is meant to feed 10 billion people by 2050 while remaining within the biophysical limits of the Earth (14). The Planetary Health Diet emphasizes consumption of vegetables, fruit, whole grains, legumes, nuts, and fish; optional amounts of poultry, eggs, and dairy; and limited intakes of red meat and starchy vegetables. However, its adoption would require substantial shifts from current dietary patterns, including doubling global consumption of fruits, vegetables, nuts, and legumes and halving consumption of red meat. Moreover, since its publication, the report has received rampant criticism regarding its affordability in low- and middle-income countries (68), inverse associations with disease mortality (69), and acceptability across cultures (70). Importantly, the use of food availability data to quantify food-related environmental impacts as implemented in the EAT-Lancet report (71, 72) may not be an accurate representation of individual's habitual dietary intake. Hence, there is a need to address human and planetary health in tandem by assessing self-selected food consumption while accounting for local cultural preferences and economic constraints.

2.6 Sustainability in food-based dietary guidelines

Given the growing body of research on the relationship between diets and environmental sustainability, countries have been progressively including sustainability principles into their FBDG (**Table 2.6**). A recent review found that 45% of countries (37 out of 83 countries whose FBDG were listed on the Food and Agriculture Organization website and could be translated to English) mentioned environmental sustainability in their FBDG (11). Only FBDG with an explicit mention of environmental sustainability were included. Forty-six percent of countries referred to environmental sustainability in their consumer documents compared to 86% in their background documents. Environmental sustainability was most often included in FBDG from Europe and central Asia and less often from south and east Asia and Pacific regions. Twenty-seven percent of low-income countries referred to environmental sustainability in their FBDG compared to 47% of middle- and high-income countries. There was little mention of environmental sustainability in FBDG published prior to 2010, however, there was mention in 90% of FBDG published since 2019. Along with respecting local culture and practices and mention of environmental impacts, biodiversity, and food waste, one of the most common guiding principles for sustainable healthy diets from the health domain was to increase consumption of plant-based foods and to reduce consumption of animal-based foods (each mentioned by 62% of countries).

In Canada, the newest dietary guidelines were designed based solely on evidence of foods that reduce the risk of nutrient deficiencies and nutrition-related chronic diseases. While Health Canada made mention of the environmental impact of food choices in their background document intended for health professionals and policy makers, this was not explicitly stated in the guidelines geared at consumers (12). They stated that there are potential environmental benefits from shifting from current dietary patterns to ones that adhere more closely to CFG, as diets with a higher content of plant-based foods and a lower content of animal-source foods have been shown to have lesser environmental impacts. They also acknowledged food waste as a contributor to environmental impact and encouraged further awareness as to the importance of reducing food waste along the food supply chain, including at the household level.

Table 2.6 Percentage of countries that included environmental sustainability in their FBDG by region and income status

	% of countries that include environmental sustainability in their FBDG (n = 37)	% of countries that do not include environmental sustainability in their FBDG (n = 46)
Region		
East Asia and Pacific	33% (n = 3)	67% (n = 6)
Europe and central Asia	61% (n = 17)	39% (n = 11)
Latin America and the Caribbean	39% (n = 11)	61% (n = 17)
Middle East and north Africa	33% (n = 2)	67% (n = 4)
North America	50% (n = 1)	50% (n = 1)
South Asia	0% (n = 0)	100% (n = 3)
Sub-Saharan Africa	43% (n = 3)	57% (n = 4)
Income status		
Low	100% (n = 1)	0% (n = 0)
Low-middle	20% (n = 2)	80% (n = 8)
Upper-middle	39% (n = 12)	61% (n = 19)
High	54% (n = 22)	46% (n = 19)

Data are from James-Martin et al. (11). n = number of countries whose FBDG were listed on the Food and Agriculture Organization website and could be translated to English.

2.7 Summary

Protein foods are a vital component to healthy eating. However, there is ample research from LCA showing that the environmental impacts of animal protein foods exceed that of plant protein foods. Studies linking the environmental impacts of foods to those reported by individuals from nutrition surveys and cohorts have the advantage of assessing the environmental, nutrition, and health impacts of foods in the grander context of self-selected diets. Diet modeling further enables the assessment of shifts from current dietary patterns to diets that are healthier and more sustainable. This research is essential for the development of dietary guidance and public policy that integrates sociocultural, economic, health, and environmental dimensions to meet global scientific targets for climate change.

Bridge statement 1

CFG recommends consuming protein from plants more often. However, implications for protein inadequacy and concomitant intakes of other nutrients stemming from the adoption of CFG's protein recommendations were unknown. In the next chapter, we used data from the 2015 CCHS – Nutrition to characterize baseline protein intake, including usual intakes, inadequacy, and the contribution of animal- and plant-based sources to total intakes of protein and other nutrients, among a nationally representative sample of the Canadian adult population.

Chapter 3: Manuscript 1 – Protein consumption in Canada

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Protein consumption in Canadian habitual diets: usual intake, inadequacy, and the contribution of animal- and plant-based foods to nutrient intakes

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3.1 Abstract

The 2019 Canada's Food Guide (CFG) emphasizes consumption of plant protein with implications for protein adequacy and nutrient intakes, yet a baseline with which to compare future dietary trends that may result from its adoption is not available. The objectives were to assess usual protein intake, inadequacy, and the contribution of animal- and plant-based foods to intake of protein, nutrients, and energy in Canada. Twenty-four-hour dietary recalls from the 2015 Canadian Community Health Survey – Nutrition were used to assess dietary intake among adults (n = 13 616). The National Cancer Institute method was used to estimate usual protein intake and inadequacy. Population ratios were used to determine the contribution of animal- and plant-based foods to intake of protein, nutrients, and energy. Usual protein intake averaged 79.47 ± 0.70 g/d; inadequacy was highest for females ≥71 y (9.76 ± 2.04%). Top protein contributors were 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%). Dairy contributed most to calcium (53.4 ± 0.61%), vitamin D (38.7 ± 1.01%), but also saturated fat (40.6 ± 0.69%), whereas cereals, grains, and breads contributed most to iron (46.5 ± 0.57%) and vegetables and fruit to potassium (32 ± 0.45%). Given that animal sources contributed overwhelmingly to protein intake in 2015, dietary shifts towards plant protein needed to meet the 2019 CFG recommendations may pose a challenge, particularly for populations most at risk of inadequacy.

Novelty:

• Older adults and females are most at risk of not meeting protein recommendations.

• Animal sources contribute two-thirds of the protein consumed by Canadian adults.

3.2 Résumé

Le Guide alimentaire canadien (« CFG ») 2019 met l'accent sur la consommation de protéines végétales, ce qui a des répercussions sur l'adéquation des protéines et les apports en éléments nutritifs, mais il n'existe pas de base de référence avec laquelle comparer les tendances alimentaires futures qui pourraient résulter de son adoption. Les objectifs sont d'évaluer l'apport habituel en protéines, l'insuffisance et la contribution des aliments d'origine animale et végétale à l'apport en protéines, en nutriments et en énérgie au Canada. Les rappels alimentaires de 24 heures de l'Enquête sur la santé dans les collectivités canadiennes − Nutrition 2015 sont utilisés pour évaluer l'apport alimentaire chez les adultes (n = 13 616). La méthode de l'Institut national du cancer est utilisée pour estimer l'apport et l'insuffisance habituels. Les ratios de population sont utilisés pour déterminer la contribution des aliments d'origine animale et végétale à l'apport en protéines, nutriments et énergie. L'apport protéique habituel est en moyenne de 79,47 ± 0,70 g/jour ; l'inadéquation est la plus élevée chez les femmes ≥ 71 ans (9,76 ± 2,04 %). Les principaux contributeurs en protéines sont la viande rouge et transformée (21,6 ± 0,55 %), la volaille et les œufs (20,1 ± 0,81 %), les céréales, les grains et le pain (19,5 ± 0,31 %) et les produits laitiers (16,7 ± 0,38 %). Les produits laitiers contribuent le plus au calcium (53,4 ± 0,61 %), à la vitamine D (38,7 ± 1,01 %), mais aussi aux gras saturés (40,6 ± 0,69 %), tandis que les céréales, les grains et le pain contribuent le plus au fer (46,5 ± 0,57 %) et légumes et fruits au potassium (32 ± 0,45 %). Étant donné que les sources animales contribuent largement à l'apport en protéines en 2015, les changements alimentaires vers les protéines végétales requises pour répondre aux recommandations du CFG 2019 peuvent représenter un défi, en particulier pour les populations les plus à risque d'insuffisance. [Traduit par la Rédaction].

Les nouveautés :

• Les personnes âgées et les femmes sont les plus à risque de ne pas satisfaire aux recommandations en matière de protéines.

• Les sources animales contribuent aux deux tiers des protéines consommées par les adultes canadiens.

3.3 Introduction

Protein consumption has important implications for nutrition, human health, and environmental sustainability. The Dietary Reference Intakes (DRI) express protein recommendations as the Estimated Average Requirement (EAR) and the Acceptable Macronutrient Distribution Range (AMDR), which do not vary by age or sex for individuals aged ≥19 y (24). The EAR is the median daily intake of protein needed to meet the needs of half the healthy individuals in a particular life stage and age-sex group, which is set at 0.66 g/kg of body weight (BW)/d. The AMDR is the range of calories, expressed as a percentage of total energy intake, that is associated with a lower risk of chronic disease while providing adequate intake of a macronutrient. For protein, the AMDR is set at 10 to 35% of total energy intake. Data from the United States National Health and Nutrition Examination Survey (NHANES) 2011–2014 revealed that usual protein intake among American adults averaged 80 g/d and 16% of total energy intake (41). The percent of total energy intake from protein averaged 17% for Canadian adults in 2015 (43). However, information pertaining to inadequate protein intake, which is determined by the percentage of the population below the EAR (24), is currently lacking.

Animal- and plant-based foods differ in their quantity and quality of protein and content of other essential nutrients. Animal protein is deemed high quality because it provides all 9 essential amino acids and is more bioavailable compared with plants (24, 73). Consuming plant-based protein sources with complementary amino acid profiles (31, 74) is encouraged to ensure adequate intake of all essential amino acids, particularly for vegetarians (24). Commonly consumed animal- and plant-based protein sources also supply a range of essential nutrients (75), some of which are deemed of public health concern in Canada (calcium, vitamin D, iron, and potassium) as individuals fall below recommendations (76). However, they also confer nutrients to limit (sodium, added sugars, and saturated fat), among which animal-based protein sources contribute significantly to intake of saturated fat, a nutrient that is often scrutinized for its putative harmful association with cardiovascular health (12). The choice of protein source is an important determinant of human health, as epidemiological studies have shown that high intakes of plant protein are inversely associated with cardiometabolic indicators and mortality (77, 78). Yet, there is also evidence that replacement of protein from red and processed meats with that from other animal sources such as fish, poultry, and low-fat dairy products may help lower cardiometabolic risk factors (79). Moreover, animal sources have a substantially greater carbon footprint than plants per gram of protein (80-82). However, modeling studies have demonstrated that partial replacement of animal-based foods with plant-based alternatives resulted in lower carbon footprint diets that included moderate amounts of nutrient dense animal-source foods (65, 83). Despite the importance of dietary protein sources to human and planetary health, the respective contribution of animal- and plant-based foods to total protein intake in Canadian habitual diets is unknown.

In January 2019, Health Canada published the first revamp of the nation's food guide in over a decade. The new Canada's Food Guide (hereafter referred to as the 2019 CFG) encourages largely plant-based diets, including vegetables and fruit, whole grains, and protein foods. Although the guide does not provide a definition for protein foods, emphasis is placed on consuming protein from plants more often (12). At present, the implications of the 2019 CFG on intakes of shortfall nutrients is not known, yet available evidence raises concern as to its nutritional adequacy. Barr (84) estimated the nutrient content of foods in the food guide snapshot based on a standard 2000 kcal diet and found that the percent Daily Value was not met for calcium, vitamin D, and potassium. Moreover, a recent report on a scientific expert meeting identified knowledge gaps brought about by the new protein foods group, including protein inadequacy among vulnerable populations and intake of other essential nutrients by Canadians (85). To assess the implications of the 2019 CFG's protein recommendations, it is important to first characterize protein intake trends in Canadian habitual diets as a baseline with which to compare future dietary shifts. In particular, estimating the contribution of animal- and plant-based foods to intake of protein and other nutrients may help define targets to shape public policy interventions aimed at meeting current dietary guidance. Therefore, the primary objective of this study was to assess usual protein intake and inadequacy for adults using data from the 2015 Canadian Community Health Survey (CCHS) – Nutrition. The secondary objective was to determine the contribution of animal- and plant-based foods to intake of protein and nutrients, particularly nutrients of public health concern and to limit.

3.4 Materials and methods

2015 CCHS – Nutrition

The CCHS is a nationally representative cross-sectional survey that collects information regarding Canadians' health status, health determinants, and utilization of the healthcare system that is administered on a yearly basis (86). The survey is a multi-stage, clustered design to ensure a sample representative of the Canadian population with respect to age, sex, geography, and socioeconomic status. The CCHS targets individuals aged ≥1 y residing in the 10 provinces and excludes members of the Canadian Forces and individuals residing in the Territories, Aboriginal settlements, or institutions.

The 2015 CCHS – Nutrition (n = 20 487) is the second of 2 nutrition-focused surveys (the first having been conducted in 2004) that employed 24-hour dietary recalls to collect information pertaining to the foods and beverages consumed by respondents in the previous 24 hours, from midnight to midnight (86). The Automated Multiple Pass Method was used to facilitate respondents' recollection and reporting of foods in their 24-hour dietary recalls. Interviews were administered in-person, year-round, and on all days of the week (including weekends). The response rate for the 2015 CCHS – Nutrition was 61.6%. Just over one-third of respondents were randomly selected to complete a second non-consecutive 24-hour dietary recall by telephone to be used for estimating distributions of usual intake. The recall day was identified by a variable in the CCHS (SUPPID). Information pertaining to respondents' weight and height, physical activity, chronic health conditions, sociodemographic characteristics, and supplement intake was also collected. Measures of body weight and height were obtained provided the consent of survey participants. However, 30% of respondents were asked to self-report because they either refused or were not physically able to have their weight and height measured (e.g., could not stand unassisted). In addition, the 18-item United States Household Food Security Survey Module was employed to assess the food security status of Canadian households. The module included questions pertaining to whether respondents worried about running out of food, went an entire day without eating, and had to cut the size of their meals or skip them completely (87). Respondents were classified as food secure, moderately food insecure, and severely food insecure by Statistics Canada. For the purpose of this study, respondents were classified as food secure or food insecure (moderately and severely combined).

Participants aged <19 y (n = 6568; 32.06% of sample), pregnant (n = 116; 0.57% of sample), and breastfeeding (n = 187; 0.91% of sample) women were excluded due to differing protein requirements (24). Intake of vitamins and minerals from supplements were excluded to obtain estimates of nutrient intakes from foods alone. Although this may lead to underestimations of total nutrient intakes, dietary guidelines emphasize getting nutrients from foods as opposed to supplements (88). The final sample size was 13 616. Access to the 2015 CCHS – Nutrition Master Files was granted by Statistics Canada (project no. 18-SSH-MCG-5516). Population surveys conducted by Statistics Canada were granted ethical approval under the authority of the Statistics Act of Canada.

Classification of animal- and plant-based foods

The Canadian Nutrient File, Canada's reference food composition database, was used by Statistics Canada to link foods and beverages reported in the 2015 CCHS – Nutrition to their nutrient profiles (89). The Bureau of Nutritional Sciences (BNS) food and recipe groups are a set of codes developed by Health Canada to categorize foods reported in the 24-hour dietary recalls to analyze diet composition and the contribution of select foods and beverages to total nutrient intakes (86). BNS food codes were used to classify foods and beverages into the following categories: 1) cereals, grains, and breads, 2) vegetables and fruit, 3) nuts, seeds, and legumes, 4) dairy, 5) poultry and eggs, 6) red and processed meat, 7) fish and shellfish, and 8) miscellaneous foods and beverages. All foods reported in the CCHS were accounted for, including basic foods and recipe ingredients, as well as processed and unprocessed foods, to align with foods in the 2019 CFG. The Nutrition Survey System food codes were used to classify plant-based beverages (BNS food code: 10J). For example, rice beverage was assigned to cereals, grains, and breads, whereas soy, almond, cashew, and coconut beverages were assigned to nuts, seeds, and legumes. BNS food codes used to classify foods and beverages are in **Supplementary Table 3.1**.

Estimation of usual protein intake

The 24-hour dietary recalls capture detailed information regarding food and beverage consumption; however, they are not necessarily representative of individuals' usual or long-term dietary intake, which fluctuates from day-to-day (90). This intra-individual variation can lead to over- or under-estimation of nutrient intakes (91). Since dietary recommendations are meant to be met over the long-term, usual intakes are an important consideration in the analysis of nationally representative nutrition survey data (92). The NCI method is recommended by Health Canada and Statistics Canada for estimating usual intakes with the 2015 CCHS – Nutrition (86). The NCI method uses statistical modeling to estimate the distribution of usual intake for nutrients and foods using data from 2 non-consecutive 24-hour dietary recalls (92). The NCI method fits a 2-part statistical model that considers both the probability of consumption on a given day and the amount consumed. For ubiquitously consumed foods in which less than 10% of recalls reported zero intake (cereals, grains, and breads, vegetables and fruit, dairy, and miscellaneous), the 1-part or amount-only model was used (90). For episodically consumed foods in which more than 10% of recalls reported zero intake (nuts, seeds, and legumes, poultry and eggs, red and processed meat, and fish and shellfish), the 2-part model was used. Age, sex, and nuisance effects (i.e., weekend and recall sequence) were used as covariates in all models.

Prevalence of usual protein intake below DRI

The NCI method was used to estimate usual protein intake in absolute (g/d) and relative amounts (g/kg of BW/d). A subsample of respondents with measured anthropometry (n = 9175) was used to discern the percent of the population below the EAR for protein, since it is expressed as 0.66 g/kg of BW/d. Similar to the method of Berryman et al. (41), protein was expressed as g/kg of ideal BW (IBW)/d for respondents whose body mass index (BMI) (in kg/m2; calculated based on measured weight and height) was below 18.5 (underweight) or above 24.9 (overweight). Equations for IBW were taken from Peterson et al. (93). Specifically, for males and females whose measured BMI was <18.5, IBW (kg) = 2.2 × (18.5) + 3.5 × (18.5) × (measured height in m − 1.5 m). For males and females whose measured BMI was >24.9, IBW (kg) = 2.2 × (24.9) + 3.5 × (24.9) × (measured height in m − 1.5 m). Usual protein intake as a percent of total energy was derived by dividing total protein intake (g) times 4 kcal/g by total energy intake (kcal) and multiplying by 100; this was used to determine the prevalence of the population below the lower (10%) and upper bounds (35%) of the AMDR for the entire sample.

Contribution of foods to intake of protein, nutrients, and energy

Population ratios, which have been shown to provide better estimates of population usual intakes in contrast to other methods (94), were used to determine the percent contribution of foods to protein, nutrients of concern, nutrients to limit, and energy, as done previously by our group (46). Nutrients of public health concern are defined based on a significant proportion of the population falling below the EAR (10%), as well as biomarker data and clinical signs of deficiency (76). In Canada, these nutrients are calcium, vitamin D, iron, and potassium. The 2019 CFG considers sodium, added sugars, and saturated fat nutrients to limit due to evidence linking their excess consumption to increased risk of chronic disease (95). Population ratios were also used to assess the contribution of single food categories to protein intake from each of the animal- and plant-based food groupings, as well as total protein and total energy.

Statistical analyses

For the percent of the population below DRI, significant differences among age-sex groups were identified by the z statistic. Descriptive statistics were generated using SUDAAN software version 11.0.1 (RTI International, Durham, N.C., USA). PROC CROSSTAB was used to determine demographic characteristics, PROC DESCRIPT was used to estimate mean 1-d intakes for nutrients and energy, and PROC RATIO was used to calculate population ratios. Sample weights, calculated and assigned to each respondent by Statistics Canada, correspond to the number of individuals within the population represented by that respondent. The sample weights have a related bootstrap weight file, which is recommended for use with the CCHS to account for its complex multi-stage sampling frame. Both sample and bootstrap weights were applied in SUDAAN to obtain representative estimates for the Canadian population and to calculate confidence intervals around point estimates, respectively. All statistical analyses were performed using SAS software version 9.3 (SAS Institute Inc., Cary, N.C., USA) and SAS-callable SUDAAN software available at the McGill−Concordia Laboratory of the Quebec Inter-University Centre for Social Statistics. Alpha was set at 0.05 for all statistical tests.

3.5 Results

Protein intake and inadequacy

The final sample was split evenly among males and females. The majority of respondents were 31–50 y of age (~38%), Caucasian (~74%), food secure (~92%), had some post-secondary education (~34%), a yearly household income of $CAD <50 000/y (~34%), and exercised more than 150 min/week (~55%) (**Table 3.1**). Differences among demographic characteristics for the final sample compared with the subsample with measured anthropometrics (n = 9175) were considered negligible (±1%) and are not reported. For all age-sex groups combined, mean usual protein intake was 79.47 ± 0.70 g/d, 1.20 ± 0.01 g/kg of BW/d (expressed as g/kg of IBW/d for those with a BMI outside the range of 18.5 and 24.9), and 16.96 ± 0.11% of total energy intake.

Overall, 3.11 ± 0.95% of the population were below the EAR for protein (**Table 3.2**). Protein inadequacy (% below the EAR) was higher for females compared with males and increased with age (males ≥71 y vs. 19–30 y: +3.18%; females ≥71 y vs. 19–30 y: +8.15%). The highest proportion of adults below the EAR was females aged ≥71 y, which was different from that of males in the same age bracket (+6.01; P = 0.007). The proportion of respondents that were below the lower bound of the AMDR was <0.5% and did not differ among age-sex groups. All respondents fell below the upper bound of the AMDR.

Contribution of foods to intake of protein, nutrients, and energy

Mean usual intake of protein from animal- and plant-based foods are in **Figure 3.1**. Usual intake (in g/d) was highest for red and processed meat (17.45 ± 0.44), followed by poultry and eggs (16.06 ± 0.48), cereals, grains, and breads (15.46 ± 0.17), and dairy (13.28 ± 0.25). Usual intake for all remaining food groupings was 4 to 5 g/d each.

The contribution of animal- and plant-based foods to total protein intake is in **Figure 3.2**. Sixty-four percent of total protein intake derived from animal-source foods, ~30% from plant-based foods, and the remaining ~6% from miscellaneous foods and beverages. Top sources of protein were red and processed meat, poultry and eggs, and cereals, grains, and breads (each ~20%), followed by dairy (~17%). All remaining food groupings each contributed roughly 5% to total protein intake.

The contribution of animal- and plant-based foods to intake of nutrients of concern, nutrients to limit, and energy are in **Table 3.3**. Dairy contributed the most to intakes of calcium (~53%), vitamin D (~39%), and saturated fat (~41%), whereas cereals, grains, and breads contributed most to iron (~47%) and vegetables and fruit to potassium (~32%). Most sodium (~45%) and total sugars (~46%) derived from miscellaneous foods and beverages. Poultry and eggs contributed ~9% to intakes of vitamin D and ~8% to saturated fat. Despite contributing ~11% to total iron intake, red and processed meat was also a source of sodium (~11%) and saturated fat (~15%). Fish and shellfish contributed nearly one-fifth of total vitamin D intake. The contribution of nuts, seeds, and legumes to nutrient intakes ranged between ~2% (vitamin D) and ~7% (iron).

Contribution of single food categories to intake of protein and energy

The contribution of single food categories to intake of protein from animal- and plant-based foods, total protein, and total energy are in **Table 3.4** and **Table 3.5**, respectively. Food categories were ranked based on their contribution to protein intake from each of the food groupings; food categories that accounted for <1% of protein intake was considered negligible and thus were not reported. Cheese (>10% milk fat) and milk (2% milk fat) accounted for two-thirds of protein intake from dairy (n = 12 food categories) and 1 to 4% for total protein and energy intake. Chicken and eggs contributed 73 and 21% to protein intake from poultry and eggs (n = 5), respectively, whereas chicken alone contributed 13% to total protein and 4% to energy intake. Beef contributed nearly half of protein from red and processed meat (n = 10), as well as 10% to total protein and 3% to energy intake. Half of protein intake from fish and shellfish (n = 3) derived from fish containing <6% total fat, which contributed <2% to total protein and energy intake. Half of protein intake from cereals, grains, and breads (n = 11) derived from an array of food categories, including cereal grains and flours, rolls, bagels, pita bread, croutons, dumplings, matzo, tortilla, and white bread, altogether contributing <5% to total protein and energy. The largest contributors to protein intake from vegetables and fruit (n = 21) were potatoes and tomatoes (17 and 13%, respectively), together accounting for <2% of total protein and energy.

Nuts, nut spreads, and legumes contributed three-quarters to protein intake from nuts, seeds, and legumes (n = 8), whereas their contribution to total protein and energy intake was <3%. Food categories constituting miscellaneous foods and beverages contributed negligible amounts of protein (≤1% to total protein intake), but most to total energy intake (~29%) and are reported in Supplementary **Table 3.2** The largest contributor to protein intake from miscellaneous foods and beverages was meal replacements (~19%), followed by soups without vegetables and beer (each ~9%).

3.6 Discussion

Given the recent changes to the 2019 CFG that place emphasis on plant protein, population diet studies are necessary to provide information as to which nutrient-rich protein sources Canadians should be incorporating into their diets (85). The present study addressed many of the uncertainties and knowledge gaps that arose from the introduction of the new protein foods group in the 2019 CFG, particularly protein intake and inadequacy in the Canadian population with a particular focus on animal- and plant-based foods. Based on our findings, most Canadians were in line with protein recommendations except for females aged ≥71 y, who had the highest prevalence of inadequacy. Moreover, two-thirds of Canadians' total protein intake derived from animal-based foods for which dairy was a top source of nutrients of concern (calcium and vitamin D) and a nutrient to limit (saturated fat).

Despite assumptions of protein adequacy in the Canadian population (85), our findings confirm that older adults are most at risk of not meeting recommendations. The percent of the population below the EAR for protein was similar to the pattern observed in the United States (41, 75, 96). Phillips et al. (36) proposed that higher protein intake within the range of 1.2 to 1.6 g/kg of

BW/d may help promote healthy ageing, appetite control, and weight management. For the elderly, higher protein intake may prevent sarcopenia, a disease characterized by the progressive loss of muscle mass and strength that leads to impaired physical function, frailty, and mortality (36, 37). Current protein requirements based on nitrogen balance studies may underestimate actual requirements, especially for the elderly population (36). As food intake decreases with age (96), the body resorts to utilizing protein for energy; since energy to protein ratios are highest for individuals with the lowest energy requirements, sedentary elderly women with higher BMIs are likely to have higher protein requirements compared with other demographics (97). The 2019 CFG may encourage Canadians to consume more protein-rich foods, but the lack of suggested serving sizes and age- and sex-specific recommendations limits its usefulness, particularly for those most at risk of falling below the EAR.

Total protein intake from animal-source foods was more than double that contributed by plant-based foods, similar to observations in the United States and United Kingdom (73, 75, 96). We found that chicken and beef alone contributed the most to total protein intake, whereas protein from plant sources derived from a wider range of food categories, albeit contributing relatively little protein. Similarly, data from NHANES 2007–2010 revealed that chicken and beef contributed one-quarter of protein intake from animal sources and 13% of total protein intake (42). We also found that cheese and fluid milk were the top dairy sources of total protein, although cheeses contributing the most protein were also particularly high in fat (>25% and 10 to 25% milk fat). Among plant-based foods, cereals, grains, and breads contributed the most to total protein intake. However, top sources were refined products as opposed to whole grain food categories. One analysis using data from the 2015 CCHS – Nutrition classified respondents into clusters based on their consumption of grain-based foods and found that only 8% of Canadian adults followed a 'Whole Wheat & Whole-Grain Bread' dietary pattern (98), which did not align with recommendations to consume most grains as whole (12, 99). Although nuts, seeds, and legumes have a higher overall protein content compared with other plant-based foods, they are consumed in smaller quantities and thus contributed negligible amounts to total protein intake. Although current dietary guidance promotes consumption of protein from plants more often, particularly from sources exemplified by this group (13), our findings revealed that Canadians obtained relatively little protein from nuts, seeds, and legumes compared with animal-based foods and even cereals, grains, and breads. Substantial shifts in Canadian dietary patterns are required to increase the prominence of plant-based protein from a variety of sources, particularly from nuts, seeds, and legumes, as recommended in the 2019 CFG.

One of the major knowledge gaps regarding population-wide protein intake in Canada is the contribution of various protein sources to intakes of nutrients of public health concern (85). Our findings show that dairy contributed the most to intake of calcium and vitamin D, cereals, grains, and breads to intake of iron, and vegetables and fruit to intake of potassium. In the United States, animal-based protein sources contributed greater amounts of iron, zinc, vitamin B12, and phosphorus compared with plant sources, which contributed more dietary fibre, vitamin E, and magnesium (75). Our previous work showed that milk and alternatives contributed 53% of calcium and 39% of vitamin D in Canadian habitual diets, in addition to a range of other essential nutrients (46). In Canada, mandatory fortification of milk with vitamin D under the Food and Drugs Act (100) explains its contribution to intake of this nutrient. Diet modeling of NHANES 2003–2006 revealed that it would be difficult to replace nutrients from dairy with non-dairy foods (101). For example, replacing the calcium from dairy with a non-dairy calcium composite (either fortified soy-based beverage or orange juice, bony fish, or leafy greens) would result in lower overall intake of protein, total fat, vitamin B12, riboflavin, phosphorus, zinc, saturated fat, and sodium, whereas intake of magnesium, potassium, and vitamin A would increase, with no change in vitamin D. Based on our results, there is concern as to whether dietary shifts aligning with those in the 2019 CFG, particularly with regards to protein foods, may further compromise intake of certain nutrients of public health concern provided no changes in the mandatory fortification of foods or additional dietary guidance.

Animal- and plant-based foods also contributed to intake of nutrients to limit. Our results show that dairy was the top source of saturated fat, which was 2 and a half times that contributed by red and processed meat. The 2019 CFG encourages the replacement of foods that are high in saturated fat with foods containing unsaturated fat as a means of promoting cardiovascular health (12). A similar rationale was proposed in the World Health Organization's draft guidelines on saturated fat. However, Astrup et al. (102) argue that the type of saturated fatty acid and the food matrix are both critical factors for informing dietary recommendations. Substantial evidence points to an inverse association between plant protein and cardiometabolic health (78, 103), which have also been shown to have a lesser environmental impact than animal protein (104). Therefore, the type of animal- and plant-based protein making up habitual diets is fundamental in addressing human and planetary health in tandem.

Strengths of this study include the use of data from a nationally representative survey and the estimation of usual protein intake using the NCI method. Moreover, to our knowledge, this is the first study to provide estimates of protein inadequacy in the Canadian population. However, limitations include the self-reported nature of 24-hour dietary recalls, which are prone to bias through misreporting. However, according to Garriguet (105), energy misreporting was not a major source of bias in the 2015 CCHS – Nutrition. Furthermore, the 2019 CFG does not yet provide a definition for protein foods; therefore, we used examples in the guide to broadly classify all foods and beverages reported in the CCHS into animal- and plant-based food groupings. Although protein recommendations are based on consumption of high-quality protein (WHO/FAO/UNU Expert Consultation 2007), there is a lack of data pertaining to protein quality for foods based on the Digestible Indispensable Amino Acid Score (106). At present, there is insufficient information to assess the influence of protein quality on protein inadequacy. Moreover, the degree of detail with which we categorized foods was limited (e.g., grouping eggs with poultry) due to the computationally intensive nature of the NCI method (91). Finally, since the Canadian Nutrient File does not distinguish between total and free sugars, the present analysis accounts solely for total sugars, despite recommendations in the 2019 CFG that are geared towards free sugars.

In conclusion, most Canadian adults were in line with the DRI for protein; however, special attention should be warranted to older adults and females who were more prone to fall short of requirements. Except for cereals, grains, and breads, the majority of protein intake was derived from animal-based foods. Yet, animal sources were not top contributors of nutrients of concern, with the exception of dairy, which also contributed significant amounts of saturated fat. Moreover, miscellaneous foods and beverages contributed negligible amounts of protein but were top sources of sodium and total sugars. Based on Canadian habitual diets in 2015, our results show that major adjustments are needed to meet the recommendations in the 2019 CFG, specifically regarding the shift towards plant-based protein foods. Despite the guide’s holistic approach to healthy eating, such transitions may pose implications on future prevalence of inadequacy for protein and nutrients of concern in Canada, particularly for older adults and females.

Conflict of interest statement

S.A.B. received grant support from Dairy Farmers of Canada outside of this work. O.A. declares no conflict of interest.

Author contributions

O.A. and S.A.B. designed research; O.A. conducted research; O.A. analyzed data; O.A. performed statistical analyses; O.A. and S.A.B. wrote the paper; S.A.B. had primary responsibility for final content. All authors read and approved the final manuscript.

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Table 3.1 Demographic characteristics of the study sample from the 2015 Canadian Community Health Survey – Nutrition (*n* = 13 616).

Demographic variable	Proportion (%)
Sex	
Male	49.99±0.10
Female	50.01±0.10
Age group	
19 to 30 y	16.23±0.65
31 to 50 y	38.08±0.66
51 to 70 y	33.49±0.07
≥71 y	12.21±0.02
Ethnicity	
Caucasian	73.69±0.94
Non-Caucasian	26.31±0.94
Food security	
Food secure	92.17±0.46
Food insecure	7.83±0.46
Education	
Less than secondary	12.34±0.49
Secondary	25.96±0.76
Some-post secondary	34.00±0.83
Post-secondary	27.70±0.86
Income ($CAD/y)	
Less than 50 000	34.19±0.85
50 000-100 000	32.42±0.82
100 000-150 000	19.67±0.75
More than 150 000	13.73±0.68
Physical activity	
<150 min per week	45.14±0.93
≥150 min per week	54.86±0.93

Note: Values are percentage ± SE.

Table 3.2 Percent below DRI and mean usual intake for protein by age and sex for Canadian adults (≥19 y) from the 2015 Canadian Community Health Survey – Nutrition.

Age, y[a]	Sex	n^b	Protein intake (g/kg of IBW/d)[c]	Population below EAR (%)[d]	n^e	Protein intake as total energy (%)	Population below AMDR (%)[f]
19-30	Male	655	1.38±0.03	0.57±0.37	882	17.62±0.19	0.08±0.09
31-50	Male	1407	1.24±0.02	1.02±0.56	2077	17.32±0.20	0.22±0.14
51-70	Male	1509	1.31±0.02	2.13±0.89	2249	17.29±0.15	0.28±0.18
≥71	Male	783	1.16±0.02	3.75±1.35	1246	16.95±0.15	0.28±0.21
19-30	Female	681	1.21±0.02	1.61±0.86	897	16.91±0.14	0.15±0.11
31-50	Female	1568	1.08±0.01	3.04±1.15	2288	16.58±0.14	0.10±0.12
51-70	Female	1584	1.13±0.02	5.65±1.52*	2421	16.55±0.17	0.16±0.17
≥71	Female	988	1.00±0.02	9.76±2.04*	1556	16.21±0.17	0.38±0.25

Note: Values are means or percentage ± SE based on usual intakes. AMDR, Acceptable Macronutrient Distribution Range; DRI, Dietary Reference Intake; EAR, Estimated Average Requirement; IBW, ideal body weight; RDA, Recommended Dietary Allowance.
[a]Age categories are based on DRI cut-offs.
[b]A subsample of respondents with measured anthropometry (n = 9175) was used to estimate mean usual protein intake and the percent of the population below the EAR.
[c]Protein was expressed as g/kg of IBW/d for respondents whose measured BMI was below 18.5 or above 24.9.
[d]The EAR is 0.66 g/kg of BW/d for males and females ≥19 y.
[e]Protein intake as a percent of total energy and the percent of the population below the AMDR was estimated for the entire sample (n = 13 616).
[f]Refers to the lower bound of the AMDR set at 10% of total energy intake.
*Significant difference from males of the same age group based on the z statistic, P = 0.05. Covariates included were age, sex, and nuisance effects (i.e., weekend and recall sequence).

Table 3.3 Mean 1-d intakes and percent contribution of animal- and plant-based foods to intakes of nutrients of concern, nutrients to limit, and energy among Canadian adults (≥19 y) from the 2015 Canadian Community Health Survey – Nutrition (*n* = 13 616).

	Cereals, grains, and breads	Vegetables and fruit	Nuts, seeds, and legumes	Dairy	Poultry and eggs	Red and processed meat	Fish and shellfish	Miscellaneous
Mean 1-d intakes[a]								
Energy, kcal	500.35±5.46	183.86±2.86	99.95±3.58	249.64±4.27	125.08±4.06	158.43±3.83	24.76±1.22	535.48±7.38
Calcium, mg	99.68±1.36	70.05±2.86	38.09±1.84	417.31±7.44	18.66±0.56	11.46±0.37	9.18±0.61	117.74±2.17
Iron, mg	5.74±0.07	1.65±0.03	0.86±0.03	0.20±0.005	0.81±0.02	1.35±0.04	0.17±0.02	1.56±0.03
Potassium, mg	248.99±3.08	857.48±13.19	147.71±4.95	345.89±6.41	150.44±4.72	226.76±5.00	65.39±3.36	644.55±8.77
Vitamin D, µg	0.20±0.01	0.01±0.002	0.08±0.01	1.83±0.04	0.44±0.02	0.20±0.01	0.88±0.07	1.08±0.03
Sodium, mg	511.26±7.68	163.92±5.57	61.60±2.96	353.75±7.61	76.11±2.29	293.26±9.12	51.10±3.29	1 223.29±17.79
Sugar, g	8.80±0.15	21.97±0.38	1.82±0.07	13.91±0.29	0.22±0.01	0.21±0.01	0.02±0.004	39.92±0.73
Saturated fat, g	1.86±0.05	0.26±0.01	1.02±0.04	9.23±0.18	1.80±0.07	3.40±0.10	0.18±0.01	4.98±0.09
Percent contribution[b]								
Energy	26.65±0.26	9.79±0.15	5.32±0.18	13.30±0.20	6.66±0.21	8.44±0.19	1.32±0.07	28.52±0.30
Calcium	12.74±0.26	8.96±0.17	4.87±0.23	53.35±0.47	2.39±0.07	1.47±0.05	1.17±0.08	15.05±0.27
Iron	46.48±0.41	13.40±0.22	6.95±0.25	1.60±0.04	6.59±0.18	10.93±0.30	1.41±0.14	12.65±0.23
Potassium	9.27±0.12	31.91±0.36	5.50±0.18	12.87±0.22	5.60±0.18	8.44±0.18	2.43±0.13	23.99±0.29
Vitamin D	4.21±0.13	0.30±0.03	1.66±0.16	38.28±0.78	9.38±0.32	4.24±0.23	18.64±1.16	22.90±0.61
Sodium	18.70±0.27	6.00±0.19	2.25±0.11	12.94±0.25	2.78±0.08	10.73±0.30	1.87±0.12	44.74±0.46
Sugar	10.13±0.16	25.29±0.44	2.09±0.08	16.01±0.31	0.26±0.01	0.25±0.01	0.02±0.00004	45.95±0.56
Saturated fat	8.18±0.21	1.13±0.04	4.48±0.19	40.63±0.49	7.94±0.30	14.96±0.38	0.78±0.05	21.91±0.36

[a]Values are means ± SE.
[b]Values are percentage ± SE based on population ratios.

Table 3.4 Percent contribution of individual food categories to intake of protein from animal-based foods, total protein, and total energy among Canadian adults (≥19 y) based on 1-d intakes from the 2015 Canadian Community Health Survey – Nutrition (*n* = 13 616).

	Food category			Total protein			Total energy		
	Rank	%	SE	Rank	%	SE	Rank	%	SE
Dairy									
Cheese, more than 25% MF	1	24.78	0.77	1	4.13	0.16	1	2.92	0.11
Milk, 2% MF	2	19.87	0.57	2	3.31	0.10	2	2.16	0.07
Cheese, 10% MF to 25% MF	3	17.15	0.63	3	2.86	0.12	3	1.62	0.06
Milk, 1% MF	4	9.46	0.41	4	1.58	0.07	6	0.91	0.04
Yoghurts, more than 2.1% MF	5	5.42	0.33	5	0.90	0.06	8	0.70	0.04
Milk, whole	6	5.09	0.47	6	0.85	0.08	7	0.70	0.07
Milk, skim	7	4.42	0.26	7	0.74	0.04	9	0.32	0.02
Yoghurts, less than 2% MF	8	4.34	0.31	8	0.72	0.05	10	0.31	0.02
Ice cream	9	3.08	0.20	9	0.51	0.03	4	1.26	0.08
Cottage cheese	10	1.52	0.24	10	0.25	0.04	15	0.08	0.01
Cheese, less than 10% MF	11	1.11	0.13	11	0.19	0.02	17	0.07	0.01
Half and half cream	12	1.02	0.10	12	0.17	0.02	11	0.28	0.03
Poultry and eggs									
Chicken, meat only	1	55.15	1.66	1	11.07	0.43	1	2.74	0.11
Egg	2	21.01	0.80	2	4.22	0.15	2	2.16	0.08
Chicken, meat and skin	3	18.76	1.78	3	3.77	3.77	3	1.49	0.16
Turkey, meat only	4	3.45	0.51	4	0.69	0.11	4	0.16	0.02
Turkey, meat and skin (including ground turkey)	5	1.33	0.29	5	0.27	0.06	5	0.07	0.02
Red and processed meat									
Beef, ground	1	24.32	1.29	1	5.24	0.31	1	2.26	0.14
Beef, lean only	2	21.45	1.11	2	4.63	0.26	2	1.21	0.07
Luncheon meat	3	10.83	0.55	3	2.33	0.11	4	1.06	0.07
Pork, fresh, lean only	4	8.88	0.60	4	1.91	0.13	6	0.51	0.04
Pork, fresh, lean and fat (including ground pork)	5	8.54	0.98	5	1.84	0.22	5	0.76	0.09
Beef, lean and fat	6	7.44	0.81	6	1.61	0.18	7	0.50	0.06
Sausage	7	6.87	0.49	7	1.48	0.11	3	1.10	0.08
Bacon	8	4.01	0.27	8	0.87	0.06	8	0.49	0.03
Ham, cured, lean only	9	2.16	0.29	9	0.47	0.06	9	0.14	0.02
Game meat	10	1.40	0.31	10	0.30	0.07	11	0.07	0.01
Fish and shellfish									

Fish, less than 6% total fat	1	49.57	2.01	1	2.61	0.17	2	0.54	0.03
Fish, superior or equal to 6% total fat	2	35.25	2.06	2	1.85	0.15	1	0.59	0.05
Shellfish	3	15.18	1.25	3	0.80	0.07	3	0.19	0.02

Note: Values are percentage ± SE based on population ratios. Food categories that contributed <1% (*n* = 71; 45% of Bureau of Nutritional Sciences food codes) of protein to a given food group are not reported. MF, milk fat.

Table 3.5 Percent contribution of individual food categories to intake of protein from plant-based protein foods, total protein, and total energy among Canadian adults (≥19 y) based on 1-d intakes from the 2015 Canadian Community Health Survey – Nutrition (*n* = 13 616)[a]

	Food category			Total protein			Total energy		
	Rank	%	SE	Rank	%	SE	Rank	%	SE
Cereals, grains, and breads									
Cereal grains and flours	1	17.51	0.51	1	3.42	0.10	1	4.35	0.13
Rolls, bagels, pita bread, croutons, dumplings, matzo, tortilla	2	17.27	0.55	2	3.37	0.12	2	4.27	0.15
White bread	3	16.28	0.56	3	3.18	0.12	3	3.82	0.14
Pasta	4	11.30	0.46	4	2.21	0.10	5	2.66	0.11
Whole grain, oats, and high fibre breakfast cereals	5	7.69	0.32	5	1.50	0.06	6	2.13	0.09
Other whole grain breads	6	7.48	0.28	6	1.46	0.06	7	1.53	0.06
Whole wheat breads	7	7.42	0.28	7	1.45	0.06	8	1.48	0.06
Rice	8	7.08	0.28	8	1.38	0.06	4	2.74	0.11
Cookies, commercial	9	1.63	0.08	9	0.32	0.02	9	1.08	0.05
Crackers and crisp breads	10	1.33	0.09	10	0.26	0.02	11	0.53	0.04
Granola bar	11	1.06	0.10	11	0.21	0.02	10	0.55	0.04
Vegetables and fruit									
Potato	1	17.43	0.69	1	0.92	0.04	1	1.70	0.07
Tomatoes	2	12.85	0.37	2	0.68	0.02	5	0.71	0.02
Other vegetables (cucumber, immature beans, Brussels sprouts, beets, turnip)	3	8.36	0.34	3	0.44	0.02	6	0.51	0.02
Banana	4	7.85	0.24	4	0.41	0.01	2	1.43	0.05
Lettuces and leafy greens (spinach mustard greens, etc.)	5	5.82	0.25	5	0.31	0.01	15	0.15	0.01
Broccoli	6	5.28	0.34	6	0.28	0.02	14	0.15	0.01
Other fruits (blueberries, dates, kiwis, fruit salads, etc.)	7	5.12	0.28	7	0.27	0.02	4	0.98	0.05
Onion, green onions, leeks, garlic	8	4.76	0.13	8	0.25	0.01	9	0.34	0.01
Citrus fruits (oranges, grapefruits, lemons, etc.)	9	4.36	0.21	9	0.23	0.01	7	0.51	0.03
Corn	10	3.85	0.33	10	0.20	0.02	10	0.26	0.02
Cabbage and kale	11	3.49	0.27	11	0.18	0.02	19	0.10	0.01
Carrots	12	2.50	0.11	12	0.13	0.01	11	0.25	0.01
Apple	13	2.38	0.09	13	0.13	0.01	3	1.07	0.04
Mushrooms	14	2.23	0.17	14	0.12	0.01	24	0.05	0.01

Peppers, red and green	15	1.87	0.10	15	0.10	0.01	17	0.11	0.01
Melons (canteloup, honeydew, watermelon)	16	1.84	0.21	16	0.10	0.01	12	0.20	0.02
Grapes and raisins	17	1.80	0.13	17	0.10	0.01	8	0.39	0.03
Juices, tomato and vegetable	18	1.44	0.17	18	0.08	0.01	21	0.08	0.01
Cauliflower	19	1.32	0.17	19	0.07	0.01	26	0.04	0.01
Peaches, nectarines	20	1.06	0.10	20	0.06	0.01	18	0.11	0.01
Squashes	21	1.05	0.12	21	0.06	0.01	23	0.06	0.01
Nuts, seeds, and legumes									
Nuts	1	32.03	1.73	1	1.71	0.11	1	2.17	0.14
Peanut butter and other nut spreads	2	21.34	1.29	2	1.14	0.07	2	1.26	0.08
Legumes	3	21.13	1.40	3	1.13	0.08	3	0.77	0.05
Foods made with vegetable proteins (tofu)	4	9.44	1.29	4	0.50	0.07	5	0.27	0.05
Seeds	5	7.25	1.18	5	0.39	0.07	4	0.44	0.08
Peas and snow peas	6	4.11	0.34	6	0.22	0.02	7	0.14	0.01
Plant-based beverage (soy, almond, cashew, and coconut)	7	2.74	0.35	7	0.15	0.02	6	0.20	0.02
Beans	8	1.97	0.19	8	0.11	0.01	8	0.08	0.01

Note: Values are percentage ± SE based on population ratios. Food categories that contributed <1% (*n* = 71; 45% of Bureau of Nutritional Sciences food codes) of protein to a given food group are not reported.

Figure 3.1 Mean (±SE) usual intake of protein from animal- and plant-based foods among Canadian adults (≥19 y) from the 2015 Canadian Community Health Survey – 2015 (*n* = 13 616).

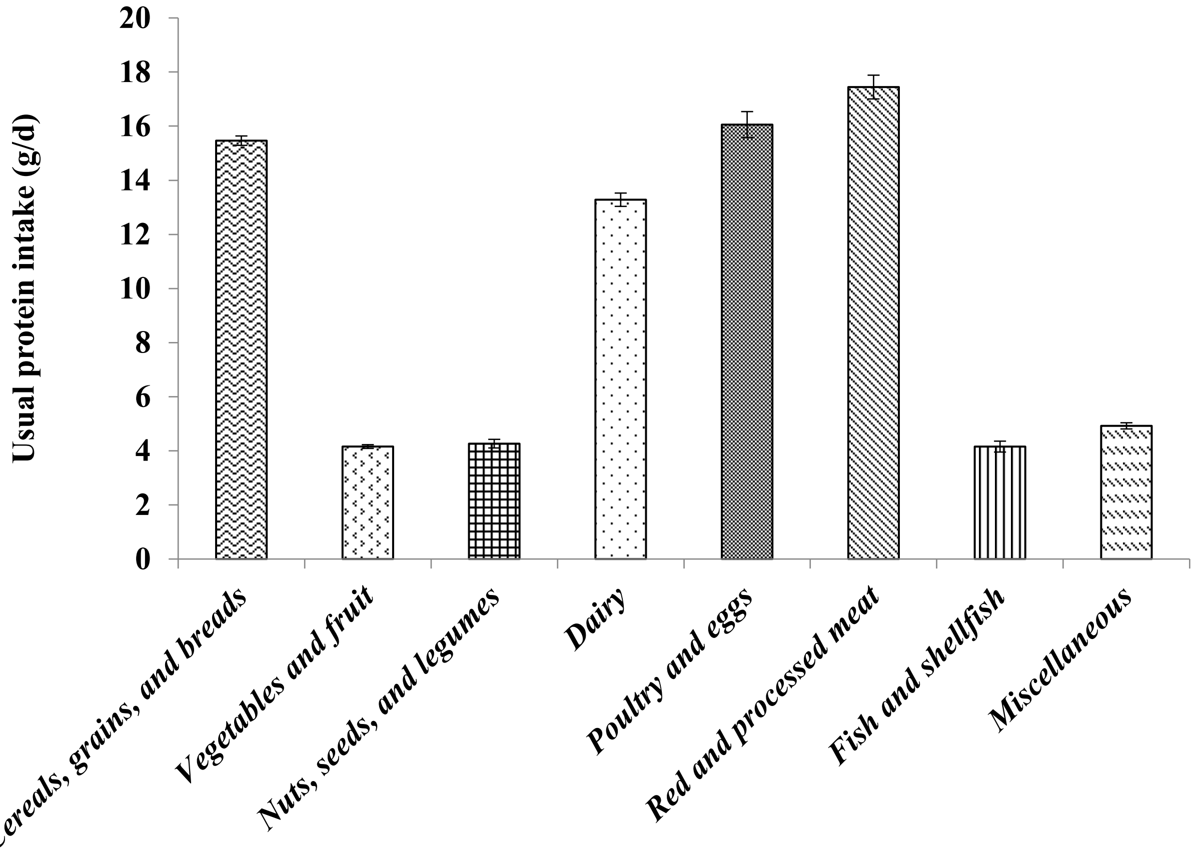
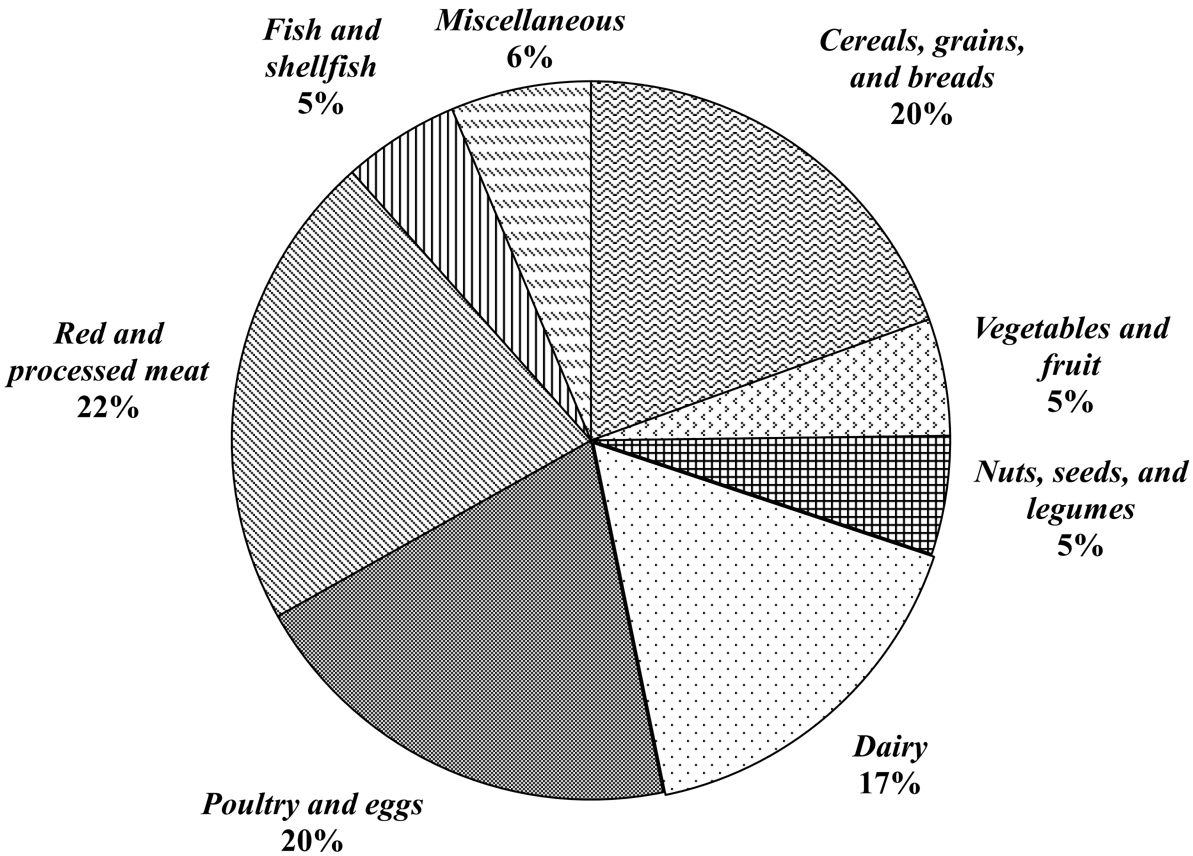


Figure 3.2 Percent contribution of protein from animal- and plant-based food to total protein among Canadian adults (≥19 y) based on 1-d intakes from the 2015 Canadian Community Health Survey – 2015. Values are percentage (%) based on population ratios (*n* = 13 616).



Supplementary Table 3.1 BNS codes used to classify foods from the 2015 Canadian Community Health Survey – Nutrition

Protein source	BNS food code	Description
Cereals, grains, and breads	1A	Pasta
	1B	Rice
	1C	Cereal grains and flour
	2A	White bread
	3A	Whole wheat breads
	3B	Other whole grain breads
	4A	Rolls, bagels, pita bread, croutons, dumplings, matzo, tortilla
	4B	Crackers and crisp breads
	4C	Muffins and English muffins
	4D	Pancakes and waffles
	4E	Croissants, piecrusts, and phyllo dough
	4F	Dry mixes (cakes, muffins, pancakes)
	5A	Whole grain, oats, and high fibre breakfast cereals
	6A	Breakfast cereal (other)
	7A	Cookies, commercial
	7B	Biscuits, commercial
	7C	Granola bar
	8A	Pies, commercial (Pop Tarts)
	8B	Cakes, commercial (frozen cake)
	8C	Danishes, doughnuts, and other pastries, commercial
	10J	Plant-based beverage (rice beverage)
Vegetables and fruit	36B	Broccoli
	36C	Cabbage and kale
	36D	Cauliflower
	36E	Carrots
	36F	Celery
	36G	Corn
	36H	Lettuces and leafy greens (spinach, mustard greens, etc.)
	36I	Mushrooms
	36J	Onion, green onions, leeks, garlic
	36L	Peppers, red and green

	36M	Squashes
	36N	Tomatoes
	36O	Juices, tomato and vegetable
	36P	Other vegetables (cucumber, immature beans, Brussels sprouts, beets, turnip)
	39A	Potato
	40A	Citrus fruits (oranges, grapefruits, lemons, etc.)
	40B	Apple
	40C	Banana
	40D	Cherries
	40E	Grapes and raisins
	40F	Melons (canteloupe, honeydew, watermelon)
	40G	Peaches, nectarines
	40H	Pears
	40I	Pineapple
	40J	Plums and prunes
	40K	Strawberries
	40L	Other fruits (blueberries, dates, kiwis, fruit salads, etc.)
Nuts, seeds, and legumes	33A	Nuts
	33B	Seeds
	33C	Peanut butter and other nut spreads
	36A	Beans
	36K	Peas and snow peas
	37A	Legumes
	37B	Foods made with vegetable proteins (tofu)
	10J	Plant-based beverage (soy, almond, cashew, and coconut)
Dairy	9A	Ice cream
	9B	Ice milk
	9C	Frozen yoghurt
	10A	Milk, whole
	10B	Milk, 2% MF
	10C	Milk, 1% MF
	10D	Milk, skim
	10E	Milk, evaporated, whole
	10F	Milk, evaporated, 2% MF

	10G	Milk, evaporated, skim
	10H	Milk, condensed
	10I	Other types of milk (whey, buttermilk)
	10K	Goat and sheep milk
	13A	Whipping cream
	13B	Table cream
	13C	Half and half cream
	13D	Sour cream
	14A	Cottage cheese
	14B	Cheese, less than 10% MF
	14C	Cheese, 10% MF to 25% MF
	14D	Cheese, more than 25% MF
	15A	Yoghurts, less than 2% MF
	15B	Yoghurts, more than 2.1% MF
	17A	Butter
Poultry and eggs	16A	Egg
	27A	Chicken, meat only
	27B	Chicken, meat and skin
	27C	Turkey, meat only
	27D	Turkey, meat and skin (including ground turkey)
	27E	Other birds (duck, pheasant, pigeon)
	27F	Birds, skin only
Red and processed meat	22A	Beef, lean only
	22B	Beef, lean and fat
	22C	Beef, ground
	23A	Veal, lean only
	23B	Veal, lean and fat (including ground veal)
	24A	Lamb, lean only
	24B	Lamb, lean and fat (including ground lamb)
	25A	Pork, fresh, lean only
	25B	Pork, fresh, lean and fat (including ground pork)
	25C	Bacon
	25D	Ham, cured, lean only
	25E	Ham, cured, lean and fat
	28A	Liver
	28B	Liver pate

	29A	Offal
	30A	Sausage
	31A	Game meat
	32A	Luncheon meat
Fish and shellfish	34A	Fish, less than 6% total fat
	34B	Fish, superior or equal to 6% total fat
	35A	Shellfish
Miscellaneous	16B	Egg substitutes
	18A	Regular tub margarine
	18B	Calorie-reduced tub margarine
	20A	Block margarine
	21A	Vegetable oils
	21B	Animal fats
	21C	Shortening
	38A	Potato chips
	38B	Fried or roasted potatoes
	41A	Sugars (white and brown)
	41B	Jams, jellies, and marmalade
	41C	Other sugars (syrups, molasses, honey, etc.)
	41D	Sugar substitutes (aspartame, dextrose)
	42A	Popcorn, plain and pretzels
	42B	Salty and high-fat snacks (including tortilla chips)
	43A	Candies, gums, etc.
	43B	Ice pop, sherbet
	43C	Jello, dessert toppings, and pudding mixes, commercial
	44A	Chocolate bar
	45A	Fruit juice
	46A	Soft drinks, regular
	46B	Soft drinks, aspartame
	46C	Fruit drinks
	46D	Other beverages (malted milk, chocolate beverage)
	46E	Energy drink
	46F	Vitamin water
	46G	Sports drink
	47A	Spirits
	47B	Liqueurs

48A	Wine
49A	Beer
49B	Coolers
50A	Soups with vegetables
50B	Soups without vegetables
50C	Gravies
50D	Sauces (white, Bérnaise, soya, tartar, ketchup, etc.)
50E	Salad dressings (with or without oil)
50F	Seasonings (salt, vinegar, etc.)
51A	Tea (including iced tea)
51B	Coffee
51C	Water (well and mineral)
52A	Baby food product
52B	Infant formula
53A	Spices
53B	Others (baking soda, baking powder, yeast, etc.)
54A	Energy bar
54B	Protein bar and shake
54C	Meal replacements
130A	Spaghetti
227A	Fats and oils (recipe sub-group)
231D	Milk-based beverages (milk shakes, malted milk, hot cocoa, instant breakfast, etc.)

Note: BNS food codes based on the variable FID_FGR were used to classify foods. All food categories reported in the CCHS were accounted for, totalling 159 BNS food codes. BNS, Bureau of Nutritional Sciences; MF, milk fat.

Supplementary Table 3.2 Percent contribution of individual food categories to protein intake from *miscellaneous* foods and beverages, total protein, and total energy among Canadian adults (≥19 y) based on 1-d intakes from the 2015 Canadian Community Health Survey – Nutrition (*n* = 13 616)[a]

	Miscellaneous		Total protein		Total energy	
	Rank	%±SE	Rank	%±SE	Rank	%±SE
Meal replacements	1	18.59±2.16	1	1.18±0.16	19	0.41±0.05
Soups without vegetables	2	8.54±0.55	2	0.54±0.03	20	0.39±0.04
Beer	3	8.51±0.55	3	0.54±0.04	2	2.23±0.14
Coffee	4	7.52±0.27	4	0.48±0.01	26	0.14±0.02
Fruit juice	5	6.44±0.32	5	0.41±0.02	8	1.60±0.07
Fried or roasted potatoes	6	6.20±0.43	6	0.39±0.03	10	1.15±0.07
Salty and high-fat snacks (including tortilla chips)	7	5.81±0.51	7	0.37±0.03	13	1.004±0.08
Chocolate bar	8	5.77±0.43	8	0.37±0.03	9	1.16±0.08
Sauces (white, bernaise, soya, tartar, ketchup, etc.)	9	4.97±0.26	9	0.31±0.01	18	0.53±0.03
Potato chips	10	4.93±0.40	10	0.31±0.03	11	1.13±0.09
Soups with vegetables	11	4.50±0.43	11	0.29±0.03	21	0.38±0.04
Protein bar and shake	12	2.03±0.43	12	0.13±0.03	36	0.07±0.02
Popcorn, plain and pretzels	13	2.01±0.33	13	0.13±0.02	24	0.23±0.04
Gravies	14	1.89±0.22	14	0.12±0.01	30	0.11±0.01
Others (baking soda, baking powder, yeast, etc.)	15	1.87±0.10	15	0.12±0.01	28	0.13±0.01
Candies, gums, etc.	16	1.70±0.49	16	0.11±0.03	16	0.66±0.10
Salad dressing (with or without oil)	17	1.45±0.07	17	0.09±0.003	3	2.12±0.07
Energy bar	18	1.06±0.35	18	0.07±0.02	35	0.08±0.03

[a]Values are based on population ratios.
Note: Food categories that contributed <1% (n = 71; 45% of BNS food codes) of protein to a given food group are not reported.

Bridge statement 2

In the previous chapter, we demonstrated that while most Canadians have adequate protein intakes, the majority derived from animal sources, notably red and processed meat, poultry and eggs, and dairy. Albeit recognition of the environmental impact of animal-based foods in CFG, the food guide was informed solely by foods contributing to nutrient recommendations and inverse associations with chronic diseases. Facilitating the transition to healthy and sustainable diets will not only require an understanding of the environmental impact of animal- and plant-based foods but their contribution to other dimensions of diet sustainability. In the next chapter, we quantified the carbon footprint of self-selected diets among Canadian adults and compared intake of food groups, nutrients, and diet quality between respondents consuming low- and high-GHGE diets.

Chapter 4: Manuscript 2 – Carbon footprint of Canadian diets

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Carbon footprint of Canadian self-selected diets: Comparing intake of foods, nutrients, and diet quality between low- and high-greenhouse gas emission diets

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4.1 Abstract

Individuals' dietary choices are critical determinants of human and planetary health. Although the carbon footprint of animal-based foods typically exceeds that of plants, trade-offs among nutritional outcomes and environmental sustainability in the context of regional self-selected diets are less understood. The objectives were to estimate the carbon footprint of Canadian self-selected diets and to compare intake of food groups, nutrients, and diet quality between low- and high-greenhouse gas emission (GHGE) diets. Dietary intake was assessed using 24-h recalls from the 2015 Canadian Community Health Survey (CCHS) – Nutrition for adults ≥19 y (n = 13,612). Estimates from the database of Food Impacts on the Environment for Linking to Diets were used to link foods and beverages reported in the CCHS to their GHGE. Boundaries for GHGE estimates were mostly cradle-to-farm gate and for certain processed products, cradle-to-processing gate. Data from Statistics Canada were used to account for food loss at the retail and consumer levels in our calculation of GHGE. The Alternative Healthy Eating Index-2010 was used to calculate diet quality. The study sample was divided into quintiles based on their diet-related GHGE expressed per 1,000 kcal; low- and high-GHGE diets were those of respondents in the lowest and highest quintiles, respectively. Dietary GHGE (mean ± SE) was 3.98 ± 0.06 kg carbon dioxide-equivalents (CO_2eq) per person per d or 2.15 ± 0.03 kg CO_2eq per 1,000 kcal. Animal-based foods contributed three-quarters of Canadians' total diet-related GHGE, with red and processed meat alone accounting for 47.05 ± 0.82%. High-GHGE diets contained more animal-based foods, vegetables and fruit, and miscellaneous foods and beverages, whereas low-GHGE diets contained more cereals, grains, and breads. Moreover, high-GHGE diet respondents had higher intakes of nutrients of public health concern (calcium, vitamin D, iron, and potassium), but also higher intakes of saturated fat and sodium, and a lower overall diet quality compared to low-GHGE diet respondents (47.27 ± 0.46 vs. 55.31 ± 0.49 points). These nutritional and environmental trade-offs warrant attention in shaping future food policy and dietary guidance in Canada aimed at meeting global targets for climate change.

Keywords

Canada's Food Guide; Canadian Community Health Survey; Dietary pattern; Life cycle assessment; Nationally representative survey; Sustainable diet.

Highlights

• In 2015, Canadian self-selected diets averaged 3.98 kg CO_2equivalents per person per day.

• The carbon footprint of individuals in the lowest and highest quintiles differed 5-fold.

• Three-quarters of dietary greenhouse gas emissions derived from animal-based foods.

• Canadians with the highest carbon footprint had higher intakes of nutrients of concern.

• Canadians with the lowest carbon footprint had a higher overall diet quality.

4.2 Introduction

The Paris Agreement aims to limit global temperature rise to 1.5 °C above pre-industrial levels, failure of which would lead to irreversible impacts for people and ecosystems (107). To achieve this goal, global anthropogenic greenhouse gas emissions (GHGE) must be reduced by 45% from 2010 levels by 2030 (108). Globally, the food supply chain accounts for one-third of anthropogenic GHGE (16). Current trends in GHGE from the food system are on a trajectory that would preclude achievement of the 1.5 °C target by 2100, even if fossil fuel and non-food related emissions were halted (1). Therefore, reducing GHGE from the food sector is essential to meeting global targets for climate change.

Recognition of the significant impact of food production on the environment has prompted research into the relationships between diets and environmental sustainability. Life cycle assessment (LCA) studies are an international standard by which to capture the environmental impacts of a food product throughout its life span, including GHGE, water use, land use, eutrophication, acidification, and loss of biodiversity. Meta-analyses of global LCA studies have generally shown that the impacts of animal-source foods exceed that of plants (5). To quantify the population-wide environmental footprint of self-selected diets, food intake by a representative sample of individuals from national nutrition surveys are linked to LCA estimates for single foods. Despite the numerous environmental impacts incurred by agriculture, self-selected diet studies have mainly focused on GHGE since this is the impact for which most data are available. Using this approach, studies have consistently found that self-selected diets containing greater amounts of plant-based foods have a lower carbon footprint relative to diets containing larger quantities of animal-source foods (7-9, 60, 61). However, given that the primary role of dietary guidance is to promote the nutritional well-being and health of populations (12, 109), translating these findings into concrete recommendations would require weighing the GHGE of single foods with their contribution to nutrient intakes and health.

Quantifying diet-related GHGE in conjunction with nutritional outcomes for populations provides insight into the compatibility of these two dimensions of diet sustainability. For example, high-nutritional quality self-selected diets in France had higher dietary GHGE than did low-nutritional quality diets (60). In the US, however, high-GHGE diets had higher intakes of vitamins A and D, choline, calcium, iron, and potassium, but lower overall diet quality scores based on the Healthy Eating Index compared to low-GHGE diets (7). Importantly, differences in food-associated GHGE and dietary intake among regions requires country-specific assessments into potential trade-offs and synergies between environmental and nutritional outcomes. Currently, there are no studies that have quantified the carbon footprint of self-selected diets in Canada.

Given the influence of food choices on diet-related GHGE, several countries have incorporated considerations of environmental sustainability into their national dietary guidelines (110). The latest version of Canada's Food Guide (CFG) published in 2019 promotes consumption of largely plant-based diets, including vegetables and fruit, whole grains, and protein foods. Primarily intended to encourage healthy eating, the new CFG acknowledges the environmental impact of food choices, but this is not explicitly implemented in the guidelines (12). Assessing the carbon footprint of Canadian self-selected diets together with nutritional outcomes would inform public health nutrition interventions and dietary guidance that facilitate the transition to diets that address both human and planetary health. Therefore, the primary objective of this study was to estimate the carbon footprint of self-selected Canadian diets. The secondary objective was to compare intake of food groups, nutrients, and diet quality between low- and high-GHGE diets.

4.3 Materials and methods

2015 Canadian Community Health Survey – Nutrition

The 2015 Canadian Community Health Survey (CCHS) – Nutrition (n = 20,487) is a nationally representative cross-sectional survey that collected detailed information pertaining to Canadians' dietary intake, as well as weight and height, physical activity, chronic health conditions, sociodemographic characteristics, and supplement intake (86). The survey targeted individuals 1 y of age and older and excluded members of the Canadian Forces and individuals residing in the Territories, Aboriginal settlements, or institutions. The response rate for the 2015 CCHS – Nutrition was 61.6%. Information pertaining to Canadians' dietary intake was collected using 24-h recalls. The Automated Multiple Pass Method was used to prompt respondents' recollection of foods and beverages consumed the day prior, from midnight to midnight. Interviews were administered in-person, year-round, and on all days of the week (including weekends). One-third of respondents completed a second 24-h dietary recall, but for the purpose of this study only the 1st recall day was used. The Canadian Nutrient File (CNF) served as the main nutrient database for the 2015 CCHS – Nutrition. The Nutrition Survey System (NSS) food codes were used by Statistics Canada to link CNF foods to those in the 24-h dietary recalls. Respondents <19 y (n = 6,568; 32.06% of sample), pregnant (n = 116; 0.57% of sample) and breastfeeding women (n = 187; 0.91% of sample), as well as those who did not complete a 24-h dietary recall (n = 4; 0.03% of sample), were excluded in the present study. Since dietary guidelines recommend getting nutrients from foods as opposed to supplements, nutrient intakes from supplements were not accounted for. The final sample size was 13,612. Access to the 2015 CCHS – Nutrition Master Files was granted by Statistics Canada (project no. 20-MAPA-MCG-6679). Population surveys conducted by Statistics Canada are granted ethical approval under the authority of the Statistics

Act of Canada. Analyses were conducted at the McGill-Concordia Laboratory of the Quebec Inter-University Centre for Social Statistics.

Linking GHGE to foods reported in the CCHS

To link CCHS foods to their GHGE, estimates were taken from the database of Food Impacts on the Environment for Linking to Diets (dataFIELD) (version 1.0; obtained online from http://css.umich.edu/page/datafield). A schematic illustrating the process of linking databases is in **Figure 4.1**. DataFIELD was developed to link environmental impacts associated with the production of food commodities to foods reported in What We Eat in America (WWEIA), the dietary intake interview component of the National Health and Nutrition Examination Survey. The development of dataFIELD is described in detail elsewhere (111). Briefly, GHGE for 332 commodity foods were obtained from global LCA studies published between 2005 and 2016 and assigned to commodities in the US EPA's Food Commodity Intake Database (FCID). Estimates were expressed as kg of carbon dioxide-equivalents (CO_2-eq) per kg of commodity to account for differences in the global warming potential of greenhouse gases over a 100-year horizon, unless otherwise stated in dataFIELD. The LCA boundaries were cradle-to-farm gate for most food commodities and cradle-to-processing gate for certain refined products. To account for food loss in our calculation of diet-related GHGE, percent loss estimates for commodities were taken from Statistics Canada (112) or the USDA's Loss-Adjusted Food Availability data series when Canadian estimates were not available. Estimates accounted for loss at both the retail and consumer levels and were taken from 2015 to correspond to the CCHS.

To assign GHGE to foods reported in the CCHS, we first linked GHGE and loss estimates to commodities in the FCID Recipe Database 2005–10 (obtained online from https://fcid.foodrisk.org/dbc/). The FCID Recipe Database consists of WWEIA foods translated into commodity form through recipes. GHGE and loss estimates were merged with the FCID Recipe Database by commodity codes (variable name: FCID_Code). A variable for GHGE accounting for losses was calculated for each WWEIA food by multiplying the proportion of each commodity with its corresponding GHGE and loss estimates. GHGE for each commodity was then aggregated for every WWEIA food to obtain an estimate for CO_2-eq per kg of food.

Next, WWEIA foods and their corresponding GHGE were linked to foods in the CCHS (variable name: Food_Code). A file linking WWEIA and CCHS foods was obtained from Dr. Sharon Kirkpatrick (University of Waterloo, personal communication, 2020). In certain cases, the codes for WWEIA foods in this file did not correspond to those in the FCID Recipe Database; these codes were thus overridden with those of similar WWEIA foods present in the FCID Recipe Database. GHGE estimates were then linked to foods reported in the CCHS respondents' 24-h dietary recalls (variable name: FID_CDE).

Selected processed foods (i.e., tofu, cheese, yoghurt, carbonated drinks, beer, liquor, and snail) were linked to their GHGE at the CCHS level because LCA studies provided better estimates than those aggregated from their commodities, as done previously by Rose et al. (7). GHGE estimates for these foods were taken from Heller et al. (111), with the exception of cheese and yoghurt. Dairy products are present in dataFIELD as the commodities milk water, milk fat, and milk non-fat solids, whose aggregated GHGE estimates serve as proxies for dairy foods. Therefore, in addition to cheese and yoghurt, we overrode GHGE estimates for all dairy products at the CCHS level using cradle-to-processing gate Canadian values from Vergé et al. (113). The Bureau of Nutritional Sciences (BNS) food and recipe groups, a set of codes categorizing foods reported in the CCHS, were used to identify dairy products (114, 115). For buttermilk, powders, and certain ice cream products, the NSS food codes were used. Food loss estimates for dairy products were taken from Statistics Canada. Classification of dairy products and their estimates for GHGE and percent loss are available in **Supplementary Table 4.1**. Certain herbs and spices were linked directly to dataFIELD estimates at the CCHS level since these food items were not present in the FCID Recipe Database. Overall, 98% of CCHS foods consumed by the study sample were linked to their GHGE. GHGE estimates were aggregated for each respondent from foods reported in their 24-h dietary recall and expressed in kg CO_2-eq per 1,000 kcal to correct for total energy intake. More details for linking dataFIELD estimates to CCHS foods are available in the Supplementary Material.

Intake of food groups and subgroups

All foods reported in the CCHS were categorized into food groups and subgroups using the BNS codes, including both basic foods and recipe ingredients. Food groups were designed to align with foods in CFG, as we did previously (116). Food groups were: cereals, grains, and breads; vegetables and fruit; nuts, seeds, and legumes; red and processed meat; poultry and eggs; dairy; and fish and shellfish. Foods and beverages that did not fall into any of the groupings were classified as miscellaneous. The NSS food codes were used to classify plant-based beverages (BNS code: 10J) to the appropriate food group; rice beverage was assigned to cereals, grains, and breads, whereas soy, almond, cashew, and coconut beverages were assigned to nuts, seeds, and legumes. Food groups were further divided into 28 subgroups. Classification of food groups and subgroups is detailed in **Supplementary Table 4.2**. Intake of food groups and subgroups were aggregated per respondent and expressed as g per 1,000 kcal.

Nutrient intakes and diet quality

In Canada, calcium, vitamin D, iron, and potassium are considered nutrients of public health concern since individuals are prone to fall below recommendations (76). Moreover, CFG considers sodium, added sugars, and saturated fat nutrients to limit due to evidence linking their excess consumption to increased risk of chronic disease (12). Since information on added sugars is not available in the CNF, intake of total sugars was calculated instead. Nutrient intakes were aggregated per respondent and expressed per 1,000 kcal.

The Alternative Healthy Eating Index (AHEI)-2010 is an 11-component estimate of diet quality based on foods and nutrients associated with the risk of diet-related chronic disease (117). The BNS codes were used to classify CCHS foods into AHEI-2010 components (i.e., vegetables, whole grains, nuts and legumes, long chain omega-3 fatty acids, polyunsaturated fatty acids, alcohol, sugar-sweetened drinks and fruit juice, red and processed meat, trans fats, and sodium). Grain foods were classified as whole grains if they had a carbohydrate to fiber ratio of no more than 10:1 (118). Since information on trans fats was not available in the CCHS, a file containing the trans fat content of CNF foods was obtained upon request from Health Canada (Rita Klutka, personal communication, 2020). Each component was scored from 0 to 10 based on amounts meeting the minimum or maximum criteria with proportional scoring in between. Component scores were aggregated for each respondent to obtain a total AHEI-2010 score out of 110 points; higher scores were indicative of better overall diet quality. The classification of CCHS foods into components and scoring method for the AHEI-2010 are in **Supplementary Table 4.3**.

Statistical analyses

Survey and bootstrap weights were used to obtain representative estimates for the Canadian population and to calculate confidence intervals around point estimates, respectively (115). All statistical analyses were performed using SAS software version 9.3 (SAS Institute Inc., Cary, NC) and SAS-callable SUDAAN software version 11.0.1 (RTI International, Durham, NC). Weighted percentile cut-offs were used to classify respondents into quintiles based on their energy-adjusted dietary GHGE; individuals in the first and fifth quintiles are hereafter referred to as low- and high-GHGE diet respondents, respectively. Cross-tabulations were employed to determine the demographic characteristics of the study sample. Population ratios were used to estimate the percent contribution of food groups and subgroups to total dietary GHGE. Age- and sex-standardized means were generated for intake of food groups, nutrients, and diet quality for low- and high-GHGE diets. A variable in the CCHS categorizing respondents into age-sex groups corresponding to those in the Dietary Reference Intakes was used as the standardizing variable (variable name: DHHDDRI). t-tests were used to detect significant differences between GHGE diet groups. Alpha was set at 0.05 for all statistical tests.

4.4 Results

Carbon footprint of Canadian self-selected diets

Self-selected dietary GHGE among Canadian adults was (mean ± SE) 3.98 ± 0.06 kg CO_2-eq per person per day or 2.15 ± 0.03 kg CO_2-eq per 1,000 kcal. High-GHGE diet respondents had a carbon footprint five-fold that of low-GHGE diet respondents (4.65 ± 0.07 vs. 0.90 ± 0.01 CO_2-eq per 1,000 kcal). Overall, the sample was split evenly between males and females (**Table 4.1**).

The majority of respondents were between the ages of 31 and 50 y (38%), Caucasian (74%), had some post-secondary education (34%), and a household income less than CAD$50,000 per y (34%). The high-GHGE diet group had a higher proportion of males (+11.87%) and Caucasians (+7.35%) compared to the low-GHGE diet group.

Contribution of food groups and subgroups to dietary GHGE

The carbon footprint of self-selected diets was largely attributable to animal-based foods, which contributed three-quarters of Canadians' total diet-related GHGE (**Figure 4.2**). Red and processed meat contributed nearly half of all dietary GHGE, an amount 3.4-fold that contributed by the second highest source, dairy. Miscellaneous foods and beverages, poultry and eggs, and vegetables and fruit contributed similarly to dietary GHGE (8–10% each), as did fish and shellfish and cereals, grains, and breads (4–5% each). The smallest contributor was nuts, seeds, and legumes (2%).

To better understand the share of diet-associated GHGE from animal- and plant-based foods, food groups were further divided into 28 subgroups. Subgroups were ranked according to their contribution to total diet-related GHGE (**Supplementary Table 4.4**). The single top contributor was beef (36%), followed by luncheon and other meats (7%), poultry (6%), milk (6%), and cheese (4%). All other subgroups each contributed <4% of total dietary GHGE.

Intake of food groups and subgroups between low- and high-GHGE diets

Stark differences were observed for intake of animal- and plant-based food groups and subgroups between low- and high-GHGE diet respondents. Intake of animal-based foods was generally greater for high- compared to low-GHGE diet consumers (**Table 4.2**). In particular, high-GHGE diets were characterized by higher intakes (all g/1,000 kcal) of red and processed meat (+78.14), dairy (+26.23), and fish and shellfish (+5.49), as well as miscellaneous foods and beverages (+112.38) and vegetables and fruit (+81.46). On the contrary, low-GHGE diet respondents had higher intakes of cereals, grains, and breads (+32.34). Intake of poultry and eggs and nuts, seeds, and legumes did not differ between GHGE diet groups. However, individually, intake of poultry was greater for low-compared to high-GHGE diet consumers (+6.07), whereas intake of eggs was lower (−6.37). Moreover, high-GHGE diet respondents consumed more plant-based beverages (+5.77). Intake of single dairy products did not differ between groups except for milk (+18.3) and yoghurt (+4.83) which was greater for high-GHGE diet respondents. Intake of shellfish, specifically, was also greater for high-compared to low-GHGE diet consumers (+5.6). Among miscellaneous foods and beverages, intake of non-alcoholic beverages (+118.12) was greater for high- compared to low-GHGE diet consumers, whereas intake of confectionary (−6.54) and oils and fats (−2.4) was lesser.

Intake of nutrients between low- and high-GHGE diets

Intakes of nutrients of concern were greater for high- compared to low-GHGE diet consumers, but so were intakes of nutrients to limit. Per 1,000 kcal, high-GHGE diet respondents consumed more calcium (+39.94 mg), vitamin D (+0.34 μg), iron (+0.97 mg), and potassium (+369.17 mg) (**Table 4.3**). However, respondents consuming high-GHGE diets also had greater intakes of saturated fat (+1.51 g) and sodium (+185.01 mg). Intake of total sugars was higher for low-GHGE diet consumers (+3.12 g).

Among macronutrients, intake of protein was greater for high- compared to low-GHGE diet respondents (+18.1 g), whereas intakes of carbohydrates and fibre were lower (−19.28 g and −1.29 g, respectively) (**Supplementary Table 4.5**). Total fat intake did not differ between GHGE diet groups. However, intake of cholesterol in the high-GHGE diet group was double that of the low-GHGE diet group. High-GHGE diet respondents also had higher intakes of monounsaturated fats and most vitamins (A, C, thiamin, riboflavin, niacin, B6, and B12) and minerals (phosphorus and zinc). Yet, intakes of polyunsaturated (+2.55 g) and essential fatty acids (linoleic acid: +2.49 g and linolenic: +0.13 g) were higher for low-GHGE diet respondents.

Diet quality between low- and high-GHGE diets

Despite having lower intakes of nutrients of concern, low-GHGE diet consumers had a better overall diet quality than high-GHGE diet consumers. Specifically, the total AHEI-2010 score was 8 points higher for low-compared to high-GHGE diet respondents (**Table 4.4**). Among components, the biggest difference was observed for red and processed meat, whose points were +6.48 for low-GHGE diets. The low-GHGE diet group also scored higher for whole grains (+0.94 points), nuts and legumes (+1.14 points), and polyunsaturated fatty acids (+1.94 points), but lower for vegetables (−1.18 points), trans fats (−0.85 points), and alcohol (−0.47 points). Scores for fruit, sugar sweetened-beverages and fruit juice, long-chain omega-3 fats, and sodium did not differ between GHGE diet groups.

4.5 Discussion

The present study was the first to estimate the carbon footprint of self-selected diets in Canada in conjunction with nutritional outcomes. Most diet-related GHGE derived from animal-based foods, specifically red and processed meat. Diets with the highest GHGE were characterized by higher intakes of animal-based foods, vegetables and fruit, and miscellaneous foods and beverages, and lower intakes of cereals, grains, and breads. High-GHGE diet respondents had higher intakes of nutrients of concern (calcium, vitamin D, iron, and potassium), but also nutrients to limit (saturated fat and sodium), and a lower overall diet quality. These findings point to incompatibilities between environmental and nutritional outcomes in the context of self-selected diets in Canada.

Dietary GHGE of Canadian self-selected diets was slightly lower than that of the US (4.72 kg CO_2-eq/person/d) (7), but still within range with estimates from France (4.092 kg CO_2-eq/person/d) (60) and the Netherlands (3.9 kg CO_2-eq/person/d) (8). Moreover, Canadian and US estimates were markedly similar when adjusted for caloric intake (2.15 vs. 2.21 CO_2-eq/1,000 kcal, respectively) (7). Parallel to our findings, high-GHGE diets in the US also had an energy-adjusted carbon footprint 5-fold that of low-GHGE diets. The stark difference in diet-related GHGE among Canadians highlights the potential for dietary guidance aimed at reducing the nation's overall carbon footprint, a soft policy lever that some countries have already incorporated into their own food guides.

Contribution of food groups and subgroups to dietary GHGE

The carbon footprint of self-selected diets in Canada was largely attributable to animal-based foods. Animal products generally have higher associated GHGE compared to plants, however impacts differ widely among foods. A global meta-analysis of LCA studies found that per 100 g of protein, the average impact of beef is 50 kg CO_2-eq, double that of any other protein-rich commodity food (5). High variation was observed even for similar products, which may be explained in part by differences in production practices among geographical regions. In dataFIELD, the global average GHGE for beef was 33 kg CO_2-eq/kg of food. However, this was not much different from the average calculated from LCA studies of Canadian beef (29 kg CO_2-eq/kg of food) included in dataFIELD (119-121). Moreover, while GHGE associated with the production of grass-fed beef may be lower than that of conventional grain-fed beef (122), we were unable to account for this since dataFIELD consists of average GHGE values and the CCHS does not contain variables detailing how or where reported foods items were produced. Nevertheless, existing evidence suggests that reducing intake of red and processed meat could lead to lower diet-associated GHGE. For example, one simulation study showed that cutting red meat consumption to "medical recommendations" (between 15 and 25 kg of cooked red meat per y) as a proxy for those in CFG in combination with various production scenarios could lower the carbon footprint of the Canadian livestock sector by up to 31% (123). In the Netherlands, a 50% reduction in red and processed meat consumed at dinner by individuals in the highest tertile of diet-related GHGE was estimated to reduce emissions by 15%, but also resulted in lower intakes of iron and protein (124). Our previous work with the 2015 CCHS – Nutrition revealed that most Canadians consumed enough protein, nearly one-quarter of which derived from red and processed meat (116). Yet, this food group was not a main contributor to intake of nutrients of concern. Therefore, reducing red and processed meat consumption may be beneficial from an environmental perspective without necessarily compromising protein adequacy for most segments of the population.

The diet-related GHGE imparted by other animal-based foods was less than that of red and processed meat. Poultry was among the top sources of dietary GHGE in Canadian diets, but its contribution was six times less than that of beef. One modeling study showed that replacing 100% of beef with poultry in the self-selected diets of individuals receptive to making dietary changes (i.e., "potential changers") in the US reduced dietary GHGE by 35.7% (63). This scenario also increased diet quality based on the Healthy Eating Index by 1.7% and reduced diet cost by 1.7%. Fluid milk and cheese were also within the top five contributors of dietary GHGE in Canadian self-selected diets. In France, regression analysis revealed dairy as having the weakest effect on diet-related GHGE among foods analyzed, as a one g increase in milk and cheese was associated with an increase of 1.89 and 1.47 g CO_2-eq per d for French males and females, respectively (125). Comparatively, a one g increase in meat and deli meat changed dietary GHGE by 16–17 g CO_2-eq per d. Moreover, our previous work demonstrated that milk and alternatives contributed 53 and 39% to Canadians' 1-d intakes of calcium and vitamin D, respectively, but also 29% to intake of saturated fat (46). Therefore, shifting towards consumption of alternative protein sources associated with lower GHGE could help reduce Canada's dietary carbon footprint while contributing similarly to intake of nutrients of concern.

Plant-based foods contributed the least to dietary GHGE in Canada, which parallels findings from other self-selected diet studies (8, 60, 111). Plant-based dietary patterns have been consistently shown to have the lowest environmental impact. For example, a study based on dietary patterns in Ontario, Canada, revealed that the calorie-adjusted food baskets of vegans and vegetarians had lower global warming potentials than those of omnivores (955 and 1,053 kg CO_2-eq/person/y, respectively vs. 2,282 kg CO_2-eq/person/y), although these diets represented only 0.4 and 7% of the population, respectively (126). Moreover, replacing 100% of meat and dairy in Dutch self-selected diets with plant-based alternatives resulted in a >40% reduction in diet-related GHGE and land use, but intakes of vitamin A, thiamin, vitamin B12, and zinc fell below recommendations (65). Alternatively, replacing only 30% of meat and dairy reduced environmental impacts by 14% without compromising nutrient adequacy. Therefore, making simple substitutions to reduce the disproportionately large quantity of animal-based foods making up Western diets could reduce population dietary GHGE while staying in line with nutrient recommendations.

Intake of food groups and subgroups by low- and high-GHGE diets

High-GHGE diet respondents had higher intakes of animal-based foods, as well as vegetables and fruit and miscellaneous foods and beverages compared to their low-GHGE diet counterparts. These findings are consistent with that of Rose et al. (7), who found that high-GHGE diet respondents in the US consumed more meat, dairy, seafood, and vegetables. Higher intakes of vegetables and fruit for the high-GHGE diet group could be explained by greater consumption of other plant-based food groups for the low-GHGE diet group, notably cereals, grains, and breads. Likewise, poultry intake may have been higher for low-GHGE diet consumers due the inordinately large intake of red and processed meat for high-GHGE diet consumers. The inclusion of both animal- and plant-based foods in more sustainable self-selected diets in Europe, which were characterized as having a good compromise between diet-related GHGE and nutritional quality, did not require complete exclusion of any single food group (9). Therefore, the type of animal- and plant-based foods constituting population diets is an important consideration for reducing diet-associated GHGE, but so is the proportion in which they are consumed. Shifting dietary intake to include lower carbon footprint plant-based foods without elimination of any particular food group may help with GHGE mitigation by consumers without compromising the overall healthfulness of diets.

Although high-GHGE diet respondents had higher intakes of miscellaneous foods and beverages overall, low-GHGE diet consumers had higher intakes of confectionary. Similarly, findings from one self-selected diet study in France found that consumption of sweets and salted snacks was negatively correlated with GHGE after adjusting for age, sex, and energy intake (60). However, another study observed that high consumption of discretionary foods was linked to "lower quality, higher GHGE" self-selected diets in Australia, although their broad categorization of discretionary foods included processed meat, mixed dishes, and certain dairy products (127). Heterogeneity among study designs and classification of foods make it difficult to draw cross-country comparisons, which sometimes leads to contradictory conclusions. Since the focus of this study was on animal- and plant-based foods, we categorized foods based on examples provided in CFG. Regardless, both low- and high-GHGE diet respondents had much higher intakes of miscellaneous foods and beverages than any other food group. Moreover, we previously reported that miscellaneous foods and beverages contributed 45–46% to Canadians' intakes of sodium and sugars, as well as 22% to intake of saturated fat (116). Therefore, Canadians would benefit from future dietary guidance aimed at displacing intake of miscellaneous foods and beverages with other more healthful food categories, provided these contribute little to diet-related GHGE.

Nutrient intakes and diet quality between low- and high-GHGE diets

The use of two nutritional outcomes in this study led to contradictory interpretations with diet-related GHGE. On the one hand, high-GHGE diet respondents had greater intakes of nutrients of concern (calcium, vitamin D, iron, and potassium), but also nutrients to limit (saturated fat and sodium). Yet, low-GHGE diet consumers had higher intakes of total sugars and a higher overall diet quality. Greater intakes of nutrients of concern were also observed for high-GHGE diet respondents in the US (7) and several European countries (8, 57). Moreover, one systematic review reported lower intakes of saturated fat and sodium among low-GHGE diet consumers but higher intakes of sugars (128). Taken together, these findings highlight the concern that healthy diets are not necessarily more environmentally sustainable, although this depends largely on the measures employed to assess health. In this study, we assessed average nutrient intakes based on 1-d intakes, but these do not necessarily reflect nutrient inadequacy in a population. We also used the AHEI-2010 as an indicator of overall diet quality. Despite the presence of several diet quality indices, many of which are based on adherence to specific dietary patterns (e.g., DASH, Mediterranean) or guidelines (e.g., Health Eating Index), there is currently no such score to measure adherence to the recommendations in the 2019 CFG. Therefore, we chose the AHEI-2010 since it is generalized (i.e., not specific to adherence to any one diet) and is made up of both foods and nutrients associated with markers of disease risk (117, 129). The lower diet quality score observed for high-GHGE diet respondents was attributable in large part to the penalty of red and processed meat. These findings parallel those from the US, although diet quality was measured using the Healthy Eating Index (7). Therefore, although differences in associations of diet-related GHGE and markers of nutrition and health can stem from differences in populations and dietary patterns, how these associations are interpreted depends largely on which measures are used.

Even so, the choice of diet quality score alone can largely impact associations with carbon footprint (130). For example, in France (60, 61) and Europe (9), self-selected diets with the lowest carbon footprint also had the lowest nutritional quality based on various indicators of adequate and excess nutrient intakes (i.e., mean adequacy ratio and mean excess ratio, respectively). Moreover, different diet quality scores can yield different results even within the same population. In the US, higher diet quality was associated with lower agricultural land use (131), but the direction of the association for use of fertilizers, pesticides, and water was dependent on the measure of diet quality used (i.e., Healthy Eating Index-2015 vs. AHEI-2010). Future research should consider several validated measures of nutritional adequacy and diet quality when assessing compatibility of healthy alternative dietary patterns with environmental outcomes in the Canadian context.

Strengths and limitations

One of the strengths of this study was the use of the 2015 CCHS – Nutrition as a nationally representative survey and the assessment of self-selected diets based on actual food consumption. In addition, we used a curated peer-reviewed database for linking the GHGE of commodities to foods reported in the CCHS, which was used previously to estimate the carbon footprint of self-selected diets in the US (7, 111), and accounted for associated food loss using Canadian estimates when available. Limitations include the use of mean 1-d intakes to assess nutrient intakes, which may not be reflective of usual intake. Moreover, dataFIELD estimates are global averages and thus not necessarily specific to the Canadian or North American market. Therefore, heterogeneity stemming from geographic location, but also production practices and LCA methodology (111) were not accounted for. Hence, there is a need for a Canadian-specific database of GHGE and other environmental impacts to account for the high heterogeneity among estimates for similar food products. In addition, LCA boundaries were mostly farm-to-farm gate, such that impacts associated with storage, preparation, and end-of-life were not accounted for, which could have led to underestimations of GHGE, particularly for processed and ultra-processed foods. Although two-thirds of GHGE occur on the farm for food commodities (5), cooking can account for 6–61% of a food's emissions (132). This may disproportionally affect the GHGE of plant-based foods, since the contribution of home cooking to total GHGE is greatest for some vegetables, tubers, and legumes, yet absolute impacts are still highest for meats. Also, GHGE estimates were expressed in CO_2-eq which has been ubiquitously used in self-selected diet studies. However, the use of alternative climate metrics, particularly those that treat methane differently, may have substantially altered our findings, especially for foods for which methane is a major contributor (e.g., milk and meat from ruminants). Finally, although

GHGE are a primary driver of climate change, future research should incorporate additional environmental impacts and dimensions of diet sustainability.

4.6 Conclusions

The present study provides the first assessment of Canadians' diet-related carbon footprint, showcasing intake of food groups, nutrients, and diet quality between low- and high-GHGE diets. Animal-based foods, and in particular, red and processed meat, contributed the most to dietary GHGE. Moreover, intakes of nutrients of concern, but also saturated fat and sodium, were greater for high-GHGE diet respondents, whereas diet quality was lesser, revealing inconsistencies regarding the compatibility of diet-related GHGE with nutrient intakes and diet quality. Future food policy and dietary guidance in Canada aimed at improving human health should do so in a way that also facilitates meeting scientific targets for climate change while accounting for the various synergies and trade-offs among dimensions of sustainable diets.

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Author contributions

Data curation, OA; Formal analysis, OA; Investigation, OA; Roles/Writing - original draft, OA; Visualization, OA; Conceptualization, SB; Methodology, SB; Project administration, SB; Supervision, SB; Validation, SB; Writing - review & editing, SB.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. SB received grant support from Dairy Farmers of Canada outside of this work. OA declares no conflict of interest.

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Table 4.1 Demographic characteristics of the study sample and low- and high-GHGE diets respondents from the 2015 Canadian Community Health Survey – Nutrition.

Demographics	Total sample (*n*=13,612)		Low-GHGE diets (*n*=2,849)		High-GHGE diets (*n*=2,562)		P
	%	SE	%	SE	%	SE	
Sex							
Male	49.97	0.10	44.86	1.67	56.73	1.87	<0.0001
Female	50.03	0.10	55.14	1.67	43.27	1.87	<0.0001
Age group							
19-30 y	16.24	0.65	16.81	1.43	17.52	1.74	0.7439
31-50 y	38.09	0.66	40.08	1.81	37.33	1.83	0.3019
51-70 y	33.46	0.07	30.88	1.42	34.27	1.65	0.1659
71+ y	12.21	0.02	12.23	0.74	10.88	0.77	0.258
Ethnicity							
Caucasian	73.71	0.94	68.62	1.96	75.97	1.71	0.0041
Non-Caucasian	26.29	0.94	31.38	1.96	24.03	1.71	0.0041
Level of education							
Less than secondary	12.34	0.49	14.04	1.20	11.99	1.05	0.1871
Secondary	25.97	0.76	28.12	1.55	27.99	1.85	0.9537
Some post-secondary	33.98	0.83	28.52	1.68	32.73	1.78	0.1053
Post-secondary	27.70	0.86	29.32	1.86	27.28	1.94	0.4281
Household income ($CAD/y)							
Less than 50,000	34.20	0.85	37.96	1.80	34.14	2.03	0.1415
50,000-100,000	32.39	0.82	31.16	1.70	29.26	1.73	0.4053
100,000-150,000	19.67	0.75	17.92	1.42	21.41	1.73	0.1238
More than 150,000	13.74	0.68	12.96	1.54	15.19	1.54	0.2802

Abbreviations: GHGE, greenhouse gas emissions.
P-values denote difference between low- and high-GHGE diets by *t* test.

Table 4.2 Mean 1-d intake of food groups and subgroups between low- and high-GHGE diet respondents from the 2015 Canadian Community Health Survey – Nutrition.

Food group[a]	Low-GHGE diets (*n*=2,849)		High-GHGE diets (*n*=2,562)		P
	Mean	SE	Mean	SE	
Cereals, grains, and breads	**130.88**	**3.34**	**98.54**	**2.79**	**<0.0001**
Whole grains	34.97	2.09	22.76	1.54	<0.0001
Refined grains	95.92	2.69	75.77	2.43	<0.0001
Vegetables and fruits	**155.39**	**4.99**	**236.85**	**11.9**	**<0.0001**
Vegetables	70.24	2.79	115.74	9.75	<0.0001
Potatoes	14.5	1.16	25.48	2.38	0.0001
Fruit	70.65	3.1	95.62	6.62	0.0006
Nuts, seeds, and legumes	**28.62**	**1.66**	**25.23**	**2.55**	**0.2588**
Nuts and nut butters	7.5	0.71	3.48	0.35	<0.0001
Seeds	2.2	0.78	0.33	0.08	0.0168
Legumes	15.74	1.27	12.48	1.62	0.1283
Plant-based beverages (excluding rice beverage)	3.18	0.63	8.95	2.11	0.0088
Red and processed meat	**6.87**	**0.44**	**85.01**	**1.76**	**<0.0001**
Beef (including veal)	0.23	0.06	64.58	1.72	<0.0001
Lamb	0	0	2.06	0.44	<0.0001
Pork	2.3	0.23	5.92	0.67	<0.0001
Luncheon and other meat (liver, offal, game meat)	4.35	0.39	12.45	1.15	<0.0001
Poultry and eggs	**24.95**	**1.3**	**25.25**	**1.57**	**0.8806**
Poultry	17.66	1.18	11.59	1.23	0.0004
Eggs	7.29	0.48	13.66	1	<0.0001
Dairy	**92.63**	**3.16**	**118.86**	**5.04**	**<0.0001**
Milk	61.65	3.05	79.95	4.12	0.0007
Cream	3.95	0.33	4.62	0.41	0.227
Cheese	12.39	0.6	13.16	0.86	0.463
Yoghurt	7.79	0.69	12.62	1.22	0.0006
Butter	1.67	0.14	1.56	0.13	0.5754
Frozen dairy	5.18	0.78	6.96	1.17	0.1995
Fish and shellfish	**5.63**	**0.62**	**11.12**	**1.05**	**<0.0001**
Fish	5.35	0.61	5.24	0.69	0.9066
Shellfish	0.28	0.08	5.88	0.77	<0.0001
Miscellaneous	**1130.26**	**28.48**	**1242.64**	**44.29**	**0.0457**
Alcoholic beverages	61.76	6.91	72.27	5.96	0.213
Non-alcoholic beverages (including fruit juice, tea, coffee)	977.15	26.75	1095.35	44.2	0.0296
Confectionary (including	19.04	0.92	12.5	0.63	<0.0001

sugars, syrups, and preserves)					
Oils and fats (including margarine)	8.88	0.31	6.48	0.22	<0.0001
Other (including savory snacks, soups, sauces, seasonings)	63.43	4.88	56.04	4.39	0.2821

Abbreviations: GHGE, greenhouse gas emissions.
[a]Units are in g/1,000 kcal.

Table 4.3 Mean 1-d intake of nutrients of concern and to limit between low- and high-GHGE diet respondents from the 2015 Canadian Community Health Survey – Nutrition.

Nutrients	Low-GHGE diets (*n*=2,849)		High-GHGE diets (*n*=2,562)		P
	Mean	SE	Mean	SE	
Nutrients of concern					
Calcium, mg/1,000 kcal	379.15	6.07	419.09	8.63	0.0002
Vitamin D, µg/1,000 kcal	2.01	0.08	2.35	0.1	0.0066
Iron, mg/1,000 kcal	6.69	0.08	7.66	0.09	<0.0001
Potassium, mg/1,000 kcal	1277.57	16.73	1646.74	25.51	<0.0001
Nutrients to limit					
Saturated fat, g/1,000 kcal	10.81	0.16	12.32	0.18	<0.0001
Total sugars, g/1,000 kcal	47.28	0.75	44.16	0.87	0.0076
Sodium, mg/1,000 kcal	1393.76	17.29	1578.77	25.16	<0.0001

Abbreviations: GHGE, greenhouse gas emissions.

Table 4.4 Mean 1-d Alternative Healthy Eating Index-2010 total and component scores between low- and high-GHGE diet respondents from the 2015 Canadian Community Health Survey – Nutrition[a].

Component	Maximum score	Low-GHGE diets		High-GHGE diets		P[b]
		(*n*=2,849)		(*n*=2,562)		
		Mean	SE	Mean	SE	
To encourage[c]						
Vegetables	10	5.29	0.16	6.47	0.14	<0.0001
Fruit	10	3.88	0.15	4.29	0.18	0.0855
Whole grains	10	4.03	0.17	3.09	0.14	<0.0001
Nuts and legumes	10	4.13	0.17	2.99	0.18	<0.0001
Long-chain (n-3) fats (EPA and DHA)	10	1.28	0.07	1.19	0.06	0.3245
Polyunsaturated fats	10	6.48	0.11	4.54	0.11	<0.0001
To limit[d]						
Sugar-sweetened beverages and fruit juice	10	8.58	0.08	8.55	0.08	0.7519
Red and processed meat	10	9.1	0.06	2.62	0.14	<0.0001
Trans fat	10	3.72	0.16	4.57	0.15	0.0001
Sodium	10	5.79	0.11	5.47	0.13	0.0681
In moderation[e]						
Alcohol	10	3.03	0.08	3.5	0.11	0.0006
Total score	110	55.31	0.49	47.27	0.46	<0.0001

Abbreviations: DHA, docosahexaenoic acid; EPA, eicosapentaenoic acid; GHGE, greenhouse gas emissions.

[a]The Alternative Healthy Eating Index-2010 is a measure of diet quality based on evidence of associations between food and nutrients with disease risk. The maximum score for each component is 10 for a possible total of 110 points. Higher scores are indicative of better diet quality.

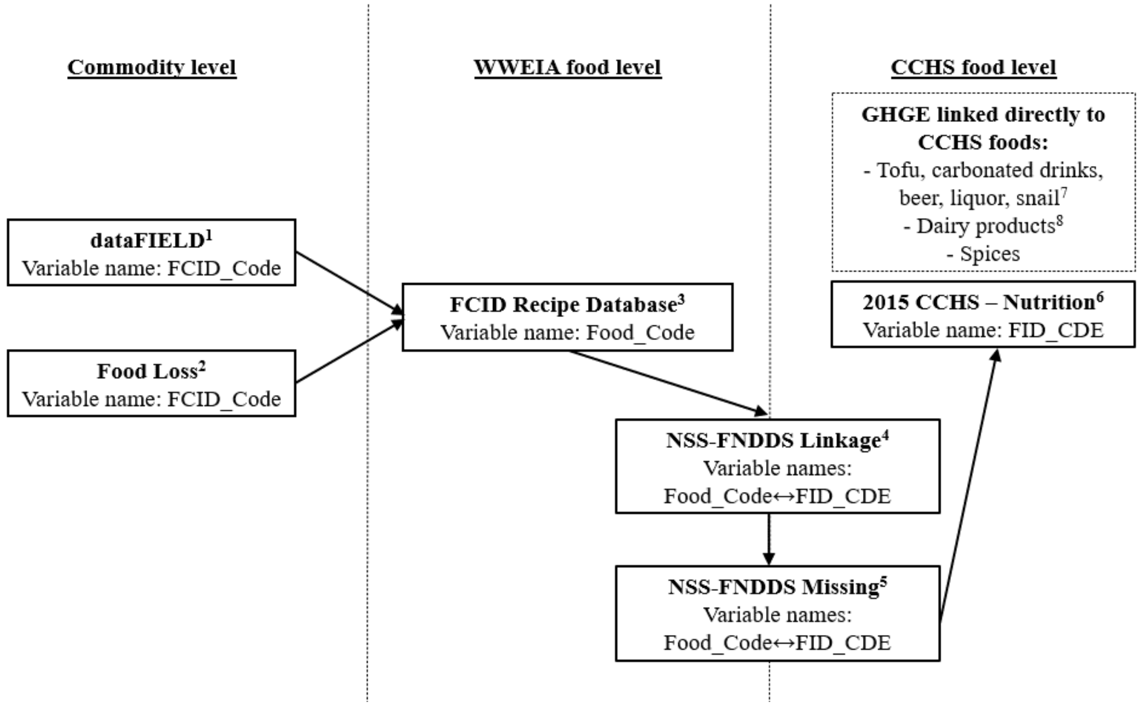
[b]Determined by *t*-test.

[c]Higher scores correspond to higher intakes.

[d]Higher scores correspond to lower intakes.

[e]Higher scores correspond to moderate intake. Lower scores correspond to heavy intake. Non-drinkers received a score of 2.5.

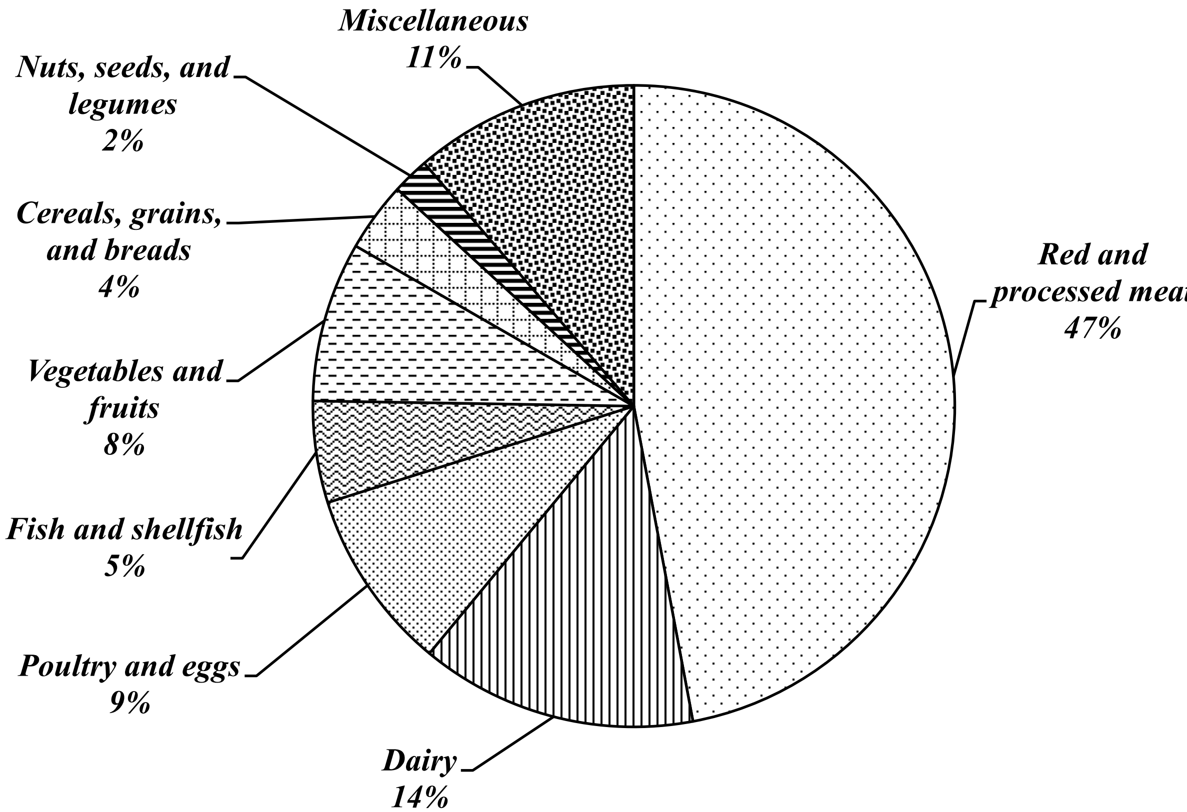
Figure 4.1 Linking estimates of GHGE and food loss for commodities to foods reported in the 2015 Canadian Community Health Survey – Nutrition.



Notes: Variable name refers to the variable used to link the datasets.
[1]Database containing GHGE estimates for commodity foods. Obtained online from http://css.umich.edu/page/datafield.
[2]Database curated from estimates for food loss in North America obtained from Statistics Canada and the USDA's LAFA data series. Statistics Canada values were obtained online from https://www150.statcan.gc.ca/t1/tbl1/en/cv.action?pid=3210005401. LAFA values were obtained online from https://www.ers.usda.gov/data-products/food-availability-per-capita-data-system/.
[3]Database containing WWEIA foods broken down into commodities. Obtained online from https://fcid.foodrisk.org/dbc/.
[4]File linking WWEIA and CCHS foods. Obtained upon request from Dr. Sharon Kirkpatrick (University of Waterloo, personal communication, 2020).
[5]Codes for certain CCHS foods did not link to those in NSS-FNDDS Linkage. Therefore, NSS-FNDDS Missing was a file created to override WWEIA codes with those for similar foods available in the FCID Recipe Database.
[6]Access to the 2015 CCHS – Nutrition Master Files was granted by Statistics Canada (project no. 20-MAPA-MCG-6679).
[7]GHGE estimates for these foods were linked directly to CCHS foods. Estimates were taken from Heller et al. (111).
[8]GHGE estimates for dairy products were linked directly to CCHS foods. Estimates were taken from Vergé et al. (113).
Abbreviations: CCHS, Canadian Community Health Survey; dataFIELD, Database of Food Impacts on the Environment for Linking to Diets; FCID, Food Commodity Intake Database;

FNDDS, Food and Nutrient Database for Dietary Studies; LAFA, Loss-Adjusted Food Availability; NSS, Nutrition Survey System; WWEIA, What We Eat in America.

Figure 4.2 Contribution of animal- and plant-based food groups to total dietary GHGE based on 1-d consumption by respondents in the 2015 Canadian Community Health Survey – Nutrition (*n*=13,612).



Values are percent contribution to total diet-related GHGE based on population ratios.

Supplementary Table 4.1 Classification of dairy products and their estimates for greenhouse gas emissions and food loss

Dairy product	BNS food groups	NSS food codes	GHGE (kg CO_2eq/kg)[1]	Food loss (%)[2]	Food loss proxy[3]
Cheese	Cheese, less than 10% M.F. (14B); cheese, 10 to 25% M.F. (14C); cheese, more than 25% M.F. (14D).	-	5.3	20.1	Variety cheese
Cottage cheese	Cottage cheese (14A).	-	1.8	40	-
Yogurt	Yoghurts, less than 2% M.F. (15A); yoghurts, more than 2.1% M.F. (15B); frozen yoghurt (09C).	-	1.5	30.5	-
Fluid milk	Milk, whole (10A); milk, 2% (10B); milk, 1% (10C); milk, skim (10D).	-	1	29.5	Milk, 3.25% M.F.
Buttermilk	-	Milk, fluid, buttermilk, cultured, 1% M.F. (124); milk, fluid, buttermilk, cultured, 2% M.F. (5487); milk, fluid, buttermilk, cultured, whole (7024).	1.1	28.1	-
Powders	-	Milk, dry, buttermilk, sweet cream (67); whey, acid, dry (78); whey, sweet, dry (80); milk, dry, skim, powder, instant (115); milk, dry, skim, powder, regular (134); malted milk, natural flavour, enriched powder (2896); malted milk, chocolate flavour, enriched powder (2900).	10.1	42	Skim milk powder
Concentrates	Milk, evaporated, whole (10E);	-	3.1	25.5	Concentrated whole milk

	milk, evaporated, 2% (10F); milk, evaporated, skim (10G); milk, condensed (10H).				
Creams	Whipping cream (13A); table cream (13B); half and half cream (13C).	-	2.1	22.6	Table cream, 18% M.F.
Sour cream	Sour cream (13D).	-	2.5	19.2	-
Butter	Butter (17A).	-	7.3	39.4	-
Frozen dairy	Ice cream (09A); ice milk (09B).	Milk shake, chocolate, thick (75); milk shake, vanilla, thick (76).	2.1	33	Ice cream

[1]Canadian GHGE estimates for dairy products taken from Vergé et al. (113).
[2]Percent food loss estimates from Statistics Canada.
[3]If food loss estimates were not available for specific dairy products, proxies were used.
Abbreviations: BNS, Bureau of Nutritional Sciences; CO_2eq, carbon dioxide equivalents; GHGE, greenhouse gas emissions; M.F., milk fat; NSS, Nutrition Survey System.

Supplementary Table 4.2 Classification of food groups and subgroups in the 2015 Canadian Community Health Survey – Nutrition

Food group/subgroup	Classification based on BNS food groups
Cereals, grains, and breads	
Whole and refined grains[1]	Pasta (01A); rice (01B); cereal grains and flours (01C); white bread (02A); whole wheat breads (03A); other whole grain breads (03B); rolls, bagels, pita bread, croutons, dumplings, matzo, tortilla (04A); crackers and crispbreads (04B); muffins and English muffins (04C); pancakes and waffles (04D); croissants, piecrusts and phyllo dough (04E); dry mixes (04F); whole grain oats and high fibre breakfast cereals (05A); breakfast cereal (other) (06A); cookies, commercial (07A); biscuits, commercial (07B); granola bar (07C); pies, commercial (08A); cakes, commercial (08B); danishes, donuts and other pastries, commercial (08C); plant-based beverage (10J, but only rice, enriched, fid_cde=4780).
Vegetables and fruits	
Vegetables	Broccoli (36B); cabbage and kale (36C); cauliflower (36D); carrots (36E); celery (36F); corn (36G); lettuces and leafy greens (36H); mushrooms (36I); onion, leeks, and garlic (36J); peppers (36L); squashes (36M); tomatoes (36N); juices, tomato and vegetable (36O); other vegetables (36P).
Potatoes	Potato (39A).
Fruit	Citrus fruit (40A); apple (40B); banana (40C); cherries (40D); grapes and raisins (40E); melons (40F); peaches and nectarines (40G); pears (40H); pineapple (40I); plums and prunes (40J); strawberries (40K); other fruits (40L).
Nuts, seeds, and legumes	
Nuts and nut butters	Nuts (33A); peanut butter and other nut spreads (33C).
Seeds	Seeds (33B).
Legumes	Beans (36A); peas and snow peas (36K); legumes (37A); foods made with vegetable proteins (tofu) (37B).
Plant-based beverages (excluding rice beverage)[2]	Plant-based beverage (10J, but only soy, enriched, chocolate, fid_cde=6329; soy, enriched, all flavors, unsweetened, fid_cde=6330; soy, enriched, all flavors, fid_cde=6720; almond, enriched, vanilla, sweetened, fid_cde=7225; almond, enriched, chocolate, sweetened, fid_cde=7226; coconut, enriched, all flavors, sweetened, all flavors, fid_cde=7478; cashew, enriched, enriched, sweetened, fid_cde=7480).
Red and processed meat	

Beef (including veal)	Beef, lean only (22A); beef, lean and fat (22B); beef, ground (22C); veal, lean only (23A); veal, lean and fat (including ground) (23B).
Lamb	Lamb, lean only (24A); lamb, lean and fat (including ground) (24B).
Pork	Pork, fresh, lean only (25A); pork, fresh, lean and fat (including ground) (25B); bacon (25C); ham, cured, lean only (25D); ham, cured, lean and fat (25E).
Luncheon and other meat (liver, offal, game meat)	Liver (28A); liver pâté (28B); offal (29A); sausage (30A); game meat (31A); luncheon meat (32A).
Poultry and eggs	
Poultry	Chicken, meat only (27A); chicken, meat and skin (27B); turkey, meat only (27C); turkey, meat and skin (including ground) (27D); other birds (duck, pheasant, pigeon) (27E); birds, skin only (27F).
Eggs	Egg (16A).
Dairy	
Milk	Milk, whole (10A); milk, 2% (10B); milk, 1% (10C); milk, skim (10D); milk, evaporated, whole (10E); milk, evaporated, 2% (10F); milk, evaporated, skim (10G); milk, condensed (10H); other types of milk (whey, buttermilk) (10I); goat and sheep milk (10K).
Cream	Whipping cream (13A); table cream (13B); half and half cream (13C); sour cream (13D).
Cheese	Cottage cheese (14A); cheese, less than 10% M.F. (14B); cheese, 10 to 25% M.F. (14C); cheese, more than 25% M.F. (14D).
Yoghurt	Yoghurts, less than 2% M.F. (15A); yoghurts, more than 2.1% M.F. (15B).
Butter	Butter (17A).
Frozen dairy	Ice cream (09A); ice milk (09B); frozen yoghurt (09C).
Fish and shellfish	
Fish	Fish, less than 6% total fat (34A); fish, superior of equal to 6% total fat (34B).
Shellfish	Shellfish (35A).
Miscellaneous	
Alcoholic beverages	Spirits (47A); liqueurs (47B); wine (48A); beer (49A); coolers (49B).
Non-alcoholic beverages (including fruit juice, tea, coffee)	Fruit juice (45A); soft drinks, regular (46A); soft drinks, aspartame (46B); fruit drinks (46C); other beverages (malted milk, chocolate beverage) (46D); energy drinks (46E); vitamin

	water (46F); sports drinks (46G); tea (including iced) (51A); coffee (51B); water (51C).
Confectionary (including sugars, syrups, and preserves)	Sugars, white and brown (41A); jams, jellies and marmalade (41B); other sugars (syrups, molasses, honey) (41C); sugar substitutes (aspartame, dextrose) (41D); candies, gums (43A); ice pop, sherbet (43B); Jello, dessert toppings and pudding mixes (43C); chocolate bar (44A).
Oils and fats (including margarine)	Regular tub margarine (18A); calorie-reduced tub margarine (18B); block margarine (20A); vegetable oils (21A); animal fats (21B); shortening (21C).
Other (including savory snacks, soups, sauces, seasonings)	Egg substitutes (16B); potato chips (38A); fried or roasted potatoes (38B); popcorn, plain and pretzels (42A); salty and high-fat snacks (including tortilla chips) (42B); soups with vegetables (50A); soups without vegetables (50B); gravies (50C); sauces (50D); salad dressings (50E); seasonings (50F); babyfood product (52A); infant formula (52B); spices (53A); baking soda, baking powder, yeast (53B); energy bar (54A); protein bar and shake (54B); meal replacements (54C); Mexican recipes (99A).

[1]Whole grains were considered those whose carbohydrate to fibre ratio was no more than 10:1 as done by Wang et al. (118). All other grain foods were considered refined.
[2]The Nutrition Survey System codes (fid_cde) were used to classify plant-based beverages (BNS food group: 10J) to the appropriate food group.
Abbreviations: BNS, Bureau of Nutritional Sciences; M.F., milk fat.

Supplementary Table 4.3 Scoring method for the Alternative Healthy Eating Index-2010[1]

Component	Criteria for min score (0)	Criteria for max score (10)	Serving size[2] (g)	BNS food code
Vegetables, servings/d (excluding potatoes and juices)	0	≥5	65	Broccoli (36B); cabbage and kale (36C); cauliflower (36D); carrots (36E); celery (36F); corn (36G); lettuces and leafy greens (36H); mushrooms (36I); onion, leeks, and garlic (36J); peppers (36L); squashes (36M); tomatoes (36N); juices, tomato and vegetable (36O); other vegetables (36P).
Fruit, servings/d	0	≥4	65	Citrus fruit (40A); apple (40B); banana (40C); cherries (40D); grapes and raisins (40E); melons (40F); peaches and nectarines (40G); pears (40H); pineapple (40I); plums and prunes (40J); strawberries (40K); other fruits (40L).
Whole grains, g/d[3]	0			Pasta (01A); rice (01B); cereal grains and flours (01C); white bread (02A); whole wheat breads (03A); other whole grain breads (03B); rolls, bagels, pita bread, croutons, dumplings, matzo, tortilla (04A); crackers and crispbreads (04B); muffins and English muffins (04C); pancakes and waffles (04D); croissants, piecrusts and phyllo dough (04E); dry mixes (04F); whole grain oats and high fibre breakfast cereals (05A); breakfast cereal (other) (06A); cookies, commercial (07A); biscuits, commercial (07B); granola bar (07C); pies, commercial (08A); cakes, commercial (08B); danishes, donuts and other pastries, commercial (08C).
Women		75		
Men		90		
Sugar-sweetened beverages and fruit juice, servings/d	≥1	0		
Sugar-sweetened beverages			226.8	Soft drinks, regular (46A); soft drinks, aspartame (46B); fruit drinks

				(46C); other beverages (malted milk, chocolate beverage) (46D); energy drinks (46E); vitamin water (46F); sports drinks (46G).
100% fruit juice			113.4	Fruit juice (45A).
Nuts and legumes, servings/d	0	≥1		
Nuts, legumes, seeds			50	Beans (36A); peas and snow peas (36K); nuts (33A); legumes (37A).
Nut butters			32	Peanut butter and other nut spreads (33C).
Tofu			50	Foods made with vegetable proteins (tofu) (37B).
Red and/or processed meats, servings/d	≥1.5	0	100	Beef, lean only (22A); beef, lean and fat (22B); beef, ground (22C); veal, lean only (23A); veal, lean and fat (including ground) (23B); pork, fresh, lean only (25A); pork, fresh, lean and fat (including ground) (25B); bacon (25C); ham, cured, lean only (25D); ham, cured, lean and fat (25E); sausage (30A); luncheon meat (32A).
***Trans* fats, % of energy**	≥4	≤0.5		
Long-chain omega-3 fats (EPA+DHA), mg/d	0	250		
PUFA, % of energy	≤2	≥10		
Sodium, mg/d	Highest decile	Lowest decile		
Alcohol, drinks/d				
Women	≥2.5	0.5-1.5		
Men	≥3.5	0.5-2.0		
Wine			141.75	Wine (48A).
Beer			340.2	Beer (49A); coolers (49B).
Liquor			42.53	Spirits (47A); liqueurs (47B).
Total score	0	110		

[1]The scoring scheme for the Alternative Healthy Eating Index-2010 was taken from Chiuve et al. (117).
[2]Serving sizes for components were taken from Wang et al. (118).

[3]Among these grain foods, whole grains were considered those whose carbohydrate to fibre ratio was no more than 10:1 as done by Wang et al. (118).
Abbreviations: BNS, Bureau of Nutritional Sciences; DHA, docosahexaenoic acid; EPA, eicosapentaenoic acid, PUFA, polyunsaturated fat.

Supplementary Table 4.4 Mean and percent contribution of food groups and subgroups to diet-related GHGE as consumed based on 1-d intake from the 2015 Canadian Community Health Survey – Nutrition (*n*=13,612)

	Rank[1]	Contribution[2]		kg CO_2eq/person/d[3]		kg CO_2eq/person/1,000 kcal[3]	
		%	SE	Mean	SE	Mean	SE
Red and processed meat		**47.05**	**0.82**	**1.875**	**0.055**	**0.978**	**0.027**
Beef (including veal)	1	35.8	0.93	1.426	0.053	0.742	0.026
Lamb	18	1.13	0.23	0.045	0.009	0.024	0.004
Pork	10	3.4	0.17	0.136	0.006	0.071	0.003
Luncheon and other meat (liver, offal, game meat)	2	6.72	0.4	0.268	0.016	0.141	0.009
Dairy		**13.94**	**0.24**	**0.555**	**0.009**	**0.296**	**0.004**
Milk	4	5.56	0.14	0.222	0.006	0.122	0.003
Cream	24	0.62	0.03	0.025	0.001	0.013	0.001
Cheese	5	4.39	0.13	0.175	0.005	0.088	0.002
Yoghurt	17	1.39	0.07	0.055	0.003	0.032	0.002
Butter	20	0.98	0.05	0.039	0.002	0.02	0.001
Frozen dairy	19	1	0.06	0.04	0.002	0.02	0.001
Miscellaneous		**11.32**	**0.23**	**0.451**	**0.008**	**0.242**	**0.004**
Alcoholic beverages	14	2.46	0.11	0.098	0.004	0.047	0.002
Non-alcoholic beverages (including fruit juice, tea, coffee)	8	3.68	0.1	0.147	0.004	0.085	0.002
Confectionary (including sugars, syrups, and preserves)	16	1.79	0.08	0.071	0.003	0.036	0.001
Oils and fats (including margarine)	21	0.87	0.02	0.035	0.001	0.0183	0.0004
Other (including savory snacks, soups, sauces, seasonings)	13	2.52	0.12	0.1	0.005	0.055	0.002
Poultry and eggs		**9.15**	**0.3**	**0.364**	**0.01**	**0.203**	**0.005**
Poultry	3	5.71	0.24	0.228	0.009	0.127	0.004
Eggs	9	3.43	0.13	0.137	0.005	0.076	0.003
Vegetables and fruits		**8.06**	**0.23**	**0.321**	**0.009**	**0.195**	**0.007**
Vegetables	7	3.8	0.11	0.151	0.004	0.091	0.003
Potatoes	27	0.28	0.01	0.011	0.001	0.006	0.0003
Fruit	6	3.99	0.19	0.159	0.008	0.097	0.006
Fish and shellfish		**5.12**	**0.35**	**0.204**	**0.014**	**0.119**	**0.009**
Fish	15	1.86	0.1	0.074	0.004	0.043	0.002

Shellfish	11	3.26	0.33	0.13	0.013	0.076	0.008
Cereals, grains, and breads		**3.5**	**0.09**	**0.14**	**0.003**	**0.078**	**0.001**
Whole grains	22	0.74	0.04	0.03	0.001	0.017	0.001
Refined grains	12	2.76	0.07	0.11	0.002	0.061	0.001
Nuts, seeds, and legumes		**1.86**	**0.08**	**0.074**	**0.003**	**0.042**	**0.002**
Nuts and nut butters	25	0.61	0.04	0.024	0.002	0.012	0.001
Seeds	28	0.03	0.01	0.001	0.0003	0.001	0.0002
Legumes	23	0.73	0.04	0.029	0.002	0.017	0.001
Plant-based beverages (excluding rice beverage)	26	0.49	0.06	0.02	0.002	0.012	0.002

[1]Food subgroups were ranked based on their percent contribution to dietary GHGE.
[2]Estimates are based on population ratios.
[3]Estimates are age- and sex-standardized means.
Abbreviations: CO_2eq, carbon dioxide equivalents; GHGE, greenhouse gas emissions.

Supplementary Table 4.5 Mean 1-d intake of macro- and micronutrients among low- and high-GHGE diet respondents from the 2015 Canadian Community Health Survey – Nutrition

	Low-GHGE diets (*n*=2,849)		High-GHGE diets (*n*=2,562)		P
	Mean	SE	Mean	SE	
Macronutrients					
Carbohydrates, g/1,000	131.66	1.05	112.38	1.09	<0.0001
Fat, g/1,000	36.42	0.44	35.87	0.36	0.3285
Protein, g/1,000	32.98	0.32	51.08	0.53	<0.0001
Fibre, g/1,000	10.40	0.17	9.11	0.22	<0.0001
Monounsaturated fats, g/1,000 kcal	13.28	0.21	13.86	0.17	0.0371
Polyunsaturated fats, g/1,000 kcal	9.05	0.23	6.50	0.13	<0.0001
Linoleic acid, g/1,000 kcal	7.93	0.23	5.44	0.11	<0.0001
Linolenic acid, g/1,000 kcal	0.90	0.02	0.77	0.02	<0.0001
DHA, g/1,000 kcal	0.04	0.004	0.05	0.005	0.3039
EPA, g/1,000 kcal	0.02	0.002	0.03	0.003	0.0548
Micronutrients					
Cholesterol, mg/1,000 kcal	85.9	2.29	170.49	4.19	<0.0001
Vitamin A, µg/1,000 kcal	288.98	8.68	406.78	21.93	<0.0001
Vitamin C, mg/1,000 kcal	42.29	1.47	60.09	4.46	0.0001
Thiamin, mg/1,000 kcal	0.86	0.01	0.83	0.01	0.0625
Riboflavin, mg/1,000 kcal	0.88	0.01	1.15	0.02	<0.0001
Niacin, mg/1,000 kcal	17.64	0.20	23.50	0.31	<0.0001
Vitamin B6, mg/1,000 kcal	0.76	0.01	1.01	0.02	<0.0001
Vitamin B12, mcg/1,000 kcal	1.11	0.03	3.75	0.12	<0.0001
Phosphorus, mg/1,000 kcal	613.23	8.84	732.40	7.77	<0.0001
Magnesium, mg/1,000 kcal	164.45	2.25	175.13	3.28	0.0089
Zinc, mg/1,000 kcal	4.22	0.08	8.62	0.11	<0.0001

Abbreviations: CO_2eq, carbon dioxide equivalents; DHA, docosahexaenoic acid; EPA, eicosapentaenoic acid; GHGE, greenhouse gas emissions.

Bridge statement 3

In the previous chapter, we found that high-GHGE self-selected diets were composed mainly of animal-based foods, particularly red and processed meat and dairy. Moreover, despite having higher intakes of nutrients of concern, high-GHGE diets also had higher intakes of saturated fat and sodium and a lower overall diet quality compared to low-GHGE diets, revealing incompatibilities among dimensions of diet sustainability. FBDG from high-income countries are progressively including messaging aimed at encouraging individuals to increase their consumption of plant-based foods. However, studies assessing the impact of simple substitutions of animal with plant protein foods on diet-related GHGE together with other diet sustainability dimensions are lacking. Therefore, in the next chapter, we aimed to systematically review studies that modeled substitutions of animal with plant protein foods in self-selected diets on diet-related GHGE in combination with nutrition or health outcomes.

Chapter 5: Manuscript 3 – Systematic review of modeling studies

Submitted

The impact of substituting animal with plant protein foods in adults' self-selected diets on diet-related greenhouse gas emissions and prevalence below or above nutrient recommendations: A systematic review of modeling studies

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5.1 Abstract

Background: Dietary guidelines in high-income countries encourage individuals to increase their consumption of plant-based foods. However, the population-level impact of substituting animal with plant protein foods on a combination of diet sustainability dimensions is unknown.

Objective: To systematically review studies that modeled replacements of animal with plant protein foods in self-selected diets on diet-related greenhouse gas emissions (GHGE), nutrition, and health outcomes.

Methods: We searched PubMed, Scopus, and EMBASE in January 2023. Eligible studies modeled substitutions of meat or dairy with plant protein foods (nuts, seeds, legumes, pulses, soy-based alternatives) using dietary data from nutrition surveys or cohorts. Studies had to report data for diet-related GHGE for observed and modeled diets and, optionally, data for the percentage of the population meeting nutrient recommendations or changes to life expectancy.

Results: Six of the 1,188 studies retrieved were included. All reported on diet-related GHGE, two on nutrition outcomes, and none on health outcomes. Four were set in Europe and two in US populations. Replacing 17-100% of meat led to the greatest reductions in diet-related GHGE (3-55%), most of which was attributed to beef alone (10-40%). Partially substituting meat increased the percentage of the population meeting fibre, calcium, potassium, and iron requirements by 1-5%. Replacing meat and dairy decreased the percentage below requirements for iron (5-15%) and vitamin D (2-7%) and above recommendations for saturated fat (10-76%), but increased the proportion below requirements for calcium (9-33%) and vitamin A (8-48%).

Conclusions: Substituting meat, and to a lesser extent dairy, with plant protein foods had synergistic beneficial effects for diet-related GHGE and intakes of iron and vitamin D. More

studies on the climate impacts of protein food substitutions with joint analyses for nutrition and health outcomes are needed to parse synergies and trade-offs in facilitating the shift towards healthier and more sustainable diets.

PROSPERO registration number: CRD42023392104.

5.2 Introduction

Human diets contribute majorly to climate change and nutrition-related chronic diseases. Climate modeling studies have shown that greenhouse gas emissions (GHGE) from food systems alone are enough to surpass a global temperature rise of 1.5°C above pre-industrial levels as set out in the Paris Agreement, with just over half of this projected warming attributed to ruminant meat and dairy consumption (2, 16). Moreover, diets higher in healthful plant-based foods have been associated with a lower risk of cardiovascular disease, type 2 diabetes, and all-cause mortality than diets higher in animal products (133). Nevertheless, animal-source foods are widely consumed in many countries and supply several bioavailable nutrients (134). Thus, food policies must weigh the contribution of animal and plant-based food consumption on human nutrition and health together with diet-related GHGE.

Food-based dietary guidelines (FBDG) are primarily intended to promote nutrient adequacy and prevent nutrition-related chronic diseases yet are progressively including environmental messaging. A recent review found that nearly two-thirds of FBDGs with environmental messaging promoted an increase in plant-based foods or a decrease in animal-based foods (11). Half of FBDG categorize animal- and plant-based foods into a single ‘protein foods’ group consisting mainly of legumes, nuts, seeds, meat, poultry, fish, eggs, and in some cases, dairy, with one-third of FBDG with protein food messaging presenting plant proteins as substitutes for animal-source foods (39). Given the growing emphasis on plant-based foods in FBDG, it is crucial to identify studies that have quantified the population-level impacts of substituting animal with plant protein foods on multiple dimensions of diet sustainability.

To date, population studies have used self-reported dietary data as a baseline with which to simulate theoretical diets that adhere to FBDG or to optimize diets that fulfill selected constraints relevant to one or more dimensions of sustainability (e.g., environment, nutrition, socioeconomic) (66, 67). Despite being a useful benchmark for understanding the changes necessary for achieving healthy and sustainable diets, these may not be feasible for consumers who may be more inclined to make simple substitutions instead of overhauling their dietary patterns. Studies modeling substitutions of animal- with plant-based foods in self-selected diets have typically assessed environmental, nutritional, or health outcomes separately, which impedes the weighing of potential synergies and trade-offs among multiple dimensions of diet sustainability. Systematic reviews examining the environmental and health impacts of diets have focused more broadly on dietary patterns than simple substitutions or included studies that simulated optimized diets (135, 136). Moreover, many of the studies included in these reviews assessed aggregate diets for the population or used food expenditure or availability data, which are not representative of self-selected diets based on actual food consumption. One systematic review of the environmental and nutritional quality focused on subclasses of self-selected diets (e.g., "lower carbon", "higher quality") instead of the general population (137). None of these reviews focused specifically on substitutions of animal with plant protein foods in self-selected diets. Therefore, our systematic review aimed to synthesize available evidence from modeling studies on the impacts of replacing animal with plant protein foods in individuals' self-selected diets on diet-related greenhouse gas emissions and nutrition or health outcomes.

5.3 Materials and methods

We conducted our systematic review according to the Cochrane Handbook for Systematic Reviews of Interventions (138) and the Preferred Reporting Items for Systematic Reviews and

Meta-Analyses recommendations (139). The review was registered in the International Prospective Register of Systematic Reviews in January 2023 (CRD42023392104).

Eligibility criteria

We included studies that modeled replacements of animal with plant protein foods in self-selected diets using the dietary data of adults ≥18 y in national nutrition surveys or prospective (baseline only) or cross-sectional cohorts. In particular, we selected studies that modeled substitutions of red and processed meat or dairy with the following plant protein foods: nuts, seeds, legumes, tofu, plant-based meat alternatives, and soy beverages. Since studies may not always distinguish meats from other animal products, we included those that grouped red and processed meat with other types of meat or dairy products. Studies had to include data for diet-related GHGE expressed in kg carbon dioxide equivalents (CO_2eq) per person per day for observed and modeled diets (primary outcome). Additionally, studies could include data for the percentage of the population below requirements for nutrients of public health concern (calcium, fibre, iodine, iron, potassium, vitamin A, vitamin D) and above recommendations for nutrients to limit (sodium, saturated fat, free sugars), or changes to life expectancy expressed in time (e.g., months or years) or years of life lost or gained expressed in million years (secondary outcomes). Nutrients of concern and to limit were chosen based on those defined by North American (76, 109) and European (140) government agencies and the World Health Organization (141). Health outcomes were chosen as those we deemed related to diet and most relevant to public health. We excluded studies that used national food availability data or assessed aggregate diets as a proxy for individual dietary intake, employed optimization or other modeling techniques instead of simple food replacements, modeled reductions of animal protein foods without substitutions, and finally, studies that did not assess diet-related GHGE expressed in CO_2eq per person per day.

Literature search

The search was run on 16 January 2023 in the electronic databases PubMed, Scopus, and Embase Classic + Embase. The search strategy was framed using a combination of the following keywords: replace, dietary change, scenario; greenhouse gas emissions, carbon footprint, environmental sustainability; meat, beef, dairy, plant, animal; self-selected diet, dietary pattern, and nutrition survey. The full natural language search is in the Supplementary Materials (**Appendix 5.1**). Only peer-reviewed published primary research articles were included. Duplicates were removed in EndNote. Titles, abstracts, and keywords were screened independently by two reviewers (OA and YJ) using Rayyan (142). Conflicts were resolved by a third independent reviewer (SAB). The same procedure was used to assess full-text articles for eligibility using a pre-defined set of inclusion and exclusion criteria listed above.

Data collection process

Pre-specified data items were extracted from eligible studies independently by two reviewers (OA and YJ) using a pilot-tested form. Disagreements were resolved by a third reviewer (SAB). For each study, quantitative data relating to primary and secondary outcomes were collected for observed and modeled diets. Qualitative data were also collected for study design, country of origin, sample size, population characteristics (i.e., age, sex, and ethnicity), unit of replacement (i.e., weight, energy, portion, or protein), type of environmental assessment (e.g., life cycle assessment, input-output), number of foods with environmental impacts, a description of other environmental impacts assessed, type of dietary assessment (e.g., 24-h recall), and whether estimates were based on 1-d or usual dietary intakes. Data that was missing or expressed in a manner different than what was specified in the protocol was requested by contacting corresponding authors.

Risk of bias assessment

The Appraisal tool for Cross-Sectional Studies (AXIS) was used to assess risk of bias (143). AXIS consists of 20 components, each evaluated using 'Yes', 'No', or 'Don't know'. We applied a subset of questions relating to the reference population and non-responders to the original survey or study that collected the dietary information. We used N/A for the components not directly applicable to the included studies. Independent reviewers (OA and YJ) conducted the risk of bias assessment, and conflicts were resolved by a third reviewer (SAB).

Synthesis of results

Studies were grouped by type(s) of animal protein foods and the proportions in which they were replaced. For studies that did not express scenarios in terms of the proportion of animal protein food that was replaced, we divided grams of animal protein food consumed in observed diets by that in modeled diets. We calculated the percentage change to primary and secondary outcome measures for data presented as absolute values between observed diets and modeled replacement scenarios. For studies that presented the percentage of the population meeting nutrient requirements by age and sex groups, we calculated the sample average. The results of the critical appraisal were incorporated into the narrative synthesis.

5.4 Results

Study selection

We obtained 1,188 articles through the systematic literature research (**Figure 5.1**). After removing duplicates, titles and abstracts for 858 records were screened. Thirty-one papers were selected for full-text screening. Of these, 25 articles were excluded because they used food availability data (n = 8), were the wrong study design (n = 5), used optimization or other forms of modeling (n = 4), assessed dietary patterns (n = 4), conducted replacements at the aggregate level (n = 2), did not express diet-related GHGE in kg CO_2eq per person per day (n = 1), or were the wrong publication type (n = 1). Therefore, six articles were included in our systematic review consisting of seven different replacement scenarios (11 when considering the graded nature of the replacements). We contacted the corresponding authors for all articles to obtain missing data and received responses from all six about the quantity of protein foods consumed and the percentage of the population below the requirements for additional nutrients.

Study characteristics

Characteristics of the included studies are in **Table 5.1**. All studies were secondary analyses of 24-h recalls from national nutrition surveys published between 2017 and 2022. Four were set in Europe (i.e., Netherlands, France, Switzerland), and two in the United States. The study samples were generally split evenly between males and females. Most respondents were Caucasian (70%, US studies only) and between the ages of 30 and 49 y (30-42%). Protein food substitutions were either gram per gram (n = 2), isocaloric (n = 2), portion-matched (n = 1), or protein-matched (n = 1). Three studies modeled replacing a combination of meats (i.e., beef, lamb, pork, processed meat, and poultry), one replaced meat and dairy, one replaced beef, and one replaced cheese with plant protein foods. One study substituted milk with soy beverage. Four studies used life cycle assessment, one used environmental input-output analyses, and one used a hybrid approach to link estimates of GHGE for 180 to 402 foods to those reported in the 24-h recalls. In addition to diet-related GHGE, several studies quantified additional environmental impacts: land use (n = 2), water use (n = 1), acidification (n = 1), eutrophication (n = 1), and nitrogen surplus (n = 1). Two studies reported data for the percentage of the population meeting nutrient recommendations. No studies reported health outcomes as specified in the protocol.

Risk of bias within studies

Results of the critical appraisal step using the AXIS tool are in **Supplementary Table 5.1**. Studies met 15 to 20 of the AXIS criteria. Most of the criteria that were not met stemmed from uncertainties about the reference population and non-responders.

Replacing meat with plant protein foods

Three studies modeled substitutions of a combination of meats with plant protein foods (63, 144, 145). Meat consisted of non-processed and processed beef, pork, and poultry. Plant protein foods included one or a combination of nuts, seeds, and legumes (including pulses – beans, peas, and lentils). Among these studies, one assessed nutrient outcomes (145). Intake of meat was eight-fold that of plant protein foods for observed diets (114 vs. 14 g/d, respectively) (**Table 5.2**). Replacing 17-100% of meat with plant protein foods led to dose-dependent decreases in diet-related GHGE of 3-55% (**Figure 5.2**). Gazan et al. (145) simulated increases in the quantity of pulses consumed by 1,853 individuals (90% of the sample) in Esteban 2014-16 that did not meet the French guideline of 57 g/d (referred to as InAdeq diets) in replacement of an equivalent portion of meat. The substitution analysis resulted in a ~17% reduction in total meat intake (mean±SE) from 116.6±3.2 g/d for observed diets to 96.5±3.1 g/d for modeled diets and increase in total pulse intake from 6.1±0.4 to 57.9±0.2 g/d. Partially replacing meat with pulses decreased diet-related GHGE by 3.3%. The percentage of the population below requirements for iron (accounting for bioavailability based on serum ferritin levels) decreased from 71.4% for observed diets to 70.3% after replacement with pulses (**Table 5.3**). Compared to observed diets, the percentage of the population below Dietary Reference Values also decreased for fibre (−5.3%), calcium (−2.9%), and potassium (−1.2%), but increased for vitamin A (+1.3%). There was no change in the percentage of the population below Dietary Reference Values for vitamin D and iodine. Frehner et al. (144) simulated graded replacements of meat with pulses to match the protein content of observed diets using dietary data from the Swiss national nutrition survey menuCH 2014-15 (n = 2,057). Intake of meat decreased in a stepwise manner from 113.6 g/d for observed diets to 0 g/d in the most stringent scenario (100% replaced), whereas intake of pulses increased from 6.9 g/d to 193.9 g/d. Substituting 25%, 50%, and 100% of meat with pulses decreased diet-related GHGE by 14.8%, 29.1%, and 55.3%, respectively. Similarly, Willits-Smith et al. (63) modeled graded isocaloric substitutions of meat with nuts, seeds, and legumes among a sample of adults from NHANES 2007-10 most receptive to making changes in their diets given the inclusion of environmental messaging in American FBDG deemed "potential changers" (n = 1,026 out of 7,188; 14% of sample). Meat intake decreased from 111.6 g/d to 0 g/d when all meat was replaced and intake of nuts, seeds, and legumes increased from 29.7 g/d to 121.2 g/d. Replacing 25%, 50%, and 100% of meat with plant protein foods (nuts, seeds, and legumes) decreased diet-related GHGE decreased by 12.1%, 24.8%, and 49.6%, respectively.

Replacing meat and dairy with plant protein foods

Seves et al. (65) substituted meat and dairy with plant-based alternatives in a nationally representative sample of Dutch adults (n = 2,102). Replacements were assigned based on similarity in terms of consumption occasion and included plant-based meat alternatives (e.g., vegetarian hamburger, pulses, soy products), sandwich fillings (e.g., vegetarian ham, peanut butter, apple syrup), sweet or savory snacks (e.g., falafel, sweet popcorn), and soy-based drinks and desserts. Most plant-based meat alternatives were fortified with iron and soy beverage with calcium and vitamin D. Since milk was not fortified, dairy products did not contain any iron or vitamin D. Replacing 30% or 100% of meat and dairy decreased diet-related GHGE by 14% and 47%, respectively. The percentage of the population below the Estimated Average Requirement (EAR) for iron decreased by 8 to 31% for females 19-30 y of age and 10 to 26% for females 31-50 y of age when 30% and 100% of meat and dairy was replaced with plant-based alternatives relative to observed diets (**Supplementary Table 5.2**). The percentage of females 51-69 y of age below the EAR for iron did not change across scenarios, while the percentage of males 19-69 y decreased by 1% when all meat and dairy was replaced. The percentage of females 19-69 y and males 31-50 y below the AI for vitamin D decreased by 1 to 7%, while the percentage below the AI for calcium increased by 9 to 30% (no data was available for males 19-30 y and 51-69 y). The percentage below the EAR for vitamin A increased by 9 to 48% for males and by 8 to 39% for females across scenarios. The percentage of the population above the UL for saturated fat decreased by 8% to 78% for males and by 12% to 74% for females.

Replacing beef with plant protein foods

Willits-Smith et al. (63) modeled graded replacements of beef with a combination of nuts, seeds, and legumes in the self-selected diets of "potential changers" from NHANES. Beef intake (mean (95% CI)) decreased from 37.7 g/d (32.3 to 43 g/d) for observed diets to 0 g/d when all beef was replaced, whereas intake of nuts, seeds, and legumes increased from 29.7 g/d to 60.3 g/d. Substituting 25%, 50%, and 100% led to respective decreases in diet-related GHGE of 10.1%, 20.1%, and 40.3%.

Replacing milk with soy beverage or cheese with plant protein foods

Using data from NHANES 2005-2010, Rose et al. (64) estimated changes to diet-related GHGE stemming from the replacement of cow's milk with soy beverage for individuals who reported consuming milk at least once in their 24-h recall (n = 6,995 out of 16,800; 42% of sample). Milk intake (mean±SE) decreased by ~80% from 316±7 g/d for observed diets to 66±3 g/d for modeled diets, while intake of soy beverage increased from 2±1 g/d to 252±5 g/d. The substitution scenario decreased diet-related GHGE by 3.5%. van de Kamp et al. (124) modeled the replacement of cheese consumed as a snack in between meals, constituting about 20% of total cheese consumed, with equal grams of plant protein foods in a sample of Dutch adults in the highest tertile of diet-related GHGE (n = 700 out of 2,102; 33% of sample). Cheese was substituted with peanut butter or vegetable sandwich spread if consumed with bread, or cherry tomatoes or unsalted mixed nuts if consumed without bread. Replacements decreased diet-related GHGE by 1.5% for males and by 2% for females.

5.5 Discussion

Replacing meat, particularly beef, led to the greatest reductions in diet-related GHGE, with total replacement accounting for more than half of individuals' diet-related carbon footprint. Partially substituting meat slightly decreased the percentage of the population below requirements for fibre, calcium, potassium, and iron. Substituting meat and dairy decreased the percentage below requirements for iron and vitamin D and above recommendations for saturated fat but led to trade-offs with calcium and vitamin A. Based on the limited number of studies available, substituting meat with plant protein foods showed beneficial synergistic effects for diet-related GHGE and prevalence of population above recommendations for iron and vitamin D. However, more studies assessing the impact of dietary changes aligned with recommendations in national FBDG on multiple dimensions of diet sustainability are needed.

High heterogeneity among food substitution studies

Studies with combined analyses of diet-related GHGE and nutrient outcomes were heterogeneous. For environmental impacts, GHGE databases linked to dietary records covered a variable number of foods, which sometimes differed in assessment method and system boundaries (i.e., scope of processes included in the analyses). The categorization of replacement foods was also inconsistent among studies, sometimes including foods beyond the scope of our definition for plant protein foods (e.g., cherry tomatoes or sweets). Furthermore, comparison among studies was difficult due to differences in the replacement unit and quantity of animal protein foods being replaced. For example, reductions in diet-related GHGE resulting from the replacement of milk or cheese were considerably less than those for meat or beef but were not directly comparable, at least for cheese which was replaced in much smaller quantities. This heterogeneity posed a challenge for combining outcomes across replacement scenarios and hindered meta-analysis of the studies. Future modeling studies assessing the combined impacts of food substitutions on human and planetary health outcomes should use harmonized methods for drawing comparisons across a range of scenarios directly relevant to public health.

Changes to diet-related GHGE depend on animal protein food type

Despite heterogeneity in study design, we found that reductions in diet-related GHGE stemming from replacements of animal with plant protein foods were generally consistent with studies showing that self-selected diets with greater quantities of plant-based foods and smaller amounts of animal products have the lowest diet-related carbon footprint (7, 9, 61, 146). However, as with most studies in our systematic review that substituted a combination of meats, and in one instance meat and dairy, grouping animal products could lead to different interpretations of outcomes assessed. For example, replacing 80% of milk with soy beverage led to comparable reductions in diet-related GHGE to substituting less than 35% of meat or beef with plant protein foods. Since climate impacts are dominated by ruminant meats (5), it is important to avoid making general conclusions about animal protein foods and their impact on diet sustainability.

Food fortification as a determinant of nutrient outcomes

Changes in the percentage of the population meeting or exceeding nutrient recommendations were largely determined by the fortification status of replacement foods. For example, the decrease in the percentage of the population, particularly pre-menopausal females, below requirements for iron when substituting meat with or without dairy was likely due to replacement with a variety of selected iron-fortified plant-based alternatives, as opposed to single whole foods or food groups as in most other studies. However, despite the absorption of non-heme iron is plants as less than that of heme iron in meat (147), Gazan et al. (145) still showed a slight reduction in the percentage of the population below iron requirements when accounting for absorbed iron from partially replacing meat with pulses. Similarly, the reduction in the percentage of the population below requirements for vitamin D from replacing meat and dairy was also likely due to substitutions with fortified soy beverage and their low vitamin D content. Unlike the US and Canada, fortifying milk with vitamin D is not mandatory in the Netherlands (148), underscoring that changes to the percentage meeting or exceeding nutrient recommendations due to replacements are context-specific. Moreover, while partially replacing meat decreased the percentage of the population below requirements for calcium, including dairy in the substitutions exacerbated the proportion not meeting recommendations for calcium and vitamin A. Despite the use of calcium-fortified soy beverage as a replacement for most dairy products, meat and cheese consumed as sandwich fillings, snacks, or meals were replaced with plant-based alternatives that were not fortified with either calcium or vitamin A. Therefore, policymakers must monitor the growing supply and demand for plant-based alternatives to ensure their fortification with essential vitamins and minerals often contained in the foods they might replace.

Unprocessed versus ultra-processed plant protein foods

Despite the focus of our systematic review on mostly unprocessed plant protein foods, we included studies that may have grouped these with processed plant-based alternatives. For example, Seves et al. (65) conducted meat and dairy replacements with a combination of whole foods like pulses and processed plant-based alternatives like vegetarian meats. Despite having lower environmental impacts than their meat and dairy counterparts, some of these ultra-processed plant-based alternatives may have exacerbated repercussions for nutrients of concern. There is research to suggest that substituting animal products with novel plant-based alternatives meant to mimic the taste and sensory properties of meat can lead to unintended consequences for micronutrient intakes, specifically calcium, potassium, magnesium, zinc, and vitamin B12, and exacerbate excess intakes of saturated fat, sodium, and sugar compared to replacements with whole foods (149). Therefore, while certain ultra-processed plant-based alternatives may still have a place in healthy and sustainable diets, a distinction must be made between healthful and unhealthful plant-based foods on the part of policymakers and consumers.

Strengths and limitations

Unlike previous systematic reviews that assessed the impacts of loosely defined sustainable diets, we captured the climate and, where available, nutrition impacts of a clearly framed intervention – substituting animal with plant protein foods. We also highlighted impacts stemming from graded replacements, a useful benchmark for assessing the degree of change attainable by making simple substitutions in individuals' self-selected diets instead of eliminating animal products. However, there were also several important limitations to our study. We accounted solely for greenhouse gas emissions since it is the impact for which data is most available despite studies having found trade-offs among environmental impacts. For example, 'sustainable diets' containing more plant-sourced foods and less animal-sourced foods had a lower diet-related GHGE but higher water footprint than observed diets (137). Another limitation was the lack of suitable tools for risk of bias assessment of modeling studies. Moreover, the percentage of the population below requirements for nutrients of concern assessed in this study was estimated using various methods and cut-offs and thus may not necessarily infer inadequacy (24). Finally, since all studies were conducted in high-income nations, the scenarios presented do not reflect the impact of replacing animal and plant protein foods on meeting the nutritional needs of individuals from low- and middle-income nations where livestock-derived products play a crucial role in contributing to nutrient adequacy (150).

5.6 Conclusions

Total and partial substitutions of meat with plant protein foods in individual self-selected diets led to proportional reductions in diet-related GHGE and modest improvements in the percentage of the population meeting requirements for fibre, calcium, potassium, and iron. Despite largely decreasing the prevalence below requirements for iron and vitamin D, including dairy in substitutions with meat exacerbated the percentage of the population below recommendations for calcium and vitamin A and led to smaller reductions to diet-related GHGE. Further modeling studies examining the impact of food replacements on nutrition and health outcomes in conjunction with environmental indicators are needed in the context of changing dietary guidance, which is shifting towards emphasis on plant protein foods in place of animal sources.

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Statement of authors' contributions to manuscript OA and SAB designed the research; OA and YJ conducted the research; OA analyzed data; OA wrote the paper; SAB and YJ edited the paper; SAB had primary responsibility for the final content. All authors have read and approved the final manuscript.

Data sharing Template data collection forms and data extracted from included studies will be made available in full upon request to SAB.

Table 5.1 Characteristics of the included studies

First author et al., y	Study design	Name of survey or cohort, y	Study population	n[1]	Replacement scenarios	Environmental outcomes	Type of environmental assessment	Number of foods	Nutrition outcomes[2]	Type of dietary assessment
Frehner et al., 2022	Nationally representative survey	menuCH, 2014-15	Swiss adults (18-75 y)	2,057	Meat → pulses	GHGE, land use, nitrogen surplus	Input-output	180	–	24-h recall (×2), average of recalls
Gazan et al., 2021	Nationally representative survey	Esteban, 2014-16	French adults (18-74 y)	1,853	Meat → pulses	GHGE, acidification, eutrophication	Hybrid method (input-output + LCA)	402	Ca, Fe, I, K, vitamin D, vitamin A, SFA, Na, free sugars	24-h recall (×3), average of recalls
Willits-Smith et al., 2020	Nationally representative survey	NHANES, 2007-10	American adults (18-65 y)	1,150	Meat or beef → nuts, seeds, legumes	GHGE	LCA	332	–	24-h recall (×1), 1-d intake
Seves et al., 2017	Nationally representative survey	DNFCS, 2007-10	Dutch adults (19-69 y)	2,102	Meat and dairy → plant-based alternatives	GHGE, land use	LCA	254	Ca, Fe, vitamin D, vitamin A, SFA	24-h recall (×2), usual intakes
Rose et al., 2022	Nationally representative survey	NHANES, 2005-10	American adults (>18 y)	6,995	Milk → soy beverage	GHGE, water use	LCA	306	–	24-h recall (×2), Usual intakes
Van de Kamp et al., 2018	Nationally representative survey	DNFCS, 2007-10	Dutch adults (19-69 y)	700	Cheese → plant-based alternatives	GHGE	LCA	332	–	24-h recall (×1), 1-d intake

[1]Entire sample or in some cases, a subset of respondents for whom replacements were made. [2]Percentage below or above nutrient recommendations. [3]The Appraisal tool for Cross-Sectional Studies was used to assess risk of bias. Higher scores indicate lower risk of bias. – indicates that no data was available. Abbreviations: DNFCS, Dutch National Food Consumption Survey; GHGE, greenhouse gas emissions; LCA, Life cycle assessment.

Table 5.2 Changes in intake of animal and plant protein foods among adults from modeled substitution scenarios relative to observed diets

First author et al., y	Replacement scenarios	Type of replacement	Intake of animal protein foods for observed diets (g/d)	Intake of plant protein foods for observed diets (g/d)	Quantity replaced (%)	Absolute change in intake of animal protein foods (g/d)	Absolute change in intake of plant protein foods (g/d)
Frehner et al., 2022	Meat → pulses	Protein-matched	114	7	25	-28	47
					50	-57	94
					100	-114	187
Gazan et al., 2021	Meat → pulses	Portion-matched	117	6	17	-20	52
Willits-Smith et al., 2020	Meat → nuts, seeds, legumes	Isocaloric	112	30	25	-28	23
					50	-56	46
					100	-112	92
Seves et al., 2017	Meat and dairy → plant-based alternatives	Gram per gram	–	–	30	–	–
					100	–	–
Willits-Smith et al., 2020	Beef → nuts, seeds, legumes	Isocaloric	38	30	25	-10	8
					50	-19	15
					100	-38	31
Rose et al., 2022	Milk → soy beverage	Isocaloric	316	2	80	-250	250
Van de Kamp et al., 2018	Cheese → plant-based alternatives	Gram per gram	–	–	20	–	–

– indicates that no data was available.

Table 5.3 Changes in the percentage of the adult population below recommendations for nutrients of concern and above recommendations for nutrients to limit stemming from modeled graded replacements of animal with plant protein foods compared to observed diets

Replacement	**Meat**[1]	**Meat and dairy**[2]	
Percentage replaced	**17%**	**30%**	**100%**
n	1,853	2,102	2,102
Nutrients of concern			
Iron	−1%	−5%	−15%
Calcium	−3%	9%	30%
Fibre	−5%	–	–
Vitamin A	1%	9%	44%
Vitamin D	0%	−1%	−7%
Potassium	−1%	–	–
Iodine	0%	–	–
Nutrients to limit			
Saturated fat	−2%	− 10%	−76%
Sodium	4%	–	–
Added sugars	0%	–	–

[1]Based on findings from Gazan et al. (145). [2]Based on findings from Seves et al. (65). Negative values indicate a decrease in the percentage of the population below recommendations for nutrients of concern or above recommendations for nutrients to limit. Positive values indicate an increase in the percentage of the population below requirements for nutrients of concern or above recommendations for nutrients to limit. Zero values indicate no change from observed diets. – indicates that no data was available.

Figure 5.1 Preferred reporting items for systematic reviews and meta-analyses flow diagram

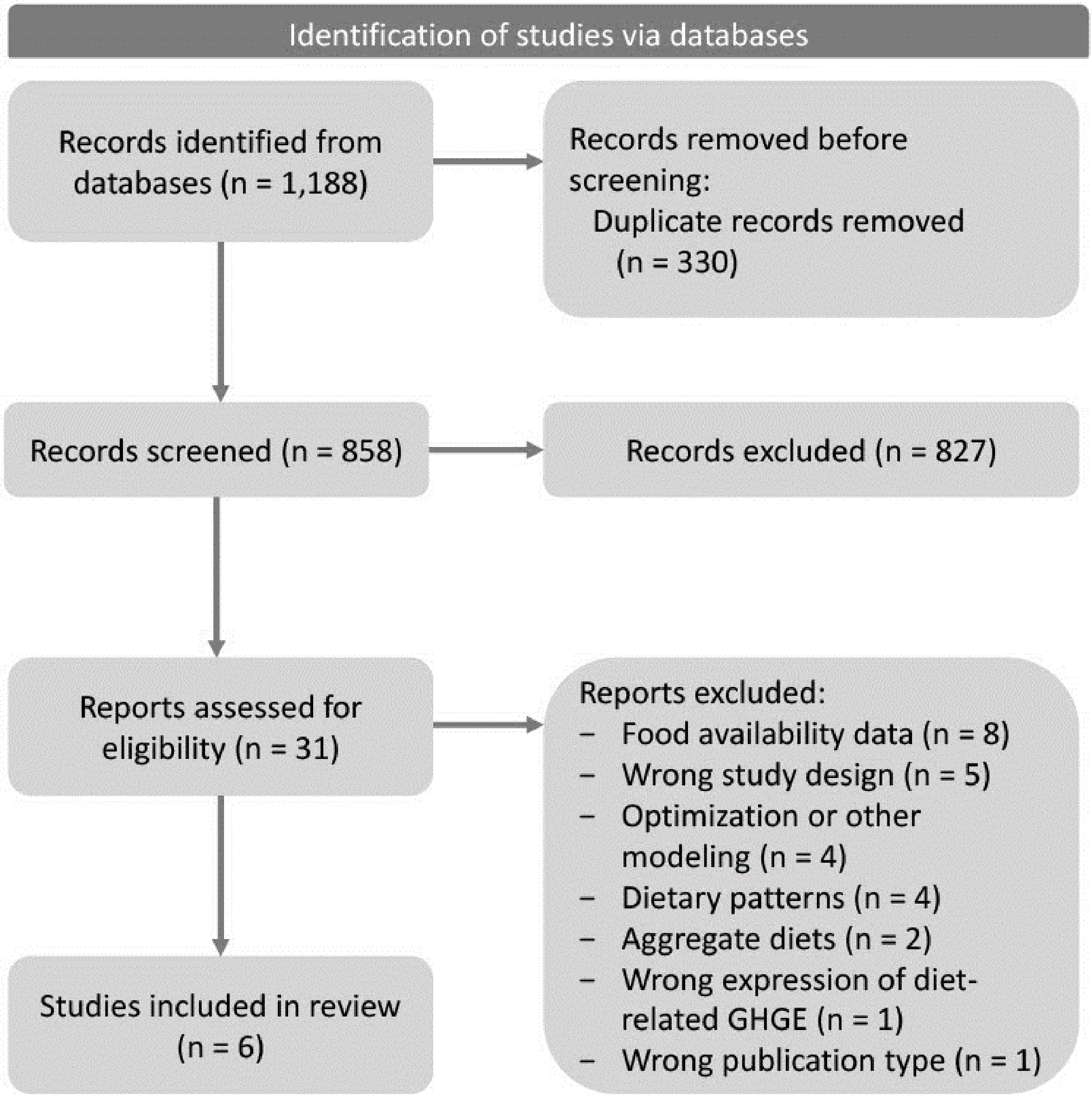
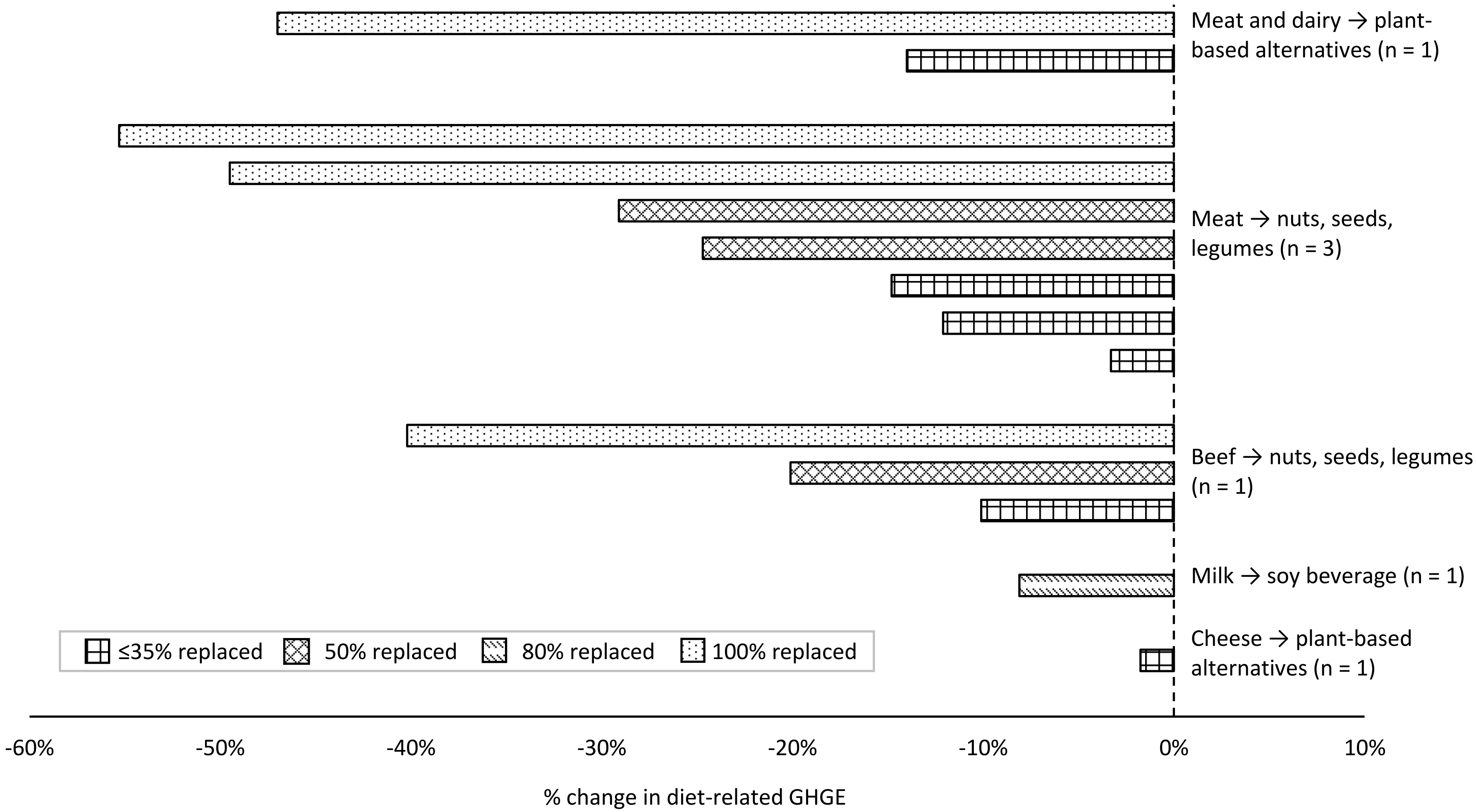


Figure 5.2 Changes to diet-related greenhouse gas emissions stemming from modeled graded replacements of animal with plant protein foods relative to observed diets



Supplementary Table 5.1 Critical appraisal using the Appraisal tool for Cross-Sectional Studies (AXIS) for studies included in the systematic review (n = 7)

	Frehner et al., 2022	Gazan et al., 2021	Rose et al., 2022	Seves et al., 2017	Van de Kamp et al., 2018	Willits-Smith et al., 2020
1 Were the aims/objectives of the study clear?	Yes	Yes	Yes	Yes	Yes	Yes
Methods						
2 Was the study design appropriate for the stated aim(s)?	Yes	Yes	Yes	Yes	Yes	Yes
3 Was the sample size justified?	Yes	Yes	Yes	Yes	Yes	Yes
4 Was the target/reference population clearly defined? (Is it clear who the research was about?)	Yes	Yes	Yes	Yes	Yes	Yes
5 Was the sample frame taken from an appropriate population base so that it closely represented the target/reference population under investigation?	Yes	Yes	Yes	Yes	Yes	Yes
6 Was the selection process likely to select subjects/participants that were representative of the target/reference population under investigation?	Don't know	Yes	Yes	Yes	Yes	Yes
7 Were measures undertaken to address and categorise non-responders?	Yes	Don't know	Yes	Yes	Yes	Yes
8 Were the risk factor and outcome variables measured appropriate to the aims of the study?	Yes	Yes	Yes	Yes	Yes	Yes
9 Were the risk factor and outcome variables measured correctly using instruments/measurements that had been trialled, piloted or published previously?	Yes	Don't know	Yes	Yes	Yes	Yes
10 Is it clear what was used to determined statistical significance and/or precision estimates? (eg, p values, CIs)	No	Yes	Yes	Yes	Yes	Yes

11 Were the methods (including statistical methods) sufficiently described to enable them to be repeated?	No	Yes	Yes	Yes	Yes	Yes
Results						
12 Were the basic data adequately described?	Yes	Yes	Yes	Yes	Yes	Yes
13 Does the response rate raise concerns about non-response bias?	Yes	Don't know	Don't know	Yes	Yes	Don't know
14 If appropriate, was information about non-responders described?	Yes	Don't know	No	Yes	Yes	No
15 Were the results internally consistent?	No	No	Yes	No	Yes	No
16 Were the results for the analyses described in the methods, presented?	Yes	Yes	Yes	Yes	Yes	Yes
Discussion						
17 Were the authors' discussions and conclusions justified by the results?	Yes	Yes	Yes	Yes	Yes	Yes
18 Were the limitations of the study discussed?	Yes	Yes	Yes	Yes	Yes	Yes
Other						
19 Were there any funding sources or conflicts of interest that may affect the authors' interpretation of the results?	No	No	No	No	No	No
20 Was ethical approval or consent of participants attained?	N/A	N/A	N/A	N/A	N/A	N/A
Number of AXIS criteria met	16	15	18	19	20	17

Supplementary Table 5.2 Changes in the percentage of the population below requirements for nutrients of concern and above recommendations for nutrients to limit stemming from graded modeled replacements of animal with plant protein foods in self-selected diets

First author et al., y	Scenario	% replaced	Nutrient	Population group	Change in %<EAR from observed (%)	Requirement, source	Sample average
Nutrients of concern							
Gazan et al., 2021	All meats	17	Iron	M & F 18-74 y	-1%	0.95 (M) or 1.1 (F) mg/d (absorbed iron)	
Seves et al., 2017	Meat and dairy	30	Iron	F 19-30 y	-8%	10 mg/d, EAR	**-5%**
Seves et al., 2017	Meat and dairy	30	Iron	F 31-50 y	-10%	10 mg/d, EAR	
Seves et al., 2017	Meat and dairy	30	Iron	F 51-69 y	0%	6 mg/d, EAR	
Seves et al., 2017	Meat and dairy	30	Iron	M 19-69 y	0%	7 mg/d, EAR	
Seves et al., 2017	Meat and dairy	100	Iron	F 19-30 y	-31%	10 mg/d, EAR	**-15%**
Seves et al., 2017	Meat and dairy	100	Iron	F 31-50 y	-26%	10 mg/d, EAR	
Seves et al., 2017	Meat and dairy	100	Iron	F 51-69 y	0%	6 mg/d, EAR	
Seves et al., 2017	Meat and dairy	100	Iron	M 19-69 y	-1%	7 mg/d, EAR	
Gazan et al., 2021	All meats	17	Calcium	M & F 18-74 y	-3%	900 or 1200 mg/d (age dependant)	
Seves et al., 2017	Meat and dairy	30	Calcium	M 31-50 y	10%	1000 mg/d, AI	**9%**

Seves et al., 2017	Meat and dairy	30	Calcium	F 19-50 y	10%	1000 mg/d, AI	
Seves et al., 2017	Meat and dairy	30	Calcium	F 51-69 y	8%	1100 mg/d, AI	
Seves et al., 2017	Meat and dairy	100	Calcium	M 31-50 y	33%	1000 mg/d, AI	
Seves et al., 2017	Meat and dairy	100	Calcium	F 19-50 y	30%	1000 mg/d, AI	**30%**
Seves et al., 2017	Meat and dairy	100	Calcium	F 51-69 y	28%	1100 mg/d, AI	
Gazan et al., 2021	All meats	17	Fibre	M & F 18-74 y	-5%	30 g/d	
Gazan et al., 2021	All meats	17	Vitamin A	M & F 18-74 y	1%	800 (M) or 600 (F) RAE/d	
Seves et al., 2017	Meat and dairy	30	Vitamin A	M 19-69 y	9%	620/610 mcg RAE/d, EAR	**9%**
Seves et al., 2017	Meat and dairy	30	Vitamin A	F 19-69 y	8%	530 mcg RAE/d, EAR	
Seves et al., 2017	Meat and dairy	100	Vitamin A	M 19-69 y	48%	620/610 mcg RAE/d, EAR	**44%**
Seves et al., 2017	Meat and dairy	100	Vitamin A	F 19-69 y	39%	530 mcg RAE/d, EAR	
Gazan et al., 2021	All meats	17	Vitamin D	M & F 18-74 y	0%	5 mcg/d	
Seves et al., 2017	Meat and dairy	30	Vitamin D	M 31-50 y	-2%	10 mg/d, AI	**-1%**
Seves et al., 2017	Meat and dairy	30	Vitamin D	F 19-69 y	0%	10 mg/d, AI	
Seves et al., 2017	Meat and dairy	100	Vitamin D	M 31-50 y	-9%	10 mg/d, AI	**-7%**
Seves et al., 2017	Meat and dairy	100	Vitamin D	F 19-69 y	-5%	10 mg/d, AI	

Gazan et al., 2021	All meats	17	Potassium	M & F 18-74 y	-1%	3100 mg/d	
Gazan et al., 2021	All meats	17	Iodine	M & F 18-74 y	0%	150 mcg/d	
Nutrients to limit							
Gazan et al., 2021	All meats	17	Saturated fat	M & F 18-74 y	-2%	10%E	
Seves et al., 2017	Meat and dairy	30	Saturated fat	M 19-69 y	-8%	10%E, UL	**-10%**
Seves et al., 2017	Meat and dairy	30	Saturated fat	F 19-69 y	-12%	10%E, UL	
Seves et al., 2017	Meat and dairy	100	Saturated fat	M 19-69 y	-78%	10%E, UL	**-76%**
Seves et al., 2017	Meat and dairy	100	Saturated fat	F 19-69 y	-74%	10%E, UL	
Gazan et al., 2021	All meats	17	Sodium	M & F 18-74 y	4%	3153 mg/d	
Gazan et al., 2021	All meats	17	Added sugars	M & F 18-74 y	0%	10%E	

Negative values indicate a decrease in the percentage of the population below recommendations for nutrients of concern or above recommendations for nutrients to limit. Positive values indicate an increase in the percentage of the population below requirements for nutrients of concern or above recommendations for nutrients to limit. Zero values indicate no change from observed diets. For calcium and vitamin D from Seves et al. (65), data is presented for selected age groups (e.g., M 31-50 y) based on those provided by Dr. Liesbeth Temme (Centre for Nutrition and Health, National Institute for Public Health and the Environment, personal communication, 2023). Therefore, averages may not reflect that of the entire sample. Cutt-offs used in Seves et al. (65) are from the Nordic Council of Ministers or Health Council of the Netherlands. Cut-offs used in Gazan et al. (145) are referred to as Dietary Reference Values based on nutrient recommendations set by the European Food Safety Authority. Abbreviations: AI, Adequate Intakes; E, energy; F, females; EAR, Estimated Average Requirement; M, males; RAE, Retinol Activity Equivalents; UL, Upper Limit.

Appendix 5.1 Natural language search strategy

("substitut*" OR "replace*" OR "reduc*" OR "diet* change" OR "scenario*") AND ("sustain* diet" OR "sustain* food" OR "greenhouse gas*" OR "greenhouse gas emission*" OR "carbon footprint*" OR "environment* sustain*") AND ("meat*" OR "beef" OR "dairy" OR "milk" OR "cheese" OR "yoghurt" OR "yogurt" OR "yoghourt" OR "yogourt" OR "pork" OR "ruminant" OR "processed meat*" OR "lamb" OR "bean*" OR "pea*" OR "legume*" OR "lentil*" OR "tofu" OR "meat alternative*" OR "soy beverage*" OR "plant beverage*" OR "plant-based beverage*" OR "plant milk" OR "plant-based milk" OR "plant" OR "animal") AND ("self-selected diet*" OR "habitual diet*" OR "diet* pattern*" OR "diet* survey" OR "nut* survey" OR "food consumption" OR "dietary intake")

Bridge statement 4

In the previous chapter, we found that replacing meat, and particularly beef, with plant protein foods in self-selected diets led to the greatest reductions to diet-related GHGE and induced small improvements for intakes of nutrients of concern, whereas including dairy in the substitutions posed trade-offs for calcium and vitamin A. Importantly, these findings were based on a few selected studies that assessed diet-related GHGE in conjunction with nutrient outcomes; none of these studies contained information for health outcomes. Given the disparities between observed diets and CFG's recommendation to consume protein from plant sources more often, the next chapter sought to quantify the impact of modeled replacements of either red and processed meat or dairy with plant protein foods on a combination of nutrition, health, and climate outcomes.

Chapter 6: Manuscript 4 – Replacing animal with plant protein foods

Submitted

Modeling the replacement of red and processed meat or dairy with plant protein foods in Canadian diets: impact on nutrient inadequacy, health outcomes, and greenhouse gas emissions

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6.1 Abstract

Dietary guidelines emphasize consumption of plant protein foods, but the implications of replacing animal with plant sources on a combination of diet sustainability dimensions are unknown. We assessed the impact of partially substituting red and processed meat or dairy with plant protein foods in Canadian self-selected diets on nutrition, health, and climate outcomes. Substitutions induced minor changes to the percentage of the population below requirements for nutrients of concern, but increased calcium inadequacy by up to 14% when dairy was replaced. Replacing red and processed meat or dairy increased life expectancy by up to 8.7 or 7.6 months, respectively. Diet-related greenhouse gas emissions decreased by up to 25% for red and processed meat and by up to 5% for dairy replacements. Co-benefits of partially substituting red and processed meat with plant protein foods among nutrition, health, and climate outcomes are relevant for reshaping consumer food choices in addressing human and planetary health.

6.2 Introduction

Dietary choices contribute considerably to chronic diseases and climate change. In high-income countries, this double burden is partly attributed to excessive consumption of animal-source foods and low intake of plant-based foods. Studies modeling the replacement of animal- with plant-source foods in population-based self-selected diets have generally found co-benefits for human health and environmental sustainability (63, 65, 151). However, most studies have assessed diets with simultaneous changes to intakes of red meat and dairy despite differences in nutrient profiles, associations with chronic diseases, and greenhouse gas emissions (GHGE) (8, 65, 152). Moreover, many have assessed the impacts of dietary replacements on surrogate measures of diet healthfulness, such as diet quality (60, 63, 64), rather than population-level outcomes relevant to public health such as nutrient inadequacy and life expectancy. To our knowledge, no studies have modeled the separate impacts of replacing meat or dairy with plant protein foods on a combination of nutrition, health, and climate outcomes in self-selected diets.

In recent years, food-based dietary guidelines in high-income countries have emphasized consumption of plant-based foods to promote the intake of essential nutrients and reduce chronic disease risk, with some countries also addressing environmental concerns. The newest iteration of Canada's Food Guide (CFG) recommends consuming vegetables and fruit, whole grains, and protein foods, among which plant protein foods – namely nuts, seeds, beans, peas, lentils, tofu, and fortified soy beverages – should be consumed more often (12). Yet plant protein foods comprised only 5% of Canadian adults' total protein intakes in 2015, with red and processed meat and dairy each accounting for roughly 20% (116). Furthermore, animal-source foods contributed largely to intakes of nutrients of public health concern, with dairy alone accounting for half of Canadian adults' total intakes of calcium and nearly 40% of vitamin D, but also 30%

of saturated fat (46). Despite the prominent role of animal protein foods in Canadian diets, the impact of adhering more closely to CFG by displacing animal with plant protein sources on dimensions of diet sustainability is not yet known. The objective of this study was to assess the implications of partial substitutions of red and processed meat or dairy with plant protein foods consistent with CFG recommendations in Canadian self-selected diets on nutrient inadequacy, health outcomes, and diet-related GHGE.

6.3 Materials and methods

Population sample and dietary data

Dietary data was derived from the 2015 CCHS – Nutrition, a nationally representative cross-sectional survey that used 24-h dietary recalls to collect information on the foods and beverages consumed by Canadians (*n* = 20,487) (86). Primary interviews were conducted in person, with a subset of respondents (~35%) randomly selected to complete a second 24-h recall by telephone 3 to 10 days after the first interview for the purpose of estimating usual intakes. The Canadian Nutrient File (89), Canada's reference food composition database, was used by Statistics Canada to link foods and beverages reported in the CCHS (*n* = 2,621) to their nutrient profiles. Respondents <19 y (*n* = 6,568; 32% of sample), pregnant (*n* = 116; 0.57% of sample) and breastfeeding women (*n* = 187; 0.91% of sample), and respondents that did not complete a 24-h recall (*n* = 4; 0.03% of sample) were excluded. We focused on the general adult population since they are more likely to make conscious dietary changes than children. The final sample size was 13,612 individuals. Access to the 2015 CCHS – Nutrition Master Files was approved by Statistics Canada (project no. 20-MAPA-MCG-6679). Statistics Canada surveys are granted ethical approval under the authority of the Statistics Act of Canada.

Replacement scenarios

Since CFG recommends consuming protein from plants more often, we designed graded replacements (25 and 50%) of either (1) red and processed meat or (2) dairy with equal grams of plant protein foods. We focused our scenarios on red and processed meat and dairy since these were commonly consumed animal protein foods that contributed most to Canadians' diet-related GHGE in 2015 (146). We replaced 25 and 50% since these quantities would be more feasible to implement by individuals than higher quantities or the exclusion of red and processed meat or dairy altogether. We substituted grams to produce more realistic scenarios since individuals typically prepare and consume foods based on weight or volume rather than calories or protein. For example, it would require two-and-a-half times the amount of pulses to replace ground beef on an equivalent calorie basis. Red and processed meat consisted of beef and veal, lamb, pork, and luncheon and other meats (e.g., liver and liver pate, offal, sausage, game meat). Dairy included milk, cheese, yoghurt, cream, butter, and frozen dairy. Plant protein foods comprised nuts and nut butters, seeds, legumes, and tofu and soy-based meat alternatives (e.g., "meatless" chicken). Fortified soy beverage was included in the dairy scenarios as a direct replacement for milk since it was a commonly consumed plant-based beverage in the CCHS and the only one included as an example of a plant protein food in CFG. Classification of red and processed meat, dairy, and plant protein foods is in **Supplementary Table 6.1**. Replacements accounted for all foods, whether consumed whole or as part of mixed dishes. To account for personal preferences, animal products were replaced in proportions originally consumed by each respondent or by the sample average for those who did not report consuming any as done by Willits-Smith et al. (63). For respondents that did not consume red and processed meat or dairy, no replacement was done but they were still included in the analysis. We did not account for the addition or removal of foods that may accompany reduced intakes of red and processed meat or dairy. Methodological details on modeling replacement scenarios are in the Supplementary Materials.

Adherence to Canada's Food Guide

Adherence to CFG recommendations was calculated using the HEFI−2019 – consisting of 10 components including foods, beverages, and nutrients – that is scored out of 80 points, with higher scores indicating greater adherence (153). Since CFG does not contain age- and sex-specific serving sizes, Reference Amounts (similar to the concept of a serving) were used to calculate food proportions as presented in the food guide snapshot, a plate consisting of half vegetables and fruit, one-quarter whole-grain foods, and one-quarter protein foods. We calculated the HEFI−2019 using the population ratio method, which uses only one 24-h recall per individual. More information on the HEFI−2019 is included in the Supplementary Materials.

Prevalence of inadequate or excess nutrient intakes

The National Cancer Institute (NCI) method was used to estimate the percentage of the population with usual intakes below DRI (38) for protein and nutrients of public health concern in Canada (calcium, vitamin D, iron, potassium) (76) and above CFG recommendations for nutrients to limit (sodium, free sugars, saturated fat) (12). The NCI method uses data from two non-consecutive 24-h recalls to model usual intakes (92, 154). Age, sex, and nuisance effects (i.e., weekend and recall sequence) were included as covariates in all models. The EAR cut-point method (i.e., percentage of the population below the EAR) was used to discern the prevalence of inadequacy for protein, vitamin D, and calcium, since the distribution of their requirements are symmetrical (86). Inadequacy could not be determined for iron since its requirements are skewed for women of reproductive ages, nor for potassium since it has an AI but not an EAR. Nutrient intakes from supplements were not included since dietary guidance recommends getting nutrients primarily from foods. However, since Health Canada recommends a vitamin D supplement of 10 μg for individuals 51 years of age and older or those that do not consume vitamin D-containing foods on a daily basis (155), we conducted an additional analysis for the percentage of the population below requirements for vitamin D from foods and beverages (hereafter referred to as foods) and supplements. The analysis was conducted for supplement users and non-users separately and then combined as recommended by Statistics Canada (156). We also performed these additional analyses for calcium, iron, and potassium since supplement data was available for these nutrients. More information on the NCI method and details for combining intakes for supplement users and non-users are in the Supplementary Materials.

Modeling changes to health outcomes

The IOMLIFET life table model (157) was used to estimate changes to life expectancy and life years as done previously (158). Given age- and sex-specific mortality rates, the model estimates survival patterns in a population stemming from changes in mortality risk due to modeled dietary changes. All-cause and cause-specific mortality rates for ischemic heart disease, type 2 diabetes, and colorectal cancer were calculated using age- and sex-specific data for population size from Statistics Canada (159) and mortality data from the GBD results tool. RR associated with intake of animal and plant protein foods for the selected diseases were taken from the GBD Study 2017 (**Supplementary Table 6.2**) (51). Separate life tables were created for males and females due to differences in underlying mortality rates and food consumption. Changes to intake of animal and plant protein foods under the modeled substitution scenarios were estimated using the NCI method to reflect usual intakes. To estimate the sensitivity of health outcomes, lower and upper bounds were calculated using 95% CI of the RR.

Estimation of diet-related greenhouse gas emissions

Foods in the CCHS were linked to GHGE estimates from the database of Food Impacts on the Environment for Linking to Diets (dataFIELD; version 1.0) as described elsewhere (146). Briefly, dataFIELD is a curated database of environmental impacts for 332 commodity foods collected from global life cycle assessment studies published between 2005 and 2016 (111). Estimates were expressed as kg of CO_2eq per kg of commodity food to account for differences in the global warming potential of greenhouse gases over a 100-y horizon (unless otherwise stated in dataFIELD). The boundaries were cradle-to-farm gate for food commodities or cradle-to-processing gate for most processed foods. To assign GHGE estimates to foods in the CCHS, we linked dataFIELD commodities to the United States Environmental Protection Agency's Recipe Database 2005-10, which contains foods from the National Health and Nutrition Examination Survey broken down into commodities. We aggregated GHGE estimates for each food and linked these to foods reported in the CCHS 24-h recalls using food codes. Since dataFIELD used milk components as proxies for dairy commodities, we instead used cradle-to-processing gate Canadian estimates for dairy products from Vergé and colleagues (113) to link directly to foods in the CCHS 24-h recalls. We accounted for food losses in our calculation of GHGE using estimates from Statistics Canada or United States Department of Agriculture’s Loss-Adjusted Food Availability data series. The diet-related GHGE of individuals was aggregated from foods reported in their 24-h recalls and estimated based on usual intakes using the NCI method. To put our scenarios into the global context, we estimated the percentage of diet-related GHGE exceeding the per capita planetary boundary for CO_2eq for observed and modeled diets as done previously by Hallström et al. (160). Details for modeling diet-related GHGE for scenarios and estimating the percentage exceeding the planetary boundary for CO_2eq are in the Supplementary Materials.

Statistical analyses

Statistical analyses were conducted in SAS version 9.3 (SAS Institute Inc., Cary, NC, USA) using SAS-callable SUDAAN version 11.0 .1 (RTI International, Durham, NC, USA) or RStudio (version 2022.02.3) for life tables. Sample and bootstrap weights available in the CCHS were used to obtain representative estimates for the Canadian population and to calculate CI around point estimates, respectively. Descriptive statistics were used to estimate intake of animal and plant protein foods and adherence to CFG; differences between observed and modeled diets were detected using two-sided paired *t*-tests. Differences in diet-related GHGE and the percentage of the population below or above nutrient recommendations were detected using paired one-sided *z*-tests. Differences between males and females were detected using unpaired two-sided *z*-tests. The p-values were adjusted for multiple comparisons using the Benjamini-Hochberg procedure. Adjusted p-values < 0.05 were considered statistically significant.

6.4 Results

Characteristics of observed and modeled diets

Average intake of protein foods (unadjusted for energy intake) in observed diets was 69 g/d for red and processed meat, 231 g/d for dairy, and 38 g/d for plant protein foods (**Supplementary Table 6.3**). Nearly half of red and processed meat was consumed as beef and veal, two-thirds of dairy was consumed as milk, and half of plant protein foods was consumed as legumes. Overall consumption of red and processed meat, dairy, and plant protein foods was greater for males compared to females (**Supplementary Table 6.4**). After implementing the substitutions, intake of plant protein foods increased proportionally in the scenarios to nearly double when half of red and processed meat was replaced and quadruple when half of dairy was substituted. The greater intake of plant protein foods in the dairy compared to red and processed meat scenarios was due to the large intake of fluid milk in observed diets, which was replaced directly by fortified soy beverage in these scenarios. Total energy intake remained relatively constant across scenarios, ranging between +18 and +39 kcal/d from observed diets (1,878 kcal/d; 95% confidence interval (CI): 1,851, 1,906 kcal/d).

Adherence to dietary guidance

Replacing red and processed meat or dairy with plant protein foods resulted in greater overall adherence to CFG based on the Healthy Eating Food Index (HEFI)−2019 (**Figure 6.1** and **Supplementary Table 6.5**). Relative to observed diets, the total HEFI−2019 score increased by 14% (50.2 points; 95% CI: 49.8, 50.5) when half of red and processed meat was substituted and by 12% when half of dairy was substituted (49.1 points; 95% CI: 48.8, 49.5) ($p<0.0001$). Gains to total HEFI−2019 scores increased to a similar extent when one-quarter of red and processed meat or dairy was substituted (by 12 or 9%, respectively; $p<0.0001$). Notably, component scores for plant-based protein foods increased by 79% when half of red and processed meat was replaced and by 95% when dairy was substituted ($p<0.0001$).

Changes to the percentage of the population below or above nutrient recommendations

Replacing red and processed meat, but not dairy, increased protein inadequacy by 0.8 to 1.9% ($p<0.0001$) relative to observed diets (**Supplementary Table 6.6**). Changes to the percentage of the population below recommendations for nutrients of concern from foods relative to observed diets are shown in **Figure 6.2** and absolute values by Dietary Reference Intakes (DRI) age-sex groups are in **Supplementary Tables 6.7-6.10**. Inadequacy of vitamin D (presented as percentage change from observed diets) increased for all age-sex groups in the dairy scenarios (0.3 to 1.2%; $p<0.0008$), but for males only in the red and processed meat scenarios (0.2 to 0.5%; $p<0.004$). For all age-sex groups, calcium inadequacy decreased by up to 3.7% ($p<0.0001$) when red and processed meat was replaced but increased by up to 6.5% and 13.9% ($p<0.0001$) when one-quarter and half of dairy was substituted, respectively. Calcium inadequacy was greatest for females and older adults. The percentage of the population below the Estimated Average Requirement (EAR) for iron decreased for most age-sex groups when dairy was replaced, with the largest percentage change for premenopausal females aged 31 to 50 y (4.1 to 6.9%; $p<0.03$). Replacing red and processed meat also decreased the percentage of adults below iron recommendations, although to a lesser degree (<1%; $p<0.05$). The percentage of adults below the Adequate Intake (AI) for potassium decreased slightly in all scenarios (≤1%; $p<0.04$).

The percentage of the population below requirements for nutrients from foods and supplements is in Supplementary Tables 5.11-5.14. When accounting for intakes from supplements, the percentage of the population below the EAR for vitamin D fell by 28% and by up to 45% for females 51 y of age and older. Reductions in the percentage below the EAR for calcium were also stark for females above the age of 51 y (17%). However, since nutrient intakes from supplements remained constant across scenarios, differences between observed and modeled diets were relatively unchanged compared to those from foods alone. Changes to the percentage of the population below recommendations for iron and potassium from foods compared to supplements were small.

Changes to the percentage of the population exceeding recommendations for nutrients to limit from foods relative to observed diets are in **Figure 6.3** and absolute values by DRI age-sex groups are in **Supplementary Tables 6.15-6.17**. The prevalence of excess intakes of saturated fat decreased in all scenarios but was especially apparent when dairy was replaced (13.3 to 33.1%; $p<0.0001$). For free sugars, the percentage of the population exceeding recommendations decreased slightly in the red and processed meat scenarios (0.4 to 1.3%; $p<0.002$) but increased for most males in the dairy scenarios (0.4 to 1%; $p<0.04$). The percentage of adults exceeding sodium recommendations decreased to a similar extent in all scenarios (0.8 to 4.3%; $p<0.0001$).

Changes to health outcomes

Substituting red and processed meat or dairy with plant protein foods led to gains to life expectancy and life years stemming from a reduced risk of chronic diseases (**Table 6.1**). Replacing half of red and processed meat or dairy increased life expectancy at birth by 8.7 or 7.6 months, respectively, with proportional increases in the 25% scenarios. Gains to life expectancy for males were more than double those for females in the red and processed meat scenarios (males: 6.9 to 12.0 months; females: 2.9 to 5.5 months), with smaller differences observed in the dairy scenarios (males: 4.7 to 8.6 months; females: 3.8 to 6.5 months). Eighty percent of the changes to life expectancy in the red and processed meat scenarios were attributed to increases in plant protein foods, while the remaining 20% resulted from reductions in red and processed meat. In the dairy scenarios, however, reducing milk consumption slightly decreased life expectancy but was compensated for by increases in plant protein intake. Replacing red and processed meat or dairy led to an additional 1 to 2 million years of life gained over the next 20 years. Compared to females, 70% of gains to life years in the red and processed meat scenarios and 60% of gains in the dairy scenarios were in males.

Changes to diet-related GHGE

The observed diet-related GHGE of Canadian adults was 3.99 kg carbon dioxide equivalents (CO_2eq)/person/d (95% CI: 3.88, 4.11) (**Table 6.2**). Males' diet-related GHGE was 1.5-fold that of females. Diet-related GHGE decreased up to 25% when half of red and processed meat was replaced with plant protein foods (27% for males, 21% for females; $p<0.0001$), but only up to 5% when half of dairy was substituted (males and females; $p<0.0001$). Reductions were proportionally less when one-quarter of animal protein foods were replaced for both combined and sex-stratified data. Observed diets exceeded the per capita planetary boundary for CO_2eq by 2.1-fold compared to 1.7-fold or 2.0-fold when 50% of red and processed meat or dairy were replaced, respectively.

6.5 Discussion

The implications of dietary guidance emphasizing greater consumption of plant protein foods depend largely on the types of animal-source foods being displaced. We found that partially replacing red and processed meat led to the greatest co-benefits across dimensions of diet sustainability. In comparison, substituting dairy attenuated synergies to health outcomes and diet-related GHGE, and despite decreasing excess intakes of saturated fat, posed a trade-off with calcium inadequacy. Importantly, while replacing red and processed meat with plant proteins worked synergistically to increase life expectancy, decreases in life expectancy stemming from reducing milk intakes were compensated for by increasing intakes of plant protein foods in the dairy scenarios. Our findings suggest that current dietary guidance in Canada can lead to substantial gains for human health and environmental sustainability if shifts to incorporate more plant protein foods coupled with reductions to red and processed meat, in particular, are implemented in practice.

Similar to our findings, substituting meat and dairy with plant-based alternatives in self-selected diets in the Netherlands increased intakes of iron, but decreased intakes of calcium (65). An advantage of assessing replacements of meat or dairy separately, however, was that we were able to parse changes to nutrient inadequacy as stemming mostly from the dairy scenarios. Likewise, replacing milk with plant-based beverage substitutes in French self-selected diets increased the probability of adequacy for iron and decreased the probability of adequacy for calcium, but only when substitutes were unfortified (161). Despite mandatory fortification of plant-based beverages with calcium under the Food and Drugs Act in Canada (162), fortification levels for calcium did not match those for all milk products (e.g., powdered milk). Moreover, dairy products, such as cheese and yoghurt, were replaced with plant protein foods with naturally low calcium contents. Therefore, since dairy products contributed more than half of Canadian adults' total calcium intakes in 2015 (46), their replacement could affect calcium status in vulnerable populations (i.e., females and older adults). Although our replacements improved intakes of iron, particularly for premenopausal females, non-heme iron from plants is less bioavailable than heme iron from animal products. Indeed, studies on blood biomarkers have generally shown that the prevalence of iron deficiency anemia is highest among vegetarian females (163). Trade-offs with calcium inadequacy and bioavailable iron present a challenge in meeting requirements for these nutrients from foods alone when substituting animal with plant protein sources. However, we found that accounting for supplements drastically reduced levels of inadequacy for calcium among females and older adults, but only slightly for iron among premenopausal females. Supplements also reduced the percentage of the population with inadequate vitamin D intake, however, differences between observed and modeled diets were less than 1% regardless of whether intakes were from foods alone or combined with supplements. Including age- and sex-specific recommendations for supplementation in CFG, particularly for calcium, and targeting fortification of plant protein foods to align with changes to dietary guidance could be useful in ensuring that at-risk subpopulations meet requirements for these shortfall nutrients.

Replacing red and processed meat, but especially dairy, with plant protein foods greatly reduced the percentage of adults exceeding recommendations for saturated fat. Another analysis of the 2015 Canadian Community Health Survey (CCHS) – Nutrition found that substituting animal-source foods high in saturated fat with plant-based foods could ensure that all Canadians keep their saturated fat intakes below 10% of total energy intake (164). Despite evidence of the putative harmful association of saturated fat with cardiovascular health, some argue that the food matrix may be more important in determining associations with diet-related chronic diseases (165). Indeed, dose-response meta-analyses have generally found neutral associations between dairy product consumption and cardiovascular disease (166). Modeling diet-disease relationships for cardiovascular outcomes when relative risks (RR) for milk and other dairy products from the Global Burden of Disease (GBD) study become available may provide a clearer understanding of the overall effects of dairy on health.

In our study, replacing red and processed meat or dairy with plant protein foods led to positive health outcomes. In particular, replacing red and processed meat as opposed to dairy led to greater health impacts, especially for males. Similarly, replacing 25 and 50% of red and processed meat with vegetables and legumes in a representative sample of Swedish adults resulted in 0.3 and 0.5 million fewer years of life lost over 20 years, respectively, of which gains among males were double those of females (56). As in our study, the authors found that replacing milk with a plant-based substitute increased years of life lost. Therefore, the types of animal protein foods being displaced and sex will define the magnitude of overall gains to health resulting from dietary guidance emphasizing plant protein foods.

We also found that substituting red and processed meat reduced diet-related GHGE to a greater extent than did replacing dairy. Studies from North America and Europe found that substituting 25 to 50% of red meat or beef with plant proteins reduced diet-related GHGE by 10 to 29% (63, 144). However, fewer studies have assessed the environmental impacts of replacing dairy with plant protein foods independently of meat and other animal protein sources. Moreover, while other studies have shown that males have a higher diet-related GHGE compared to females (60), ours can attribute this finding to higher observed intakes of red and processed meat as opposed to dairy, which led to the attenuation of sex differences among diet-related GHGE in the dairy scenarios. Importantly, even the largest reductions to diet-related GHGE from substituting half of red and processed meat with plant protein foods would exceed the per capita planetary boundary. Therefore, dietary change must be coupled with complementary interventions on the part of producers and consumers, such as improving production practices and reducing food loss and waste, to avoid the most detrimental impacts of climate change.

The graded nature of our replacement scenarios showcased the degree of impacts potentially attainable from substituting partial amounts of red and processed meat or dairy with plant protein foods, as opposed to excluding them altogether. Interestingly, low-GHGE/high-nutritional quality observed European diets did not require complete exclusion of any single food group (9). Furthermore, studies have found that more Canadians reported making an effort to reduce their red meat consumption (as opposed to all meats or dairy) than those who reported following a plant-based dietary pattern (167). For context, our most stringent scenario led to an increase in plant protein food intake equivalent to three-quarter cups of boiled lentils per day. Since meat and dairy consumption are engrained in western culture, partial replacements could be a culturally acceptable alternative towards more sustainable diets.

Our study had several strengths and limitations. Integrating three outcomes focused on nutrition, health, and diet-related GHGE enabled us to assess the compatibility of scenarios involving two distinct groups of animal protein foods, which revealed synergies from substituting red and processed meat but trade-offs from replacing dairy. Although there are intrinsic differences in the timeframes of the outcomes reported, we based our outcomes on usual intakes to reflect habitual dietary patterns (92), which if maintained long-term would address these differences. We accounted for individual preferences by replacing plant protein foods in the proportions in which they were originally consumed. A limitation of our approach is that the classification scheme we used combined traditional (e.g., tofu) and novel soy-based foods (e.g., soy burger) despite their nutritional discrepancies. However, these foods comprised a small proportion of total plant protein foods consumed by our sample (6.8%), so changes to nutrient inadequacy that may arise from this would likely be minor. Furthermore, we used standardized RR for foods available in the GBD 2017 to model population-level health outcome responses to dietary scenarios, but these did not capture all protein foods assessed in our study. While dietary risks were chosen by the GBD collaborators based on probable or convincing evidence of a causal relationship with chronic disease, food-disease relationships are contentious, particularly for unprocessed red meat, and are subject to change as new methodological approaches and data become available (52). A limitation of using RR in modeling health outcomes is the possibility for residual confounding despite being adjusted for age, sex, smoking, and physical activity (51). We used the 95% CI of RR to provide nominal lower and upper bounds of health outcomes, but these may overestimate the CI widths due to aggregation across disease endpoints. Moreover, we predict that the small increases in total energy intake from observed diets across replacement scenarios of up to 39 kcal/d would lead to 1.2 kg in weight gain over 3 years which are not accounted for in our modeling of health outcomes (168). Finally, despite our use of GHGE as the sole indicator of environmental impact, the level of granularity achieved from linking the impacts of dataFIELD commodities to over 2,000 foods reported in the CCHS through use of recipe files and crossover between American and Canadian nutrient databases would be challenging from use of alternative datasets that report additional impacts. Although beef originates from beef and dairy cattle, we used the average beef GHGE estimate from dataFIELD (which includes 10 out 119 entries from dairy cattle) as it is not possible to accurately estimate dairy's contribution to the Canadian beef supply from publicly available data. Incorporating more environmental impacts from foods that account for specific production systems into population-level dietary analyses will be important for providing more holistic assessments.

The present study provides evidence that diets adhering more closely to CFG's recommendation to consume protein from plants more often have overall co-benefits for nutrition, health, and climate outcomes, but these depend largely on the type and amount of animal protein being displaced. Replacing red and processed meat improved health outcomes and greatly reduced diet-related GHGE, for males especially, while leading to minor changes to nutrient inadequacy. Replacing dairy, on the other hand, attenuated gains to health outcomes and diet-related GHGE, and despite improvements to intakes of saturated fat, increased calcium inadequacy. Integrated assessments incorporating more sustainability dimensions (e.g., economic, social) will be crucial for creating harmonized messaging that accounts for the interplay of synergies and trade-offs among dimensions of diet sustainability to shape future consumer food choices.

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Author contributions

OA: conceptualization, data curation, formal analysis, investigation, methodology, software, visualization, writing – original draft, writing – review & editing. PEC: methodology, resources, software, validation, writing – review & editing. JM: methodology, resources, software, validation, writing – review & editing. SAB: conceptualization, methodology, project administration, supervision, validation, visualization, writing – review & editing.

Competing interests

OA, PEC, and JM declare no competing interests. SAB reports receiving grants from Dairy Farmers of Canada for research unrelated to this manuscript.

Data sharing

Access to the 2015 CCHS – Nutrition Microdata Files is restricted to accredited researchers. To become accredited, individuals must apply for access by submitting a project proposal to Statistics Canada: https://www.statcan.gc.ca/en/microdata/data-centres/access. The authors declare that all other data utilized in this study are available as specified throughout the article and Supplementary Materials. SAS and R code (health outcomes) will be made available upon request to sergio.burgos@mcgill.ca.

Table 6.1 Changes to life expectancy and years of life gained for modeled dietary substitutions relative to observed diets

	LE attributed to changes in consumption of animal and plant protein foods (months)[1]	LE attributed to changes in consumption of animal protein foods only (months)	LE attributed to changes in consumption of plant protein foods only (months)	Years of life gained over 20 y attributed to changes in consumption of animal and plant protein foods (millions)
Red and processed meat (25%)	**4.91 (2.66, 6.71)**	**1.16 (0.17, 1.85)**	**3.91 (2.49, 5.22)**	**1.16 (0.64, 1.57)**
Male	6.91 (3.75, 9.39)	1.69 (0.24, 2.68)	5.50 (3.52, 7.30)	0.82 (0.45, 1.10)
Female	2.90 (1.56, 4.03)	0.64 (0.10, 1.02)	2.32 (1.47, 3.13)	0.34 (0.19, 0.47)
Red and processed meat (50%)	**8.74 (4.97, 11.46)**	**2.27 (0.34, 3.57)**	**7.06 (4.66, 9.10)**	**2.04 (1.18, 2.63)**
Male	12.02 (6.90, 15.05)	3.28 (0.47, 5.14)	9.71 (6.47, 12.39)	1.41 (0.82, 1.79)
Female	5.46 (3.03, 7.38)	1.26 (0.20, 2.00)	4.41 (2.84, 5.82)	0.63 (0.36, 0.84)
Dairy (25%)	**4.28 (2.63, 5.78)**	**−0.09 (−0.03, −0.16)**	**4.37 (2.79, 5.81)**	**1.06 (0.68, 1.41)**
Male	4.71 (2.89, 6.38)	−0.10 (−0.04, −0.17)	4.81 (3.06, 6.42)	0.59 (0.37, 0.78)
Female	3.84 (2.37, 5.17)	−0.08 (−0.03, −0.14)	3.92 (2.51, 5.20)	0.47 (0.30, 0.63)
Dairy (50%)	**7.57 (4.81, 9.89)**	**−0.18 (−0.07, −0.32)**	**7.75 (5.13, 9.96)**	**1.87 (1.24, 2.39)**
Male	8.63 (5.49, 11.29)	−0.20 (−0.07, −0.35)	8.83 (5.84, 11.36)	1.07 (0.71, 1.37)
Female	6.50 (4.13, 8.49)	−0.16 (−0.06, −0.29)	6.67 (4.42, 8.55)	0.80 (0.53, 1.02)

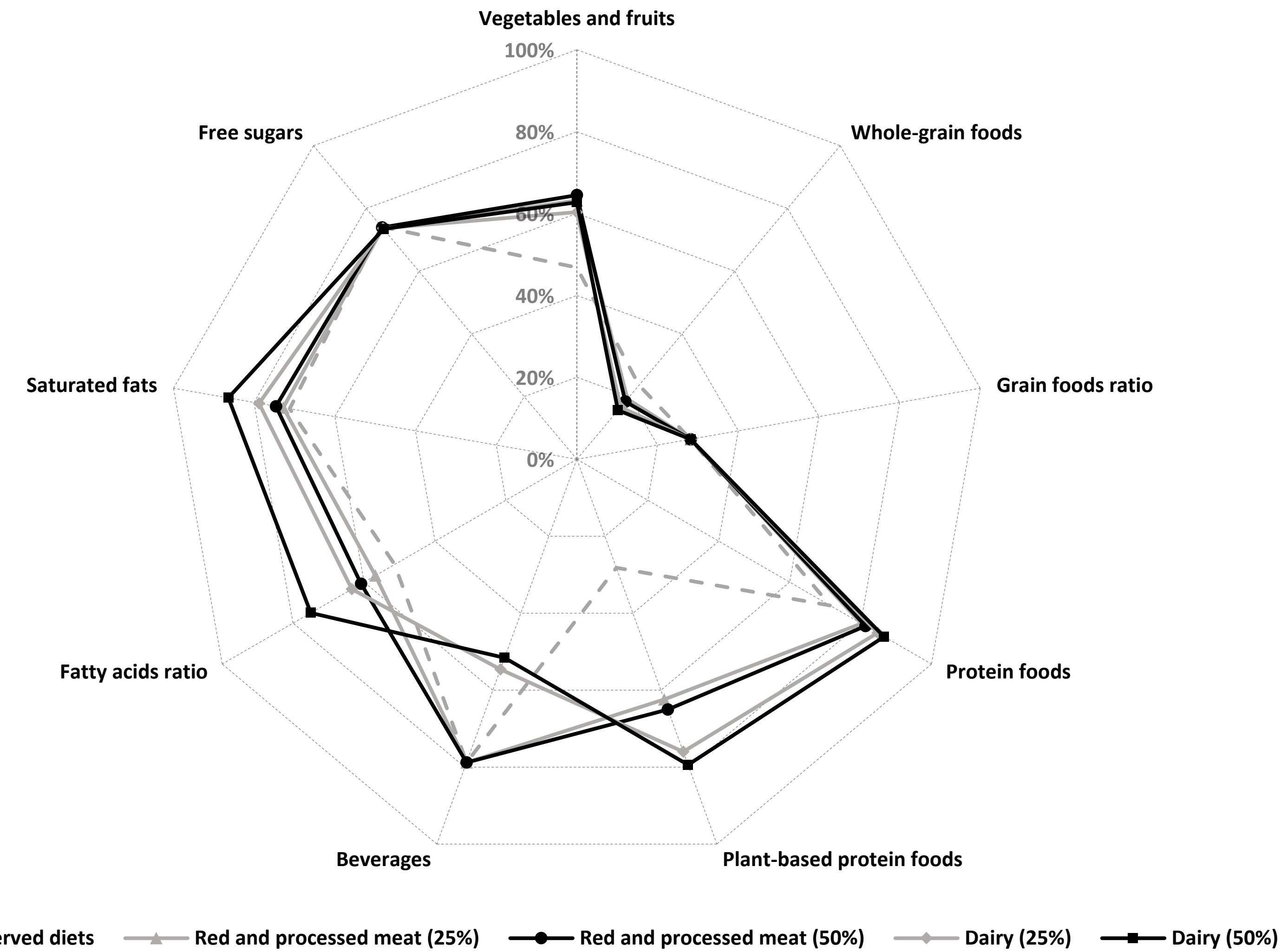
[1]Changes to average LE at birth of the baseline population. Estimates were generated using the IOMLIFET life table model based on relative risk estimates from the Global Burden of Disease Study 2017. Lower and upper bounds (in parentheses) were generated using lower and upper 95% CIs of the relative risks, respectively. Since dietary risks for the same disease are multiplied, LE attributed to changes in consumption of animal and plant protein foods does not necessarily equate to the sum of LE attributed to changes in consumption of animal protein foods only and plant protein foods only. LE=life expectancy.

Table 6.2 Diet-related greenhouse gas emissions and percentage exceeding the per capita planetary boundary for observed and modeled dietary substitutions

	kg CO_2eq/person/d[1]	% > per capita planetary boundary[2]
Observed diets	**3.99 (3.88, 4.11)**	**214**
Male	4.72 (4.53, 4.91)†	257
Female	3.27 (3.17, 3.37)	171
Red and processed meat (25%)	**3.56 (3.47, 3.65)***	**191**
Male	4.16 (4.01, 4.31)*†	226
Female	2.95 (2.87, 3.03)*	155
Red and processed meat (50%)	**3.12 (3.05, 3.19)***	**167**
Male	3.60 (3.49, 3.72)*†	195
Female	2.63 (2.57, 2.69)*	138
Dairy (25%)	**3.89 (3.78, 4.01)***	**208**
Male	4.61 (4.42, 4.79)*†	251
Female	3.18 (3.08, 3.27)*	166
Dairy (50%)	**3.79 (3.67, 3.90)***	**203**
Male	4.50 (4.31, 4.68)*†	244
Female	3.08 (2.98, 3.18)*	161

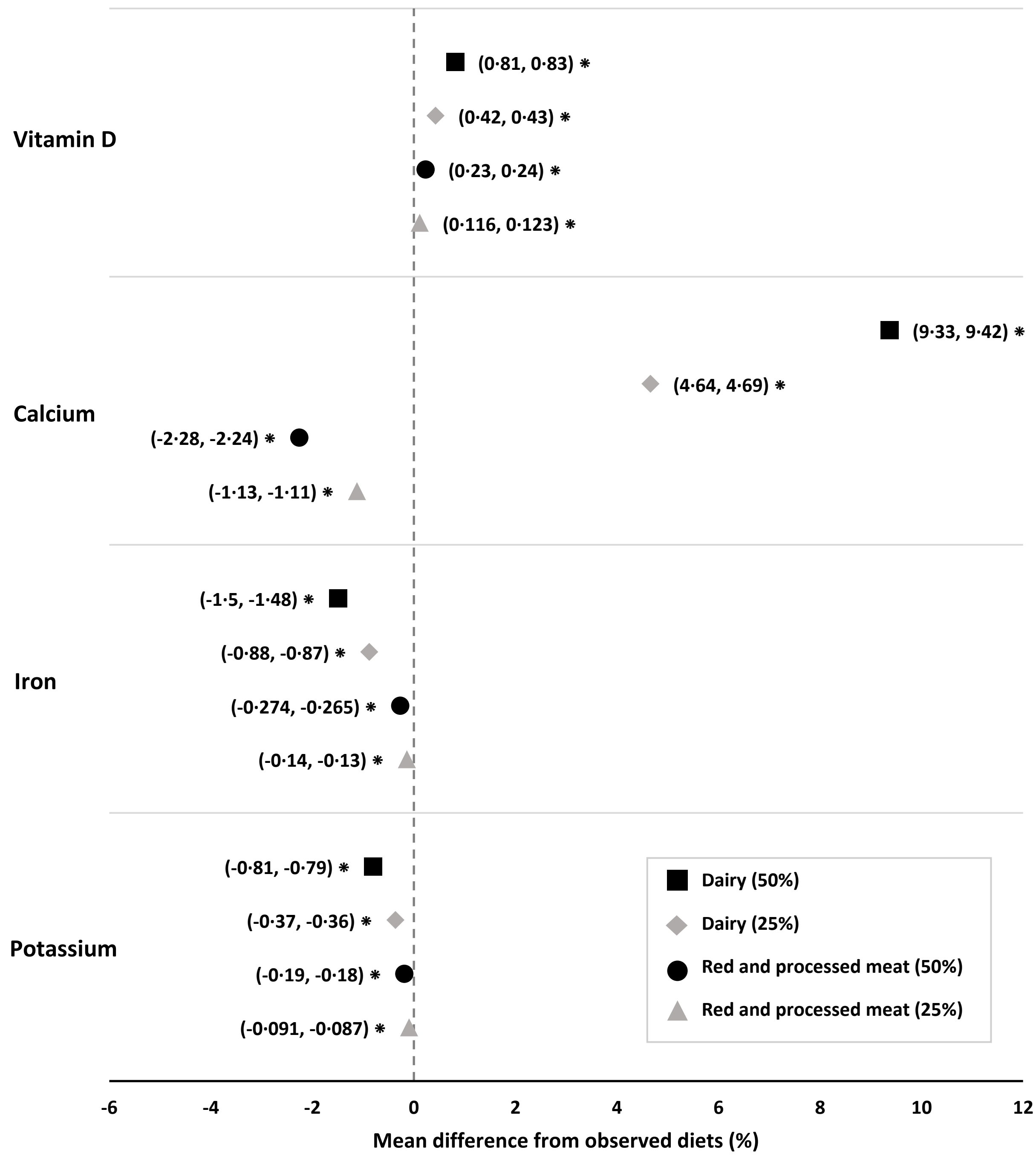
[1]Estimates are mean (95% CI) based on usual intakes. * = $p<0.05$ vs. observed diets by two-tailed paired *z*-tests. † = $p<0.05$ vs. females by two-tailed unpaired *z*-tests. The p-values are adjusted for multiple comparisons. [2]The percentage of diet-related CO_2eq exceeding the per capita planetary boundary was calculated according to the method of Hallström et al. (160). The per capita planetary boundary for CO_2eq (680 kg CO_2eq) was taken from Moberg et al. (169). CO_2eq=carbon dioxide equivalents.

Figure 6.1 Adherence of observed and modeled diets to Canada's Food Guide based on the Healthy Eating Food Index−2019



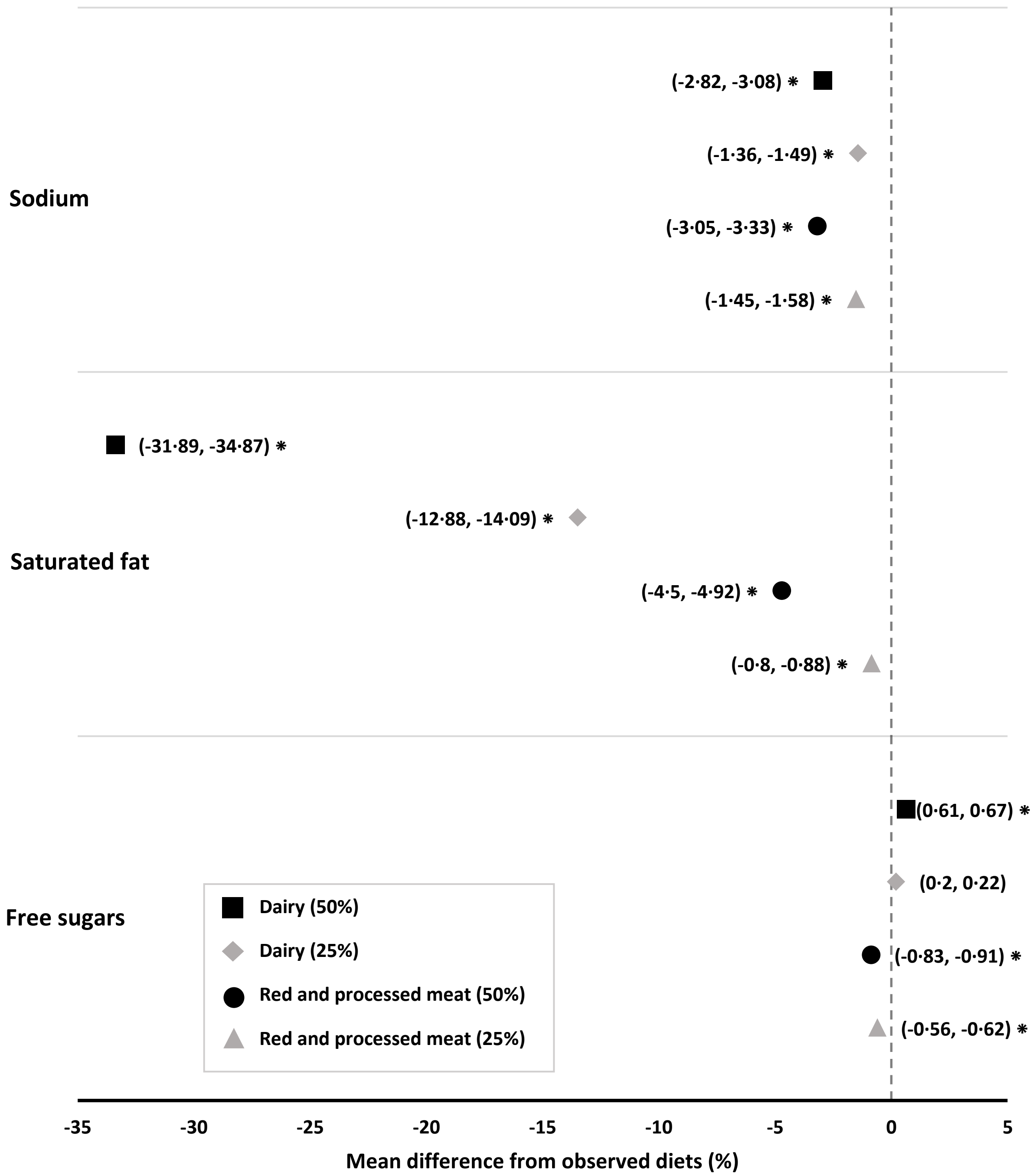
Component scores are standardized to percentages.

Figure 6.2 Changes to the percentage of the population below Dietary Reference Intakes for nutrients of concern for modeled dietary substitutions relative to observed diets



Estimates are mean differences (95% CI) in the percentage of the population below Dietary Reference Intakes (Estimated Average Requirement or Adequate Intake for potassium) relative to observed diets based on usual intakes from foods. Estimates for calcium and iron were weighted by the proportion of respondents in each Dietary Reference Intake age-sex group. * = $p<0.05$ vs. observed diets by paired *z*-tests.

Figure 6.3 Changes to the percentage of the population exceeding Canada's Food Guide recommendations for nutrients to limit for modeled dietary substitutions relative to observed diets



Estimates are mean differences (95% CI) in the percentage of the population above Canada's Food Guide recommendations relative to observed diets based on usual intakes from foods. * = $p<0.05$ vs. observed diets by paired *z*-tests.

Supplementary Table 6.1 Classification of protein foods in the 2015 Canadian Community Health Survey – Nutrition using the Bureau of Nutritional Sciences and Nutrition Survey System food codes

Protein foods	Food codes
Red and processed meat	
Beef and veal	Beef, lean only (22A); beef, lean + fat (22B); beef, ground (22C); veal, lean only (23A); veal, lean + fat (including ground veal) (23B).
Lamb	Lamb, lean only (24A); lamb, lean and fat (including ground) (24B).
Pork	Pork, fresh, lean only (25A); pork, fresh, lean and fat (including ground) (25B); bacon (25C); ham, cured, lean only (25D); ham, cured, lean and fat (25E).
Luncheon and other meats	Liver (28A); liver pâté (28B); offal (29A); sausage (30A); game meat (31A); luncheon meat (32A).
Dairy	
Milk	Milk, whole (10A); milk, 2% (10B); milk, 1% (10C); milk, skim (10D); milk, evaporated, whole (10E); milk, evaporated, 2% (10F); milk, evaporated, skim (10G); milk, condensed (10H); other types of milk (whey, buttermilk) (10I); goat and sheep milk (10K).
Cheese	Cottage cheese (14A); cheese, less than 10% M.F. (14B); cheese, 10 to 25% M.F. (14C); cheese, more than 25% M.F. (14D).
Yoghurt	Yoghurts, less than 2% M.F. (15A); yoghurts, more than 2.1% M.F. (15B).
Cream	Whipping cream (13A); table cream (13B); half and half cream (13C); sour cream (13D).
Butter	Butter (17A).
Frozen dairy	Ice cream (09A); ice milk (09B); frozen yoghurt (09C).
Plant protein foods	
Nuts and nut butters	Nuts (33A); peanut butter and other nut spreads (33C).
Seeds	Seeds (33B).
Legumes	Beans (36A); peas and snow peas (36K); legumes (37A).
Tofu and soy-based meat alternatives	Foods made with vegetable proteins (tofu) (37B).
Soy beverage*	Plant-based beverage, soy, enriched, chocolate (6329); Plant-based beverage, soy, enriched, all flavours, unsweetened (6330); Plant-based beverage, soy, enriched, all flavours (6720).

Animal and plant protein foods were classified using the Bureau of Nutritional Sciences food codes, except for soy beverage, which was classified using the Nutrition Survey System codes. *Soy beverage termed 'enriched' is indeed fortified, but the terminology used in the Canadian Nutrient File from 2015 was not updated to reflect this.

Supplementary Table 6.2 Relative Risks from the Global Burden of Disease Study 2017 used to estimate health outcomes

Disease	Units (g/d)	RR (95% CI)
Red meat		
Ischemic heart disease	–	–
Type 2 diabetes	–100	0.86 (0.76, 0.97)
Colorectal cancer	–100	0.82 (0.71, 0.97)
Processed meat		
Ischemic heart disease	–50	0.64 (0.48, 0.98)
Type 2 diabetes	–50	0.62 (0.54, 0.79)
Colorectal cancer	–50	0.85 (0.79, 0.91)
Milk		
Colorectal cancer	–226.8	1.11 (1.04, 1.20)
Nuts and seeds		
Ischemic heart disease	+4.05	0.91 (0.88, 0.94)
Type 2 diabetes	+4.05	0.96 (0.95, 0.98)
Legumes		
Ischemic heart disease	+50	0.81 (0.72, 0.91)

RR were taken from Afshin et al. (51). RRs were weighted by GBD age groups. RRs for red meat and processed meat were inverted to reflect changes in risk associated with a decrease in consumption, and those for legumes and nuts and seeds to reflect changes in risk associated with an increase in consumption (underlined). RR=relative risk.

Supplementary Table 6.3 Intake (g/d) of animal and plant protein foods for observed and modeled diets

Protein food	Observed diets	Red and processed meat (25%)	Red and processed meat (50%)	Dairy (25%)	Dairy (50%)
Red and processed meat	68.5 (65.4, 71.5)	51.36 (49.1, 53.6)	34.2 (32.7, 35.8)	–	–
Beef and veal	33.0 (30.6, 35.4)	24.72 (22.9, 26.5)	16.5 (15.3, 17.7)	–	–
Lamb	0.9 (0.5, 1.3)	0.67 (0.4, 0.9)	0.5 (0.3, 0.6)	–	–
Pork	15.1 (13.5, 16.6)	11.29 (10.1, 12.4)	7.5 (6.8, 8.3)	–	–
Luncheon and other meats	19.6 (18.0, 21.2)	14.67 (13.5, 15.84)	9.8 (9, 10.6)	–	–
Dairy	230.8 (222.6, 239.0)	–	–	173.1 (166.9, 179.3)	115.4 (111.3, 119.5)
Milk	152.7 (145.3, 160.1)	–	–	114.5 (109, 120)	76.3 (72.7, 80)
Cheese	27.4 (25.8, 28.9)	–	–	20.5 (19.3, 21.7)	13.7 (12.9, 14.5)
Yoghurt	25.6 (23.3, 27.9)	–	–	19.2 (17.5, 20.9)	12.8 (11.6, 14)
Cream	9.0 (8.0, 10.0)	–	–	6.7 (6, 7.5)	4.5 (4, 5)
Butter	3.2 (2.9, 3.6)	–	–	2.4 (2.2, 2.7)	1.6 (1.5, 1.8)
Frozen dairy	13.0 (11.4, 14.5)	–	–	9.7 (8.6, 10.9)	6.5 (5.7, 7.2)
Plant protein foods	37.8 (35.4, 40.2)	54.9 (52.3, 57.5)	72 (69.1, 74.9)	95.5 (92.3, 98.6)	153.2 (148.4, 157.9)
Nuts and nut butters	10.8 (9.8, 11.8)	17.9 (16.6, 19.2)	25 (23.3, 26.7)	18.9 (17.7, 20.1)	26.9 (25.3, 28.5)
Seeds	1.5 (0.9, 2.0)	2.1 (1.5, 2.6)	2.7 (2.1, 3.3)	2.4 (1.8, 2.9)	3.3 (2.6, 3.9)
Legumes	19.0 (17.3, 20.8)	27.3 (25.4, 29.2)	35.6 (33.5, 37.7)	28.5 (26.6, 30.5)	38 (35.8, 40.3)

Tofu and soy-based meat alternatives	3.0 (2.2, 3.8)	4.1 (3.2, 5.1)	5.1 (0.6, 4.1)	4.1 (3.2, 5)	5.1 (4.2, 6.1)
Soy beverage	3.5 (2.7, 4.6)	–	–	41.7 (39.7, 43.7)	79.9 (76.1, 83.6)

Estimates are mean (95% CI) based on 1-d intakes. – no change from observed diets.

Supplementary Table 6.4 Intake (g/d) of animal and plant protein foods among males and females for observed and modeled diets

Protein food	Observed diets		Red and processed meat (25%)		Red and processed meat (50%)		Dairy (25%)		Dairy (50%)	
	M	F	M	F	M	F	M	F	M	F
Red and processed meat	88.9 (83.5, 94.3)†	48.1 (45.3, 50.9)	66.7 (62.6, 70.8)†	36.1 (33.9, 38.2)	44.5 (41.8, 47.2)†	24 (22.6, 25.4)	–	–	–	–
Beef and veal	42.8 (38.5, 47.1)†	23.2 (21.1, 25.2)	32.1 (28.8, 35.3)†	17.4 (15.8, 18.9)	21.4 (19.2, 23.6)†	11.6 (10.6, 12.6)	–	–	–	–
Lamb	1.2 (0.6, 1.9)	0.6 (0.3, 0.9)	0.9 (0.4, 1.4)	0.4 (0.2, 0.7)	0.6 (0.3, 0.9)	0.3 (0.2, 0.4)	–	–	–	–
Pork	18.4 (15.6, 21.2)†	11.7 (10.4, 13)	13.8 (11.7, 15.9)†	8.8 (7.8, 9.8)	9.2 (7.8, 10.6)†	5.9 (5.2, 6.5)	–	–	–	–
Luncheon and other meats	26.5 (23.9, 29.2)†	12.6 (11, 14.1)	19.9 (17.9, 21.9)†	9.4 (8.3, 10.6)	13.3 (12, 14.6)†	6.3 (5.5, 7.1)	–	–	–	–
Dairy	247.1 (234.2, 259.9)†	214.6 (204.1, 224.7)	–	–	–	–	185.3 (175.7, 194.9)†	160.9 (153.3, 168.5)	123.5 (117.1, 130)†	107.3 (102.2, 112.4)
Milk	167.5 (156, 179)†	137.9 (129, 146.8)	–	–	–	–	125.6 (117, 134.2)†	103.4 (96.8, 110.1)	83.7 (78, 89.5)†	69 (64.5, 73.4)
Cheese	31.4 (28.7, 34.1)†	23.3 (21.7, 24.9)	–	–	–	–	23.5 (21.5, 25.6)†	17.5 (16.3, 18.7)	15.7 (14.3, 17.1)†	11.7 (10.9, 12.5)

Yoghurt	21.1 (18, 24.2)†	30.1 (26.6, 33.6)	–	–	–	–	15.8 (13.5, 18.2)†	22.6 (19.9, 25.2)	10.6 (9, 12.1)†	15 (13.3, 16.8)
Cream	10.2 (8.3, 12)†	7.8 (6.9, 8.7)	–	–	–	–	7.6 (6.3, 9)†	5.9 (5.2, 6.5)	5.1 (4.2, 6)†	3.9 (3.5, 4.3)
Butter	3.4 (3, 3.8)	3.1 (2.6, 3.6)	–	–	–	–	2.5 (2.2, 2.8)	2.3 (2, 2.7)	1.7 (1.5, 1.9)	1.6 (1.3, 1.8)
Frozen dairy	13.6 (11.3, 15.8)	12.3 (10.4, 14.3)	–	–	–	–	10.2 (8.5, 11.9)	9.3 (7.8, 10.7)	6.8 (5.7, 7.9)	6.2 (5.2, 7.2)
Plant protein foods	37.3 (33.8, 40.8)†	31.2 (28.6, 33.8)	62.7 (58.5, 66.8)†	47.1 (44.2, 50.1)	84.9 (80.1, 89.7)†	59.2 (56, 62.3)	102.2 (97.4, 107)†	88.8 (84.9, 92.7)	164 (156.8, 171.2)†	142.4 (136.5, 148.3)
Nuts and nut butters	12.9 (11.2, 14.7)†	8.7 (7.8, 9.6)	22.5 (20.2, 24.8)†	13.3 (12.3, 14.3)	32 (29, 35.1)†	18 (16.8, 19.2)	21.1 (19, 23.2)†	16.6 (15.4, 17.9)	29.3 (26.7, 31.9)†	24.6 (22.7, 26.4)
Seeds	1.1 (0.7, 1.4)	1.8 (0.9, 2.8)	1.8 (1.3, 2.2)	2.4 (1.4, 3.3)	2.5 (2, 3)	2.9 (1.9, 3.9)	1.9 (1.4, 2.4)	2.9 (1.8, 4)	2.7 (2, 3.3)	3.9 (2.7, 5.1)
Legumes	19.9 (17.2, 22.7)	18.1 (16, 20.3)	30.2 (27.3, 33.2)†	24.4 (22.1, 26.6)	40.5 (37.2, 43.9)†	30.6 (28.2, 33)	29.6 (26.5, 32.8)	27.4 (25, 29.8)	39.3 (35.7, 43)	36.7 (33.9, 39.5)
Tofu and soy-based meat alternatives	3.4 (2.1, 4.8)	2.6 (1.7, 3.5)	5.1 (3.5, 6.7)	3.2 (2.3, 4.1)	6.7 (4.8, 8.7)†	3.8 (2.8, 4.7)	4.7 (3.2, 6.1)	3.5 (2.5, 4.4)	5.9 (4.3, 7.5)	4.4 (3.4, 5.4)
Soy beverage	3.1 (1.5, 4.8)	3.9 (2.7, 5.2)	–	–	–	–	45 (41.9, 48.1)†	38.4 (35.9, 40.9)	86.9 (81.1, 92.6)†	72.9 (68.3, 77.5)

Estimates are mean (95% CI) based on 1-d intakes. – no change from observed diets. † = $p<0.05$ vs. females by unpaired *t*-test. The p-values are adjusted for multiple comparisons.

Supplementary Table 6.5 Healthy Eating Food Index–2019 total and component scores for observed and modeled diets

HEFI–2019 components	Maximum points	Observed diets	Red and processed meat (25%)	Red and processed meat (50%)	Dairy (25%)	Dairy (50%)
Total	80	43.47 (43.06, 43.88)	49.22 (48.86, 49.57)*	50.16 (49.80, 50.51)*	47.62 (47.28, 47.95)*	49.13 (48.81, 49.45)*
Vegetables and fruit	20	9.36 (9.17, 9.56)	12.64 (12.43, 12.85)*	12.90 (12.68, 13.12)*	12.07 (11.86, 12.28)*	12.55 (12.33, 12.77)*
Whole grain foods	5	1.18 (1.14, 1.23)	0.96 (0.92, 1.01)*	0.92 (0.88, 0.97)*	0.83 (0.79, 0.87)*	0.78 (0.74, 0.82)*
Grain foods ratio	5	1.41 (1.36, 1.46)	–	–	–	–
Protein foods	5	3.57 (3.52, 3.61)	4.01 (3.97, 4.05)*	4.07 (4.03, 4.11)*	4.24 (4.20, 4.28)*	4.33 (4.29, 4.36)*
Plant-based protein foods	5	1.41 (1.34, 1.48)	3.12 (3.05, 3.19)*	3.25 (3.18, 3.32)*	3.80 (3.74, 3.86)*	3.97 (3.91, 4.03)*
Beverages	10	7.88 (7.81, 7.96)	–	–	5.46 (5.38, 5.53)*	5.16 (5.08, 5.23)*
Fatty acids ratio	5	2.57 (2.51, 2.64)	2.84 (2.78, 2.90)*	3.04 (2.98, 3.11)*	3.17 (3.11, 3.23)*	3.75 (3.70, 3.80)*
Saturated fats	5	3.56 (3.50, 3.63)	3.64 (3.58, 3.70)*	3.73 (3.67, 3.79)*	3.94 (3.89, 3.99)*	4.32 (4.27, 4.36)*
Free sugars	10	7.41 (7.29, 7.54)	7.37 (7.25, 7.50)	7.39 (7.27, 7.52)	7.36 (7.23, 7.48)*	7.34 (7.22, 7.47)*
Sodium	10	5.10 (4.98, 5.21)	5.34 (5.22, 5.45)*	5.55 (5.44, 5.67)*	5.34 (5.22, 5.45)*	5.52 (5.40, 5.63)*

Estimates are mean (95% CI) based on 1-d intakes. * = $p<0.05$ vs. observed diets by paired *t*-test. The p-values are adjusted for multiple comparisons. – no change from observed diets. HEFI-2019=Healthy Eating Food Index-2019.

Supplementary Table 6.6 Percentage of the Canadian adult population below the Estimated Average Requirement for protein

Age	Sex	n	EAR	Observed diets	Red and processed meat (25%)	Red and processed meat (50%)	Dairy (25%)	Dairy (50%)
Combined	Combined	9,174	0.66 g/kg/d	3.1 (1.3, 5)	4.0 (2.1, 5.9)*	5.0 (3.1, 6.9)*	3.1 (1.4, 4.9)	3.2 (1.5, 4.9)
19-30 y	Male	655	0.66 g/kg/d	0.5 (0.0, 1.2)	0.8 (0.0, 1.6)*†	1.2 (0.2, 2.1)*†	0.6 (0.0, 1.3)	0.7 (0.0, 1.4)*
31-50 y	Male	1,407	0.66 g/kg/d	1.1 (0.1, 2.2)	1.5 (0.4, 2.7)*†	2.1 (0.7, 3.4)*†	1.2 (0.2, 2.2)	1.3 (0.2, 2.3)*†
51-70 y	Male	1,508	0.66 g/kg/d	2.0 (0.3, 3.8)†	2.9 (1.0, 4.7)*†	3.8 (1.8, 5.8)*†	2.1 (0.5, 3.8)†	2.2 (0.6, 3.8)†
71+ y	Male	783	0.66 g/kg/d	3.9 (1.3, 6.4)†	5.0 (2.2, 7.7)*†	6.5 (3.6, 9.4)*†	3.9 (1.4, 6.3)†	3.9 (1.6, 6.2)†
19-30 y	Female	681	0.66 g/kg/d	1.9 (0.3, 3.4)	2.4 (0.8, 4.1)*	3.1 (1.4, 4.9)*	2.0 (0.4, 3.5)	2.1 (0.6, 3.6)
31-50 y	Female	1,568	0.66 g/kg/d	3.1 (0.9, 5.3)	3.9 (1.7, 6.2)*	5.0 (2.7, 7.3)*	3.1 (1.0, 5.2)	3.2 (1.2, 5.3)
51 to 70 y	Female	1,584	0.66 g/kg/d	5.6 (2.6, 8.6)	6.9 (4.0, 9.8)*	8.3 (5.4, 11.3)*	5.5 (2.7, 8.3)	5.5 (2.8, 8.1)
71 + y	Female	988	0.66 g/kg/d	9.8 (5.9, 13.8)	11.5 (7.6, 15.4)*	13.7 (9.8, 17.6)*	9.5 (5.8, 13.2)*	9.2 (5.7, 12.7)*

Estimates are percentage below the EAR (95% CI) based on usual intakes from foods. * = $p<0.05$ vs. observed diets by paired *z*-test. † = $p<0.05$ vs. females by unpaired *z*-test. The p-values are adjusted for multiple comparisons. A subsample of respondents with measured height and weight were used to estimate the percentage of the population below the EAR for protein since it is expressed as g/kg of body weight/d. Protein was expressed as g/kg of ideal body weight/d for respondents whose measured body mass index was below 18.5 or above 24.9. EAR=Estimated Average Requirement.

Supplementary Table 6.7 Percentage of the Canadian adult population below the Estimated Average Requirement for vitamin D

Age	Sex	n	EAR	Observed diets	Red and processed meat (25%)	Red and processed meat (50%)	Dairy (25%)	Dairy (50%)
Combined	Combined	13,612	10 µg	96.5 (95.3, 97.8)	96.7 (95.4, 97.9)*	96.8 (95.6, 98.0)*	97.0 (95.8, 98.2)*	97.4 (96.2, 98.5)*
19-30 y	Male	882	10 µg	96.0 (94.3, 97.7)†	96.3 (94.6, 97.9)*†	96.4 (94.9, 98.0)*†	96.6 (95.1, 98.2)*†	97.1 (95.6, 98.5)*†
31-50 y	Male	2,077	10 µg	95.5 (93.8, 97.2)†	95.7 (94.1, 97.3)*†	95.9 (94.3, 97.5)*†	96.1 (94.5, 97.6)*†	96.5 (95.0, 98.0)*†
51-70 y	Male	2,246	10 µg	94.5 (92.7, 96.4)†	94.8 (93.0, 96.6)*†	95.0 (93.2, 96.8)*†	95.2 (93.4, 97.0)*†	95.7 (94.0, 97.4)*†
71+ y	Male	1,246	10 µg	93.3 (91.0, 95.6)†	93.6 (91.4, 95.8)*†	93.8 (91.6, 96.0)*†	94.0 (91.8, 96.1)*†	94.5 (92.5, 96.6)*†
19-30 y	Female	897	10 µg	98.6 (97.7, 99.4)	95.6 (97.7, 99.4)	98.6 (97.8, 99.4)	98.8 (98.0, 100)*	99.0 (98.3, 99.7)*
31-50 y	Female	2,288	10 µg	98.1 (97.2, 99.1)	98.2 (97.3, 99.1)	98.2 (97.3, 99.1)	98.4 (97.6, 99.3)*	98.7 (97.9, 99.5)*
51 to 70 y	Female	2,420	10 µg	97.9 (96.8, 99)	98.0 (96.9, 99.0)	98.0 (96.9, 99.0)	98.2 (97.2, 99.2)*	98.5 (97.6, 99.4)*
71 + y	Female	1,556	10 µg	97.3 (95.9, 98.6)	97.3 (96.0, 98.6)	97.3 (96.0, 98.6)	97.7 (96.4, 98.9)*	98.0 (96.9, 99.2)*

Estimates are percentage below the EAR (95% CI) based on usual intakes from foods. * = p<0.05 vs. observed diets by paired *z*-test. † = p<0.05 vs. females by unpaired *z*-test. The p-values are adjusted for multiple comparisons. EAR=Estimated Average Requirement.

Supplementary Table 6.8 Percentage of the Canadian adult population below the Estimated Average Requirement for calcium

Age	Sex	n	EAR	Observed diets	Red and processed meat (25%)	Red and processed meat (50%)	Dairy (25%)	Dairy (50%)
Combined	Combined	13,612	–	65.7 (65.6, 65.8)	66.8 (66.7, 66.9)*	64.6 (64.4, 64.7)*	71.5 (71.4, 71.6)*	76.2 (76.1, 76.3)*
19-30 y	Male	882	800 mg	41.6 (36.9, 46.4)†	39.8 (35.0, 44.5)*†	38.0 (33.2, 42.7)*†	48.1 (43.3, 52.9)*†	55.5 (50.8, 60.2)*†
31-50 y	Male	2,077	800 mg	47.1 (43.4, 50.7)†	45.2 (41.6, 48.9)*†	43.4 (39.8, 47.1)*†	53.3 (49.8, 56.8)*†	59.9 (56.6, 63.3)*†
51-70 y	Male	2,246	800 mg	53.8 (50.8, 56.8)	51.9 (48.9, 55.0)*	50.2 (47.1, 53.3)*	59.4 (56.5, 62.2)*	65.4 (62.7, 68.0)*
71+ y	Male	1,246	1000 mg	80.4 (77.5, 83.3)†	79.4 (76.4, 82.3)*†	78.3 (75.3, 81.3)*†	84.2 (81.6, 86.8)*†	87.3 (85.1, 89.5)*†
19-30 y	Female	897	800 mg	59.7 (55.4, 63.9)	58.6 (54.3, 62.8)*	57.5 (53.2, 61.8)*	65.7 (61.7, 69.7)*	71.9 (68.2, 75.6)*
31-50 y	Female	2,288	800 mg	64.4 (61.5, 67.3)	63.4 (60.5, 66.4)*	62.5 (59.6, 65.4)*	69.7 (66.9, 72.5)*	75.0 (72.3, 77.7)*
51 to 70 y	Female	2,420	1000 mg	87.7 (85.8, 89.5)	87.2 (85.4, 89.1)*	86.7 (84.8, 88.6)*	90.5 (88.8, 92.2)*	92.9 (91.4, 94.4)*
71 + y	Female	1,556	1000 mg	90.5 (88.5, 92.4)	90.2 (88.2, 92.1)*	89.8 (87.7, 91.8)*	92.5 (90.8, 94.2)*	94.2 (92.8, 95.6)*

Estimates are percentage below the EAR (95% CI) based on usual intakes from foods. * = $p<0.05$ vs. observed diets by paired *z*-test. † = $p<0.05$ vs. females by unpaired *z*-test. The p-values are adjusted for multiple comparisons. Males 51-70 y could not be compared to females 51-70 y due to differing recommendations. EAR=Estimated Average Requirement.

Supplementary Table 6.9 Percentage of the Canadian adult population below the Estimated Average Requirement for iron

Age	Sex	n	EAR	Observed diets	Red and processed meat (25%)	Red and processed meat (50%)	Dairy (25%)	Dairy (50%)
Combined	Combined	13,612	–	4.3 (4.2, 4.3)	4.1 (4.1, 4.2)*	4.0 (3.9, 4.0)*	3.3 (3.2, 3.3)*	2.6 (2.5, 2.6)*
19-30 y	Male	882	6 mg	0.2 (0.0, 0.4)	0.2 (0.0, 0.4)	0.2 (0.0, 0.4)	0.2 (0.0, 0.4)	0.1 (0.0, 0.3)
31-50 y	Male	2,077	6 mg	0.2 (0.0, 0.5)	0.2 (0.0, 0.4)	0.2 (0.0, 0.4)*	0.2 (0.0, 0.4)*	0.1 (0.0, 0.3)*
51-70 y	Male	2,246	6 mg	0.4 (0.0, 0.8)	0.3 (0.0, 0.7)*	0.3 (0.0, 0.6)*	0.3 (0.0, 0.6)*	0.2 (0.0, 0.4)*
71+ y	Male	1,246	6 mg	0.5 (0.0, 1.1)	0.5 (0.0, 1)*	0.5 (0.0, 0.9)*	0.4 (0.0, 0.8)*	0.3 (0.0, 0.6)*
19-30 y	Female	897	8.1 mg	14.5 (10.9, 18.1)	14.0 (10.5, 17.7)*	13.5 (10.1, 17.0)*	11.2 (8.0, 14.4)*	8.8 (6.0, 11.7)*
31-50 y	Female	2,288	8.1 mg	17.6 (14.2, 20.9)	17.0 (13.7, 20.4)*	16.5 (13.2, 19.8)*	13.5 (10.4, 16.6)*	10.7 (7.8, 13.6)*
51 to 70 y	Female	2,420	5 mg	1.3 (0.5, 2.1)	1.2 (0.5, 2.0)	1.2 (0.4, 1.9)*	0.8 (0.3, 1.5)*	0.6 (0.2, 1.1)*
71 + y	Female	1,556	5 mg	1.7 (0.5, 2.8)	1.6 (0.5, 2.7)	1.5 (0.4, 2.6)	1.1 (0.3, 2.0)*	0.9 (0.2, 1.5)*

Estimates are percentage below the EAR (95% CI) based on usual intakes from foods. Certain estimates may appear equal due to rounding. * = $p<0.05$ vs. observed diets by paired *z*-test. The p-values are adjusted for multiple comparisons. Males could not be compared to females due to differing recommendations. EAR=Estimated Average Requirement.

Supplementary Table 6.10 Percentage of the Canadian adult population below the Adequate Intake for potassium

Age	Sex	n	AI	Observed diets	Red and processed meat (25%)	Red and processed meat (50%)	Dairy (25%)	Dairy (50%)
Combined	Combined	13,612	4700 mg	98.7 (98.1, 99.3)	98.6 (98.0, 99.3)*	98.5 (97.9, 99.2)*	98.3 (97.6, 99.1)*	97.9 (97.1, 98.7)*
19-30 y	Male	882	4700 mg	97.3 (96.0, 98.6)†	97.2 (95.9, 98.5)*†	97.0 (95.7, 98.4)*†	96.6 (95.2, 98.1)*†	95.7 (94, 97.3)*†
31-50 y	Male	2,077	4700 mg	97.6 (96.5, 98.7)†	97.5 (96.4, 98.6)*†	97.3 (96.2, 98.4)*†	97.0 (95.8, 98.2)*†	96.3 (94.9, 97.7)*†
51-70 y	Male	2,246	4700 mg	97.9 (96.9, 99.0)†	97.9 (96.9, 98.9)*†	97.7 (96.7, 98.8)*†	97.4 (96.3, 98.6)*†	96.7 (95.5, 98)*†
71+ y	Male	1,246	4700 mg	98.2 (97.1, 99.2)†	98.1 (97.0, 99.1)*†	97.9 (96.9, 99.0)*†	97.6 (96.5, 98.8)*†	97.0 (95.7, 98.3)*†
19-30 y	Female	897	4700 mg	99.6 (99.3, 99.9)	99.6 (99.2, 99.9)	99.6 (99.2, 99.9)*	99.5 (99.0, 99.9)*	99.2 (98.7, 99.7)*
31-50 y	Female	2,288	4700 mg	99.6 (99.3, 99.9)	99.6 (99.3, 99.9)*	99.6 (99.3, 99.9)*	99.5 (99.1, 99.8)*	99.3 (98.9, 99.7)*
51 to 70 y	Female	2,420	4700 mg	99.7 (99.5, 99.9)	99.7 (99.5, 100)*	99.7 (99.4, 100)*	99.6 (99.3, 99.9)*	99.4 (99.0, 99.8)*
71 + y	Female	1,556	4700 mg	99.8 (99.5, 100)	99.8 (99.5, 100)*	99.7 (99.5, 100)*	99.7 (99.3, 100)*	99.5 (99.1, 99.9)*

Estimates are percentage below the AI (95% CI) based on usual intakes from foods. Certain estimates may appear equal due to rounding. * = $p<0.05$ vs. observed diets by paired *z*-test. † = $p<0.05$ vs. females by unpaired *z*-test. The p-values are adjusted for multiple comparisons. AI=Adequate Intake.

Supplementary Table 6.11 Percentage of the Canadian adult population below the Estimated Average Requirement for vitamin D from foods and supplements

Age	Sex	n	n (supplement users)	EAR	Observed diets	Red and processed meat (25%)	Red and processed meat (50%)	Dairy (25%)	Dairy (50%)
Combined	Combined	13,612	4,673	10 µg	68.2 (66.2, 70.1)	68.5 (66.5, 70.4)*	68.6 (66.7, 70.5)*	68.5 (66.6, 70.4)*	68.8 (67.0, 70.7)*
19-30 y	Male	882	166	10 µg	83.4 (80.7, 86.1)†	83.7 (81.1, 86.3)*†	83.9 (81.3, 86.5)*†	83.8 (81.2, 86.4)*†	84.1 (81.6, 86.6)*†
31-50 y	Male	2,077	475	10 µg	78.1 (75.3, 81.0)†	78.5 (75.7, 81.3)*†	78.7 (76.0, 81.5)*†	78.6 (75.8, 81.1)*†	79.0 (76.3, 81.7)*†
51-70 y	Male	2,246	672	10 µg	70.0 (67.3, 72.7)†	70.4.1 (67.7, 73.0)*†	70.6 (68.0, 73.2)*†	70.5 (67.8, 73.1)*†	70.9 (68.3, 73.5)*†
71+ y	Male	1,246	453	10 µg	62.1 (59.1, 65.1)†	62.5 (59.6, 65.5)*†	62.8 (59.9, 65.6)*†	62.6 (59.7, 65.5)*†	63.1 (60.3, 65.9)*†
19-30 y	Female	897	236	10 µg	78.8 (76.8, 80.8)	79.0 (77.0, 80.9)*	79.1 (77.1, 81.0)*	79.0 (77.1, 81.0)*	79.2 (77.3, 81.1)*
31-50 y	Female	2,288	730	10 µg	72.0 (70.2, 73.8)	72.2 (70.4, 74.0)*	72.3 (70.5, 74.1)*	72.2 (70.4, 74.0)*	72.5 (70.7, 74.2)*
51 to 70 y	Female	2,420	1,143	10 µg	55.5 (54.0, 57.0)	55.7 (54.2, 57.2)*	55.8 (54.3, 57.2)*	55.7 (54.3, 57.2)*	55.9 (54.5, 57.4)*
71 + y	Female	1,556	798	10 µg	50.8 (48.9, 52.7)	50.9 (49.0, 52.8)*	51.0 (49.1, 52.9)*	51.0 (49.1, 52.9)*	51.2 (49.3, 53.1)*

Estimates are percentage below the EAR (95% CI) based on usual intakes. Separate estimates were obtained for supplement users and non-users and then combined according to the method of Garriguet.[11] * = p<0.05 vs. observed diets by paired *z*-test. † = p<0.05 vs. females by unpaired *z*-test. The p-values are adjusted for multiple comparisons. EAR=Estimated Average Requirement.

Supplementary Table 6.12 Percentage of the Canadian adult population below the Estimated Average Requirement for calcium from foods and supplements

Age	Sex	n	n (supplement users)	EAR	Observed diets	Red and processed meat (25%)	Red and processed meat (50%)	Dairy (25%)	Dairy (50%)
Combined	Combined	13,612	3,380	–	58.1 (58.0, 58.2)	57.5 (57.3, 57.6)*	56.3 (56.2, 56.5)*	62.5 (62.3, 62.6)*	66.9 (66.8, 67.1)*
19-30 y	Male	882	124	800 mg	40.3 (34.6, 46.0)†	39.0 (33.2, 44.8)*†	37.3 (31.5, 43.2)*†	46.8 (41.0, 52.5)*†	54.1 (48.4, 59.7)*†
31-50 y	Male	2,077	355	800 mg	44.3 (39.9, 48.8)†	43.2 (38.7, 47.7)*†	41.6 (37.0, 46.1)*†	50.5 (46.1, 54.8)*†	57.9 (52.9, 61.2)*†
51-70 y	Male	2,246	485	800 mg	47.5 (43.7, 51.2)	46.3 (42.5, 50.1)*	44.8 (41.0, 48.6)*	52.4 (48.7, 56.1)*	57.9 (54.3, 61.4)*
71+ y	Male	1,246	268	1000 mg	72.6 (68.6, 76.5)	71.9 (67.9, 75.9)*	70.7 (66.7, 74.7)*	76.0 (72.3, 79.6)*	79.2 (75.7, 82.7)*
19-30 y	Female	897	175	800 mg	55.2 (50.2, 60.2)	54.7 (49.7, 59.8)*	53.7 (48.6, 58.8)*	61.1 (56.3, 65.9)*	66.9 (62.3, 71.5)*
31-50 y	Female	2,288	543	800 mg	56.6 (52.9, 60.3)	56.3 (52.6, 60.0)*	55.3 (51.6, 59.0)*	61.6 (58.1, 65.0)*	66.4 (63.1, 69.7)*
51 to 70 y	Female	2,420	864	1000 mg	72.4 (69.4, 75.3)	72.2 (69.2, 75.2)	71.6 (68.6, 74.7)*	75.0 (72.2, 77.7)*	77.4 (74.8, 80.0)*
71 + y	Female	1,556	566	1000 mg	72.5 (68.9, 76.2)	72.5 (68.8, 76.2)	71.9 (68.2, 75.7)*	74.6 (73.6, 75.8)*	76.4 (73.1, 79.7)*

Estimates are percentage below the EAR (95% CI) based on usual intakes. Separate estimates were obtained for supplement users and non-users and then combined according to the method of Garriguet.[11] * = $p<0.05$ vs. observed diets by paired z-test. † = $p<0.05$ vs. females by unpaired z-test. The p-values are adjusted for multiple comparisons. Males 51-70 y could not be compared to females 51-70 y due to differing recommendations. EAR=Estimated Average Requirement.

Supplementary Table 6.13 Percentage of the Canadian adult population below the Estimated Average Requirement for iron from foods and supplements

Age	Sex	n	n (supplement users)	EAR	Observed diets	Red and processed meat (25%)	Red and processed meat (50%)	Dairy (25%)	Dairy (50%)
Combined	Combined	13,612	2,066	–	3.9 (3.8, 4.0)	3.8 (3.7, 3.9)	3.7 (3.6, 3.7)*	2.9 (2.9, 3.0)*	2.3 (2.2, 2.3)*
I19-30 y	Male	882	97	6 mg	0.2 (0.0, 0.5)	0.2 (0.0, 0.5)	0.1 (0.0, 0.4)	0.1 (0.0, 0.4)	0.1 (0.0, 0.3)*
31-50 y	Male	2,077	250	6 mg	0.3 (0.0, 0.6)	0.3 (0.0, 0.6)	0.2 (0.0, 0.5)*	0.2 (0.0, 0.5)*	0.2 (0.0, 0.4)*
51-70 y	Male	2,246	297	6 mg	0.4 (0.0, 0.9)	0.4 (0.0, 0.8)	0.3 (0.0, 0.8)*	0.3 (0.0, 0.7)*	0.2 (0.0, 0.5)*
71+ y	Male	1,246	152	6 mg	0.5 (0.0, 1.2)	0.5 (0.0, 1.1)	0.5 (0.0, 1.1)*	0.4 (0.0, 0.9)*	0.3 (0.0, 0.7)*
19-30 y	Female	897	149	8.1 mg	12.9 (9.2, 16.7)	12.6 (9.9, 16.3)*	12.2 (8.5, 15.9)*	9.9 (6.5, 13.3)*	7.6 (4.6, 10.5)*
31-50 y	Female	2,288	451	8.1 mg	15.0 (11.5, 18.6)	14.7 (11.2, 18.3)*	14.3 (10.8, 17.9)*	11.5 (8.2, 14.8)*	8.9 (5.9, 11.9)*
51 to 70 y	Female	2,420	415	5 mg	1.0 (0.2, 1.8)	1.0 (0.2, 1.8)	0.9 (0.2, 1.7)	0.7 (0.1, 1.3)*	0.5 (0.0, 0.9)*
71 + y	Female	1,556	255	5 mg	1.3 (0.2, 2.5)	1.9 (0.4, 3.4)	1.2 (0.1, 2.3)	0.9 (0.1, 1.7)*	0.6 (0.0, 1.3)*

Estimates are percentage below the EAR (95% CI) based on usual intakes. Separate estimates were obtained for supplement users and non-users and then combined according to the method of Garriguet.[11] Certain estimates may appear equal due to rounding. * = $p<0.05$ vs. observed diets by paired *z*-test. The p-values are adjusted for multiple comparisons. Males could not be compared to females due to differing recommendations. EAR=Estimated Average Requirement.

Supplementary Table 6.14 Percentage of the Canadian adult population below the Adequate Intake for potassium from foods and supplements

Age	Sex	n	n (supplement users)	AI	Observed diets	Red and processed meat (25%)	Red and processed meat (50%)	Dairy (25%)	Dairy (50%)
Combined	Combined	13,612	1,468	4,700 mg	98.6 (97.8, 99.5)	98.6 (97.7, 99.4)*	98.5 (97.6, 99.4)*	98.3 (97.3, 99.2)*	97.1 (96.7, 98.9)*
19-30 y	Male	882	70	4,700 mg	93.5 (87.1, 99.9)	93.3 (86.8, 99.8)	92.9 (86.3, 99.5)	92.5 (85.6, 99.3)*	91.5 (84.0, 98.9)*
31-50 y	Male	2,077	196	4,700 mg	94.3 (97.4, 100.0)†	94.2 (89.7, 98.7)†	93.9 (89.3, 98.6)†	93.3 (88.4, 98.2)* †	92.4 (87.1, 97.7)*†
51-70 y	Male	2,246	286	4,700 mg	97.9 (96.6, 99.2)†	97.8 (96.5, 99.2)*†	97.6 (96.3, 99.0)*†	97.3 (95.8, 98.8)*†	96.7 (95.0, 98.4)*†
71+ y	Male	1,246	153	4,700 mg	98.2 (96.9, 100.0)†	98.1 (96.8, 99.4)*†	97.9 (96.6, 99.3)*†	97.7 (96.3, 99.1)*†	97.1 (95.5, 98.7)*†
19-30 y	Female	897	47	4,700 mg	98.8 (96.9, 100.0)	98.8 (96.9, 100.0)	98.8 (96.8, 100.0)	98.7 (96.4, 100.0)	98.4 (95.7, 100.0)*
31-50 y	Female	2,288	195	4,700 mg	98.8 (97.4, 100.0)	98.8 (97.4, 100.0)	98.8 (97.3, 100.0)	98.5 (96.8, 100.0)*	98.0 (96.1, 100.0)*
51 to 70 y	Female	2,420	312	4,700 mg	99.7 (99.3, 100.0)	99.7 (99.3, 100.0)	99.7 (99.3, 100.0)	99.6 (99.1, 100.0)*	99.4 (98.8, 99.9)*
71 + y	Female	1,556	209	4,700 mg	99.7 (99.4, 100.0)	99.7 (99.4, 100.0)	99.7 (99.4, 100.0)	99.6 (99.2, 100.0)*	99.4 (99.0, 99.9)*

Estimates are percentage below the AI (95% CI) based on usual intakes. Separate estimates were obtained for supplement users and non-users and then combined according to the method of Garriguet.[11] Certain estimates may appear equal due to rounding. * = $p<0.05$ vs. observed diets by paired *z*-test. † = $p<0.05$ vs. females by unpaired *z*-test. The p-values are adjusted for multiple comparisons. AI=Adequate Intake.

Supplementary Table 6.15 Percentage of the Canadian adult population above Canada's Food Guide recommendations for sodium

Age	Sex	n	CFG	Observed diets	Red and processed meat (25%)	Red and processed meat (50%)	Dairy (25%)	Dairy (50%)
Combined	Combined	13,612	2300 mg	66.6 (69.0, 64.2)	65.0 (67.4, 62.7)*	63.4 (65.7, 61.0)*	65.2 (62.8, 67.3)*	63.7 (61.4, 66.0)*
19-30 y	Male	882	2300 mg	90.9 (94.1, 87.7)†	90.1 (93.4, 86.7)*†	89.1 (92.6, 85.5)*†	90.0 (86.6, 93.4)*†	89.0 (85.5, 92.5)*†
31-50 y	Male	2,077	2300 mg	87.4 (90.7, 84.1)†	86.3 (89.7, 82.9)*†	85.0 (88.5, 81.5)*†	86.4 (83.0, 89.8)*†	85.3 (81.8, 88.8)*†
51-70 y	Male	2,246	2300 mg	81.3 (84.9, 77.8)†	79.7 (83.4, 76.1)*†	78.0 (81.7, 74.3)*†	80.1 (76.5, 83.7)*†	78.8 (75.2, 82.5)*†
71+ y	Male	1,246	2300 mg	74.6 (79.1, 70.1)†	72.5 (77.1, 67.9)*†	70.3 (74.9, 65.7)*†	73.2 (68.6, 77.7)*†	71.7 (67.1, 76.3)*†
19-30 y	Female	897	2300 mg	61.3 (66.3, 56.4)	59.7 (64.7, 54.7)*	58.1 (63.0, 53.1)*	59.3 (54.4, 64.3)*	57.4 (52.4, 62.4)*
31-50 y	Female	2,288	2300 mg	53.2 (56.6, 49.7)	51.4 (54.8, 48.0)*	49.6 (53.0, 46.3)*	51.4 (48.0, 54.7)*	49.5 (46.2, 52.9)*
51 to 70 y	Female	2,420	2300 mg	43.5 (46.5, 40.6)	41.6 (44.5, 38.7)*	39.7 (42.6, 36.8)*	41.9 (39.0, 44.8)*	40.2 (37.3, 43.1)*
71 + y	Female	1,556	2300 mg	34.8 (39.0, 30.6)	32.7 (36.7, 28.6)*	30.7 (34.7, 26.7)*	33.3 (29.2, 37.4)*	31.8 (27.8, 35.9)*

Estimates are percentage above CFG recommendations (95% CI) based on usual intakes from foods. * = p<0.05 vs. observed diets by paired *z*-test. † = p<0.05 vs. females by unpaired *z*-test. The p-values are adjusted for multiple comparisons. CFG=Canada's Food Guide.

Supplementary Table 6.16 Percentage of the Canadian adult population above Canada's Food Guide recommendations for saturated fat

Age	Sex	n	CFG	Observed diets	Red and processed meat (25%)	Red and processed meat (50%)	Dairy (25%)	Dairy (50%)
Combined	Combined	13,612	10%E	56.2 (53.2, 59.3)	55.4 (52.4, 58.4)*	51.5 (48.7, 54.4)*	42.9 (40.0, 45.9)*	23.1 (19.4, 26.9)*
19-30 y	Male	882	10%E	57.3 (52, 62.6)	54.8 (49.4, 60.1)*	50.1 (44.8, 55.3)*	44.5 (39.1, 50.0)*	25.7 (20.4, 31.0)*
31-50 y	Male	2,077	10%E	55.9 (51.6, 60.2)	53.7 (49.5, 57.9)*	49.0 (44.8, 53.1)*†	42.9 (38.7, 47.1)*	23.8 (19.5, 28.1)*
51-70 y	Male	2,246	10%E	54.3 (50.5, 58.1)	52.6 (48.9, 56.4)*	48.0 (44.4, 51.7)*†	41.0 (37.3, 44.7)*	21.9 (18.0, 25.8)*
71+ y	Male	1,246	10%E	52.8 (48.1, 57.5)	51.4 (46.8, 56.0)*	47.0 (42.5, 51.5)*†	39.7 (35.3, 44.1)*	20.7 (16.5, 25.0)*
19-30 y	Female	897	10%E	59.1 (54, 64.3)	58.9 (53.7, 64.0)	55.6 (50.4, 60.9)*	45.4 (40.0, 50.8)*	24.8 (19.3, 30.2)*
31-50 y	Female	2,288	10%E	58 (54, 61.9)	58.0 (54.1, 62.1)	54.9 (51.0, 58.8)*	44.4 (40.4, 48.4)*	24.2 (19.6, 28.8)*
51 to 70 y	Female	2,420	10%E	56.2 (52.5, 59.9)	56.8 (53.1, 60.5)*	53.8 (50.2, 57.4)*	42.8 (39.2, 46.4)*	22.1 (17.9, 26.3)*
71 + y	Female	1,556	10%E	55.1 (50.2, 59.9)	56.2 (51.3, 61.1)*	53.4 (48.5, 58.3)*	41.6 (36.8, 46.5)*	20.8 (16.2, 25.5)*

Estimates are percentage above CFG recommendations (95% CI) based on usual intakes from foods. * = p<0.05 vs. observed diets by paired *z*-test. † = p<0.05 vs. females by unpaired *z*-test. The p-values are adjusted for multiple comparisons. Abbreviations: 10%E, 10% of energy intake. CFG=Canada's Food Guide.

Supplementary Table 6.17 Percentage of the Canadian adult population above Canada's Food Guide recommendations for free sugars

Age	Sex	n	CFG	Observed diets	Red and processed meat (25%)	Red and processed meat (50%)	Dairy (25%)	Dairy (50%)
Combined	Combined	13,612	10%E	53.4 (50.9, 56.0)	52.9 (50.3, 55.4)*	52.6 (50.1, 55.1)*	53.7 (51.1, 56.3)	54.1 (51.5, 56.6)*
19-30 y	Male	882	10%E	57.8 (53.2, 62.4)	57.4 (52.9, 62.0)*	57.2 (52.6, 61.7)*	58.2 (53.6, 62.8)	58.8 (54.3, 63.4)*
31-50 y	Male	2,077	10%E	55.1 (51.6, 58.6)	54.5 (51.1, 58.0)*	54.2 (50.7, 57.7)*	55.5 (52.0, 59.0)	56.1 (52.6, 59.6)*
51-70 y	Male	2,246	10%E	51.9 (48.7, 55.1)	51.2 (48.1, 54.4)*	50.8 (47.7, 54.0)*	52.3 (49.1, 55.4)*	52.8 (49.6, 56.0)*
71+ y	Male	1,246	10%E	48.6 (44.6, 52.7)	47.9 (43.8, 51.9)*	47.4 (43.4, 51.4)*	49.0 (45.0, 53.0)*	49.6 (45.6, 53.6)*
19-30 y	Female	897	10%E	57.4 (52.7, 62.0)	56.9 (52.3, 61.5)*	56.8 (52.1, 61.4)*	57.4 (52.8, 62.0)	57.7 (53.1, 62.3)
31-50 y	Female	2,288	10%E	54.6 (51.0, 58.1)	54.1 (50.6, 57.6)*	53.9 (50.4, 57.4)*	54.6 (51.1, 58.2)	54.9 (51.4, 58.4)
51 to 70 y	Female	2,420	10%E	51.3 (48.1, 54.5)	50.8 (47.6, 54.0)*	50.6 (47.4, 53.7)*	51.4 (48.2, 54.6)	51.6 (48.4, 54.8)
71 + y	Female	1,556	10%E	48.4 (44.3, 52.6)	47.8 (43.6, 51.2)*	47.5 (43.3, 51.6)*	48.5 (44.4, 52.7)	48.7 (44.6, 52.9)

Estimates are percentage above CFG recommendations (95% CI) based on usual intakes from foods. * = p<0.05 vs. observed diets by paired *z*-test. † = p<0.05 vs. females by unpaired *z*-test. The p-values are adjusted for multiple comparisons. Abbreviations: 10%E, 10% of energy intake. CFG=Canada's Food Guide.

Chapter 7:

Chapter 7: Discussion

7.1 Main outcomes

In this dissertation, we aimed to characterize the role of animal and plant protein foods in Canadian self-selected diets by: 1) assessing usual protein intake, inadequacy and the contribution of animal- and plant-based sources to intakes of protein, nutrients of concern, and nutrients to limit; 2) estimating the carbon footprint of self-selected Canadian diets and comparing intakes of food groups, nutrients, and diet quality between low- and high-GHGE diets; 3) conducting a systematic review of studies that modeled partial replacements of animal with plant protein foods in self-selected diets on diet-related GHGE, and when available, nutrition or health outcomes; and 4) determining the impact of modeled graded replacements of red and processed meat or dairy with plant protein foods consistent with CFG recommendations on nutrient inadequacy, health outcomes, and diet-related GHGE.

In Manuscript 1, we found that Canadian adults generally met minimum protein requirements, except for females and older adults who had the highest risk of falling below the EAR. Moreover, animal sources made up the majority of total protein intakes (64%) while contributing widely to intakes of calcium and vitamin D, but also to intakes of saturated fat (mostly from *dairy*), whereas plant-based sources contributed most to intakes of iron (*cereals, grains, and breads*) and potassium (*vegetables and fruit*). In Manuscript 2, we estimated that three-quarters of Canadians' diet-related carbon footprint derived from the consumption of animal-based foods, with *red and processed meat* alone accounting for nearly half. Respondents with diets in the highest quintile of energy-adjusted diet-related GHGE were characterized by higher quantities of animal-based foods but also *vegetables and fruit* and *miscellaneous* foods and beverages compared to respondents with diets in the lowest quintile. High-GHGE diet respondents had higher intakes of nutrients of concern, but also saturated fat, and a lower overall diet quality compared to low-GHGE diet respondents. In Manuscript 3, we systematically searched for studies that modeled replacements of animal with plant protein foods in individuals' self-selected diets and found six studies that estimated impacts on diet-related GHGE, among which two also estimated nutrient outcomes (none estimated health outcomes). Replacing meat, and in particular beef, led to the greatest reductions to diet-related GHGE and increased the percentage of the population that met requirements for fibre, calcium, potassium, and iron (1 to 5%); substituting a combination of meat and dairy decreased the percentage of the population below requirements for iron (5 to 15%) and vitamin D (2 to 7%) and above recommendations for saturated fat (10 to 76%), but increased the percentage below requirements for calcium (9 to 33%) and vitamin A (8 to 48%). In Manuscript 4, we modeled partial replacements of red and processed meat or dairy with plant protein foods consistent with those in CFG and found beneficial synergistic effects from substituting red and processed meat on nutrition, health, and climate outcomes; the percentage of the population below or above recommendations for nutrients of concern and to limit were minimally altered, while life expectancy increased by up to 8.7 months, and diet-related GHGE decreased by up to 25%. Meanwhile, graded dairy replacements led to trade-offs with calcium inadequacy while attenuating gains to life expectancy and reductions to diet-related GHGE.

Taken together, this dissertation provides a comprehensive overview of the role of animal and plant protein foods in self-selected diets from Canada and other high-income countries, and sheds light on the compatibility of a combination of diet sustainability dimensions in the context of modeled substitutions of animal with plant protein foods.

7.2 Protein foods in the Canadian context

In 2019, Health Canada came out with the newest version of CFG. This was the first revamp of dietary guidance in Canada since 2007's Eating Well with Canada's Food Guide, which consisted of four food groups – Vegetables and Fruit, Grain Products, Milk and Alternatives, and Meat and Alternatives – and age- and sex-specific serving sizes (99). The new guide took a more holistic approach, using the food guide snapshot to convey to consumers the types of foods encouraged for healthy eating and the proportions in which they should be consumed, half of the plate containing vegetables and fruit, one-quarter whole grains foods, and the last quarter protein foods (40). Specifically, the guide states to try to choose protein foods that come from plants every day (13).

Prior to the release of the new CFG, however, there was hardly any data that characterized protein intake in Canada. To our knowledge, the only existing data derived from simple analyses of the newly released 2015 CCHS – Nutrition data on the part of Statistics Canada showing that most Canadians were within the AMDR for protein (43), as well as the percentage of Canadians that reported consuming animal and plant sources of protein on a given day from their 24-h recalls (44). Moreover, knowledge gaps regarding the protein foods group in the new CFG were highlighted in a report of a scientific expert meeting at the Canadian Nutrition Society (85). To address the lack of data pertaining to protein intakes in Canada, we carried out Manuscript 1, which revealed discrepancies between CFG's new protein recommendations and protein as consumed in Canadian self-selected diets.

Despite consumption of animal products having plateaued in high-income countries (134), animal protein foods still play a prominent role in Western diets, having long been embedded in cultural cuisine and practices in the Global North. Animal protein foods are sources of high-quality protein and bioavailable nutrients, but their overconsumption has implications for both human and planetary health. Therefore, it was important to investigate the impact of animal and plant protein foods as consumed in Canadian self-selected diets on a combination of nutrition, health, and climate outcomes. This formed the rationale for undertaking Manuscripts 2 and 4 as part of this dissertation.

7.3 Characterizing Canadians' diet-related carbon footprint

The work we carried out in Manuscript 2 was the first to estimate the carbon footprint of self-selected diets in Canada. To our knowledge, the only other study to have linked dietary intake data from the first iteration of the CCHS – Nutrition (2004) to GHGE estimates compared the GWP of dietary patterns of Ontarians. The study found that the calorie-adjusted food baskets of vegans and vegetarians had lower carbon footprints than those of omnivores (955 and 1,053 kg CO_2eq/person/y, respectively vs. 2,282 kg CO_2eq/person/y). However, vegan and vegetarian dietary patterns represented only 0.4% and 7% of the population, respectively, compared to 30% consuming omnivorous diets (126). Moreover, the study accounted for the impacts of a limited number of commonly consumed foods making up each dietary pattern as opposed to entire diets, and did not assess dimensions of diet sustainability beyond GWP. An updated study comparing the changes in GWP for dietary patterns over ten years using data from the 2004 and 2015 CCHS – Nutrition found that dietary patterns containing beef saw the greatest decrease in GWP (Omnivorous: −8%; No Pork: −6%), but were still the dietary patterns with the highest impacts (170).

In addition to diet-related GHGE, we also sought to characterize low- and high-GHGE diets in terms of their makeup of animal and plant protein foods, nutrient intakes, and diet quality. Importantly, the use of two nutritional indicators – nutrient intakes and diet quality – revealed contradictory interpretations. Specifically, high-GHGE diet respondents had higher intakes of nutrients of concern, but also higher intakes of saturated fat and sodium, and a lower overall diet quality based on the Alternative Healthy Eating Index-2010. On the contrary, while low-GHGE diet respondents had higher overall diet quality scores, they also had higher intakes of total sugars. Taken together, these findings might indicate that healthier diets are not necessarily more environmentally sustainable. However, these conclusions depend largely on the metrics employed to assess diet sustainability dimensions. In the study, we reported 1-d intakes for nutrients and used a diet quality index as a proxy for healthy diets. However, 1-d intakes are not representative of individuals' long-term intakes, nor do they provide information about nutrient inadequacies or the percentage of the population meeting or exceeding nutrient requirements. For example, a high-GHGE diet respondent may have had a higher 1-d intake of protein compared to a low-GHGE diet respondent, but this is not wholly relevant if the low-GHGE diet respondent was meeting minimum protein requirements. Moreover, studies have drawn different conclusions depending on the type of diet quality metric used (130). Even so, diet quality is an indirect measure of health, as opposed to population-level outcomes, such as changes to life expectancy or mortality. In turn, more integrated assessments across multiple dimensions are needed to develop harmonized messaging for consumers.

7.4 Modelling studies

For Manuscript 3, we conducted a systematic review of studies that modeled replacements of animal with plant protein foods in self-selected diets on diet-related GHGE, and when available, nutrition or health outcomes. Whereas existing systematic reviews have sought to characterize the environmental and health implications of sustainable diets by focusing more broadly on dietary patterns or theoretical diets generated by means of diet optimization, ours captured simple substitutions of animal with plant protein foods in individuals' self-selected diets. In light of the growing trend of countries emphasizing more plant-based foods in their FBDG, focusing our systematic review on self-selected diets based on individuals' actual food and beverage intake provided insight into the potential implications of swapping meat and dairy with plant protien foods on a combination of outcomes related to diet sustainability. Moreover, simple substitutions of one food for another, many of which are modeled in a graded fashion, was intended to focus on interventions that are practical for consumers. However, we found that there was high heterogeneity in the types of foods chosen to be replaced (e.g., combination of meats, meat and dairy, beef), as well as outcomes assessed. While all studies reported data for diet-related GHGE changes stemming from the substitution scenarios, as per our eligibility criteria, only two studies reported data for the percentage of the population below requirements for nutrients of concern or above recommendations for nutrients to limit. None of the studies reported health outcomes. To overcome these limitations, we designed our next study to model partial graded replacements of red and processed meat or dairy with plant protein foods on a combination of nutrition, health, and climate outcomes.

7.5 Food substitutions

Part of our aim in Manuscript 4 was to test simple interventions aimed at incorporating more plant protein foods into Canadian self-selected diets in line with CFG's new protein recommendations. Therefore, we modeled partial substitutions of red and processed meat or dairy, two commonly consumed animal protein foods that accounted for the majority of

Canadians' diet-related carbon footprint and total protein intakes, with plant protein foods consistent with examples in CFG, on a combination of nutrition, health, and diet-related GHGE. The nutrition and health measures implemented in this study directly addressed the shortcomings of those assessed in the previous study. Specifically, we estimated inadequacy for protein and nutrients of concern based on usual intakes using the EAR cut-point method, and estimated changes to life expectancy and life years stemming from modeled food substitutions using life table models. We found that substituting red and processed meat, as opposed to dairy, led to the largest reductions to GHGE and gains to life expectancy, while inducing minor changes to the percentage below or above intakes for nutrients of concern and to limit, respectively. Replacing dairy, on the other hand, led to an important trade-off with calcium.

Unlike diet optimization studies, which produce theoretical diets that tend to require complex and wholescale changes relative to observed diets, our substitutions were specifically designed to be simple (i.e., two scenarios each involving one food group), minimal (i.e., 25% or 50%), and account for individuals' preferences by substituting with plant protein foods in proportions originally consumed by each respondent. In doing so, we wanted to ensure that our scenarios were both easy to understand and feasible for consumers to adopt. As opposed to pushing specific dietary patterns or the complete exclusion of any particular food group, our findings demonstrate that small-scale changes to red and processed meat intake in particular can have a relatively large impact compatible with a combination of diet sustainability dimensions. In turn, these sorts of substitutions may be much more palatable to consumers most receptive to making dietary changes.

7.6 Strengths and limitations

This dissertation has several strengths and limitations. We used 24-h recalls from a nationally representative survey to assess the self-selected dietary intake of Canadian adults. Use of self-selected dietary data allowed for an inherent accounting for cultural acceptability, including in Manuscript 4 where animal protein foods were partially replaced with plant sources in proportions originally consumed by each respondent to account for their personal preferences. Despite potential bias from misreporting due to the inherent self-reported nature of 24-h recalls, energy misreporting was not found to be a major source of bias in the 2015 CCHS – Nutrition (105). Moreover, we used a validated measure to estimate distributions of usual intake in deriving the prevalence of protein and nutrient inadequacies (92). However, despite protein recommendations being based on the consumption of high-quality protein, we did not assess protein quality given the lack of a harmonized database for DIAAS or PDCAAS values for foods, which would have had to have been comprehensive enough to link to the thousands of foods and beverages reported in the CCHS (106). Furthermore, we improved upon existing studies from the US and Europe that used surrogate measures of diet healthfulness (i.e., diet quality) by focusing on population-level outcomes that are directly relevant to public health (i.e., nutrient inadequacy and life expectancy) in Manuscripts 3 and 4. Yet, we used RR from the Global Burden of Disease 2017, which did not capture all protein foods used in our replacement scenarios and which are subject to change due to the contentious nature of food-disease relationships as new methodological approaches and data become available (52). In addition, we linked GHGE to foods reported in the 24-h recalls using estimates from dataFIELD, which contains global averages and thus are not specific to the Canadian or North American market. Moreover, the boundaries for dataFIELD estimates were cradle-to-farm gate or to processing gate for certain processed commodities, which do not account for impacts incurred from other points along the food supply chain (e.g., transportation, storage, cooking, disposal). Hence, there is a need for a database of Canadian estimates for nationally produced commodities and importantly, one that includes environmental impacts beyond GHGE alone as was the sole indicator assessed in this dissertation. Moreover, the use of alternative metrics to CO_2eq, such as the 100 y Global Temperature Change Potential as done recently by Scarborough et al. (171), would serve to better represent the long-term impacts of methane, which might shift our interpretation of environmental impacts for commodities in which methane is a main contributor (i.e., meat and milk from ruminants). Finally, as the focus of this dissertation was on Canada and other high-income countries, our findings should not be extrapolated to individuals from low- and middle-income countries where livestock derived products play a crucial role in combatting macro- and micronutrient deficiencies (150).

7.7 Future directions

7.7.1 Data gaps

Much of the research undertaken as part of this dissertation was constrained by data gaps. Canada needs better publicly-available data, particularly for food prices, which can subsequently be linked to foods in the CNF and used as yet another dimension of diet sustainability in future analyses. A systematic review and meta-analysis of studies linking food prices, diet quality, and socioeconomic status found that lower nutritional quality foods and diets cost less and were selected most often by individuals of low socioeconomic status, whereas higher nutritional quality diets were associated with higher costs (172). However, another study found that plant-based dietary patterns cost less than omnivorous diets based on an online survey representative of the Portuguese population (173). Moreover, one modeling study reported that healthy and sustainable dietary patterns cost 22 to 34% less than current diets in upper-middle-income to high-income countries, but 18 to 29% more in lower-middle-income to low-income countries (174). Since diet sustainability requires lenses from all angles, insufficient data pertaining to food prices precludes a complete understanding of diet sustainability in Canada.

There is also a need for data pertaining to the imports and exports of food commodities, as well as more LCA covering the entire food supply chain (i.e., from cradle to grave) for Canadian produced commodities. We used GHGE estimates from dataFIELD (111), a database of global LCA studies for food commodities, primarily due to the granularity achieved from translating commodities to recipes and mixed dishes, as well as the relative ease for linking foods from the FNDDS to those in the CNF. However, region-specific production practices can have different environmental impacts. For example, a meta-analysis of LCA from over 90 foods and 742 agricultural systems found that organic food production uses less energy but requires more land and produces a similar concentration of GHGE compared to conventional systems (6). Hence, country-specific assessments are needed to derive more accurate estimates of environmental impacts for food commodities.

Finally, dietary patterns are subject to change in conjunction with shifts to dietary guidance, the food environment (e.g., more plant-based alternatives entering the market), and consumer values (e.g., more environmentally sustainable products). Therefore, there needs to be more continuous updates to the CCHS – Nutrition. The 2015 CCHS – Nutrition was the second release following that of the 2004 CCHS – Nutrition, which is now nearing ten years old. In turn, many of the variables in the 2015 CCHS – Nutrition are outdated, for example, those pertaining to Eating Well with Canada's Food Guide from 2007. An updated version should include variables that pertain to the newest food guide and include additional variables serving to understand individuals' dietary choices with respect to climate, health, and other facets of sustainability.

7.7.2 Drivers and barriers of food choices

The past decade has been subject to ample studies aiming to characterize sustainable diets. Regardless of the science, there is no assuring that consumers will want to change their dietary habits to make healthier and more sustainable choices. Therefore, understanding the drivers and barriers to changing dietary habits will be an important field of investigation moving forward. Willits-Smith et al. (63) identified "potential changers" from respondents in their NHANES sample as individuals that followed American dietary guidance and acknowledged that humans contribute to climate change, the later of which was imputed from the responses of similar respondents in a separate survey (Chatham House survey). Potential changers were more likely to be female with higher educations and incomes compared to respondents not likely to change their dietary habits. Moreover, this group only made up 16% of the sample. Therefore, while replacing 25%, 50%, and 100% of beef with plant protein foods among potential changers decreased diet-related GHGE by 10 to 40%, total reductions among the entire sample were only 1 to 5%. Hence, there is both a need to accurately identify individuals who are willing to shift their diets, but also to differentiate between those who are willing and those act upon their willingness to change.

Using the dietary data of respondents of a Swiss-based online household survey, Baur et al. (175) found that intentions to eat healthy translated better to behaviour than did intentions to eat more sustainably. Moreover, despite similar intentions among sexes, males had higher Disability-Adjusted Life Years (12 minutes of healthy life lost per day) and diet-related carbon footprints compared to females (14%). One of the key challenges to consuming healthier and more sustainable diets, the authors note, is a lack of recognition of the co-benefits of plant-based diets on health and environmental outcomes. Therefore, there needs to be efforts to harmonize findings from sustainable diet research and in turn, communicate these findings to consumers through dietary guidance and other initiatives.

Online surveys conducted among 41,607 adults from Australia, Mexico, the UK, the US, and Canada found that a greater percentage of Canadians reported making an attempt to reduce their consumption of red meat (all opposed to all meats or dairy) than those that reported following a plant-based dietary pattern (167). Similar to findings described above, females and respondents with higher levels of education were more likely to report efforts to consume less red meat, as were minority ethnic groups, individuals ≥60 y of age, and respondents with a healthy BMI (18.5 to 24.9 kg/m^2). Therefore, promoting simple partial substitutions of animal with plant protein foods, and particularly red and processed meat, may be a feasible and culturally acceptable means for encouraging healthier and more sustainable diets in Canada and other high-income nations.

7.7.3 Plant-based meat and dairy alternatives

Another area deserving greater focus is plant-based alternatives to meat and dairy. Plant-based alternatives are meant to mimic the taste and sensory properties of meat, constituting foods such as Beyond Meat's Beyond Burger or plant-based beverages (e.g., almond, oat, coconut) (176). Unlike minimally processed whole foods, such as nuts, seeds, legumes, and soy as common replacements for meat and dairy products, plant-based meat alternatives are typically ultra-processed, containing high quantities of nutrients to limit. Indeed, substituting animal products with plant-based meat alternatives was found to exacerbate excess intakes of saturated fat, sodium, and sugar, leading to unintended consequences for intakes of calcium, potassium, magnesium, zinc, and vitamin B12 compared to replacements with whole foods (149). However, others have reported that while plant-based meat alternatives contained less protein and more salt per 100 g compared to animal products, they also contained less calories and saturated fat and more fibre (177). Nevertheless, in Canada, fortification of simulated meat and poultry products with thiamine, riboflavin, niacin, pyridoxine, d-pantothenic acid, folic acid, vitamin B12, iron, magnesium, potassium, zinc, copper, and the nine essential amino acids is mandatory (178). However, with the exception of a small quantity of soy-based "meatless" products and plant-based beverages reported in the CCHS – Nutrition 24-h recalls, the data, which was collected throughout 2015, does not provide much insight into the nutritional implications of consuming plant-based meat and dairy alternatives.

There is also research to suggest that plant-based alternatives have lower environmental impacts than conventional animal products. For example, compared to a conventional US beef patty, an LCA of Beyond Beef's Beyond Burger reported the cradle-to-distribution environmental impacts as nine-fold less for GHGE, two-fold less for energy use, 13-fold less for land use, and 218-fold less for water use (179). Another analysis found that plant-based beverages had 59% to 71% lower GHGE per 100 mL compared to cow's milk, as well as lower land use and eutrophication impacts (180). By combining the nutritional and environmental impacts of 57,000 food products from grocery stores cross the UK, Clark et al. (181) found that grocery aisles containing plant-based meat alternatives (e.g., tofu, vegan sausages) were win-win, having an environmental and nutritional impact score below the median of all aisles. With the growing rise of plant-based alternatives to market, it will be crucial to investigate how these products contribute to the future nutrition, health, and environmental impacts of Canadian self-selected diets.

7.8 Implications

The findings presented in this dissertation have important implications for human and planetary health. As the first to assess sustainable diets in the Canadian context, this research serves as the foundation for future studies in providing both policy makers and consumers comprehensive information pertaining to healthy and sustainable food choices in Canada.

7.8.1 Implications for dietary guidance in Canada

This research can serve to inform future iterations of dietary guidance in Canada. While having taken a more holistic approach to healthy eating, the current guide has been subject to criticism. For example, a qualitative study of parents from Ontario reported on negative perceptions of CFG, one being insufficient guidance regarding plant protein foods, and another the perceived removal of dairy from the food guide (182). On the contrary, positive perceptions to the guide included perceived benefits of consuming mostly plant-based foods for the environment, despite environmental concerns not having been explicitly stated in the guide. In Manuscript 4, we demonstrated that simple partial substitutions of red and processed meat with plant protein foods increased overall adherence to CFG by up to 14%, and specifically, increased the component score for plant protein foods by up to 79% compared to observed diets. We also showed that these scenarios led to gains to life expectancy and life years and decreased Canadians' diet-related carbon footprint by up to one-quarter while inducing minor changes to the percentage of the population below recommendations for nutrients of concern. In Manuscript 1, however, we uncovered how examples of plant protein foods in CFG make up only 5% of Canadian adults' total protein intakes. Therefore, while there are potential synergies for nutrition, health, and climate outcomes from partially replacing red and processed meat with plant protein foods, future dietary guidance must facilitate the incorporation of more plant protein foods into Canadians' diets.

We also found that partially substituting dairy increased calcium inadequacy, attenuated gains to life expectancy – which were attributed solely to the increase in plant protein foods and not to the decrease in milk consumption – and led to smaller reductions to diet-related GHGE than replacing red and processed meat (Manuscript 4). Therefore, perceived omission of dairy from the food guide snapshot could lead to important trade-offs if acted upon, that if unaddressed, could affect the calcium status of Canadians, particularly females and older adults who are most at risk of not meeting recommendations. In addition to promoting the consumption of plant-protein foods, it is important to address the implications of displacing certain nutrient-dense animal protein foods, particularly dairy, for vulnerable demographics. In turn, including age- and sex-specific recommendations for calcium and providing additional guidance on naturally-containing and fortified dietary sources of calcium is another potential means to improve future iterations of dietary guidance in Canada.

7.8.2 Implications for food fortification

The findings of this dissertation also pose implications for food policy targeting food fortification in Canada. The new CFG specifies fortified soy beverages as an example of a plant protein food. Traditionally, fortified soy-based beverages belonged to the Milk and Alternatives group in previous versions of dietary guidance in Canada since it was considered a high-calcium option for non-milk drinkers (183). However, as we found in Manuscript 4, using fortified soy beverage as a replacement for cow's milk substantially increased calcium inadequacy among adults. Despite mandatory fortification of plant-based beverages with calcium under the Food and Drugs Act, fortification levels for calcium do not match those for certain milk products, particularly powdered milk, which contain approximately 10-fold the amount of calcium in fortified soy beverage and fluid milk. Moreover, other dairy products, such as cheese and yoghurt, were replaced with nuts, seeds, legumes, and tofu and soy-based meat alternatives with naturally low calcium contents.

The fortification of milk with vitamin D is also mandatory under the Food and Drugs Act, having been originally implemented in 1975 to target the elimination of rickets in children (100). In 2022, Health Canada published regulations requiring that cow's milk contain 2 μg of vitamin D/100 mL, double the amount previously permitted (162). In turn, Health Canada increased the allowable levels of vitamin D in fortified plant-based beverages to match that of cow's milk. As we demonstrated in Manuscript 4, the prevalence of vitamin D inadequacy among Canadian adults increased from partial dairy substitutions relative to observed diets, but only by up to 1%. Indeed, in Manuscript 3, we found that changes in the percentage of the population meeting or exceeding nutrient recommendations were largely determined by the fortification status of replacements foods. For example, reductions in the percentage below the EAR for vitamin D in a nationally representative sample of the Dutch population could be attributed in part to the replacement of meat and dairy with fortified soy beverage, but also the naturally low contents of vitamin D in meat and dairy since fortification of milk with vitamin D is not mandatory in the Netherlands. Moreover, similar to findings in Manuscript 4, use of calcium-fortified soy beverage as a replacement for most dairy products was not enough to prevent an exacerbation of the percentage of the population below calcium requirements since other meat and dairy products in the scenarios were substituted with plant-based alternatives that were not fortified. Therefore, food fortification is exemplary of the potential success for food policies to address nutrient inadequacies within a population. In turn, future food policy should strongly consider shifting their fortification regulations to plant protein foods emphasized in the new CFG, since their encouraged consumption will naturally displace that of nutrient-dense or fortified animal protein foods.

7.8.3 Implications for consumers

Finally, the research undertaken as part of this dissertation has direct implications for consumers. While current dietary guidance in Canada does not explicitly address environmental sustainability, FBDG from many countries have started to. Sweden's food guide was devised based on the Nordic Nutritional Recommendations in combination with evidence of food's environmental impacts (184). Their traffic light system allows for clear messaging of foods to be encouraged (i.e., vegetables, fruit and berries, fish and shellfish, nuts and seeds), foods that should be switched (i.e., whole grains, healthy fats, low-fat dairy products), and foods and nutrients to be limited (i.e., red and processed meat, salt, sugar, alcohol), as well as information on their environmental impact. Brazil's dietary guidelines, on the other hand, contain a set of guiding principals, one of them being to consume foods that come from environmentally and socially sustainable foods systems (185). However, in most cases, recommendations pertaining to foods' environmental impacts appear primeval (based solely on findings from LCA studies), and do not necessarily account for the complexities of dietary choices overall. Future dietary guidance in Canada would serve consumers by translating findings from self-selected diet studies into concrete recommendations, but doing so would require weighing the environmental impacts of single foods with their contribution to other dimensions of diet sustainability.

Some key findings from this dissertation that could be communicated to Canadians through dietary guidance or awareness campaigns are:

- Most adults consume enough protein, but females and older adults are most at risk for not meeting recommendations.
- Protein intakes are disproportionately skewed towards animal protein foods – mainly red and processed meat, poultry, and dairy – but also cereals, grains, and breads. However, very little protein derives from plant protein foods (i.e., nuts, seeds, legumes, and tofu and spy-based meat alternatives).
- Consumption of red and processed meat contributes half of Canadians' diet-related carbon footprint.
- Choosing to follow CFG's recommendation to consume protein from plants every day might naturally displace consumption of animal protein foods. Partially substituting red and processed meat with plant protein foods is beneficial for nutrition, health, and the environment. However, partially substituting dairy products with plant protein foods could impair intakes of calcium.

Growing consumer awareness as to the link between human and planetary health is becoming more apparent. However, deriving recommendations for consumers must facilitate the shift towards more healthy and sustainable diets while accounting for how Canadians are currently eating, in addition to personal and cultural preferences. This approach will help to come up with balanced recommendations, which will likely encourage more Canadians to engage in dietary change than would an all-or-nothing approach that disregards the population's current eating habits. Importantly, recommendations must go beyond LCA data to consider the environmental impacts of foods in the context of population-wide diets in combination with nutrition, health, economic, and sociocultural dimensions of diet sustainability.

7.9 Conclusions

This dissertation sought to characterize the role of animal and plant protein foods in Canadian sustainable diets. We found that most Canadians consumed adequate protein, except for females and older adults who were most at risk of not meeting recommendations, and that total intakes derived largely from animal sources. We also showed that respondents with high-GHGE diets, characterized by higher quantities of animal protein foods, had higher intakes of nutrients of public health concern, but also higher intakes of saturated fat and sodium, and a lower overall diet quality, revealing nutritional and environmental trade-offs. A systematic review of modeling studies from population-based nutrition surveys and cohorts demonstrated benefits from substituting meat, in particular, but also the showcased the need for harmonized methods for assessing the combined impacts of modeled food substitutions on diet sustainability dimensions in future studies. Finally, modeled partial replacements of animal with plant protein foods in Canadian self-selected diets revealed beneficial synergistic effects from substituting red and processed meat on nutrition, health, and climate outcomes, but trade-offs with calcium inadequacy and an attenuation of gains to life expectancy and reductions to diet-related GHGE from substituting dairy. The findings of this dissertation show that individual action, but also the integration of human and planetary health goals into public policy, is not only essential, but possible, for meeting global scientific targets for climate change.

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