The neglected potential of red and processed meat replacement with alternative protein sources: Simulation modelling and systematic review

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Summary

Background What we eat is fundamental to human and planetary health, with the current global dietary transition towards increased red meat intakes and ultra-processed foods likely detrimental.

Methods We modelled five red and processed meat replacement scenarios to consider health, equity, greenhouse gas emissions (GHGe), and cost outcomes using an established multistate life table model using data from New Zealand as a case study of a developed, westernised country. Current red and processed meat intakes were replaced with: minimally or ultra-processed plant based meat alternatives, cellular meat, or diets in line with EAT-Lancet or Heart Foundation recommendations on red meat intake. We then conducted a systematic review of literature from database inception to 14 November 2022 to identify implemented population-level meat replacement strategies which could inform evidence-based recommendations to achieve any benefits observed in modelling. PROSPERO CRD42020200023.

Findings When compared with current red and processed meat intakes, all red and processed meat replacement scenarios were nutritionally adequate and improved overall Quality Adjusted Life Years (159–297 per 1000 people over life course for the five scenarios modelled). Age standardised per capita health gain for Māori was 1.6–2.3 times that of non-Māori. Health system cost savings were $2530–$5096 per adult, and GHGe reduced 19–35%. Finally, grocery cost varied (↓7%–↑2%) per modelled scenario when compared with baseline costs. The greatest benefits for all outcomes were achieved by meat replacement with minimally-processed plant-based foods, such as legumes. The systematic review identified only two implemented population-level strategies to reduce meat intakes within the academic literature.

Interpretation All meat replacement scenarios considered indicated appreciable health gains and GHGe reductions. Replacement with minimally-processed plant-based foods appeared consistently superior than other scenarios. Evidence of real-world population strategies to achieve these benefits however is currently lacking.

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Keywords: Human health; Planetary health; Sustainable diets; Dietary modelling; Systematic review

Introduction

What we do and don't eat is the greatest global contributor to preventable morbidity and mortality.[1] The most important dietary factors identified by the Global Burden of Disease Study for death and disability attributable to diet are the insufficient intake of whole

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Research in context

Evidence before this study

Appropriate nutrition is a cornerstone of both human and planetary health. Dietary change is necessary to help meet environmental targets and reduce health costs due to non-communicable disease.

Added value of this study

We have considered five novel scenarios to replace red and processed meat intake using a range of current and emerging protein sources using data from New Zealand as a case study of a developed, westernised country. The broad range of outcomes considered relate to health, health systems cost, equity, greenhouse gas emissions, and the grocery cost of each diet. We have also conducted a systematic review to identify successfully applied strategies to help shape future population-level meat replacement initiatives which could inform evidence-based recommendations to achieve any benefits observed in modelling.

Implications of all the available evidence

Replacing red and processed meat intakes with a range of different protein sources in the diet appears a viable method to improve both human and planetary health, with the greatest benefits observed for replacement with minimally-processed plant-based foods such as legumes. A range of population-level strategies to achieve the benefits observed with red meat replacement need to be implemented and assessed, including the use of economic tools, food reformulation, commercial promotion restriction, and providing nutrition education and skills.

grains, fruits, nuts and seeds, vegetables, seafood, fibre, polyunsaturated fats, legumes, and excess intakes of sodium, trans fats, and red and processed meats.[2] These findings have been supported by evidence synthesis undertaken as separate, independent processes to inform World Health Organization dietary recommendations,[3] and Pan-European clinical guidelines,[4] providing further evidence on the role of dietary factors in the development of cardiovascular diseases, type 2 diabetes, and certain cancers.[1,2] These data from randomised controlled trials, prospective observational studies, ecological studies, and nationally representative data collection across ethnically and geographically diverse population groups comprehensively support the fundamental need to monitor dietary intakes, regulate the food environment, and enable individuals to eat healthy foods.

If diet is currently the greatest contributor to global morbidity and mortality, climate change is this century's greatest global health threat.[5] Alongside the direct health consequences of dietary intakes what we eat is inextricably linked to climate change.[6] Food production accounts for 26% of greenhouse gas emissions globally, with beef the largest food source of emissions.[7] Current global eating patterns do not meet environmental targets for greenhouse gas emissions, freshwater use, cropland use, and fertiliser application[8] with dietary intakes transitioning globally towards greater meat intakes.[9] Previous evidence has indicated that movement away from animal source foods towards a greater diversified plant-based intake would increase the likelihood of meeting environmental targets,[10] and reduce human-made pressure on planetary boundaries for a safe operating space.[11]

To better understand the potential of reducing current red and processed meat intakes, we have modelled the effects of five diverse theoretical scenarios on current dietary intakes using data from New Zealand as a case study of a developed, westernised country. The replacement scenarios included red meat intake levels recommended by authoritative bodies as well as replacement with those foods recommended in dietary guidelines or new and emerging protein sources. A broad range of outcomes were selected to consider change in health, environmental, and individual factors. In addition to examining the potential benefits of meat replacement, we also conducted a systematic review to identify existing approaches that had successfully implemented meat replacement strategies as a means to provide practical, evidence-based support to achieve any benefits observed in scenario modelling.

Methods

A summary of the simulation modelling and systematic review methods is outlined here. Full details are shown in the Supplementary Material.

Scenarios modelled

Each scenario replaced baseline red and processed meat intake with an equivalent weight of protein-based foods. The overall dietary pattern was not considered. The scenarios were:

Heart Foundation recommendation

Red meat reduced to no more than 50 g per day, with processed meats reduced to 0 g per day. Replacement was with legumes, soy, nuts, and seeds in amounts proportional to their intake in the baseline diet.

EAT-Lancet recommendation for high protein foods[11]

Red meat reduced to 14 g per day with processed meats reduced to 0 g per day. Replacement was with poultry, eggs, seafood, legumes, and nuts in amounts proportional to their intake in the baseline diet.

Minimally-processed plant based meat alternatives (MPPB)
Red and processed red meat intakes were replaced with MPPB. These foods are legumes and legume-based mixed meals, but are not processed to mimic the texture and organoleptic properties of red and processed meats.

Ultra-processed plant based meat alternatives (UPPB)
Red and processed red meat intakes were replaced with UPPB. These products have undergone food processing techniques to mimic the texture or organoleptic properties of red and processed meats, and are not marketed as containing the foods from which they are derived.

Cellular meat
Red and processed meat intakes were replaced with cellular meats. Given the uncertainties of the nutritional content of such products and the cost of large-scale production, only the greenhouse gas emission contribution of cellular meat within the diet was modelled and presented for this scenario.

Simulation model outcomes
The primary outcome was change in health as measured by Quality Adjusted Life Years (QALY). Secondary health outcomes were indicators of health inequities by ethnicity (Māori, the indigenous population of New Zealand and non-Māori),[12] and costs or cost savings to the health care system. Greenhouse gas emissions ($kgCO_2e/kg$) of each dietary scenario were calculated on a 100-year time horizon and reported as the daily per capita value. A food emissions database relevant to New Zealand[13] was used to estimate the total change in daily diet-related emissions due to each of the modelled scenarios. Composite values for kgCO2e/kg were calculated for cellular meats and ultra-processed plant-based meat alternatives.[14] The daily cost of groceries required to support the modelled scenarios was calculated and compared with the daily grocery cost of the current dietary intakes. Standardised food prices for 340 food groups were obtained from the Nutritrack (New Zealand packaged food composition) database and inflation-adjusted to 2020. Finally, the nutrient intake of the current diet and each of the modelled scenarios were calculated and compared with the current New Zealand nutrient reference values.

Simulation model parameters
An established proportional multistate life table model ('DIET MSLT')[15] was used to estimate differences in the outcomes of each scenario when compared with current dietary intakes.[16] Within the model, the 2011 NZ population (4.4 million) is divided into 5-year age group cohorts, modelled as four separate sex by ethnic populations, and simulated until death or the year 2121, whichever is the earlier.[17] Relative risks for the associations between dietary factors (vegetables and fruit, sugar sweetened beverages, sodium, polyunsaturated fats, nuts and seeds, red meat, and processed meats) or Body Mass Index (BMI) with non-communicable disease outcomes were obtained from the 2015 Global Burden of Disease study.[1] This data set includes data from both developed and developing countries. Baseline diet data were obtained from the most recent (2008/2009) Adult Nutrition Survey of New Zealand.[18]

Systematic review methodology
We followed recognised standards for conducting and reporting systematic reviews[19] to identify peer-reviewed publications reporting on population-level strategies implemented to replace red and processed meat intakes. This topic is part of a prospectively registered review on PROSPERO: CRD42020200023. Eligible outcomes assessed related to dietary intakes, health measures (e.g., anthropometric or biochemical measures), grocery cost, or environmental sustainability measures such as greenhouse gas emissions. Eligibility was not restricted by study design, sample size, duration of follow up or language of publication. Theoretical interventions or those interventions that were described but not implemented were not considered eligible.

Search terms for this systematic review were developed in line with Cochrane processes[20] and are available in full in the Supplementary Material. Terms were run in Scopus and OVID to 14 November 2022 and augmented with searching of reference lists and news articles. No date or language restrictions were applied to the searches, and no pre-set filters were used. Two reviewers screened all titles for eligibility independently, with discrepancies resolved through discussion. Commercially available software Covidence was used to remove duplicates and aid screening.[21] Data from eligible publications were extracted using pre-tested forms[3] by one reviewer, with a double pass by a second reviewer.

Role of the funding source
This project was funded by the Healthier Lives National Science Challenge (Grant UOOX1902). The funder had no role in study design, data collection, data analysis, data interpretation, or reporting. All authors confirm they had full access to all the data in the study and accept responsibility to submit for publication.

Results
Simulation modelling
The baseline diet provided 8.6 MJ of energy per day, with modelled scenarios providing 8.4–8.6 MJ. Full

nutrient intakes are shown in the Supplementary Material. Health outcomes when replacing red and processed meat intakes with the five scenarios are shown in Table 1. All replacement scenarios resulted in substantial QALY gains (159–297 per 1000 people over life course) when compared with current red and processed meat intakes. QALY gain was higher for men than women irrespective of scenario modelled due to the higher baseline red and processed meat intakes of men. Greater QALY gains for Māori (indigenous population of New Zealand) were seen, suggesting a reduction in health inequities with red and processed meat replacement. QALY gains were even higher for Māori when their higher background rates of mortality and morbidity were adjusted for under the equity analysis. As with the overall absolute results, the sex specific results, the per capita results, and the health care systems cost savings, the greatest benefits in the equity analysis were obtained when red and processed meats were replaced with minimally processed plant-based foods (legumes). Further details, including health and healthcare systems cost savings by percentage of population uptake per scenario are shown in the Supplementary Material.

The reduction in greenhouse gas emissions per scenario relative to the current diet (5.00 $kgCO_2e$) are shown in Table 2 as a percentage of scenario uptake. The EAT-Lancet, MPPB, UPPB, and cellular meat scenarios all indicated a lower dietary GHGe contribution (their uncertainty intervals did not include the null) than the current diet. The greatest greenhouse gas emission reduction was observed for the replacement scenario with minimally processed meat alternatives (legumes).

The daily cost of groceries to the individual per diet are shown in Table 3. All scenario diets were cheaper to purchase on average than the current diet apart from the replacement with ultra-processed plant-based meat alternatives. This varied slightly by ethnicity and sex. The cheapest diet was the replacement of red and processed meats with minimally processed meat alternatives (legumes).

Systematic review

A flow chart of the study identification process is shown in Fig. 1, with only two publications identified as addressing the search objective.

Jensen et al. 2016[22] considered the effect of a Danish tax implemented in 2011 on saturated fat in food products on subsequent sales of minced beef, regular cream, and sour cream. The tax elicited a price increase for high-fat (16%) but not low- or medium-fat minced beef. Sales data were available only for the first year following the tax inception; they indicated saturated fat intake from beef mince had reduced by 4.2%. The authors themselves note while this was statistically significant the applied tax rate would only have a limited contribution in reducing current intakes. Serra-Majem et al. 2007[23] considered compliance with dietary guidelines using two representative cross-sectional samples of the Catalan population conducted before (1992–93) or after (2002–03) the 1995 guideline release. Guidelines advised to 'reduce the consumption of red meat and sausages'. Authors reported a 12.1% and 2.2% reduction in meats or sausages/ham respectively over the timeframe considered. Given the ecological study design, this change could not directly be attributed to the dietary guideline release. No other published population-level interventions to reduce red or processed meat intake with the pre-specified outcomes of interest were identified.

Discussion

Findings from scenario modelling indicate that health, environment, and cost benefits were obtained regardless of the red and processed meats replacement scenario, providing a range of current and future (cellular meat) options to suit a range of societal and cultural food preferences. This range of beneficial options is particularly relevant as we present the data assuming a 100% uptake of each scenario, where in reality sustained red and processed meat replacement might require several strategies to implement. Although uncertainty intervals overlapped between scenarios, the greatest improvement in the point estimate for all outcomes was observed when red meats were replaced with minimally-processed meat alternatives, such as legumes. This finding supporting minimally-processed foods is particularly relevant given the global transition towards ultra-processed foods[9] and the rise of ultra-processed plant-based meat alternatives, which came at a higher price for individuals in this analysis. Given the appreciable benefits observed with red and processed meat replacement, it was alarming to then identify a dearth of successfully implemented population-level strategies to replace red and processed meat in the diet.

The current analysis considers a series of novel meat replacement scenarios on a broader range of outcomes than has been previously considered. Within the systematic review for implemented population strategies to reduce red meat intakes, we also identified 34 dietary modelling publications of red meat replacement. These publications provided comment on the potential of interventions to improve health outcomes,[24] dietary adequacy,[25] cost to individuals,[26] the greenhouse gas emission profile of the diet,[27] while reducing health system costs[13] in a range of countries using different data sets and models. Our modelling may be compared with some of these studies with caution given differences in source data, in the modelling processes, in the replacement scenarios, and the outcomes considered. The greenhouse gas emission reductions we observed were comparable in magnitude (19–34%) with four

	Non-Māori	Māori	Māori	Ethnic groups combined	
	QALYs	QALYs	equity analysis QALYs	QALYs	Health System Cost Savings (2011 NZ$ billion)
Following Heart Foundation red and processed meat recommendations					
Per capita[a]	145 (145)	233 (236)	316 (321)	159	$2.5
Sex and age groups combined	542,00 (92,700–939,000)	157,000 (6090–305,000)	213,000 (11,100–398,000)	699,000 (203,000–1,140,000)	$11.2 (0.7–20.6)
Men, all ages	360,000	83,100	199,000	443,000	$7.2
Women, all ages	181,000	74,100	120,000	255,000	$4.0
Following EAT-Lancet red and processed meat recommendations					
Per capita[a]	156 (158)	356 (358)	473 (478)	187	$3.2
Sex and age groups combined	584,000 (146,000–979,000)	240,000 (104,000–363,000)	319,000 (140,000–489,000)	824,000 (351,000–1,270,000)	$14.2 (4.5–23.2)
Men, all ages	376,000	149,000	199,000	525,000	$9.2
Women, all ages	208,000	90,900	120,000	299,000	$5.1
Replacing red and processed meats with minimally processed plant-based alternatives					
Per capita[a]	250 (252)	554 (560)	738 (751)	297	$5.1
Sex and age groups combined	933,000 (582,000–1,290,000)	373,000 (258,000–489,000)	498,000 (347,000–652,000)	1,310,000 (909,000–1,730,000)	$22.5 (14.0–31.3)
Men, all ages	595,000	228,000	306,000	823,000	$14.3
Women, all ages	338,000	146,000	192,000	484,000	$8.2
Replacing red and processed meats with ultra-processed plant-based alternatives					
Per capita[a]	190 (192)	436 (440)	586 (596)	227	$3.8
Sex and age groups combined	708,000 (299,000–1,100,000)	294,000 (175,000–408,000)	395,000 (237,000–550,000)	1,000,000 (548,000–1,430,000)	$16.9 (7.8–25.9)
Men, all ages	458,000	184,000	249,000	642,000	$11.0
Women, all ages	249,000	109,000	146,000	359,000	$5.9

[a]Per capita results are QALYs per 1000 people and NZ $ per adult, all other cost results are in 2011 billion NZ $. Māori are indigenous to Aotearoa New Zealand and comprise 15% of the population. Results in brackets in the rows presenting data on sex and age groups combined are 95% Uncertainty Intervals. Results in brackets in rows presenting data per capita are age-standardised. Values are shown to three main figures.

Table 1: **Heath impacts, equity analysis, and health system costs for red and processed meat replacement scenarios.**

Scenarios	Total GHG emissions	Absolute change from current diet	Percentage change from current diet
Current diet	5.00	–	–
HF recommendation	4.05	−0.95 (UI −1.97 to 0.01)	↓19% (0–39%)
EAT-Lancet recommendation	3.77	−1.23 (UI −2.27 to −0.26)	↓25% (5–45%)
Replacement with MPPB	3.28	−1.72 (UI −2.73 to −0.72)	↓34% (9–55%)
Replacement with UPPB	3.43	−1.57 (UI −2.63 to −0.49)	↓31% (10–53%)
Replacement with cellular meat	4.01	−0.99 (UI −1.54 to −0.51)	↓20% (10–31%)

Greenhouse gas values are shown as kgCO2e.

Table 2: **Greenhouse gas emissions of the current New Zealand diet and for red and processed meat reduction scenarios.**

other publications on red and processed meat intake reduction in Italy,[28] Canada,[29] USA,[30] and across Denmark, Czech Republic, Italy, and France.[31] Our use of data from a country with entirely grass-fed beef production is a further point of novelty and provides a 'best case' scenario, with current cattle rearing greenhouse gas emissions appearing lower than the global median (21 kgCO_2-eq/kg of beef vs median 27 kgCO_2-eq/kg and 17 kgCO_2-eq/kg of lamb[13] vs median 26 kgCO_2-eq/kg[32]). It is of note that even the lower values for greenhouse gas emissions from beef or lamb are 4–5 times higher than producing the most climate-intensive plant-based foods.

While legumes may not be commonly consumed in many high-income countries, they are a traditional staple of many diets, their intake is associated with considerable health benefits,[33] they are inexpensive, widely available, and are good sources of protein, dietary fibre, and key micronutrients[34] while having a low GHGe profile. Ultra-processed meat alternatives conversely are an emerging food product to meet a market demand, as they mimic the organoleptic profile of red and processed meats without containing them.[14] Our analyses indicated overall benefits to health and greenhouse gas emissions when replacing red and processed meats with UPPB, although they increased sodium intake, the strongest predictor of stroke,[35] and came at a greater cost to the individual. This analysis relied on the sales-weighted nutrient profile of UPPB consumed in 2019, of which the dominate product was mycoprotein (Quorn). Quorn, which we considered a UPPB given its culinary use, had a different nutrient profile than other UPPB at the time being low in sodium, energy, and with minimal saturated fats. As a fast-moving area of product development, new and emerging UPPB may now capture a greater share of the UPPB market and not be associated with the same benefits. The transition towards ultra-processed foods,[9] and the potential halo effect for health benefits due to these products being 'plant-based'[36] present future concerns.

We also included one scenario on replacement with cellular meat, an emerging future alternative to red and processed meats.[14] We considered the potential greenhouse gas reduction effects, for which data were available, but not the health benefits or grocery cost as these are currently unknown. It has been discussed in the literature for several years however, that cellular meat is an opportunity to reduce the saturated fat content of meat through its replacement with polyunsaturated fats,[37] which would be expected to produce a health benefit in the model when compared with current red and processed meats. There are some other potential benefits to the future production of cellular meat, in that they may reduce waste as only the edible proportion of an animal is produced, alleviate some food safety concerns, reduce land use dedicated to meat production (by 99%), and reduce greenhouse gas emission from rearing cattle.[14,38] Cellular meat also removes many of the negative animal-cruelty aspects of current animal husbandry, although some current bioreactors for cellular meat production still rely on bovine foetal growth serum.[38]

The modelling data indicate the multiple benefits of red and processed meat replacement with alternatives,

Scenarios	Change in grocery cost	Average grocery cost	Māori men	Māori women	Non-Māori men	Non-Māori women
Current cost	–	$18.03	$21.34	$15.91	$20.33	$15.61
Heart Foundation	↓ 4%	$17.36	$20.48	$15.53	$19.35	$15.22
EAT-Lancet	↓ 1%	$17.93	$21.54	$15.76	20.15	$15.55
Replacement with MPPB	↓ 7%	$16.82	$19.95	$15.07	$18.67	$14.81
Replacement with UPPB	↑ 2%	$18.36	$22.33	$16.37	$20.63	$15.82

Table 3: **Daily grocery cost (2020 NZD) to the individual for red and processed meat replacement scenarios.**

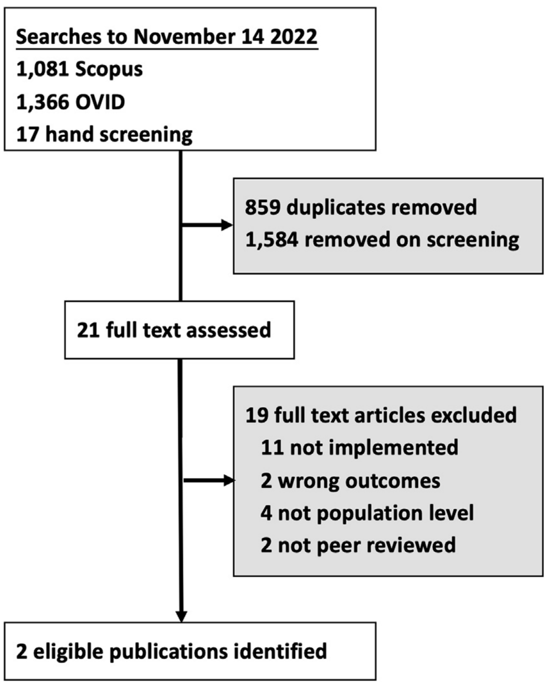

Fig. 1: Flowchart of process to identify eligible studies.

however the systematic review failed to identify clear evidence of successfully implemented population-level initiatives where red and processed meat intake was replaced, which was the largest evidence gap identified. We conducted this systematic review to develop an evidence base and provide practical support for achieving population-level red and processed meat replacement. Successful strategies may have been implemented but not measured or reported in the academic literature, undermining support for future government and regional initiatives set to deliver substantial individual and planetary benefit. In the absence of evidence, research is needed on low agency strategies such as economic tools, food supply reformulation, and change to the availability of certain foods. While the modelled scenarios did not indicate a change towards sub-optimal intakes of those nutrients associated with red meat intake: protein, iron, zinc, and vitamin B6 and B12, further research is needed on saturated fat reduction strategies, as in these analyses red meat replacement was insufficient to meet dietary recommendations limiting saturated fat as a % of total dietary energy (nutrient data shown in Supplementary Material). Broader dietary changes would be required to do so. Initiatives to increase dietary fibre intakes are also needed as although all scenarios improved intakes when compared with the current diet, the population average still did not meet the current recommendations for dietary fibre intakes.

The current modelling has limitations, each of which are likely to underestimate change in the outcomes considered. Primarily, this project relied on the most current nationally-representative dietary data, which was captured in 2008/09. Given the global shift towards ultra-processed foods over the last decade,[9] these data are likely to underrepresent current intakes. The true benefits of the modelled scenarios may be underestimated should current dietary intakes be more detrimental to health than they were in 2008/09. Given the speed of change in the food supply towards ultra-processed plant-based meat alternatives, our nutrient profile for these foods obtained from sales-weighted data in 2019 may similarly not be reflective of current products on the market. As with all studies where a change in diet has been modelled, we cannot comment on subsequent or future dietary change such as compensation due to differences in fibre or energy intake. Finally, our use of New Zealand as a case study for a developed, westernised country may underestimate the greenhouse gas emission reductions achievable with red and processed meat replacement in regions that lot-feed cattle. The primary limitation of the systematic review was that it did not assess non-peer reviewed publications, doing so many have identified government-led evaluations of programmes aimed to reduce red and processed met intakes.

Our findings confirm and extend current dietary advice to reduce red and processed meat intake,[39] increase intake of plant foods,[40] and consume minimally processed rather than ultra-processed foods.[41] Evidence from modelling the Heart Foundation and EAT-Lancet protein recommendations indicate that the complete replacement of red meat from the diet is not necessary to obtain health benefits, however both scenarios required considerable reduction in current intakes. While red and processed meat reduction without replacement might be appropriate given the obesogenic environment,[4] the scenarios modelled provide practical options of what red and processed meat should be replaced with. While we identified the most consistent and potentially largest health and environmental benefits with replacement to minimally processed plant-based foods, such as legumes, all scenarios proved effective enabling consumer preference and choice. We did not identify a large evidence-base of successfully implemented population-level initiatives to provide guidance on red and processed meat replacement. Implementing equitable interventions that support dietary change and enable the necessary changes to healthier patterns and practices is necessary, and will come with its own challenges. Until then, these and past analyses can only indicate the neglected potential of red and processed meat replacement.

Contributors
A.N.R. developed the dietary scenarios, undertook the systematic review, and wrote the first draft of the manuscript. C.N.M. provided project guidance and informed the interpretation of findings. Z.-Y.K. undertook

the systematic review screening and extraction duplication. C.C. provided project guidance, undertook the dietary modelling, and informed the interpretation of findings. A.N.R. and C.C. verify the data used in these analyses. All authors confirm they had full access to all the data in the study and accept responsibility to submit for publication.

Data sharing statement

For the systematic review, the search strategy and details of the papers identified are shown in the Supplementary Material. The technical manual for the multistate life table model 'DIET MSLT' is published, as are the key findings from the New Zealand Adult Nutrition Survey.

Declaration of interests

All authors have completed the ICMJE uniform disclosure form at www.icmje.org/coi_disclosure.pdf and declare no conflict of interest.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at https://doi.org/10.1016/j.eclinm.2022.101774.

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