

Cost and greenhouse gas emissions of current, healthy, flexitarian and vegan diets in Aotearoa (New Zealand)

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ABSTRACT

Objective To compare the costs and climate impact (greenhouse gas emissions) associated with current and healthy diets and two healthy and environmentally friendly dietary patterns: flexitarian and vegan.

Design Modelling study

Setting Aotearoa (New Zealand).

Main outcome measures The distribution of the cost and climate impact (kgCO₂e/kg of food per fortnight) of 2 weekly current, healthy, vegan and flexitarian household diets was modelled using a list of commonly consumed foods, a set of quantity/serves constraints for each, and constraints for food group and nutrient intakes based on dietary guidelines (Eating and Activity Guidelines for healthy diets and EAT-Lancet reference diet for vegan and flexitarian diets) or nutrition survey data (current diets).

Results The iterative creation of 210–237 household dietary intakes for each dietary scenario was achieved using computer software adapted for the purpose (DIETCOST). There were stepwise differences between diet scenarios ($p < 0.001$) with the *current* diet having the lowest mean cost in New Zealand Dollars (NZ\$584 (95% CI NZ\$580 to NZ\$588)) per fortnight for a family of four) but highest mean climate impact (597 kgCO₂e (95% CI 590 to 604 kgCO₂e)), followed by the healthy diet (NZ\$637 (95% CI NZ\$632 to NZ\$642), 452 kgCO₂e (95% CI 446 to 458 kgCO₂e)), the flexitarian diet (NZ\$728 (95% CI NZ\$723 to NZ\$734), 263 kgCO₂e (95% CI 261 to 265 kgCO₂e)) and the vegan diet, which had the highest mean cost and lowest mean climate impact (NZ\$789, (95% CI NZ\$784 to NZ\$794), 203 kgCO₂e (95% CI 201 to 204 kgCO₂e)). There was a negative relationship between cost and climate impact across diets and a positive relationship within diets.

Conclusions Moving from current diets towards sustainable healthy diets (SHDs) will reduce climate impact but generally at a higher cost to households. The results reflect trade-offs, with the larger constraints placed on diets, the greater cost and factors such as nutritional adequacy, variety, cost and low-emissions foods being considered. Further monitoring and policies are needed to support population transitions that are country specific from current diets to SHD.

INTRODUCTION

Food systems are a major underlying driver of the Global Syndemic of obesity, undernutrition and climate change,¹ and population dietary patterns must be considered in

health and environmental terms. In Aotearoa (New Zealand), the environmental impact of the food system is similarly represented and an increase in soil degradation, depletion of fish stocks and damage to ecosystems is predicted.^{2–4} The agricultural sector in Aotearoa accounted for 48% of gross greenhouse gas emissions in 2019. Their share of environmental damage among Organisation for Economic Co-operation and Development (OECD) countries from 2000 to 2010 was the highest in Aotearoa for nitrogen balance (average annual percentage change) and contribution of GHG emissions.^{5 6} There is an imperative in Aotearoa to move population diets towards being healthy and sustainable.

The environmental impact of the food system on Earth's natural systems has occurred simultaneously with diet and food choices becoming an increasingly significant cause of health loss.⁷ An analysis of health loss in Aotearoa shows that the contribution of non-communicable diseases (NCDs) to health loss, such as diabetes and heart disease, has increased by a fifth (19.1%) between 1990 and 2017.⁸ From analysing the leading risk factors, dietary risk, such as low fruit and vegetable consumption and high sodium intake, was the second leading cause of health loss in 2017 (8.6% of DALYs).⁸ This was closely followed by body mass index (BMI) (8.2% of DALYs). Health loss from dietary risks has reduced by a fifth since 1990 but health loss from high BMI has increased by over one-third.

Sustainable healthy diets (SHDs) are defined by the Food and Agricultural Organisation (FAO) and the WHO⁹ as involving 'dietary patterns that promote all dimensions of individuals' health and well-being; have low environmental pressure and impact; are accessible, affordable, safe and equitable; and are culturally acceptable'. Numerous factors influence dietary habits as populations

interact with the food system such as learnt experiences with food, the broader physical, social, cultural and policy environments related to food, and food cost and affordability.^{9 10} Cost is a universal concern and significant determinant of food choices in affording healthier foods compared with unhealthy foods.¹¹⁻¹³

The EAT-Lancet Commission proposed a planetary reference diet which includes global targets for healthy diets from sustainable food systems aligning with the UN Sustainable Development Goals and Paris Agreement.¹⁴ Diets similar to the planetary diet such as vegetarian, have an association with reduced risk of adverse health outcomes including diabetes, ischaemic heart disease, and cancer risk, and are projected to confer large healthcare system cost savings in Aotearoa.^{15 16} Early developments towards addressing SHDs in Aotearoa have occurred including the creation of an NZ-specific life-cycle assessment (LCA) database, sustainability recommendations from the Ministry of Health to the health sector, assessing attitudes towards SHDs and meat reduction among different sectoral professionals and the public, and optimisation modelling of SHD scenarios.¹⁶⁻²⁰

We used the DIETCOST programme (a python-based, iterative, multiple solution solver that finds diet outputs that fit various constraints²¹ to answer the question: What are the differences in costs and GHG emissions between four dietary patterns in Aotearoa: current (based on national nutrition surveys); healthy (based on dietary guidelines); and flexitarian and vegan (based on the EAT-Lancet planetary diet)?

METHODS

The DIETCOST programme and its embedded data and modelling syntax and algorithm were originally developed by Vandevijvere *et al*²¹ to model the cost differential between healthy and current (less healthy) household diets. This was an extension to the original Food Prices module and protocol of International Network for Food and Obesity/NCDs Research, Monitoring and Action Support.²² The existing data sources (programme inputs) include food composition data (FOODfiles),²³ online supermarket food price data, a list of commonly consumed foods, minimum and maximum quantities/serves constraints for each included food item, and food group and nutrient intakes based on dietary guidelines (healthy diets) and nutrition survey data (current diets).

DIETCOST uses iterative modelling where multiple diet outputs are generated for each diet scenario. Iterative modelling contrasts to linear modelling where a single optimised diet output for a diet scenario is generated. The programme's original reference household was retained for this study (adult male aged 45 years, adult female aged 45 years, adolescent boy aged 14 years and a girl aged 7 years).²¹

Patient and public involvement

This modelling study was based on population-level data and averages, which did not require the involvement of members of the public in the study conception, design, data analysis or reporting. The public was not included in advisory or consultation roles and was not invited to comment on the paper before submission.

The programme uses Python²⁴ to model the costs associated with different scenarios for 2 weekly household diets. The programme algorithm uses the Mersenne Twister as a random number generator to specify the starting meal plan and the starting value in grams for each of the common foods (figure 1). Within the acceptable range for each food item, a starting value in grams for the common foods is generated to start building a diet output. If successful in meeting the constraints, this results in a generated diet output. The serving sizes already incorporated in the DIETCOST programme were determined by the NZ Eating and Activity Guidelines (NZEAG) and Nutrient Reference Values for Australia and NZ. Serving sizes from the NZEAG were altered for the vegan and flexitarian diet scenarios by the EAT-Lancet 'Planetary Diet' reference values. Serving size targets for current diets were from average intakes found in the Ministry of Health 2002 National Children's Nutrition Survey²⁵ and 2008/2009 NZ Adult Nutrition Survey.²⁶ The minimum serve size difference between any two generated individual meal plans was set at half a serve for any common food in this study. There was 106, 105, 62 and 66 individual food items in the current, healthy, flexitarian and vegan diet scenarios, respectively. Online supplemental files provide more information on the types of food items and the nutritional breakdown of the diet scenarios included.

The DIETCOST programme's iterative process is a methodological improvement compared with linear modelling as multiple diets in the form of diet outputs can be generated, and the potential variance between modelled diets can be analysed. Multiple diet outputs therefore allow the data to be analysed and compared both within and between modelled diet scenarios. The process of the DIETCOST programme producing iterative diet outputs involves the programme going through consecutive iterations to see whether the constraints (as listed previously in minimum and maximum serve size differences) can or cannot be achieved to generate a diet output. Acceptability and variety were incorporated into the process of DIETCOST generating a diet output through the researchers collating a selection of common foods that the programme could select within a diet output and ensuring that the selected common foods were not too high or low in quantity within each diet output.

Overall a new climate impact measure, revised food prices, and two new dietary scenarios were incorporated in the existing DIETCOST programme (figure 2). A recently published (2020) LCA database for NZ foods was used to create the climate impact measure of kg of

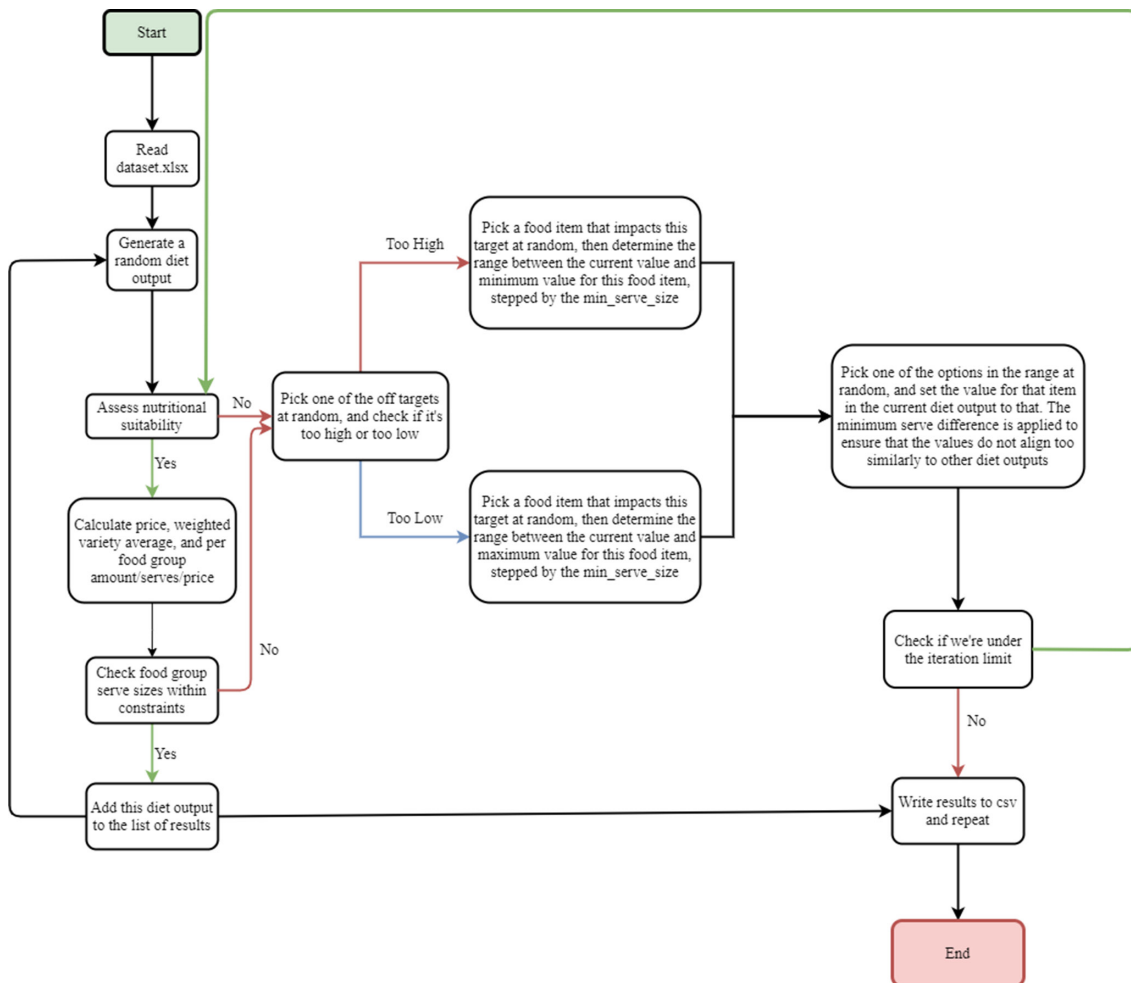


Figure 1 DIETCOST programme algorithm as adapted from Vandevijvere *et al.*²¹

CO₂ equivalent emissions per kg of food product.¹⁶ The final LCA value for each food was selected from the database, and depending on the justification, was predominantly a single LCA value deemed to be the most credible and robust, while others were a median or average value (if multiple LCA figures were deemed credible for a single

food item). These values were then modified according to the NZ context according to the lifecycle stages that contributed most to overall emissions (ie, farming and processing), and when the NZ context was likely to differ from the original LCA values (emission estimates for transportation and electricity usage).

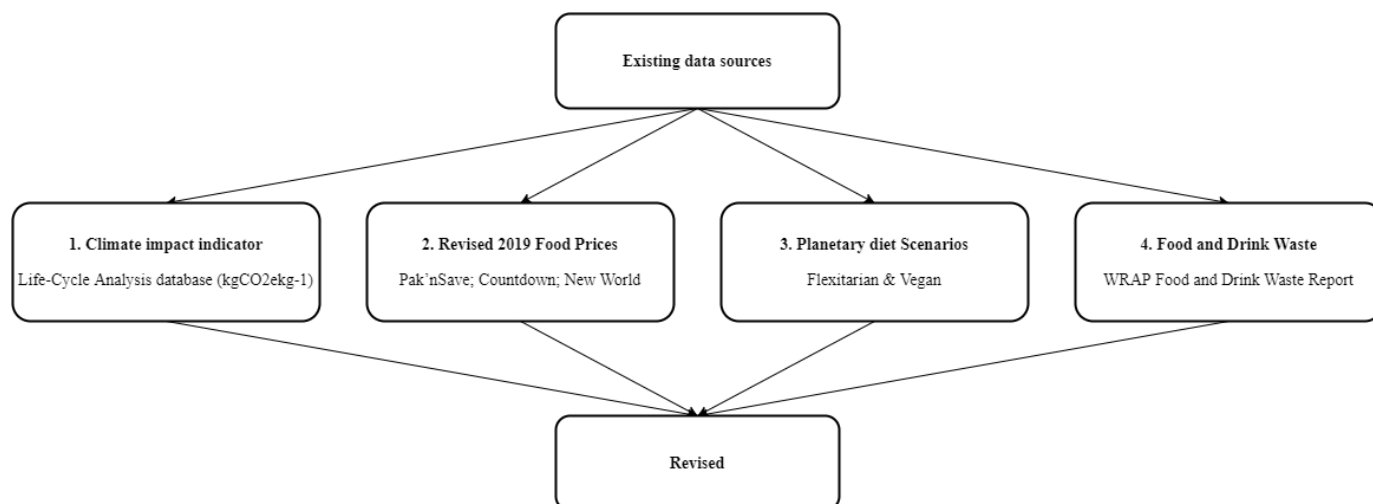


Figure 2 New data sources to revise the existing DIETCOST programme. WRAP, Waste and Resources Action Programme.

Foods such as dairy and meat had NZ-specific LCA figures, while foods with no NZ-specific LCA figures used data from the UK. Values from the UK were used given that the potential differences in LCA figures between the UK and Aotearoa are likely to be insignificant as reported by Drew *et al.*¹⁶ The LCA values from the UK were also adjusted to the New Zealand context in the other stages that are likely to differ (eg, transport and electricity). The 20-year and 100-year global warming potential (GWP) was the outcome measure of emissions, with 100-year GWP figures commonly used in the literature, and 20-year GWP figures also used to incorporate shorter-lived but more highly potent GHGs such as methane. Both figures were used to account for methane especially being a large pollutant from agriculture in the food system. An ID was created for each food group in the LCA database to align with the products in DIETCOST, with no major assumptions necessary.

Estimates of the emissions from food waste (the proportion of food wasted upstream that is, not on the consumer level) were incorporated from the Waste and Resources Action Programme 2017 report²⁷ as used by Drew *et al.*¹⁶ by multiplying the overall climate impact of each product by the added food waste for each gram included in a diet output. Online food prices were collected in 2019 during spring for each item from the three largest supermarkets: Pak'nSave, Countdown and New World. For each food item, the product with the lowest price was selected. This cost was then calculated per 100 g to offset the packet size for each food item.

Food and drink purchased from restaurants and takeaways and alcohol were not included, while ultraprocessed foods (UPF) (discretionary foods) and beverages were included in the current diet, and, to a lesser extent, in the healthy diet scenarios. This was to remove the influence of varying amounts of alcohol and takeaways between diet scenarios to focus on sustainability. This influence is demonstrated in previous research using the DIETCOST programme showing that when takeaways and alcohol were included the average cost between the healthy and current diet was \$105 more expensive over a fortnight compared with NZ\$70 when takeaways and alcohol were not included.²¹ Assessing the impact of increasing the sustainability of foods on diet cost was the main factor of interest, and to do this, the large influence alcohol and takeaways have on cost needed to be avoided.

The most recent food composition data²³ was used to create mean nutrient intakes for macronutrients (protein, fat, carbohydrates) and selected micronutrients (sodium and fibre). In establishing the total fortnightly dietary intake, maximum and minimum constraints of $\pm 30\%$ of the mean macro and sodium intakes were created. These constraints are relative to the energy of the total fortnightly dietary intake. The $\pm 30\%$ constraint was not applied for energy intake in the healthy, flexitarian and vegan scenarios which require tighter control to ensure the diet outputs maintain a healthy body weight.

Energy requirements for the healthy, flexitarian and vegan diet scenarios for adults were fixed at the same range to ensure the diet output maintains a healthy body weight (as healthiness is incorporated within these scenarios). This was calculated using the Body Weight Calculator based on a weight derived from a BMI of 23 kg/m², a mean population height, and moderate physical activity.^{28,29} Similarly for children, energy was based on the recommended energy requirements per KJ/kg per day from FAO/WHO/UNU for moderate physical activity.²⁸ For the current diet scenario, the energy requirement for adults was based on the current BMI. A moderate physical activity level (PAL) was selected as an average PAL was unknown for the population but half of adults met the physical activity guidelines.²⁸ The energy requirement for children for the current diet scenario was based on actual weight and moderate physical activity, because most children met the physical activity guidelines.³⁰ More details on the methods of the energy requirements has been published previously.³¹

The current dietary scenario exceeds recommendations for sodium, has insufficient dietary fibre, wholegrains, fruits and vegetables, and is high in UPF. The healthy dietary scenario was created to align with the 2015 dietary guidelines (NZEAG).³² The percentage range required for the different macronutrients was the Acceptable Macronutrient Distribution Range recommended by the Nutrient Reference Values for NZ and Australia.³³ The flexitarian dietary scenario was based on the EAT-Lancet Commission's criteria for a planetary diet and a vegan version of this was created to show the diverse range of dietary patterns within SHDs. See a description of the diet scenarios below (table 1).

Data analysis involved statistical comparison alongside regression analysis. Statistical comparison comprised calculating the SD, mean and their corresponding confidence intervals across the diet scenarios. Regression analysis involved calculating the household level data and examining the relationships between the diet scenario, climate impact and cost using one-way analysis of variance and regression analyses. The overall cost and average cost according to each food group was calculated. GHG emissions were calculated at each life-cycle stage and then overall emissions for both the 100-year and 20-year GWP. The stages included: farming and processing (100-year GWP and 20-year GWP), transit packaging, consumer packaging, transport, warehouse/distribution, refrigeration and supermarket overheads.

RESULTS

The persona diet outputs generated by the DIETCOST programme were combined to create a household diet output, with between 210 and 237 different fortnightly diets generated for each of the four diet scenarios. Data were calculated in the DIETCOST programme at the persona and household level, with costs and emissions modelled for each diet.



Table 1 Description of diet scenarios

Diet scenario	Description
Current	<ul style="list-style-type: none"> ▶ Survey data from the most recent NZ National Nutrition Survey (2008/2009). ▶ Used to represent 'current' diets in Aotearoa. ▶ Meets energy requirements to meet the current mean BMI of the population group of the household member (weight for children).
Healthy	<ul style="list-style-type: none"> ▶ 2015 New Zealand Eating and Activity Guidelines. ▶ Solely uses a human health lens. ▶ Does not currently incorporate sustainability. ▶ Meets energy requirements of a person of a healthy weight and moderately active.
Flexitarian	<ul style="list-style-type: none"> ▶ Modelled from the EAT-Lancet 'Planetary Diet' guidelines. ▶ Primarily vegetarian diet with the occasional inclusion of meat or fish. ▶ Incorporates both a human and planetary health lens. ▶ Meets energy requirements of a person of a healthy weight and moderately active.
Vegan	<ul style="list-style-type: none"> ▶ Modelled from the EAT-Lancet 'Planetary Diet' guidelines. ▶ No animal-based products (eg, meat or dairy). ▶ Incorporates both a human and planetary health lens. ▶ Meets energy requirements of a person of a healthy weight and moderately active.

BMI, body mass index.

The nutritional composition of the scenarios involved the overall energy levels (kJ) for the flexitarian, vegan and healthy scenarios for each persona generated diet outputs that maintained a healthy BMI due to the healthiness constraints included. The mean fortnightly household energy intake was 43 301 kJ (current), 39 919.5 kJ (healthy), 38 962 kJ (flexitarian), and 39 215 kJ (vegan). The total fibre content (g/day) for the flexitarian and vegan diet scenarios was very high (ie, vegan household 234g/day vs healthy household 164g/day) compared with the other diet scenarios. Household sodium content (mg/day) varied between the diet scenarios with the flexitarian scenario being the lowest (4175), followed by vegan (4974), healthy (7562) and current (14 388). For more details of the data at the persona and household level, see online supplemental files. The remainder of the results are presented at the household level, with the variables of cost and climate impact analysed.

Cost

Statistically significant differences were found between the costs of the various household diet scenarios with more constraints resulting in diets being more expensive. The current diet scenario had the lowest cost (NZ\$584

per fortnight), followed by healthy (NZ\$637), flexitarian (NZ\$728) and vegan (NZ\$789) (table 2). The top three contributing foods groups for each scenario were: current (discretionary foods, 33%; protein, 28%; grains, 9%); healthy (protein, 30%; fruit, 15%; dairy/alternatives, 15%); flexitarian (protein, 41%; vegetables, 23%; grains, 13%); vegan (protein, 30%; dairy/alternatives, 31%; vegetables, 20%) (figure 3). The minimum and maximum values for each diet scenario show none of the flexitarian or vegan diet outputs were cheaper than the mean cost of the current diet.

Larger servings of high protein plant foods, for example, legumes, nuts and seeds, compared with the current and healthy diets were needed to meet protein requirements in vegan and flexitarian diet scenarios and were thus more expensive. A comparison of the plant and animal-based protein sources used in the diet scenarios showed that on average, plant-based sources had nearly half the protein content per 100g. Roughly twice the volume of food is therefore required from plant-based compared with animal-based protein sources. This was also similar for the vegetables food group where the contribution was highest in the *vegan* (NZ\$151) and

Table 2 Cost of fortnightly household diet scenarios

Household diet scenario	Mean cost per fortnight (95% CI)	Minimum	Maximum	Range
Current	NZ\$584 (NZ\$580 to NZ\$588)	NZ\$524	NZ\$691	NZ\$167
Healthy	NZ\$637 (NZ\$632 to NZ\$642)	NZ\$538	NZ\$740	NZ\$202
Flexitarian	NZ\$728 (NZ\$723 to NZ\$734)	NZ\$619	NZ\$825	NZ\$206
Vegan	NZ\$789 (NZ\$784 to NZ\$794)	NZ\$650	NZ\$873	NZ\$223

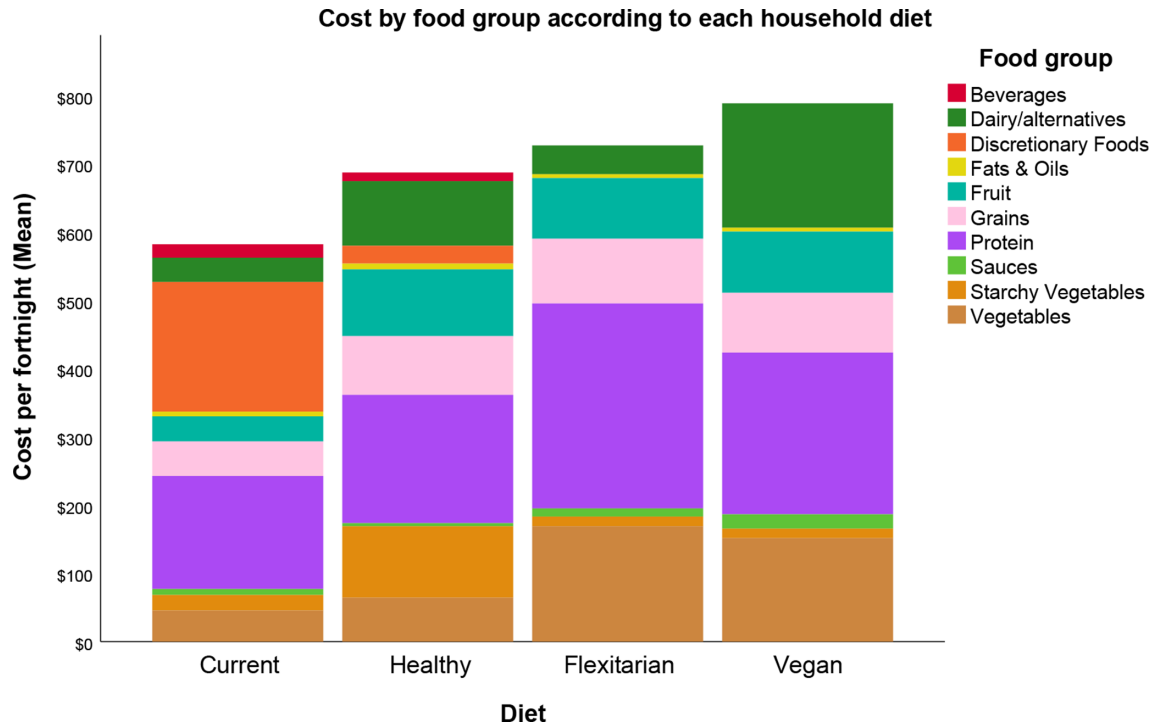


Figure 3 Contribution of food groups to household diet scenario cost.

flexitarian (NZ\$169) scenarios, and more than double the healthy scenario (NZ\$64). This difference was due to larger serving requirements of vegetables in the EAT-Lancet planetary diet guidelines compared with the NZEAG.

Another contributor to the higher cost of the *vegan* diet was the dairy alternatives which were more expensive than their dairy counterparts. The contribution of starchy vegetables was the highest in the *healthy* scenario (NZ\$104.60), followed by the current diet scenario (NZ\$22.65). The flexitarian and vegan scenarios had far less starchy vegetables (NZ\$14.20 and NZ\$13.88, respectively) because their reference values in the EAT-Lancet ‘planetary diet’ were very low due to them being deemed relatively unhealthy.¹⁴

The total fibre content for the flexitarian and vegan diet scenarios were very high compared with other diet scenarios (eg, vegan household 234g/day vs healthy household 164g/day). This is likely due to the EAT-Lancet planetary diet only including wholegrains and fibre-rich foods.

Climate impact

Mean GHG emissions, measured as 20-year or 100-year GWP, varied significantly ($p < 0.000$) across the diets (table 3). On the 20-year GWP, GHG emissions were the lowest and highest for vegan (203 kgCO₂e) and current (597 kgCO₂e) respectively. The incorporation of less animal-based products and processed foods within the scenario corresponded with a lower climate impact. The same trend was found for the 100-year GWP values.

Associations between climate impact, cost and diet

Climate impact and cost

Across diets, there was a negative relationship between the cost of 2 weekly household diets and their climate impact for 20-year and 100-year GWP figures (regression coefficient (r) = -0.471 and r = -1.170, $p < 0.001$). Higher GHG emission diets are associated with lower costs. For each unit (1 kgCO₂e) of higher 20-year GWP climate impact the cost of the household fortnightly food was about 47 cents lower (SE=0.011). For a one unit higher 100-year GWP, the household fortnightly food costs were about NZ\$1 lower (SE=0.025). There was a significant interaction between climate impact and cost by each diet scenario ($p < 0.001$) meaning there was no evidence for a uniform relationship of climate impact (both 20-year and 10-year GWP) and cost across all of the dietary patterns.

Table 3 Climate impact of household diet scenarios

Household diet scenario	Mean GHG emissions (20 year GWP kgCO ₂ e)	Mean GHG emissions (100 year GWP kgCO ₂ e)
Current	597 (590–604)	356 (354–359)
Healthy	452 (446–458)	326 (322–329)
Flexitarian	263 (261–265)	233 (231–235)
Vegan	203 (201–204)	195 (194–197)

GWP, Global Warming Potential; kgCO₂e, Kilogram of carbon dioxide equivalent.

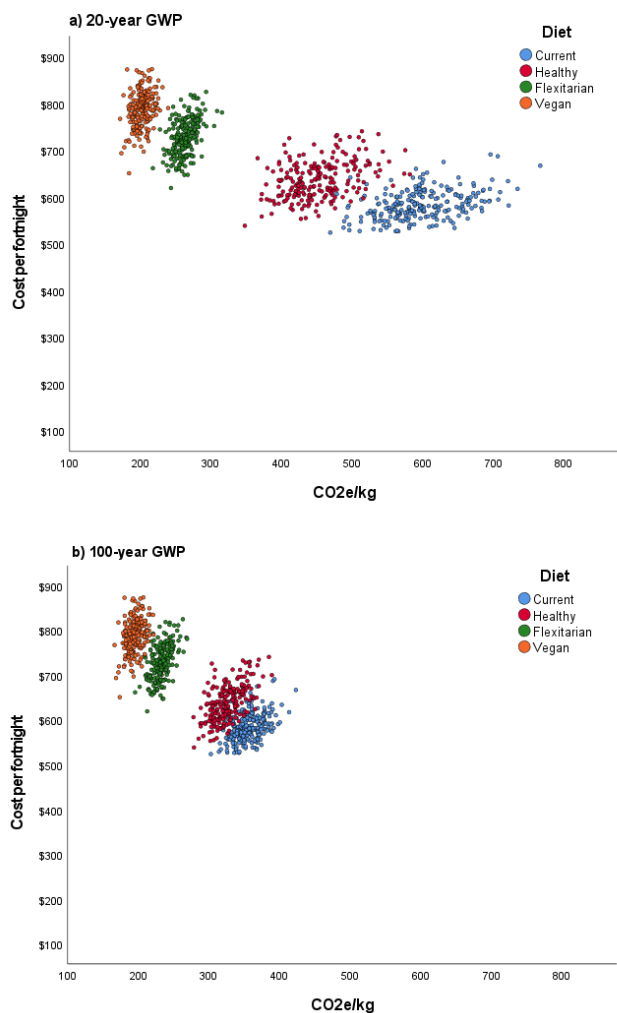


Figure 4 Grouped scatter plot of relationship between cost and climate impact. GWP, Global Warming Potential.

Climate impact and diet

The relationship between climate impact and diet was positive meaning that within diets, lower climate impact diets were less expensive. This contrasts to the inverse relationship between climate impact and cost when all diets were included in the analyses (figure 4). All correlations within and across diet scenarios were statistically significant at the 20-year GWP and 100-year GWP ($p < 0.001$). Generally, the quantity of food is associated with increasing emissions, and consequently increasing cost. For example, a unit increase (1 kg CO₂e/kg) in 20-year GWP associated with an average 23 cents (SE=0.034) increase cost of a current diet output. This contrasted to a unit increase in 20-year GWP meaning the cost of a flexitarian diet output increased by an average of NZ\$1.24 (SE=0.166). For the 100-year GWP, the variation within the separate diet scenarios was predominately similar for the vegan and flexitarian scenarios compared with the 20-year GWP. For the current and healthy scenarios, the linear relationship was weaker, and less variable compared with the 20-year GWP distribution.

DISCUSSION

We aimed to understand the interactions between the healthiness, cost and climate impact of different dietary patterns in Aotearoa. The least healthy diets (current diets) had the highest climate impact and proportion of UPF but the lowest cost. Of the three healthy dietary patterns, the patterns with the lower climate impact (vegan and flexitarian) also had a higher monetary cost compared with the healthy diet. In general, the greater the constraints on a dietary pattern, with vegan being the most constrained, the higher the cost of the diets. This is in part due to trade-offs made to ensure meeting guidelines for healthy sustainable diets, variety and acceptability. However, within each dietary pattern, the lower the climate impact, the lower the cost, generally reflecting the lower cost and climate impact of legumes and vegetables compared with higher cost and climate impact of products such as red meat. These results provide a new insight into the climate impact and cost distribution across diets in Aotearoa.

The farming and processing stage was the largest contributing LCA stage of each diet scenario overall but was much higher for the current and healthy diets due to the increased presence of animal-based products. There were also higher emissions from transport and distribution related to more plant-based products in the flexitarian and vegan diets but the contribution from the farming and processing stage was much more significant to overall emissions. This contribution of farming and processing of animal-based products directly contributes to the emissions profile of Aotearoa, regardless of whether the product itself is exported globally.³⁴

National consumption rates of meat reflect the scale of the agricultural industry in Aotearoa as a critical factor within the food system of the continuation of unsustainable diets.⁵ As stratified by type of meat, Aotearoa is thirteenth for beef and veal consumption globally, seventh for poultry meat and third for sheep meat. For example, sheep meat, has the second-highest environmental impact of meats from corresponding production, and New Zealanders consume 4.7kg per capita per year, far exceeding the OECD average.⁵

Current average weekly household expenditure figures in Aotearoa from 2019 show 16.8% of expenditure (NZ\$166–NZ\$332 per fortnight) was for food (excluding alcohol and restaurant meals and ready-to-eat food such as takeaways).³⁵ When comparing the cost of the diet scenarios in this research, the increased cost for more SHD scenarios (flexitarian and vegan) is important to consider given that over time (2016–2018) there has been a 8.3% increase in the contribution of the average weekly household expenditure towards food (excluding alcohol and restaurant meals and ready-to-eat food such as takeaways). Although there could be large health and climate gains from transitioning towards SHD in Aotearoa,^{16 20} the results highlight equity concerns given the high cost needed for GHG emission reductions to households. For example, a household transitioning from a current

to flexitarian diet would spend NZ\$144 more each fortnight, with the climate benefit of 334 kgCO₂e less GHG emissions. This cost is far higher than the current price of carbon in Aotearoa (NZ\$37.30/tonne),³⁵ emphasising the need for action within the food system to address this inequity. Further research is required to analyse the potential impact of increased food expenditure on households, weighing this increased food expenditure against the climate benefits, and whether the increased food expenditure is inequitable for specific groups.

Opposing conclusions on the relationship between cost and diet impact reflect: (1) the increasing constraints on the foods included in these diets and (2) higher costs in shifting populations from their currently unhealthy and unsustainable dietary patterns. Although, at any level of constrained dietary pattern (eg, flexitarian), the higher the plant-animal based product ratio, the lower the cost.

This is one of the few studies assessing relationships between climate impact and cost within different dietary scenarios. Other studies that have conducted modelling similar to this research did not include the feature of generating numerous iterations of their modelling data. That current eating patterns (as reflected in the current diet scenario) in Aotearoa are unsustainable and unhealthy is similarly found for other high-income countries.^{36–38} As most studies include 100-GWP figures for measuring GHG emissions, the finding that there was no substantial difference in GHG emissions in the healthy (according to nutrition guidelines) compared with the current diets is also found in the literature.^{16 37 39–43} The high-fibre content of the flexitarian and vegan diets is similar to other diets that have been modelled in the literature.^{20 38 44 45} Healthy diets having slightly less GHG emissions is reflected from Springmann *et al*,⁴⁶ who found that modelling the environmental implications of adopting national dietary guidelines (such as the NZEAG) showed work was needed to integrate sustainability into the guidelines.

Trade-offs were evident in the results and are reflected in the literature with the first being a trade-off between daily food cost and low emissions foods. For example, nutritionally dense foods such as dairy milk were substituted for more expensive but lower GHG emission alternatives, such as soy milk, to supplement the nutritional density lost from the original substitution.²⁰ It has been shown that some products, such as milk, are GHG emissions intensive but more efficient in their environmental footprint when accounting for nutrient provision in terms of nutrients per GHG emissions generated.⁴⁷

Wilson *et al*²⁰ found trade-offs between increasing dietary variety and likely acceptability with increasing cost. This trade-off is similarly discussed in Reynolds *et al*⁴⁸ when optimising low cost and low GHG diets whereby people on higher incomes achieved greater dietary variety and acceptability (when compared with their existing diets) compared with those on lower incomes. Nutritional adequacy has also been discussed, with modelling from Perignon *et al*⁴⁹ finding that stepwise reductions in

GHG emissions decreased diet cost, but occurred when the nutritional constraints only applied to macronutrients. Once nutritional constraints included all macronutrients and micronutrients, this relationship was not seen.⁴⁹ Overall more constraints placed on diets resulted in greater difficulty to reduce diet cost which is similar to our results.

Consuming an SHD is an effective tool to protect the environment and reduce the large health burden related to chronic diseases.⁵⁰ This research indicates that a large amount of effort is required to achieve the dietary shift towards SHD. The transition towards a healthier, more sustainable diet involves large reductions in UPF (currently about one-third of the diet) and large reductions in red meat and dairy. Consideration is also needed to address the large role that animal-based products (meat and dairy) contribute to exports in Aotearoa alongside a shift to reduce domestic consumption.³⁴ These are huge shifts at the population level and raise major equity challenges in achieving SHDs. Public health policies and interventions to enable the transition to SHD are needed: (1) Incorporate sustainability in the NZEAG to inform policies and interventions; (2) Promote (ie, social marketing) of sustainable, nutritious and low-cost foods such as legumes; (3) Implement a national nutrition survey in Aotearoa among adults and children with questions about dietary patterns; (4) Conduct further monitoring and advocacy towards encouraging the shift to SHD; (5) Provide more support to grow plant protein sources (ie, legumes) in Aotearoa and (6) Develop educational tools (ie, Front-of-pack labelling of climate impact) to allow consumers to make informed decisions.

Strengths and weaknesses

Strengths of this research include the LCA database of the most recent and robust sources of data available in Aotearoa. Data from the UK were used to inform the LCA figures for selected foods when NZ-specific data were unavailable, but these potential differences in LCA figures between the UK and NZ are likely insignificant. Avoidable food waste emissions (ie, emissions from food that is discarded unnecessarily or expires prior to consumption) was accounted for in the emissions for each food product, but it was not possible to account for the unavoidable food waste emissions from food waste directed to landfill.

The DIETCOST programme can generate many outputs for different diets compared with other optimisation techniques where a single figure for the various scenarios assessed such as cost is included. Limitations associated with data inputs into the DIETCOST programme includes the survey data used to develop the current diet scenario is outdated, as the data originated from the 2008/2009 Adult Nutrition Survey and the 2002 National Children's Nutrition Survey. It is uncertain how the diets of the population have changed since these surveys were completed. Alcohol and takeaways were excluded from the diet outputs to focus on the transition of increasing sustainability in the diet scenarios but contribute to 27%

of household food expenditure in Aotearoa.⁵¹ Future research could assess the sustainability of household takeaways and alcohol purchases. Only one indicator of climate impact was incorporated into the DIETCOST programme (GHG emissions) when there are other indicators such as land and water use. This study does not consider the impacts on the food system (ie, changes in food imports and exports) of a population transition to the other three diets included in our modelling (healthy, flexitarian and vegan).

CONCLUSION

In Aotearoa, unhealthy diets are the leading cause of health loss and subsequent inequity and food systems are the largest source of GHG emissions and other environmental damage. At a population level, our modelling shows that shifting existing unsustainable and unhealthy diets to being sustainable and healthier imposes increasing constraints to populations. These constraints involve factors such as nutritional adequacy, cost, climate impact, acceptability and dietary variety. In terms of cost, the most expensive dietary pattern was the vegan diet which also had the lowest GHG emission footprint. This was followed by the flexitarian, then the healthy diet with the current diet having the lowest cost and the highest GHG footprint. Although, within existing diets (eg, flexitarian) households that are not transitioning from one dietary pattern to another, are generally able to reduce diet costs with increasing the proportion of plant-based foods in their diet. These findings are locally specific and country dependent given the primary setting of Aotearoa.

Key public health policies and interventions are needed to enable the transition to SHD such as incorporating

sustainability throughout the NZEAG, promoting sustainable, nutritious and low-cost foods, updating the national nutrition survey, further support to grow plant protein sources and further monitoring and advocacy. These would ensure that the economic drivers are towards healthier, lower carbon food purchases to promote public health and protect our planet.

Dissemination to participants and related patient and public communities

The results of the study are accessible to the public and will be disseminated and shared with interested parties. Approval to access the full dataset will not be publicly available but will be shared to third parties when deemed appropriate by the study authors.

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Contributors BK contributed to the study conception and design, and led the data collection, analysis and writing of the manuscript. SM contributed to the study conception and design, data analysis and assisted with writing and critically revised the manuscript. SV contributed to the study conception and design, and critically revised the manuscript. BS contributed to the study conception and design and critically revised the manuscript.

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Data availability statement The data from this research will not be publicly available as it is specific to the DIETCOST programme and would have little relevance to the public. Third parties will be allowed to ask for permission to access the data if deemed appropriate to do so by the study authors.

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Key messages

What is already known on this topic

- ▶ Globally the food system contributes significantly to damaging our environment in biodiversity loss, deforestation, and in GHG emissions, and contributing to poor diet being a large cause of health loss.
- ▶ Cost is a universal concern and large determinant of food choices in affording healthier food compared with unhealthy food.
- ▶ A transition to sustainable healthy diets is necessary and must be equitable.

What this study adds

- ▶ The modelling showed that the transition from unsustainable and unhealthy diets to more sustainable and healthy diets imposes increasing constraints, associated with increasing cost.
- ▶ Although, within existing diets (eg, flexitarian) households are generally able to reduce diet costs by increasing the proportion of plant-based foods in their diet.
- ▶ Further action is required such as monitoring and advocacy, support for growers to supply plant protein sources (ie, legumes) in Aotearoa, integrating sustainability into the dietary guidelines, an updated national nutrition survey and promoting sustainable and healthy food choices.

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