Using Linear Programming to Determine the Role of Plant- and Animal-Sourced Foods in Least-Cost, Nutritionally Adequate Diets for Adults

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ABSTRACT

Background: The respective roles of plant- and animal-sourced foods in sustainable healthy diets for humans remain unclear. Nutritional quality and the monetary cost of diets are key criteria among others for sustainable food production.

Objective: Linear programming (LP) was used to determine the composition of nutritionally adequate dietary patterns formulated at the lowest cost. The hypothesis tested was that animal-sourced foods would be included in least-cost diets due to their high density of particular essential nutrients.

Methods: The LP modeling work was based on eating patterns, retail food prices (2020), and the daily energy (11,150 kJ, 2665 kcal) and essential nutrient requirements (29 nutrients in total) of a reference adult in New Zealand (NZ). The LP modeling approach is publicly and freely available to readily illustrate the change in dietary profiles and daily diet cost, in the simulation of changes in energy and nutrient requirements, and price fluctuations within food groups.

Results: A nutrient-adequate, least-cost dietary pattern formulated from 883 foods, with a daily cost of NZ $3.23, included both animal- and plant-based foods. The nutrients found to be equally first-limiting were biotin, calcium, molybdenum, potassium, selenium, vitamin A, pantothenic acid, and vitamin C. When a dietary scenario with no animal-sourced foods was modeled, by increasing the retail prices of animal-sourced foods by 1.05 to 10.3 times, the daily cost of this plant-only dietary pattern was NZ $4.34. Additional nutrients, such as zinc, vitamin B-12, and vitamin D, were met at their daily minimum required levels.

Conclusions: Dietary patterns formulated at the lowest cost and meeting the daily minimum requirements for energy and essential nutrients for an adult in New Zealand relied on foods sourced from animals and plants. *Curr Dev Nutr* 2021;5:nzab132.

Keywords: linear programming, diet cost, diet affordability, nutrient adequacy, animal-sourced foods, adult

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Supplemental Figure 1 and Supplemental Tables 1 and 2 are available from the "Supplementary data" link in the online posting of the article and from the same link in the online table of contents at https://academic.oup.com/cdn/.

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Abbreviations used: AI, Adequate Intake; EER, estimated energy requirement; LP, linear programming; NZ, New Zealand; RDI, Recommended Dietary Intake; UL, Upper Level of intake.

Introduction

There has been considerable debate over recent years about the role of plant- and animal-sourced foods in sustainable healthy diets for humans (1–4), and the arguments for and against the sustainability of animal compared with plant food production are multifaceted (5–8). The FAO and WHO have defined sustainable healthy diets as foods or dietary patterns that are sparing of natural resources, have low environmental impact, are easily accessible and safe, socially and culturally acceptable, affordable, and nutritionally adequate (9). These requirements are not mutually exclusive and sometimes trade-offs among the factors may be necessary. The monetary cost and affordability of diets, and the respective contributions of plant- and animal-sourced foods to these factors, are often overlooked when assessing sustainability. Animal-sourced foods along with fruits and vegetables contribute disproportionately to the cost of nutrient-adequate diets (10–12), but animal-sourced foods, in particular, are rich in protein and essential amino acids, key minerals, and vitamins (13, 14).

In an earlier study (15), dietary patterns that met the recommended nutrient requirements of an adult male in the United States were formulated at the lowest cost using a linear programming (LP) approach. Modeled diets that included both animal- and plant-based foods were found to be 40% cheaper than modeled diets consisting exclusively of plant-based foods. The retail prices of animal-sourced foods had to be increased significantly (2- to 11.5-fold) before they were no longer included in the least-cost diet, demonstrating the cost-effectiveness of animal-sourced foods in meeting the imposed nutritional requirements. However, that study was restricted to the US economy and food prices prevailing in 2009–2010 (16), and the study did not evaluate the potential bias arising from US government subsidies on animal-based foods (17). These limitations merit further analysis in the context of a country, with comprehensive contemporary food price data, and where there is little bias due to food subsidies and taxes. A potentially suitable country is New Zealand (NZ), where eating patterns are similar to those in the United States, but where food subsidies are minimal. The work reported here used LP applied to NZ food prices to determine the composition of least-cost, nutritionally adequate diets.

LP has been widely used in diet optimization studies to maximize or minimize an objective function, subject to linear constraints (4, 18–21). The aim here was to use LP to investigate the inclusion levels of animal- and plant-based foods in dietary patterns to meet the nutrient requirements of the NZ adult population, while minimizing diet cost using up-to-date (2020) food prices. The hypothesis tested was that animal-sourced food products, despite their relatively high cost per unit weight, would be included in least-cost diets, due to their high density of certain nutrients. This methodological study of the application of LP to address nutritional needs and monetary cost does not suggest or recommend any specific diets, but rather gives an insight into the types of foods needed to meet basic essential nutrient requirements at the lowest cost.

Methods

Linear programming

The same LP mathematical algorithm as described in our previously reported study (15) was used here to select a combination of foods that met stated linear constraints simultaneously at the lowest cost. The "diet" resulting from the LP analysis is not intended to be a realistic diet that should be consumed, but rather identifies the food types required to meet the constraints of recommended dietary intakes of energy and nutrients at the lowest cost. These illustrative combinations of food items in the modeled LP diets are often referred to as "dietary patterns." The linear objective function was to minimize the cost of the optimized diet. The LP model consisted of decision variables or the quantity of each food that could be selected from a comprehensive database of 883 food items, while meeting a set of linear constraints. The linear constraints included daily estimated energy requirement (EER), daily recommended intake of essential nutrients (29 nutrients in total), known nutrient upper intake limits, and maximum amounts of individual foods to be consumed daily. The Julia language (22) and the JuMP mathematical optimization library (23) were utilized to resolve the LP model, combined with Pluto as a reactive tool (24), which allowed the user to alter some constraints to observe the change in the dietary composition and minimized cost of the modeled diet. The constraints that could be changed dynamically were as follows: the inclusion or exclusion of foods of animal or plant origin or mixed foods, the daily energy requirement (in kilojoules), the daily minimum nutrient requirements for a reference adult, and the price of different food groups (increased or decreased by 5% from baseline food prices). All data and analytic code used in the study are available in an online repository at https://gitlab.com/dpgarrick/CDN-S-21–00186.

The LP model aims to minimize the cost of the optimized diet subjected to linear constraints, by solving the following equation:

Objective function: minimize

$$f\ (x) = \sum_{i=1}^{N_f} x_i c_i \qquad (1)$$

Where N_f is the number of food items included in the LP analysis, x_i is the quantity of 100 g portions of food *i*, and c_i is the cost per 100 g of food *i*.

Foods and nutritional composition

The decision variables consisted of 883 (N_f) foods, accessed from a New Zealand food-composition database (25). Food items were available under different brands and country of origin, were based on raw and cooked foods, and had different formats (fresh, canned, frozen). The selection of 883 food items was based on the popularity of the foods commonly purchased to be used in household kitchens and consumed as part of a typical NZ diet, and excluded most composite foods and restaurant and take-away foods. The 883 selected foods were categorized into 23 major food groups and 133 food subgroups (**Table 1**), and their respective nutrient composition was presented per 100 g of edible portion.

Food prices

The database of 883 foods included respective food prices assigned to food items, given in NZ dollars per 100 g of food product. Food prices were mainly obtained from the Statistics New Zealand database, based on the Food Price Index Selected Monthly Weighted Average Prices for New Zealand, as part of the Consumer Price Index in Economic Indicators (26). For this database, prices are collected monthly for 165 foods from a series of 75 supermarkets, 30 greengrocers, 30 butchers, 30 fish shops, and 50 convenience stores, across 15 main urban areas in NZ. The study used the published average consumer food prices for 98 groups of foods for the time period of January to December 2020. Published food prices were not available for seeds, and some prices were not good indicators of consumer food prices for particular food groups. For example, for the legumes food group, there were food prices for soy milk and hummus (chickpea-based dip) only, only cornflakes and muesli for the breakfast cereals food group, only olive oil for the vegetable oils food group, and only peanuts and peanut butter for the nut food group. Additional average retail food prices for 52 food items were obtained from October to December 2020 by collecting weekly original or nondiscounted prices in Palmerston North, NZ, from 3 major supermarkets (PAK'nSAVE, New World, and Countdown).

TABLE 1 New Zealand foods ($n = 883$) accessed from a database for inclusion in the linear programming analysis

Food source	Food group	Food subgroup	Number of foods
Animal	Beef	Beef blade, beef sirloin, beef mince, corned beef	69
Animal	Pork	Pork chop, roast pork, bacon rasher	39
Animal	Chicken	Chicken breast, chicken pieces, whole chicken, chicken nuggets	60
Animal	Lamb	Lamb chops, roast lamb	40
Animal	Sausages, salami, and ham	Sausages, salami, ham	34
Animal	Fish	Canned tuna, canned salmon, frozen fish fillets, fresh fish	94
Animal	Seafood	Marinated mussels, live mussels, prawns, shrimps	15
Animal	Milk	Standard milk, lite milk, trim milk, calcium-enriched milk	29
Animal	Dairy products	Salted butter, mild cheddar cheese, edam cheese, colby cheese, camembert cheese, processed cheese, cottage chesse, cream cheese, cream, yogurt, ice cream	46
Animal	Eggs	Eggs, free range eggs	7
Plant	Fruit	Orange, banana, apple, kiwifruit, avocado, mandarin, grape, pear, pineapple, dried fruit, canned fruit, frozen berries, olives	80
Plant	Vegetable	Lettuce, package leaf salad, broccoli, cabbage, tomatoes, canned tomatoes, carrots, mushrooms, potatoes, beans, capsicum, cauliflower, celery, zucchini/courgette, cucumber, kumara/sweet potatoes, onion, parsnip, pumpkin, frozen vegetables	137
Plant	Legumes	Soy milk, baked beans, chickpeas, red kidney beans, cannellini beans, black beans, mixed beans, lentil, broad beans, split peas, edamame soybean, tofu	28
Plant	Grain	White bread, wheat-meal or whole-meal bread, mixed-grain bread, bread rolls, pita bread, white flour	40
Plant	Rice	White rice	3
Plant	Pasta	Dried pasta, fresh pasta, canned spaghetti	16
Plant	Sugars and sweets	White sugar, honey, jam	9
Plant	Sauces, dressings, dips, and vinegar	Tomato sauce, tomato-based pasta sauce, soy sauce, mayonnaise, hummus, vinegar	12
Plant	Soup and pastry	Canned soup, pastry	8
Plant	Breakfast cereal	Corn flakes, muesli, wheat biscuits, wheat flakes, wheat flakes and sultana, wheat bran pellets, mixed grain extruded, mixed-grain flakes, mixed-grain flakes and dried fruit, mixed-grain clusters and nuts, puffed rice, cocoa-coated puffed rice, oats porridge, quick sachets oats porridge, rolled oats, whole-grain oats	34
Plant	Fats and oils	Vegetable oil, margarine	29
Plant	Nuts	Peanut butter, peanuts, almonds, cashew, coconut	18
Plant	Seeds	Sunflower seed, pumpkin seed, sesame seed	7
Mixed	Vegetable	Mushrooms, potatoes	3
Mixed	Pasta	Dried pasta, fresh pasta	5
Mixed	Sauces, dressings, dips, and vinegar	Mayonnaise	2
Mixed	Soup and pastry	Canned soup, pastry	13
Mixed	Breakfast cereal	Oats porridge, quick sachets oats porridge	6

Energy and nutrient requirements for an adult aged 19 to 50 y

As a measure of nutritional adequacy to maintain physiological functions of an adult, the recommended energy and nutrient intake levels for males and females were averaged to obtain values for a reference person. The nutritional constraints (**Table 2**) were based on the recommended daily intake requirements for healthy males and females aged between 19 and 50 y in NZ, as reported in the Nutrient Reference Values for Australia and NZ (27). The EER for healthy young-adult males, weighing 75 kg and being 1.85 m in height, was calculated to be 12,675 kJ (3032 kcal)/d and 9629 kJ (2304 kcal)/d for healthy young-adult females, weighing 60 kg and being 1.65 m in height (27). The average recommended energy intake requirement for a refence adult across all physical activity levels was estimated to be 11,150 kJ (2665 kcal)/d and the value for the daily EER could be dynamically altered by the model user in the current LP modeling exercise. The daily intakes for 29 key essential nutrients were based on Recommended Dietary Intakes (RDIs), which met the nutrient requirement of almost all (97.5%) healthy individuals, or Adequate Intakes (AIs), based on observed determined estimates of average nutrient intakes required daily for adequate health, when RDIs were not known (27). The daily intake requirements for protein, 7 minerals, and 9 vitamins were given as RDIs, while the requirements for total dietary fiber, 2 essential PUFAs [linoleic acid (18:2 n–6) and α-linolenic acid (18:3 n–3)], 6 minerals, and 3 vitamins were given as AIs (Table 2). Average values based on the recommended intake levels for males and females were used for the RDI for protein,

TABLE 2 The amounts of nutrients required daily by a reference adult and provided by the least-cost baseline dietary pattern (baseline diet) or dietary pattern including foods sourced from plants only (plant-only diet) for a daily energy intake of 11,150 kJ (2665 kcal)[1]

		Nutrient requirement		Baseline diet		Plant-only diet	
	Unit	RDI or AI (amount per day)	UL (amount per day)	Amount in modeled dietary pattern	Amount as % of RDI or AI	Amount in modeled dietary pattern	Amount as % of RDI or AI
Fiber, total dietary fiber	g	27.5 (AI)	—	41.1	150	39.9	145
Linoleic acid (18:2 n-6)	g	10.5 (AI)	—	27.4	261	27.5	262
α-Linolenic acid (18:3 n-3)	g	1.05 (AI)	—	3.34	318	3.37	321
Protein	g	55	—	94.4	172	80.1	146
Biotin	µg	27.5 (AI)	—	27.5	100	27.5	100
Calcium	mg	1000	2500	1000	100	1000	100
Chromium	µg	30 (AI)	—	42.9	143	52.6	175
Copper	mg	1.45 (AI)	10	2.48	171	2.60	180
Iron	mg	13	45	18.7	144	17.1	132
Magnesium	mg	362.5	—	459.5	127	441.6	122
Manganese	µg	5250 (AI)	—	7472.9	142	9238.3	176
Molybdenum	µg	45	2000	45	100	70.5	157
Phosphorus	mg	1000	4000	1782.0	178	1959.3	196
Potassium	mg	3300 (AI)	—	3300	100	3328.5	101
Selenium	µg	65	—	65	100	65	100
Sodium	mg	670 (AI)	2000	867.0	129	816.9	122
Zinc	mg	11	40	12.7	116	11	100
Vitamin A, retinol equivalents	mg	800	3000	800	100	800	100
Thiamin	mg	1.15	—	1.88	163	1.91	166
Riboflavin	mg	1.2	—	1.76	146	1.24	103
Niacin, total niacin equivalents	mg	15	35	23.6	158	25.6	171
Pantothenic acid	mg	5 (AI)	—	5	100	5	100
Vitamin B-6	mg	1.3	50	1.71	131	1.81	139
Vitamin B-12	µg	2.4	—	3.03	126	2.4	100
Folate, dietary folate equivalents	µg	400	1000	1000	250	917.8	229
Vitamin C	mg	45	1000	45	100	45	100
Vitamin D, calculated by summation	µg	5	80	7.6	131	5	100
Vitamin E, α- tocopherol equivalents	mg	8.5 (AI)	300	27.9	328	32.3	380
Vitamin K	µg	65 (AI)	—	134.8	207	79.8	123

[1] AI, Adequate Intake; RDI, Recommended Dietary Intake; UL, Upper Level of intake.

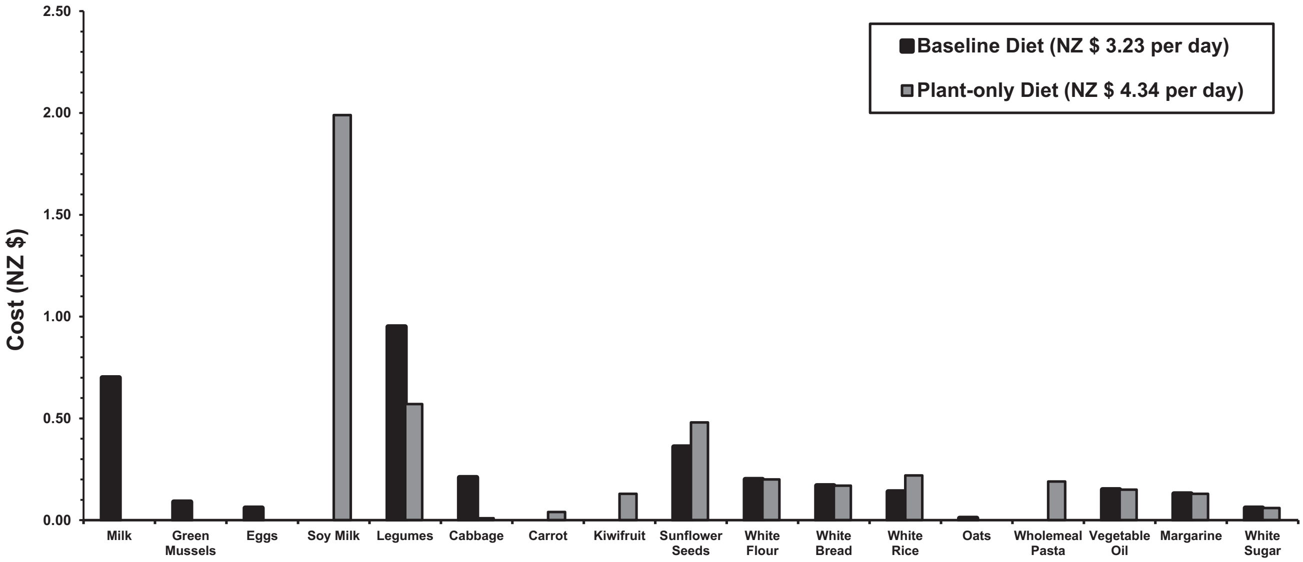

FIGURE 1 The composition of least-cost modeled baseline (Baseline Diet) and plant-only (Plant-only Diet) dietary patterns and the contributing costs of food subgroups. NZ, New Zealand.

iron, magnesium, molybdenum, selenium, zinc, vitamin A, thiamin, riboflavin, niacin, and vitamin B-6, and the AI for total dietary fiber, linoleic acid, α-linolenic acid, biotin, chromium, copper, manganese, potassium, sodium, pantothenic acid, vitamin E, and vitamin K. Upper levels of intake (UL) or tolerable upper intake levels were available for 14 nutrients (Table 2), which corresponded to the highest amount of nutrient intake likely to pose no risk of adverse health effects for almost all individuals in a population (27). The present LP modeling study allows the model user to dynamically change the values for the daily minimum required intake levels for the 29 essential nutrients, but limited to the UL values where available.

Daily allowable food intakes

To ensure practically acceptable amounts of individual foods in the least-cost dietary pattern, the daily maximum allowable amount of a single food item or food subgroup was used as a linear constraint. The daily intakes of food items or food groups were based on the recommended serving sizes published by the New Zealand Ministry of Health (28, 29). The constraint that no single food item and particular food subgroup was allowed to be consumed above 3 servings/d was applied pragmatically. The amount of food for the food subgroup white flour, white bread, vegetable oil, and cabbage was limited to a maximum of 3 servings/d. Margarine was restricted to no more than 2 servings/d, as when margarine was limited to 3 servings/d the least-cost modeled diet was deemed to be too high in fat content (providing 37% of energy) (27, 30).

Shadow price analysis

A corresponding shadow price for each constraint is obtained directly from the inherent sensitivity analysis features of LP (31). The shadow price for a given linear constraint estimates how a relaxation of a linear nutritional or food acceptability constraint, either a decrease in a constraint met at minimum or an increase in a constraint met at maximum, will result in a decrease in the minimum daily cost of the modeled diet. The shadow prices were used to identify which nutrients are the costliest to be met at their minimum recommended requirement level.

Results

Baseline diet: dietary pattern meeting the daily energy requirement and recommended nutrient intakes at the lowest cost for a reference adult

The minimum cost (objective function) of the least-cost dietary pattern meeting the daily energy and nutrient requirements and food acceptability constraints was NZ $3.23/d. The composition of the dietary pattern and the respective cost contribution of the food subgroups are given in **Figure 1**. The food subgroups that contributed to the largest extent to the total daily diet cost were dairy milk (21.6%) and chickpeas (21.1%), followed by sunflower seeds (11.2%), green split peas (8.3%), cabbage (6.5%), and starchy staples (white flour, 6.3%; white bread, 5.3%; and white rice, 4.3%). The modeled baseline dietary pattern comprised 402 g milk, 20 g green mussels, 8 g eggs, 201 g legumes, 101 g cabbage, 30 g sunflower seeds, 150 g white wheat flour, 78 g white wheat bread, 52 g white rice, 2 g rolled oats, 41 g soya bean oil, 28 g margarine, and 36 g white sugar. The plant-based subgroups white flour (19.2%), legumes (15.6% from dried chickpeas and 7.7% from dried green split peas), and vegetable oil (13.7%) contributed greatly to the total energy value of 11,150 kJ (2665 kcal) of the least-cost dietary pattern, with a further 33.4% of energy supplied by white wheat bread (7.2%), white rice (6.7%), sunflower seeds (6.5%), margarine (6.5%), white sugar (5.5%), cabbage (0.8%), and oats (0.2%). The sources of energy originating from animal-sourced foods in the least-cost dietary pattern included milk (8.9%), mussels (0.8%), and eggs (0.7%). The least-cost dietary pattern provided 94.4 g protein, 358.1 g available carbohydrate, and 101.6 g total fat; and the energy values derived from protein (13.84%), carbohydrate (52.53%), and fat (33.63%) were within the Acceptable Macronutrient Distribution Range (AMDR) of 10–20% of energy from protein, 45–65% of energy from carbohydrate, and 20–35% of energy from fat, respectively (27, 30). The diet also contained 27.4 g linoleic acid (providing 9.1% of energy) and 3.34 g α-linolenic acid (providing 1.1% of energy), which were within the acceptable range of 5–10% and 0.6–1.2% of energy accounted for by the essential fatty acids linoleic acid and α-linolenic acid, respectively (27, 30). The nutrients found to be equally first-limiting (at 100% of RDI or AI) were biotin, calcium, molybdenum, potassium, selenium, vitamin A, pantothenic acid, and vitamin C (Table 2). The minimum required intake level constraint for pantothenic acid gave the highest shadow price (−0.0674), followed by selenium and molybdenum, with a shadow price of −0.0046 and −0.0041, respectively. The primary foods that provided at least 10% of the recommended minimum required amounts of the first-limiting nutrients are presented in **Table 3**. Dairy milk (402 g, 388 mL) was a rich source of calcium, molybdenum, potassium, zinc, vitamin A, vitamin B-12, and vitamin D. The other animal-based foods, green mussels and eggs, supplied much of the vitamin B-12 and selenium and molybdenum, respectively. For the legumes food subgroup, chickpeas were rich sources of biotin, calcium, potassium, selenium, zinc, and pantothenic acid, whereas green split peas provided some potassium and zinc. The present baseline least-cost modeled diet included cabbage as the primary supplier of vitamin C, while fortified margarine provided much of the vitamin A and vitamin D.

Plant-only diet: least-cost dietary pattern meeting the daily energy and nutrient requirements, but with only foods sourced from plants

To model a plant-only least-cost dietary pattern, mixed food items originating from animals and plants were excluded from the LP modeling and the market prices of food products sourced from animals were increased incrementally in 5% steps. Increasing the price of milk by 2.2 times, green mussels by 10.3 times, eggs by 1.8 times, cheese by 3.95 times, chicken by 1.95 times, fish by 2.3 times, lamb by 1.25 times, and sausages by 1.05 times, resulted in a plant-only dietary pattern with a daily diet cost of NZ $4.34. The least-cost plant-only dietary pattern included 588 g soy milk, 109 g chickpeas, 6 g cabbage, 18 g baked carrots, 24 g green kiwifruit, 39 g sunflower seeds, 150 g white wheat flour, 78 g white wheat bread, 83 g white rice, 47 g whole-meal wheat pasta, 41 g soya bean oil, 28 g margarine, and 36 g white sugar. As shown in Figure 1, most of the diet cost contribution by the plant-based food subgroups was from soy milk (45.8%), followed by chickpeas (13.2%), sunflower seeds (11.0%), and the carbohydrate-rich sources of energy (white rice, 5.2%; white flour, 4.7%; whole-meal pasta, 4.3%; and white bread, 3.9%). White flour (19.2%), soya bean oil (13.7%), dried chickpeas (13.1%), white rice (10.7%), and soy milk (9.0%) were the richest sources of energy to achieve the total energy value of 11,150 kJ (2665 kcal) of the plant-only least-cost modeled diet, followed by sunflower seeds (8.7%), white wheat bread (6.8%), margarine (6.5%), whole-meal wheat pasta (5.8%), white sugar (5.5%), kiwifruit (0.5%), carrots (0.4%), and cabbage (0.1%). The least-cost plant-only dietary pattern contained 80.1 g protein, 361.2 g available carbohydrate, and 102.0 g total fat contributing to 11.9%, 53.8%, and 34.3% of energy, respectively, which was

TABLE 3 The amount of nutrient contributed (≥10% of the recommended required intake levels) by a food group in supplying the first-limiting nutrients included in the least-cost baseline (baseline diet) and plant-only based (plant-only diet) dietary patterns

	Baseline diet										Plant-only diet								
	Milk	Green mussels	Eggs	Chickpeas	Green split peas	Cabbage	Sunflower seeds	White flour	White bread	Margarine	Soy milk	Chickpeas	Carrot	Kiwifruit	Sunflower seeds	White flour	White bread	Whole-meal pasta	Margarine
Biotin, µg	—	—	—	89.8	—	—	—	—	—	—	—	75.6	—	—	14.1	—	—	—	—
Calcium, mg	52.2	—	—	18.2	—	11.2	—	—	—	—	67.0	15.3	—	—	—	—	—	—	—
Molybdenum, µg	22.3	—	17.7	—	—	—	—	31.7	27.7	—	101.9	—	—	—	—	31.7	22.5	—	—
Potassium, mg	17.0	—	—	31.5	21.3	—	—	—	—	—	40.3	26.5	—	—	—	—	—	—	—
Selenium, µg	—	21.3	—	12.0	—	—	23.2	15.0	—	—	12.7	10.1	—	—	32.4	15.0	10.8	10.1	—
Zinc, mg	13.1	—	—	41.2	16.1	—	14.2	11.3	—	—	—	34.7	—	—	18.6	11.3	—	12.4	—
Vitamin A, mg	21.2	—	—	—	—	28.3	—	—	—	39.0	26.6	—	29.2	—	—	—	—	—	39.0
Pantothenic acid, mg	—	—	—	42.1	—	—	41.6	—	—	—	—	35.4	—	—	48.3	—	—	—	—
Vitamin B-12, µg	72.0	49.6	—	—	—	—	—	—	—	—	98.0	—	—	—	—	—	—	—	—
Vitamin C, mg	—	—	—	—	—	87.7	—	—	—	—	—	—	—	81.5	—	—	—	—	—
Vitamin D, mg	48.2	—	—	—	—	—	—	—	—	95.9	—	—	—	—	—	—	—	—	95.9

within the recommended acceptable range of 10–25% of energy from protein, 45–65% of energy from carbohydrate, and 20–35% of energy from fat, respectively (27, 30). The energy provided by the essential fatty acids linoleic acid (9.2% of energy) and α-linolenic acid (1.1% of energy) was also found to be within the acceptable range of 5–10% and 0.6–1.2% of energy, respectively (27, 30). The nutrients that remained equally first-limiting (100% of RDI or AI) for the plant-only least-cost dietary pattern compared with the baseline diet were biotin, calcium, selenium, vitamin A, pantothenic acid, and vitamin C (Table 2). While molybdenum (at 157% of RDI) was no longer first-limiting, potassium (101% of AI) and riboflavin (103% of RDI) were close to their minimum intake requirements (Table 2). The essential nutrients zinc, vitamin B-12, and vitamin D were at their daily minimum required levels (100% of RDI or AI), when supplied by the least-cost plant-only based dietary pattern (Table 2). The shadow price for vitamin B-12 was very high (−0.6047) compared with pantothenic acid and zinc, which gave the second and third highest shadow prices of −0.0476 and −0.0392, respectively. The primary plant-based food subgroups that supplied the first-limiting nutrients are reported in Table 3. An intake of 588 g (565 mL) of fortified soy milk contributed greatly to the requirements for calcium, molybdenum, potassium, selenium, vitamin A, and vitamin B-12. Vitamin C was mainly supplied by kiwifruit, vitamin A by carrots and fortified margarine, while vitamin D was predominantly provided by fortified margarine. The dietary supply of the first-limiting nutrient zinc in the least-cost plant-only dietary pattern was mainly from chickpeas, sunflower seeds, whole-meal pasta, and white flour.

Least-cost dietary pattern meeting the daily energy and nutrient requirements for a reference adult, but removing from the formulation the requirements for all vitamins

It was considered that fortified foods may have secured their inclusion in the least-cost modeled diets, due to their elevated vitamin content. It is also possible that the daily requirements for all vitamins could be met by dietary supplements. To assess these scenarios, the daily requirements for all vitamins were removed from the following LP analysis. The daily cost of the no-vitamin dietary pattern was NZ $2.98/d, not including the cost of the dietary supplements necessary to meet the requirements for all 12 essential vitamins. The modeled diet included milk (580 g, 560 mL), green mussels (29 g), eggs (4 g), legumes (183 g), white wheat flour (150 g), white wheat bread (78 g), white rice (12 g), oats (84 g), soya bean oil (41 g), margarine (28 g), and white sugar (36 g) (**Supplemental Figure 1**). Biotin, calcium, molybdenum, potassium, selenium, and zinc were found to be the equally first-limiting nutrients (**Supplemental Table 1**). When a dietary pattern was formulated without any animal-based foods and excluding the vitamin requirements, the diet cost increased to NZ $3.16/d (Supplemental Figure 1), and dietary sodium was further identified as being first-limiting and zinc was very close to being first-limiting (Supplemental Table 1).

Discussion

Diets based predominantly on foods originating from plants have been associated with reduced negative environmental impacts and a lower risk of diet-related diseases (2–4, 32–34), but the monetary cost of these plant-based diets is often overlooked (10, 11, 12, 35). The LP approach, as applied here, is driven by daily nutrient requirements, food nutrient contents, and constraints on the amounts of a particular food that can be consumed daily, to model a nutritionally adequate diet for the lowest cost. The resulting modeled diets are not specific recommended diets that can or should be consumed and the holistic properties of foods (36) have not been considered. Rather, the approach gives an indication of the types of food that will lead to nutritionally adequate low-cost dietary patterns.

The aim of the present study was to use LP as a methodological approach to investigate the inclusion levels of plant- and animal-sourced foods in least-cost, nutritionally adequate dietary patterns for an adult. Given a basket of commonly available and consumed foods (883 foods) and retail food prices for the year 2020 in NZ, a least-cost dietary pattern was feasible with 14 foods that met the daily energy (11,150 kJ, 2665 kcal) and 29 essential nutrient requirements of an adult, for a diet cost of NZ $3.23/d (US $2.14/d, using the conversion rate of NZ $1.51 per US $ in 2020). Foods of animal origin (milk, eggs, and green mussels) were required to formulate the nutrient-adequate, least-cost dietary pattern. This outcome is in agreement with a previous NZ study that used 76 food items (37). In the present work, when the prevailing retail prices of all animal-derived foods were increased by 5% to 1030% of their baseline costs, a nutritionally adequate dietary pattern that included 13 foods sourced from plants only was formulated for a higher cost of NZ $4.34/d (US $2.87/d), which was 34% more than that of a dietary pattern that contained foods of both animal and plant origin. The higher cost of the plant-only dietary pattern appears to be driven by the need to replace the vitamin B-12 present in animal food products by the B vitamins in soy milk fortified with calcium, potassium, vitamin A, B vitamins, and vitamin D. The results demonstrate the considerable extent to which the prices of animal-sourced foods need to rise in this economy before these animal food products became too costly for their inclusion in the modeled nutrient-adequate, least-cost diets. This finding is supported by our previous LP study based in the United States, but where government subsidization of animal-sourced foods occurs, which may have influenced US retail food prices. In the US study, modeled diets that consisted of plant-only–based foods (US $3.61/d in 2010) were 40% more expensive than mixed dietary patterns that included both animal- and plant-sourced foods (US $1.98/d in 2010) (15). Nutrient-adequate, least-cost diets created with predominantly plant-based foods have been observed to be unaffordable for lower income households globally (10–12, 38, 39). To the best of our knowledge, this is the first LP modeling exercise that has been made flexible to readily illustrate the change in dietary profiles and daily diet cost, in the simulation of price fluctuations within food groups, due to factors such as seasonal local availability, marketing practices, discounted food prices, and national retail policies. It would be informative and meaningful to use the current LP modeling framework to assess the measures of uncertainty around food price estimates and to consider food price elasticities. Further investigation is warranted in developing countries (10–12, 38, 39), where the prices of animal-sourced foods may be relatively higher than the prices of plant-based foods than is the case in NZ or the United States (15). The analysis is particularly relevant to future food production sustainability in developing countries.

The focus of this study was on which food types would be included in a least-cost diet that would meet the minimum dietary nutrient intake requirements of the adult population. Nutritional adequacy underpins "healthy" diets and dietary guidelines (29) that relate the consumption levels of specific food groups to the prevalence and prevention of non-communicable diseases. The foods in the LP modeled diets were not selected to formulate a balanced healthy diet fit for human consumption, but rather to fulfill the requirements for essential nutrients of public health importance. The selection of an average daily energy requirement of 11,150 kJ (2665 kcal) for a reference adult was arbitrary and the present LP modeling study included dynamic variability in the daily energy requirement to account for possible variations in age, gender, physical activity levels, weights, and heights (27). When the daily energy (9630 kJ, 2304 kcal) and nutrient requirements for a representative female adult were applied to the model, the proportion of the food items changed but the same foods were selected to be part of the least-cost, nutritionally adequate dietary pattern, which had a daily diet cost of NZ $2.84. The first-limiting nutrients remained the vitamins and minerals, with the addition of vitamin D and iron supplied at the minimum required intake levels (**Supplemental Table 2**). Although the presence of high quantities of insoluble fiber and phytochemicals in plant-based diets have been shown to have positive attributes for human health (32–35, 40), the economic feasibility of plant-based diets to meet basic essential nutrient requirements of the population needs to be evaluated. The essential nutrients of concern that were supplied at their minimum recommended required levels by the plant-only–based, least-cost dietary patterns included zinc, vitamin B-12, vitamin D, and vitamin K (for a representative female adult; Supplemental Table 2). These findings are in line with previous other studies that reported that, when modeling a plant-based diet, the recommended minimum intake requirements for protein, calcium, iron, magnesium, vitamin A, vitamin B-12, vitamin D, vitamin E, and vitamin K were not adequately met (41–44). Given their clear importance in the formulation of a nutritionally adequate least-cost diet, better information on the bioavailability of vitamins and minerals in different food groups is needed (14, 35, 45–47). Animal-sourced foods often have higher nutrient bioavailability than their plant-based counterparts (14, 35, 45), as the anti-nutritional factors present in plant-based foods have a significantly detrimental effect on the digestibility and bioavailability of nutrients (14, 45, 46, 48).

It is important to note that the inclusion of fortified foods in the LP model may have secured their place in the least-cost, nutritionally adequate diets, due to their added vitamins and minerals rather than their intrinsic composition. When different dietary scenarios were explored within the context of the United States (15) and in the presently reported study in NZ, whereby the requirements for all vitamins were deemed to be fulfilled by dietary supplements, the findings that animal-sourced foods were necessary for the least-cost modeled diet were not altered. The no-vitamin baseline dietary pattern had a diet cost of NZ $2.98/d, while the no-vitamin plant-only dietary pattern had a higher daily diet cost of NZ $3.16, but the additional cost of providing the vitamin supplement needs to be considered. It may also be challenging for solely plant-based diets to meet the micronutrient requirements of the adult population without fortification. Food products sourced from plants have the potential to supply sufficient essential protein, fiber, and key vitamins and minerals, but the higher amount of plant-based foods that needs to be consumed to adequately meet the nutrient intake requirements of the population may, in some cases, be impractical and unaffordable.

The present LP modeling approach provides the framework for model users to explore the variability of food price estimates in achieving nutritionally adequate dietary patterns formulated at the lowest cost. This work demonstrates that the cost minimization of dietary patterns that meet multiple nutrient requirement constraints relies on foods sourced from both animals (milk, eggs, and seafood) and plants (legumes, vegetables, seeds, wheat-derived products, vegetable oils and fats, and sugar), at least for the NZ economy. The study also found a considerable price range by which the market prices of animal-sourced foods needed to be increased by to result in a modeled least-cost diet consisting of plant-based foods only. The findings that nutritionally adequate diets that are exclusively plant-based are more expensive and, in some cases, more challenging to formulate without fortification are exemplified here and in our earlier work (15). Vitamins and minerals were found to be the first-limiting nutrients in the least-cost dietary patterns, and the inherent bioavailability of these essential micronutrients in human global foods needs to be considered in further work. The results given here are specific to the NZ economy and cannot be extrapolated to other countries, especially to developing countries. There is a need for similar studies in underdeveloped countries that have different food matrices and corresponding food prices, to determine the respective roles of animal- and plant-based foods in their nutritionally adequate, least-cost diets.

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Data Availability

The data described in the manuscript and analytic code are publicly and freely available without restriction at https://gitlab.com/dpgarrick/CDN-S-21-00186.

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