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Animal-sourced foods are required for minimum-cost nutritionally adequate food patterns for the United States

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The amounts of animal-sourced foods required to achieve a least-cost nutritious diet depend on the food prices prevalent in each country. Using linear programming, we determine least-cost dietary patterns in the United States and the constituent amounts of animal-sourced foods. We considered local foods and prices from 2009–2010, and the average energy and nutrient requirements of adults. Nutrient-adequate food patterns were estimated at US$1.98 per day and included animal and plant products. Limiting nutrients were α-linolenic acid, potassium, choline, and vitamins C, D, E and K. The prices of animal-based foods had to be increased by 2–11.5 times to be excluded from the modelled food pattern, with the least cost of a plant-only diet at US$3.61. Given relative food prices in the United States, we show that animal-based foods are needed to secure adequate nutrition at the lowest cost, underscoring the role of price and market mechanisms in the choice of nutrient-adequate, sustainable diets.

The Food and Agriculture Organization of the United Nations has defined sustainable diets relative to four principal domains: nutrition, the environment, society and economics[1]. Guided by these domains, food patterns need to be nutrient adequate, sparing of natural resources and the environment, culturally acceptable and affordable[2]. Food choices should consider all of these aspects; for example, the environmental impact of animal food production may in some cases be higher than that of plant food production, but environmental costs that are not reflected in the price (that is, externalities) need to be assessed against attributes such as nutrient density and cultural and social value.

This study, which is focused on the economic domain, seeks to identify the best combination of food groups to minimize daily dietary cost while meeting energy and nutrient requirements in the United States. We used the most up-to-date, comprehensive and reliable food composition data (2016)[3] and national food prices (2009–2010)[4] available for the country. Although the detail and robustness of the dataset is a strength, that the data pertain only to the United States is also a limitation in terms of the generalizability of the findings to other regions. Yet, the price hierarchy of different food items has been shown to be the same in countries as diverse as France, the United Kingdom, the Netherlands, China, India and Australia[5,6].

In linear programming, diet formulation is determined by minimizing or maximizing (that is, optimizing) a given function while subjecting this function to several constraints[7,8]. In the present study, a linear programming algorithm was applied to verify the amounts of animal- and plant-based foods in least-cost diets and in the face of numerous constraints (such as energy and nutrient requirements, upper limits to nutrient intakes, food serving sizes, and available foods and their relative pricing). This allows a rational assessment to be made as to whether—from an economic perspective alone—animal-based foods need to be included in mixed diets for adult humans.

The linear programming analysis gives a unique solution of the combination of foods that meet all nutrient requirements at the lowest cost. The analysis is limited to the effect of food costs; the resultant food pattern has not been optimized from a health viewpoint, nor does it address other relevant aspects of food production, such as greenhouse gas emissions, natural resource use and environmental pollution. Although linear programming has been used in previous studies to evaluate diets for humans[9,10], the objective of those studies was to assess the impact of cost constraints on food choices, and to evaluate altered food intake and nutrient patterns. The linear programming modelling exercise is illustrative only, and does not purport to formulate a balanced recommended diet in a public health sense. Consistent with this, the combinations of different food items in the modelled diets are at times referred to as modelled food patterns. This study applies linear programming to derive economically optimal food patterns and identify food groups that need to be included in a nutritionally adequate modelled diet, to ensure that all nutrient requirements are met at the lowest cost. In other words, the hypothesis to be tested was whether animal-based foods, due to their high nutrient density, would be found in least-cost modelled diets for adult humans, given foods and food prices in the United States.

In total, five linear programming analyses were conducted. Linear programming analysis 1 investigated a dietary scenario whereby a modelled food pattern that met the total energy requirement of 2,600 kcal and the requirements for all key macronutrients and micronutrients (28 in total) was formulated at the lowest cost. The subsequent linear programming analyses 2 and 3 examined the effects of incremental changes in animal food prices. Linear programming analysis 4 considered a nutritional scenario whereby the requirements for the vitamins would be met by dietary supplements. Linear programming analysis 5 utilized a lower potassium recommended intake level of 3,400 mg d^{-1} (ref. [11]). Linear programming includes inherent sensitivity analysis features

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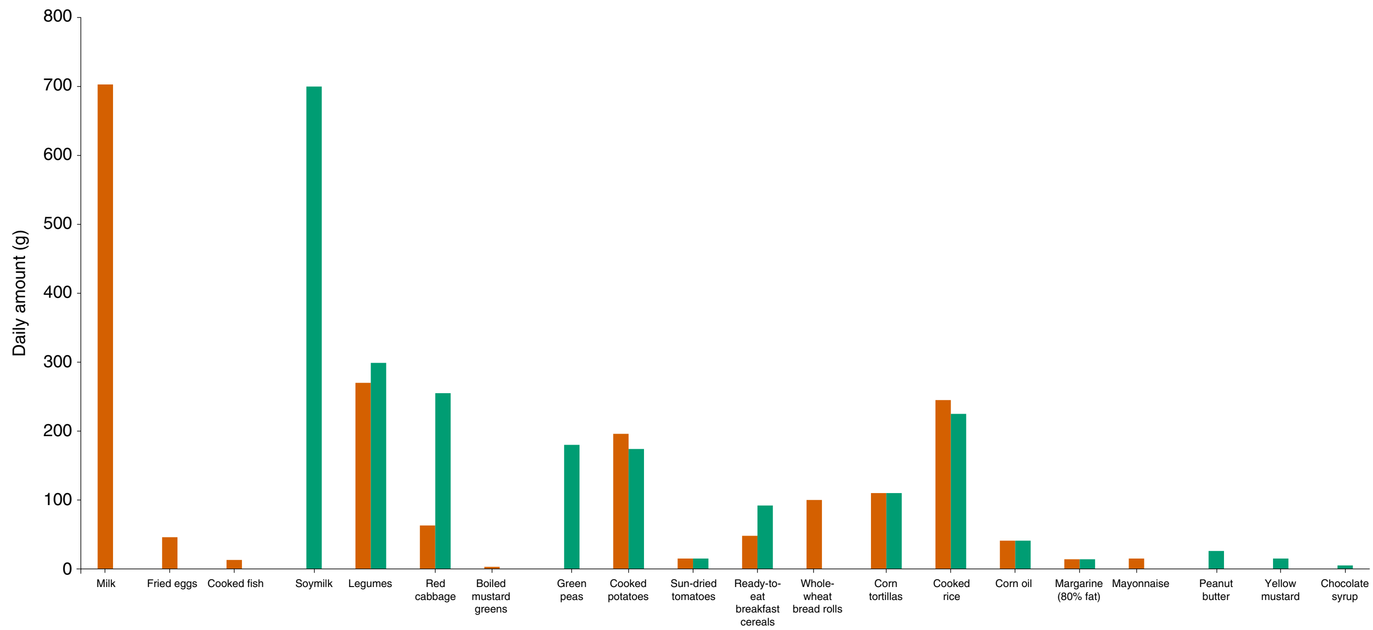

	Milk	Fried eggs	Cooked fish	Soymilk	Legumes	Red cabbage	Boiled mustard greens	Green peas	Cooked potatoes	Sun-dried tomatoes	Ready-to-eat breakfast cereals	Whole-wheat bread rolls	Corn tortillas	Cooked rice	Corn oil	Margarine (80% fat)	Mayonnaise	Peanut butter	Yellow mustard	Chocolate syrup
LP diet 1	703	46	13	–	270	63	3	–	196	15	48	100	110	245	41	14	15	–	–	–
LP diet 3	–	–	–	700	299	255	–	180	174	15	92	–	110	225	41	14	–	26	15	5

Fig. 1 | Daily intake of the 15 foods included in food pattern modelling for linear programming analysis 1 and the 14 foods for linear programming analysis 3. Food components of the least-cost modelled food patterns for linear programming analysis 1 (LP diet 1) and linear programming analysis 3 (whereby the prices of animal-based foods were increased to formulate a plant-only dietary pattern; LP diet 3).

(https://www.juliaopt.org/JuMP.jl/v0.20.0/). The sensitivity of the objective function to changes in constraints is represented by the shadow price. Specifically, the shadow price for a given constraint is the expected change of the objective function value (that is, the daily cost of the modelled diet) for an infinitesimal relaxation of the linear constraint. Sensitivity analyses were generated for all of the linear programming analyses. The sensitivity analyses, along with the shadow prices for all of the constraints that were met at minimum or maximum, for linear programming analysis 1 and linear programming analysis 3 are shown in Supplementary Table 1. Sensitivity analyses using shadow prices were undertaken for linear programming analysis 1 to understand the effect of varying constraint values.

Results

Linear programming analysis 1—least-cost nutrition under current conditions. The cost of the least-cost modelled food pattern (objective function) was US$1.98 per day and the 15 foods selected are presented in Fig. 1. Table 1 shows how the least-cost modelled food pattern provided the required nutrients. The modelled dietary pattern provided daily 2,600 kcal (10.9 MJ), 89.4 g of protein, 90.8 g of total fat and 367.2 g of carbohydrate. The linear programming diet was deemed to be nutritionally adequate as the energy amounts derived from protein (13.5%), fat (30.9%) and carbohydrate (55.6%) were within the acceptable macronutrient distribution ranges of 10–35% for protein, 20–35% for fat and 45–65% for carbohydrate, respectively[12,13]. The major nutrients found to be first limiting (100% of the recommended dietary allowance (RDA) or adequate intake) were the essential fatty acid α-linolenic acid, potassium, vitamin C, vitamin D, vitamin E, vitamin K and choline. Other nutrients providing close to their minimum required levels were vitamin A and calcium.

Applying either the shadow prices or re-running the linear programming model with modified constraints had only a small effect on the objective value, and led to similar outcomes and the same overall conclusions for linear programming analysis 1. As the constraint for the allowable amount of milk to be included in the modelled food pattern was found to be met at its maximum, the negative shadow price implied that an increase in the amount of milk to more than three servings per day would result in a decrease in the daily diet cost. Inversely, when the three servings (703 g) were reduced to two servings (468 g) and one serving (234 g), which is a further restriction of the constraint rather than a relaxation, the objective value increased, as implied by the shadow prices, from US$1.98 to US$2.04 (versus US$2.01 as predicted by the shadow price) and US$2.15 (versus US$2.05 predicted) per day, respectively. In all three milk serving scenarios tested, the maximum allowable amount of milk was included in the resulting least-cost dietary pattern, and as the maximum allowable amount of milk decreased, the amount of other animal-based food products (fried eggs and cooked fish) increased. When the allowable amount for all of the specified food groups was limited to no more than three servings per day per food group, the modelled food pattern included similar food types as those for linear programming analysis 1—particularly milk (703 g; three servings), fried eggs (42 g), cooked fish (11 g), bread rolls (150 g; three servings) and corn tortillas (165 g; three servings)—and had a slightly lower diet cost of US$1.89 per day. Overall, the conclusions based on linear programming analysis 1 were robust, and not greatly influenced by varying the respective constraint values.

Linear programming analysis 2—5–20% price increments for animal-based foods. Increasing the prevailing market prices of animal-sourced foods by 5, 10, 15 or 20% resulted in a gradual small increase in the daily cost of the modelled diet and a slight change in the foods selected (Table 2). When the prices of animal-based food products were increased by 15 or 20%, a small amount of seeds was included in the least-cost modelled food patterns and the amount of fish was reduced (Table 2). The nutrients potassium, vitamin C, vitamin D, vitamin E, vitamin K and choline remained first limiting (100% of RDA or adequate intake) for all four dietary scenarios. Compared with being first limiting (100% of adequate intake) for the baseline dietary pattern of linear programming analysis 1, and when there was a 5% increase in the original prices for the animal-based foods, the essential fatty acid α-linolenic acid was close to its minimum required level when the original costs of animal-based foods increased by 10, 15 and 20% (124% of adequate intake). As the baseline prices of animal-based foods increased from 5 to 20%, sodium, pantothenic acid and iron were closer to having their daily minimum required levels met (101–146% of the RDA or adequate intake).

Linear programming analysis 3—50% price increments for animal-based foods. The original prices of animal-based food products were increased by increments of 50% until no animal-based foods were included in the resulting least-cost modelled food pattern. A dietary pattern containing no animal-based food items became economically optimal only after an increase in the price of milk by eight times, eggs by 11.5 times, fish by 6.5 times, mayonnaise and animal-based salad dressings by five times, bread rolls and buns (which included milk and eggs) by 4.5 times, beef by 5.5 times, chicken by five times, sausages by three times, turkey by three times, cheese by three times, pork by 2.5 times, cold cuts and cured meats by twice, cooked egg noodles by twice, ice cream by twice, yogurt by 2.5 times and mashed potatoes (which included milk and/or butter) by twice their original costs, respectively. This resulted in a relatively expensive least-cost modelled food pattern with a daily cost of US$3.61, and containing 14 foods (Fig. 1). The least-cost plant-only dietary pattern provided 2,600 kcal and 77.2 g of protein, 77.3 g of total fat and 413.5 g of carbohydrate, contributing to 11.6, 26.2 and 62.2% of energy, respectively. The energy levels derived from protein, fat and carbohydrate were found to be within the recommended acceptable range of 10–35% for protein, 20–35% for fat and 45–65% for carbohydrate, respectively[13]. The nutrients that were first limiting (100% of the RDA or adequate intake) were α-linolenic acid, potassium, vitamin D, vitamin E and choline. Another nutrient that was comparable between both (animal- and plant-food-containing) least-cost modelled food patterns was pantothenic acid (vitamin B-5), which was found to be supplied at its minimum required level by the plant-based least-cost dietary pattern (100% of adequate intake). When animal-based foods became too costly to be part of the least-cost modelled dietary pattern, the requirements for vitamin C and vitamin K were met at 175% of the RDA and 234% of adequate intake, respectively, and the dietary supplies of selenium (126% of the RDA), calcium (133% of the RDA) and protein (152% of the RDA) were closer to their minimum requirements.

Linear programming analysis 4—no vitamins in the least-cost diet formulation. It was found that many food items readily available on the US market are enriched with vitamins and it was considered that this may have biased the outcomes by securing their inclusion in the least-cost modelled diets. Moreover, it is possible that vitamins could be supplied by dietary supplements. Therefore, a linear programming analysis was undertaken to minimize daily diet cost while meeting the recommended requirements for energy, the energy-providing nutrients and ten minerals. The nutrient requirements for young American adults were met with 12 food items, for a total energy value of 2,600 kcal and a daily diet cost of US$1.45. The latter cost does not include the additional cost of the necessary dietary vitamin supplements. The least-cost dietary pattern included a lower amount of milk (376 g), a higher amount of baked potatoes (330 g) and cooked rice (280 g), and no fish, eggs, cabbage, mustard greens, breakfast cereals or margarine. The amounts of boiled pinto beans, sun-dried tomatoes, whole-wheat bread rolls, corn tortillas, corn oil and mayonnaise remained the same as for linear programming analysis 1. Potassium, calcium and sodium were observed to be the first limiting nutrients (contents were 100% of the RDA or adequate intake). Zinc (112% of the RDA), iron (121% of the RDA) and the essential fatty acid α-linolenic acid (126% of adequate intake) were found to approach their minimum requirement levels.

Table 1 | Daily nutrients required by the average young adult man or woman, and provided by the least-cost modelled food pattern for linear programming analysis 1

Nutrient	Average adult requirement		Linear programming analysis 1	
	RDA or AI (amount per day)	Upper limit (amount per day)	Amount in modelled food pattern	Amount as % of RDA or AI
Carbohydrate (g)	130	–	367.2	282
Total dietary fibre (g)	31.5 (AI)	–	48.4	154
Linoleic acid (18:2 *n*-6 c,c) (g)	14.5 (AI)	–	30.3	209
α-linolenic acid (18:3 *n*-3 c,c,c) (g)	1.35 (AI)	–	1.35	100
Protein (g)	50.8	–	89.4	176
Calcium (mg)	1,000	2,500	1,343	134
Copper (mg)	0.9	10	1.8	202
Iron (mg)	13	45	20.7	159
Magnesium (mg)	355	–	524	148
Manganese (mg)	2.05 (AI)	11	6.2	302
Phosphorus (mg)	700	4,000	2,141	306
Potassium (mg)	4,700 (AI)	–	4,700	100
Selenium (µg)	55	400	140	255
Sodium (mg)	1,500 (AI)	2,300	2,300	153
Zinc (mg)	9.5	40	16.8	177
Vitamin A (RAE) (µg)	800	3,000	1,060	132
Thiamin (mg)	1.15	–	2.1	186
Riboflavin (mg)	1.2	–	3.1	256
Niacin (mg)	15	35	23.6	158
Pantothenic acid (mg)	5 (AI)	–	8.5	171
Vitamin B-6 (mg)	1.3	100	3.5	271
Vitamin B-12 (µg)	2.4	–	7.5	312
Folate (DFE) (µg)	400	1,000	1,000	250
Choline (mg)	487.5 (AI)	3,500	487.5 (AI)	100
Vitamin C (total ascorbic acid) (mg)	82.5	2,000	82.5	100
Vitamin D (IU)	600	100	600	100
Vitamin D (D2 + D3) (µg)	15	4,000	15	100
Vitamin E (α-tocopherol) (mg)	15	1,000	15	100
Vitamin K (phylloquinone) (µg)	105 (AI)	–	105	100

Average adult requirements are listed as both the RDA or adequate intake (AI) and the tolerable upper intake limit. Nutrient requirement values were sourced from the Institute of Medicine of the National Academies[12,14,35–39]. DFE, dietary folate equivalent; RAE, retinol activity equivalent.

Table 2 | Daily amounts (g) of food groups included in the least-cost modelled food patterns for linear programming analysis 1 compared with linear programming analysis 2

Food group	Linear programming analysis 1	Increase in price of animal-based foods			
		5%	10%	15%	20%
Milk	703	703	703	703	703
Fried eggs	46	46	47	47	47
Cooked fish	13	13	9	7	7
Boiled legumes	270	270	270	270	270
Vegetables	277	277	286	289	289
Breakfast cereals	43	43	52	56	56
Whole-wheat bread rolls	100	100	100	100	100
Corn tortillas	110	110	110	110	110
Cooked rice	245	245	237	218	218
Corn oil	41	41	41	41	41
Margarine	14	14	–	–	–
Vegetable oil spread	–	–	14	14	14
Mayonnaise	15	15	15	15	15
Seeds	–	–	–	2	2
Daily diet cost	US$1.98	US$2.02	US$2.06	US$2.10	US$2.14

Daily diet costs for each scenario are included in the final row.

Linear programming analysis 5—reduced daily recommended intake of potassium. It was noted that potassium was limiting in all of the least-cost modelled diets, and the recommended intake for potassium of 4,700 mg d^{-1} (ref. [14]) may be too high[11,15,16]. A recent report from the National Academies of Sciences, Engineering, and Medicine[11] suggested that the adequate intake recommendations for potassium be decreased to 3,400 mg d^{-1} for American adults aged over 18 years. When the requirement for potassium was set to 3,400 mg d^{-1} (while all other nutritional variables remained as for linear programming analysis 1), the dietary pattern was marginally cheaper, costing US$1.80 per day. Nonetheless, the results were not substantially different from those from linear programming analysis 1, whereby the modelled food pattern also included the same animal-based food products (milk, fried eggs and cooked fish), and potassium at the minimum daily intake requirement level of 3,400 mg remained first limiting (100% of adequate intake).

Discussion

The production of meat, eggs and dairy products for human consumption has been viewed by some as an inefficient use of natural resources[17]. Moreover, the recent EAT–*Lancet* report has recommended a global shift towards a diet that is more plant based, citing as part of its reasoning the environmental impact of the production of animal-based foods[18]. However, such conclusions are often based on crude comparisons between the efficiency of production of plant versus animal foods, and do not fully account for the high nutritional quality of animal-sourced foods and other factors[19]. Our aim was to assess the place of animal-sourced foods in least-cost food patterns for the United States, under current national prices.

When linear programming was applied to commonly available foods and food prices prevailing in the United States (2009–2010), animal-based foods (milk, eggs and fish meat) were selected for the formulation of dietary patterns that met the energy and nutrient requirements of healthy adults at the lowest cost. This shows that—at least for US foods and food prices in 2010—animal-based foods are required for nutritionally adequate least-cost food provision. Vitamins and minerals were the main limiting factors in the least-cost dietary patterns, and nutrient availability needs to be taken into account in future work.

The linear programming approach remains to be extended to the elderly, pregnant or lactating women, and growing children, who are more at risk with inadequate nutrient intakes and increases in food prices[5,6,9,15,16,20–22]. Yet, the present analysis illustrates the usefulness of linear programming to determine the influence of different food groups on the lowest cost of a dietary pattern. As this analysis is restricted to the US economy and to a single time period (2009–2010), the work should be repeated for other economies, especially where the relative prices of food groups may be different[6,23]. In particular, the results based on US data may not be general in that there may be food price distortions caused by animal food subsidies imposed by the US Government. However, the effects of subsidies are complex and there is evidence that subsidies have little effect on retail prices of animal-based foods[24].

The set of linear programming analyses included increasing the prices of animal-based foods in relation to plant-based foods, to evaluate to what extent the price of animal foods could rise before such foods become too costly to be included in the least-cost food pattern. This gives an indication of the margin for potential inclusion of externalities, or costs arising from the removal of subsidies, into the costs of these animal foods. Increasing market prices of animal-based foods by up to 20% had little effect on the food composition of the least-cost modelled diets. To formulate a nutritionally adequate diet at the lowest cost that no longer included any animal-based foods, the price of all animal-derived foods had to be increased by 200–1,150% of their baseline costs. The resulting plant-only diet was relatively expensive (US$3.61 compared with US$1.98 for linear programming analysis 1). A change in diet cost may mean greater or lesser affordability for particular groups of the US population. Given that the average per-capita income in 2010 was US$26,558 (ref. [25]), 5% of the annual income ((US$3.61 (daily diet cost) × 365 d) / US$26,558 (income)) would be spent on plant-only food products, relative to 2.7% of the annual income ((US$1.98 (daily diet cost) × 365 d) / US$26,558 (income)) spent on a diet that included animal- and plant-based food products. In particular, a one-person American household at the poverty threshold of US$11,139 in 2010[25] would spend 11.8% of the annual income on foods based only on plants, compared with 6.5% of the annual income on foods originating from plants and animals. When relative affordability is considered, the food pattern that included animal- and plant-sourced foods would be more affordable than the modelled dietary pattern that only consisted of plant-based foods.

A potential limitation of the present study is that the wider costs (both social and environmental) associated with animal production and increased consumption of animal-based foods are not considered. Plant food production also has associated externality costs, but these may be greater for some systems of animal production. The differences in such costs between agricultural production systems and the effects of such cost differences on the least-cost modelled diets are beyond the scope of the present study, but should be taken into account in future work. In any case, it is apparent from the present study that, when price elasticities were considered, the 2009–2010 US food retail prices of animal-based foods had to be substantially increased before the animal-derived foods disappeared from the modelled dietary pattern. This would offset to some extent any potential relatively higher externality costs associated with animal food production, compared with plant food production.

The least-cost modelled food patterns selected by the linear programming exercise take no account of the holistic properties of foods in healthy diets[26] and food attributes other than the main nutrients, and are not meant to be realistic diets to be recommended in practice. Rather, they highlight the food groups needed to be included in a dietary pattern at the lowest cost. Based on the criterion of minimum food cost alone, the animal-based food group appears to have a role in optimum cost-minimized dietary patterns.

Methods

Linear programming. The linear programming model was developed and solved using the Julia programming language[27], together with the JuMP mathematical optimization library[28], due to their flexibility and performance. The linear programming model takes into account the dietary supply of all nutrients simultaneously to meet stated nutrient requirement levels while minimizing the cost of the modelled food pattern (that is, the objective function)[7,8,29–33]. The objective function to be minimized in the linear programming model (a linear function) was formulated with the dependent variables as the quantities of each food item to be consumed and the coefficients set as the corresponding cost of each food item. Linear constraints were defined using energy and nutritional requirements and, where applicable, also included known upper nutrient intake limits and maximum daily food serving sizes. The constraints applied were as follows:

(1) Daily amounts of each food item needed to be either null or positive;
(2) The maximum quantity of a food item to be consumed per day was restricted to be no more than three times the recommended reference amount customarily consumed (RACC) at one eating occasion[34] (≤3× RACC);
(3) The energy content of the modelled food pattern was set to meet the daily estimated energy requirement of 2,600 kcal for an active young adult human[12], such that the constraint on energy was set to be 2,600 kcal d^{-1};
(4) The daily amount of each nutrient provided by the modelled food pattern was equal to or above the minimum, defined as either RDAs or adequate intakes[12,14,35–39];
(5) The daily intake of each nutrient was equal to or below the tolerable upper intake level[14,35–39].

The linear programming model described above is summarized mathematically as follows:

Minimize:

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

subject to:

$$x_i \geq 0 \ (i = 1, 2, \ldots, N_f) \quad (1)$$

$$x_i \leq 3r_i \ (i = 1, 2, \ldots, N_f) \quad (2)$$

$$\sum_{i=1}^{N_f} e_i x_i = E \quad (3)$$

$$\sum_{i=1}^{N_f} n_{ij} x_i \geq m_j \ (j = 1, 2, \ldots, N_n) \quad (4)$$

$$\sum_{i=1}^{N_f} n_{ij} x_i \leq u_j \ (j = 1, 2, \ldots, N_n) \quad (5)$$

where N_f is the number of food items included in the linear programming analysis, N_n is the number of nutrient quantities included in the linear programming analysis, x_i is the number of units of food item i to consume, c_i is the cost per unit of food item i, r_i is the recommended daily intake serving size for food item i, e_i is the energy per unit of food item i, E is the daily energy target to meet, n_{ij} is the amount of nutrient j per unit of food item i, m_j is the daily minimum required amount of nutrient j, and u_j is the daily maximum intake level of nutrient j.

The above constraints were first applied to all individual food items included in the linear programming model. Initial analyses using the above constraints led to the inclusion of multiple similar types of food items, such as several different types of bread roll, each being selected up to their allowed three servings (3× RACC) quantity in the resulting least-cost modelled food pattern. Such diets are impractical. To address this, some additional constraints as analogous to constraint (2) described above were applied to specific food groups, on the basis of the MyPlate guidelines (https://www.choosemyplate.gov/). Milk, milk substitutes, legumes, tomatoes, potatoes, vegetable oils and sugars were limited to no more than three servings per day per food group. Yeast-based breads (including bread rolls and buns), tortillas and rice were restricted to no more than two servings per day per food group. Margarine and vegetable spreads, peanut butter, mayonnaise and salad dressings were limited to no more than the recommended RACC once (1× RACC) per day per food group.

Foods. The United States Department of Agriculture What We Eat in America database was supplemented with data from the National Nutrient Database for Standard Reference 28, to provide a comprehensive list of foods and their nutrient contents[3]. A subset of foods was selected for the linear programming model that excluded mixed dishes and most composite foods and included most key foods, based on the 2011–2012 food consumption survey data from the United States Department of Agriculture National Health and Nutrition Examination Survey and that provide 75% of the nutrient intake of the total US population for selected nutrients of public health importance, as identified by Haytowitz et al.[40–42]. The 962 selected food items are commonly available and consumed in the United States. The nutrient composition of the 962 selected foods, given per 100 g of edible portions[3], was based on either raw or cooked foods and different methods of food storage (such as canned, frozen or dried). For each food item, daily intake serving sizes were based on the RACCs at one eating occasion[34]. The prices of the foods were those prevalent in the US market in 2009–2010, as given by the Center for Nutrition Policy and Promotion, and were the most up-to-date, reliable and comprehensive food prices available[4].

Energy and nutrient requirements. The daily requirements for energy and nutrients for a healthy American adult, aged between 19 and 50 years, were based on the recommendations reported by the Institute of Medicine of the National Academies (Table 1). The daily estimated energy requirement for a healthy 63.5-kg active young adult was given as 2,600 kcal, based on the average of the energy requirements for a low active and moderately active man aged 19 years, weighing 70 kg and being 1.77 m in height, and a low active and moderately active woman aged 19 years, weighing 57 kg and being 1.63 m in height[12,43]. Recommendations for daily nutrient intakes were given as either the RDA, which met the nutrient requirement of almost all (97.5%) healthy individuals, or adequate intakes, based on observed determined estimates of nutrient intake. The RDA for total available carbohydrates (sugars and starches) was 130 g d^{-1} based on the average minimum amount of glucose utilized by the brain[12]. The RDA value for protein was based on the reference equation of 0.8 g of protein per kg body weight per day and the reference body weight of 70 kg for a man and 57 kg for a woman[12,43]. Adequate intake values were used for total dietary fibre and the two polyunsaturated fatty acids required in the diet (namely, linoleic acid and α-linolenic acid)[12]. Daily nutrient requirement data for key minerals and vitamins[14,35–39] were also included (Table 1). The RDA for magnesium was given as the average intake level for an adult aged between 19 and 30 years, based on the recommended 400 mg for a man and 310 mg for a woman, respectively[35]. The RDA for vitamin A was presented as the retinol activity equivalent to account for the different bioactivities of retinol and carotenoids[38], while folate was reported as the dietary folate equivalent[36]. The daily recommended nutrient intakes for manganese, potassium, sodium, pantothenic acid, choline and vitamin K (phylloquinone) were given as adequate intakes[14,36,38]. Available maximum micronutrient intake levels[14,35–39] were also included as tolerable upper levels (Table 1).

Reporting Summary. Further information on research design is available in the Nature Research Reporting Summary linked to this article.

Data availability

All data used and generated during the current study are available from an online resource (https://gitlab.com/thetasolutionsllc/naturefood-19100372).

Code availability

The computer code required to reproduce the findings of this study is available from an online resource (https://gitlab.com/thetasolutionsllc/naturefood-19100372).

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Author contributions

S.M.S.C. and P.J.M. were responsible for the design and analysis of the study. D.P.G. was responsible for the linear programming modelling and analysis. A.D. was responsible for the provision of databases and consulting on the linear programming models. S.M.S.C. prepared the first draft of the manuscript. P.J.M revised the first draft of the manuscript. All authors participated in interpretation of the results and have read and approved the final manuscript.

Competing interests

The authors declare no competing interests.

Additional information

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