

Manuscript Title: The Role of Beef for the Lowest Cost and Adequate Provision of Bioavailable Nutrients in Modeled Diets at a Population Level in the United States

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Study Headline: When nutrient bioavailability and absorption of essential nutrients is factored into this diet modelling analysis (as compared to total nutrient amounts consumed), beef is included in the lowest-cost nutritionally adequate diets for nearly every US sub-population group. Further, beef is the lowest cost main contributor of bioavailable protein, vitamin B12, phosphorus, selenium and zinc.

Background: Sustainable food systems are described by four inter-related domains: environment, society, nutrition and affordability. No single food rates high in all four domains, therefore trade-offs among the domains need to be considered including the environmental impact, the value of societal acceptance, affordability, nutrient density and bioavailability. It has been suggested that shifts to replace animal-source foods with plant-based foods will better support sustainable healthy dietary patterns and improve its impact on the environment. This proposed shift disregards that animal-source foods often have higher amounts of certain essential nutrients and these essential nutrients are typically more bioavailable in animal source foods than in plant-source foods. Nutrient bioavailability refers to the amount a nutrient in a food is absorbed and utilized by the body. Factors such as food form or matrix and nutrient form can influence its absorption and bioavailability. In general, animal-source foods contribute nearly all dietary calcium, vitamin B12, and vitamin D, as well as nearly 60% of daily iron, zinc, niacin, and vitamin B6 requirements.

Diet cost is an important but often overlooked criterion for sustainable healthy diets. Previous research has shown that least-cost diet models that included animal-sourced foods were about 30-45% cheaper than those composed exclusively of plant-based foods.¹ Protein from plant-based foods, like tofu, edamame, and lentils, generally cost more on a per gram of protein basis than

¹ Chungchunlam SMS, Moughan PJ. Diet affordability: a key dimension in the assessment of sustainable food systems and healthy diets. Front Nutr. 2024 Aug 12;11:1399019. doi: 10.3389/fnut.2024.1399019.

animal-sourced proteins. For example, the EAT-Lancet diet that is suggested as a sustainable plant-forward dietary pattern has been reported to be unaffordable at a median global cost of \$2.84 per person per day for 24% of the world's population.² Additionally, the EAT-Lancet diet has also been found to be potentially inadequate for calcium, iron, zinc, and vitamin B-12.³

Beef is a commonly consumed nutrient-dense protein food in American diets that provides high-quality protein and bioavailable vitamins, heme iron, and zinc that can help support nutrient adequacy. The researchers aimed to determine how much beef is needed within a healthy dietary pattern, to meet nutrient requirements at the lowest cost.

Objective: This research analysis examines the respective roles of animal- and plant-source protein foods with a focus on beef in the modeling simulation of lowest-cost, most cost-effective, nutritionally adequate dietary patterns for different population groups in the United States (U.S.).

Study Design:

Dietary optimization models were developed using linear programming (LP) to assess lowest cost and most nutrient adequate diets at a population level in the U.S. The modeling took into account constraints based on serving sizes, estimated energy requirement, acceptable macronutrient distribution ranges (AMDR), minimum daily intake requirements (RDA or AI), and tolerable upper intake levels (UL).

LP is a commonly applied robust and sensitive mathematical tool used in the current study to estimate the minimum cost of dietary patterns that met the daily energy and nutrient requirements of different populations in the US. It is important to note that LP provides unique solutions for the least-cost nutritionally adequate and acceptable dietary patterns, that are not necessarily recommended or practical, but rather highlights the role of key food groups in assisting to meet nutrient needs at the lowest dietary cost. LP can simultaneously take into account commonly available foods, food serving sizes, energy and nutrient requirements, and food prices, to model unique solutions for mixtures of foods, at the lowest price possible.

The models used food and nutrient data from the USDA National Nutrient Database for Standard Reference Legacy (2018) supplemented by SR Release 28 (2016) which includes 1,977 foods across 27 main food groups. Most mixed dishes, ready meals, snacks, and beverages were excluded from the modeling analysis. Price data was derived from national mean U.S. retail food prices for June 2021, from the USDA Thrifty Food Plan 2021 supplementary datafiles.

Nutrient bioavailability estimates were reported for protein, folate, niacin, pantothenic acid, riboflavin, thiamin, vitamin A, vitamin B-6, vitamin B-12, vitamin C, vitamin D, vitamin E, vitamin K,

² Hirvonen K, Bai Y, Headey D, Masters WA. Affordability of the EAT-Lancet reference diet: a global analysis. *Lancet Glob Health*. 2020 Jan;8(1):e59-e66. doi: 10.1016/S2214-109X(19)30447-4.

³ Beal T, Ortenzi F, Fanzo J. Estimated micronutrient shortfalls of the EAT-Lancet planetary health diet. *Lancet Planet Health*. 2023 Mar;7(3):e233-e237. doi: 10.1016/S2542-5196(23)00006-2.

iron, and zinc, from specified food sources. True ileal protein digestibility data from FAO and Riddet Institute datasets (beef 98.1%, beef protein digestibility among the highest of the food groups); vitamin bioavailability factors from a prior [Chungchunlam & Moughan review](#)),⁴ iron and zinc bioavailability from published absorption studies (animal foods: 19.5% iron, 30.0% zinc; plant foods: 7.4% iron, 15.0% zinc). These are presented in Table 1 of publication.

The mean values for the daily caloric (2350 kcal) and nutrients needed for male and female adults aged 19 to 50 y were used to represent the general U.S. adult population. Ten specific subpopulations were modeled of varying age/sex: children aged 1 to 3 y; children aged 4 to 8 y; male children aged 9 to 13 y; male adolescents aged 14 to 18 y; male adults aged 19 to 50 y; male adults aged >50 y; female children aged 9 to 13 y; female adolescents aged 14 to 18 y; female adults aged 19 to 50 y; and female adults aged >50 y. These are presented in Table 2 of publication.

Two lowest-cost nutrient adequate diet scenarios were modeled: Total nutrient diets and Bioavailable nutrient diets. The total nutrient diets are modeled when nutrient contents in foods were given as total gross dietary amounts. The bioavailable nutrient diets are modeled when nutrient contents in foods were given as bioavailable amounts.

Key Findings:

Beef is nutrient-dense food, providing high quality protein and bioavailable vitamins and minerals, most notably iron and zinc, to help meet nutrient requirements at the lowest cost.

Animal-source foods, such as beef liver, milk, eggs, and fish were necessary in diet formulations that met energy and nutrient requirements at the lowest cost, when nutrient contents in foods were calculated on a total basis (i.e., total nutrient amounts, not bioavailable amounts). However, when nutrient contents in foods were calculated in bioavailable units, more animal-source foods, particularly beef, were included in the modelled lowest-cost, nutritionally adequate dietary patterns, for the lowest cost provision of bioavailable protein, vitamin A and zinc.

When the bioavailability of nutrients was taken into consideration, daily diet cost increased by 24-89% and led to the selection of more animal-source foods, particularly beef, to supply key essential nutrients to meet requirements. For instance, based on 2 allowable servings of foods per day, the least-cost dietary pattern that met the energy and nutrient requirements of the average US adult, on a total dietary nutrient basis, had a retail daily cost of \$1.14 (per kg of diet), as compared to a cost of \$5.94 when the least-cost dietary pattern used bioavailable nutrient contents. This cost discrepancy underscores the importance of accounting for the bioavailability and absorption of nutrients, to achieve both nutritional adequacy and diet affordability.

⁴ Chungchunlam SMS, Moughan PJ. Comparative bioavailability of vitamins in human foods sourced from animals and plants. Crit Rev Food Sci Nutr. 2024 Nov;64(31):11590-11625. doi: 10.1080/10408398.2023.2241541.

When nutrient bioavailability was considered, it was challenging to achieve least-cost nutritionally adequate dietary patterns for children, non-pregnant and pregnant girls and non-pregnant and pregnant women. These findings suggest that nutrient bioavailability is a critical factor for least-cost nutritionally adequate diet formulations, particularly for these most vulnerable subpopulations.

This modelling study found that beef was the greatest contributor to bioavailable protein, vitamin B12, phosphorus, selenium and zinc and has an advantageous place in ensuring adequate, bioavailable nutrient provision at the lowest cost.

Study Implications:

- The inclusion of beef in a healthy balanced diet is an affordable way to meet nutrient requirements.
- This modeling analysis on lowest-cost nutrient adequate diets shows that animal-source foods are affordable and necessary for adequate provision of key essential nutrients.
- Taking into account nutrient density and nutrient bioavailability and absorption of nutrients from foods is an integral part of formulating least-cost, nutritionally adequate diets. This modeling analysis can provide justification to include animal source foods to attain affordable nutrient adequate diets for Americans.
- The authors report that vitamins and minerals are the main limiting nutrient factors, and the inclusion of animal-source foods in these least-cost models reflect their high nutrient density and particularly high concentration of bioavailable protein and amino acids, bioavailable vitamins and minerals, most notably, bioavailable iron and zinc.

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