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Reducing ultra-processed foods and increasing diet quality in affordable and culturally acceptable diets: a study case from Brazil using linear programming

Eliseu Verly-Jr[1]*, Alessandra da Silva Pereira[2], Emanuele Souza Marques[1], Paula Martins Horta[3], Daniela Silva Canella[4] and Diana Barbosa Cunha[1]

[1]*Department of Epidemiology, Institute of Social Medicine, Rio de Janeiro State University, Rio de Janeiro, 20550-013, Brazil*
[2]*Department of Fundamental Nutrition, Nutrition School, Federal University of the State of Rio de Janeiro, Rio de Janeiro, 22290-240, Brazil*
[3]*Department of Nutrition, Nursing School, Federal University of Minas Gerais, Belo Horizonte, 30130-100, Brazil*
[4]*Department of Applied Nutrition, Institute of Nutrition, Rio de Janeiro State University, Rio de Janeiro, 20550-013, Brazil*

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Abstract

The aim was to design culturally acceptable and healthy diets with reduced energetic share of ultra-processed foods (UPF%) at no cost increment and to evaluate the impact of the change in the UPF% on diet quality. Food consumption and price data were obtained from the Household Budget Survey (*n* 55 970 households) and National Dietary Survey (*n* 32 749 individuals). Linear programming models were performed to design diets in which the mean population UPF% was reduced up to 5 % with no cost increment relative to the observed costs. The models were iso-energetic or allowed the energy content to vary according to the UPF%, and they were not constrained to nutritional goals (nutrient-free models) or maximised the compliance with dietary recommendations (nutrient-constrained models). Constraints regarding food preference were introduced in the models to obtain culturally acceptable diets. The mean population UPF% was 23·8 %. The lowest UPF% attained was approximately 10 %. The optimised diet cost was up to 20 % cheaper than the observed cost, depending on the model and the income level. In the optimised diets, the reduction in the UPF% was followed by an increase in fruits, vegetables, beans, tubers, dairy products, nuts, fibre, K, Mg, vitamin A and vitamin C in the nutrient-constrained models, compared with the observed consumption in the population. There was little variation in most nutrients across the UPF% reduction. The UPF% reduction in the nutrient-free models impacted only *trans*-fat and added sugar content. UPF% reduction and increase in diet quality are possible at no cost increment.

Key words: Ultra-processed foods: Diet cost: Linear programming: Food systems

Ultra-processed foods (UPF) are defined as industrial formulations that result from a series of industrial processes, and the ingredients often include sugar, oils, fats and salt, generally in combination, in addition to substances such as flavours, colours, emulsifiers and sweeteners[1]. This nutritionally unbalanced composition is one of the reasons why excessive consumption of UPF has been associated with obesity[2–4], hypertension[5] and some types of cancer[6]. The importance of adopting a diet with a reduced content of the UPF is explicitly recognised in the Brazilian Dietary Guidelines[7].

There are many determinants of dietary intake, such as individual, cultural, social, economic and environmental factors. Socio-economic status is one of the most important food consumption determinants, and the cost of food is a recommended indicator of food affordability in a country[8]. Although studies conducted in high-income countries have shown that foods of lower nutritional value and lower-quality diets generally cost less per kJ[9], in Brazil, UPF are still more expensive in comparison with unprocessed or minimally processed foods and processed culinary ingredients[10]. However, relative prices of UPF have been decreasing over the past 30 years as compared with other food items in the Brazilian diet[11]. This might be one reason for the observed increase in household acquisition of UPF from 20·8 % in 2003 to 25·4 % in 2009[12].

Moreover, the relatively low prices of UPF, as compared with that of unprocessed or minimally processed foods, refer to the mean price per unit energy over the foods within each group. While the mean estimated UPF price in Brazil was BRL (Brazilian Reals) 0·57/1000 kJ (equivalent to US$ 0·24), the mean price of unprocessed or minimally processed foods was BRL

Abbreviations: FV, fruits and vegetables; GES, geographic-economic strata; HBS, Household Budget Survey; NDS, National Dietary Survey; UPF, ultra-processed food.

* **Corresponding author:** Eliseu Verly-Jr, email eliseujunior@gmail.com

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0·37/1000 kJ (US$ 0·16). A decrease in UPF in the diet must be accompanied by an increase in foods required for a healthy diet, such as fruits, vegetables, fish and milk. However, the mean prices of these foods were BRL 0·99/1000 kJ (US$ 0·43), BRL 2·47/1000 kJ (US$ 1·07), BRL 2·02/1000 kJ (US$ 0·87) and BRL 0·60/1000 kJ (US$ 0·26), respectively[13]. Moreover, reducing UPF items in the diet implies the substitution with other foods, which is, at least in part, determined by the household budget and local food preferences; thus, 'healthy substitution' may not be affordable or acceptable. The adoption of a healthy and UPF-reduced diet, therefore, can be challenging unless it does not lead to an increase in the food budget, especially in the low-income groups, and takes into account the cultural aspect of the diet. Thus, an interesting research question is how can diet quality be improved and the UPF energetic share reduced at no cost increment?

This question can be answered through the use of the data optimisation technique. Linear programming models have been utilised to identify dietary changes required to achieve a desirable diet composition (foods and nutrients) while satisfying other constraints, such as local food preferences, portion sizes, cost and environmental impact[14]. It also can be useful to evaluate the feasibility of diets with multiple constraints, particularly a defined UPF energetic share, no cost increment relative to the observed diet cost and some nutritional goals, such as those established to prevent obesity and chronic diseases.

Therefore, the objectives of this study are (i) to design healthy diets with reduced UPF energetic share at no cost increment that most resemble the current food consumption and (ii) to evaluate the impact of the UPF energetic share reduction on the food and its nutrient contents.

Methods

In this study, we optimised diet changes using linear programming models, which are defined by an objective function that is optimised while considering a set of decision variables restricted by various constraints[14]. In this study, the decision variables were the foods reported by the population, and the constraints were the reduction in the mean population UPF energetic share and compliance with nutritional recommendations. Constraints limiting the food quantities according to the variation observed in the population (referred to as acceptability constraints) were also introduced in the models. Moreover, the objective function minimised the deviation between the optimised and observed food quantities to preserve, as much as possible, the cultural aspects of the diets.

Source of data

We used data from two nationwide representative samples of the Brazilian population: the National Dietary Survey (NDS) that collected information on individual food consumption and the Household Budget Survey (HBS) that collected information on household food purchases. Both surveys were conducted between 2008 and 2009 by the Brazilian Institute for Geography and Statistics and used a two-stage sampling process. In the first stage, census tracts were randomly selected, and, in the second stage, households were randomly selected from the census tracts. The NDS simultaneously collected information from a random subsample of about 25 % of the HBS.

Census tracts (*n* 12 800) were grouped into 550 household strata with geographical and socio-economic homogeneity, and the number of tracts in each stratum was proportional to the number of households in the stratum. The samples included 55 970 households (HBS) and 13 569 households (NDS). Household visits in each stratum were uniformly distributed throughout the 12 months to encompass seasonal variations in both food intake and prices. More information on the surveys and data collection can be found elsewhere[15].

Unit of analysis

Due to the large heterogeneity in the food patterns and prices throughout the macro- and micro-regions of the country, the modelled diets were designed separately for several geographically delineated sampling strata. The 550 household strata were collapsed into 26 Brazilian states and one federal district and further stratified into income level according to the *per capita* income: ≤0·5 official minimum wage (MW), >0·5 and ≤1·5 MW, >1·5 and ≤3 MW, and >3 of MW (MW: BRL415·00 equivalent to US$179·65 in January 2009), totalling 108 aggregated strata (named geographic-income strata, or geographic-economic strata (GES)). This rearrangement was adopted to improve the precision of the estimates by increasing the number of households in each unit of analysis. Due to the long period of data collection, official inflation rates (National Consumers' Prices Index) were used to adjust family income to the same reference date (31 January 2009) to allow comparability among households visited several months apart.

Model inputs

Food consumption. Dietary intake based on the NDS was obtained from the mean of two non-consecutive food records completed by 32 746 individuals ≥10 years old (pregnant and breast-feeding women excluded; *n* 1254). Participants reported the consumption of 1103 foods, from which we excluded non-nutrient and energy source foods such as coffee and tea (without sugar) and alcoholic beverages. Food subtypes, such as different types of the same food, different cooking methods or different beef cuts were grouped into a single food item (for instance, different types of cakes into 'cakes', different beef cuts into 'beef'). The final list comprised 102 food items, varying from 44 to 98 according to the GES. A Brazilian food composition database[16] was used to obtain nutrient content in both observed and optimised diets. The nutrient composition of foods clustered from food subtypes (e.g. different types of rice into 'rice') was obtained as the mean composition of the food subtypes or different cooking methods weighted by the frequency of reporting in the NDS. The diets consumed in each GES, namely the GES-specific food repertoire, were used as a starting point for the optimised diets derived from in the linear programming models.

Food prices. Prices were extracted from the HBS database, where each household registered the amount and cost of each food product purchased, and further converted into cost per 100 g of edible portion. Food prices were obtained as the mean price over the food subtypes (e.g. different types of oranges into 'orange'), weighted by the frequency of reporting in the HBS. Prices were matched to the corresponding food items reported in the NDS according to the GES, which preserved the price variation over the GES. Considering the variation in food prices throughout the collection, all prices were deflated to the same reference date (31 January 2009), using official inflation rates. Overall mean diet cost, that is the mean cost over the 108 GES, is referred to as 'mean observed cost'.

Models constraints

Acceptability food constraints. These were boundaries to which the optimised food quantities may deviate from the observed mean intake to avoid the optimised diets being culturally or socially unacceptable. Acceptability constraints may include lower and upper values, that is, the lowest and highest amounts of a given food allowed in the models. Initially, we introduced boundaries in the models, allowing optimised food quantities to vary progressively, more and less, from the observed mean intake of each food item per every 5 g, until a feasible solution was found for each GES. This was done by performing n models for each GES, imposing lower (lb) and upper boundaries (ub) that consist of $[m_{f,g} - d]$ and $[m_{f,g} + d]$, respectively, where $m_{f,g}$ is the mean quantity of the food item f observed in a given GES g, and $d = (5, 10, 15, \ldots, n)$ is the allowed deviation from the observed amount reported for each food item f. The constraints for the food item f were, however, censored to the GES-specific current 10th and 90th percentiles of intake. The percentiles for each food were estimated for each region of the country (North, Northeast, Southeast, South and Centre-West) and applied to all GES within each region. First, we obtained the mean food intake in each stratum (from all 550 strata in the full sample), and then, for each region separately, we obtained the distribution of the mean food intake, excluding strata in which the food of interest had not been reported. From each region-specific distribution, we obtained the 10th and 90th percentiles.

Acceptability food group constraints. Additional constraints were imposed on quantities from each food group. In each GES model, food group quantities were not allowed to be higher than the mean quantity for each food group on a consumption day.

Dietary constraints. Reference dietary values for the prevention of chronic disease were obtained from WHO reports, as described in Table 1. In addition, with the use of the NOVA classification system, the foods were grouped according to the extent and purpose of industrial processing; the food items were classified as (1) UPF, the group of interest in this study; and (2) non-UPF, including unprocessed or minimally processed foods, culinary ingredients and processed foods[1]. The amount of the food items (in g) that composed each NOVA group was converted into energy and the percentage of energy (% of the total dietary energy) derived from UPF was calculated for each GES.

Constraints were progressively introduced into the models, for each GES, to progressively reduce, by steps of 5 %, the UPF energetic share from 25 to 5 %. Since the purpose of this analysis was to reduce the UPF energetic share, a model was performed for a GES when its UPF percentage was higher than the targeted reduction. For example, if the UPF energetic share in a given GES was 28 %, it was constrained to 25 %, then 20 %, then 15 %, then 10 % and finally 5 %. When the UPF was, for instance, 18 %, the targets were 15 %, then 10 %, and finally 5 %. We reduced the mean population of the UPF energetic share by first reducing those in GES with high UPF%; in the ones in which the UPF% was already low, no diet modification was conducted.

We tested two sets of models for the energy content: (1) the isoenergetic model: the energy content in the optimised diets was constrained to equal to the observed energy intake in each GES and (2) the UPF-energetic model: the energy content in the optimised diets was allowed to vary according to the UPF energetic share. The second set of models accounted for the correlation between energetic intake and UPF energetic share as shown in observational studies[17–19], as well as in a recent randomised clinical trial[20]. The relationship between the UPF and total energy intake was assessed with the data of 32 746 individuals from the NDS dataset. We performed a linear regression model in which the total energy intake was the outcome variable and the UPF energetic share was the explanatory variable, adjusted by household income, age and sex. The adjusted coefficient was 146·4 kJ increase in the mean energy intake for a 5 % increase in the UPF energetic share ($P < 0{\cdot}05$). The energy intake was predicted for each GES at 25 to 5 % UPF energetic share, by steps of 5 %, given the mean income and age, and the prevalence of males in the GES.

Cost constraints. The optimised diet cost was constrained to not exceed the observed diet cost.

Objective function. Linear programming models were developed to obtain optimised diets with no cost increment, in addition to satisfying two terms in the objective function, according to the model:

(i) Nutrient-free models: both isoenergetic and UPF-energetic models were constrained to energy content and progressive reduction of the UPF energetic share. The object function 1 minimised the difference, in g, between the optimised and observed food quantities.

(ii) Nutrient-constrained models: both isoenergetic and UPF-energetic models were constrained to energy content, progressive reduction of the UPF energetic share and dietary recommendations as described in Table 1. The object function 2, in addition to minimising the difference between the optimised and observed food quantities, minimised the deviation from the dietary targets. This term refers to the difference between the nutritional constraint and the optimised content of a limiting component, that is, components whose constraint cannot be mathematically attained. For example, for a healthy component (for instance, fruits

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Table 1. Dietary constraints imposed in the models*

Component	Constraint
Energy	Observed intake (kJ) (isoenergetic model) Predicted energy intake† (UPF-energetic model)
Proteins	10–35 % energy‡
Carbohydrates	45–65 % energy‡
Total fats	20–35 % energy‡
Saturated fat	<10 % energy‡
MUFA	By difference‡§
PUFA	6–10 % energy‡
Trans-fat	< 1 % energy‡
Added sugar	<10 % energy‡
Na	≤ 2300 mg‖
K	≥ 3510 mg**
Ca	≥ 500 mg‡
Fruits and vegetables	≥ 400 g‡
Fish	≥ 43 g‡¶
UPF	Progressive reduction by steps of 5 % from the observed UPF energetic share

UPF, ultra-processed foods.
* Nutritional constraints introduced only in the nutrient-constrained models.
† See Methods section.
‡ WHO[21].
§ Not constrained in the models.
‖ WHO[22].
¶ From the recommendation of two portions/week: (150 g × 2)/7 = 43 g.
** WHO[23].

and vegetables (FV)) with a constraint of 400 g, an undesirable negative deviation of 100 g refers to an optimised diet containing only 300 g instead of 400 g. Similarly, for harmful components, such as *trans*-fat with a target of 2 g, an undesirable positive deviation of 0·5 g refers to an optimised diet having 2·5 g instead. The deviation for a given dietary component represented the least optimised difference between the constraint and solution when the constraint could not be attained. A standardised factor, that is, the proportional difference between the constraint and the actual nutrient content in relation to the constraint, was included in the optimisation model.

The objective functions were as follows:

$$\text{Minimise } Y = \sum_{i=1}^{i=g} \left| \frac{Q_i^{opt} - Q_i^{obs}}{Q_i^{obs}} \right| \quad \text{objective function 1}$$

$$\text{Minimise } Y = \sum_{i=1}^{i=g} \left| \frac{Q_i^{opt} - Q_i^{obs}}{Q_i^{obs}} \right| + \sum_{n=1}^{n=D} \left| \frac{nut_n^{opt} - nut_n^{cons}}{nut_n^{cons}} \right| \quad \text{objective function 2}$$

where Y represents the objective function to be minimised, Q_i^{opt} is the quantity of the food item i in the optimised diet, g is the total number of food items, Q_i^{obs} is the mean quantity of i in the observed diet, nut_n^{cons} is the constraint and nut_n^{opt} is the optimised amount of the dietary component n (nutrient, FV and fish). This is a non-linear function due to the use of the absolute function that was then linearised to include a set of linear constraints, following a similar procedure to that described in Darmon *et al.*[24].

Linear programming models were performed using the Optmodel Procedure in the SAS OnDemand software.

Descriptive analysis

Results were expressed as the mean optimised quantities over all the GES for the nutrients and foods, grouped as follows: beans (beans, legumes); dairy products (whole and non-fat milk, cheese, yogurt and other dairy products); FV; meats and eggs (red, processed, and white meats, fish, seafood, and eggs); nuts; oils (butter, margarine and olive); refined cereals (bread, cookies, cakes and pasta); white and brown rice; sauces (salad dressing and processed pasta sauces); sugar-sweetened beverages (SSB; soda, industrialised juices and nectars); ready-to-eat foods (pizza, sandwiches, savoury snacks and sweets); tubers (potato, cassava and yam). The full description of the food groups is presented on the online Supplementary material. Food group quantities in the optimised and observed diets were plotted against the UPF energetic share, where the highest value was the mean UPF energetic share observed in the population. The mean optimised and observed diet cost, the observed UPF energetic share, and energy intake were obtained for the sample and stratified by income levels. All the descriptive analyses were weighted by the sampling weights.

Ethics

The protocol of this research was approved by the Ethics Committee of the Instituto de Medicina Social of the Universidade do Estado do Rio de Janeiro (CAAE 0011.0.259.000-11), 19 July 2011.

Results

Table 2 presents the mean observed energy content, UPF energetic share and the diet cost for the population, stratified by income level. The mean population UPF energetic share was 23·8 %, and it was approximately twice as much in the highest

Table 2. Mean energy intake, diet cost and ultra-processed food (UPF) energetic share; Brazil and income levels, 2008–2009 (*n* 108 GES)

	Energy (kJ)	Cost (US$)	UPF energetic share (%)
Income levels			
<0·5 MW	7342	1·83	16·3
0·5–1·5 MW	7882	2·03	21·5
1·5–3 MW	8309	2·29	26·2
>3 MW	8610	2·60	30·3
Total	8066	2·19	23·8

GES, geographic-economic strata; MW, minimum wage (BRL415·00 equivalent to US$179·65 in January 2009).

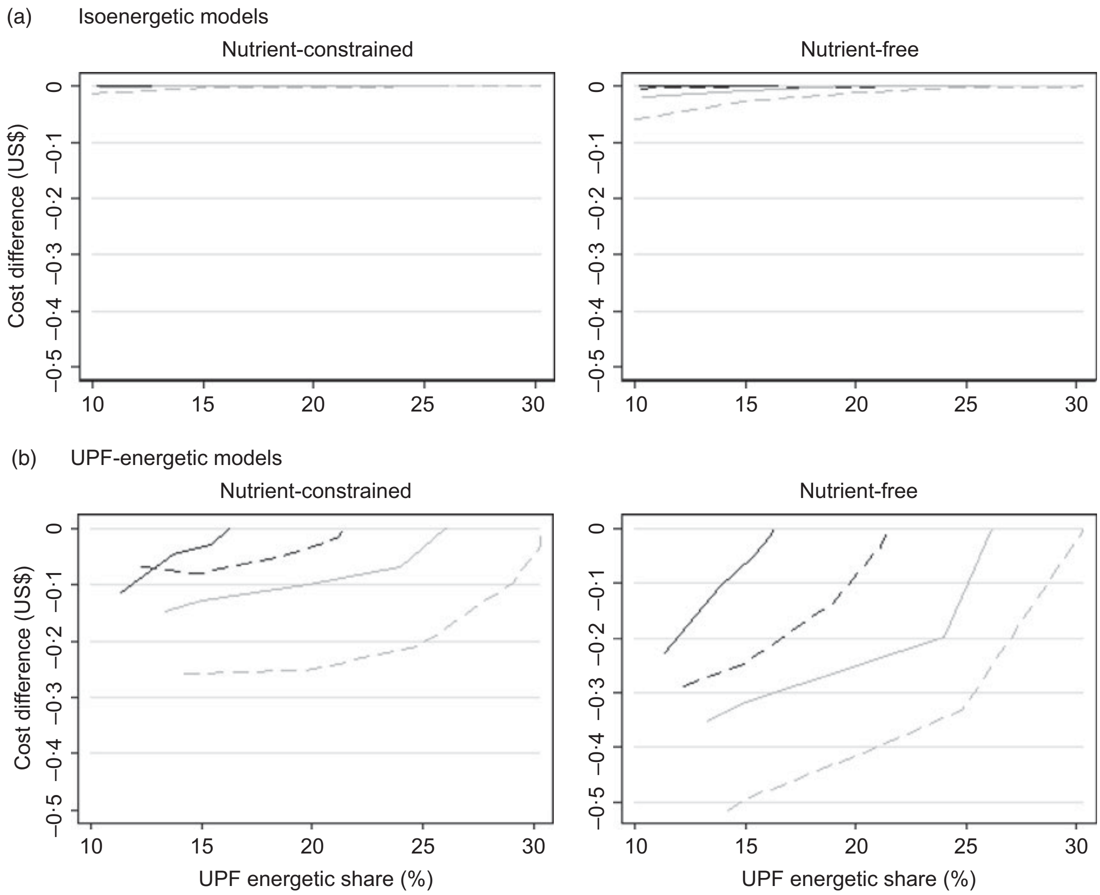

Fig. 1. Cost difference (i.e optimised cost – observed cost; US$) across the ultra-processed food (UPF) energetic share and according to the model. Brazil, 2008–2009. MW, *per capita* minimum wage (US$179·65). ——, <0·5 MW; - - - -, 0·5–1·5 MW; ——, 1·5–3 MW; - - - -, >3 MW.

(30·3 %) as opposed to the lowest (16·3 %) income group. Diet cost and energy intake also increased with income level.

There were no feasible solutions (i.e. mathematically impossible to attain all constraints in the models) for most GES when the UPF energetic share was set to 5 %; when set to 10 %, there were few GES with unfeasible solutions. Therefore, 10 % was the lowest UPF energetic share considered. On average, the lowest attainable UPF energetic share was 10·2 % (isoenergetic models) and 12·8 % (UPF-energetic models).

The cost difference (optimised minus observed) was close to zero in the isoenergetic models. In the UPF-energetic models, there was a decrease in the diet cost in all income levels, more marked in the nutrient-free UPF-energetic models that varied, on average, from US$ −0·06 in the lowest income to US$ −0·54 in the highest income level (3 and 20 % reduction, respectively) (Fig. 1).

Nutrient-constrained models

Fig. 2 shows the variation in food quantities, while the mean population UPF energetic share is reduced. In the isoenergetic optimised diets, the lower the UPF energetic share, the higher

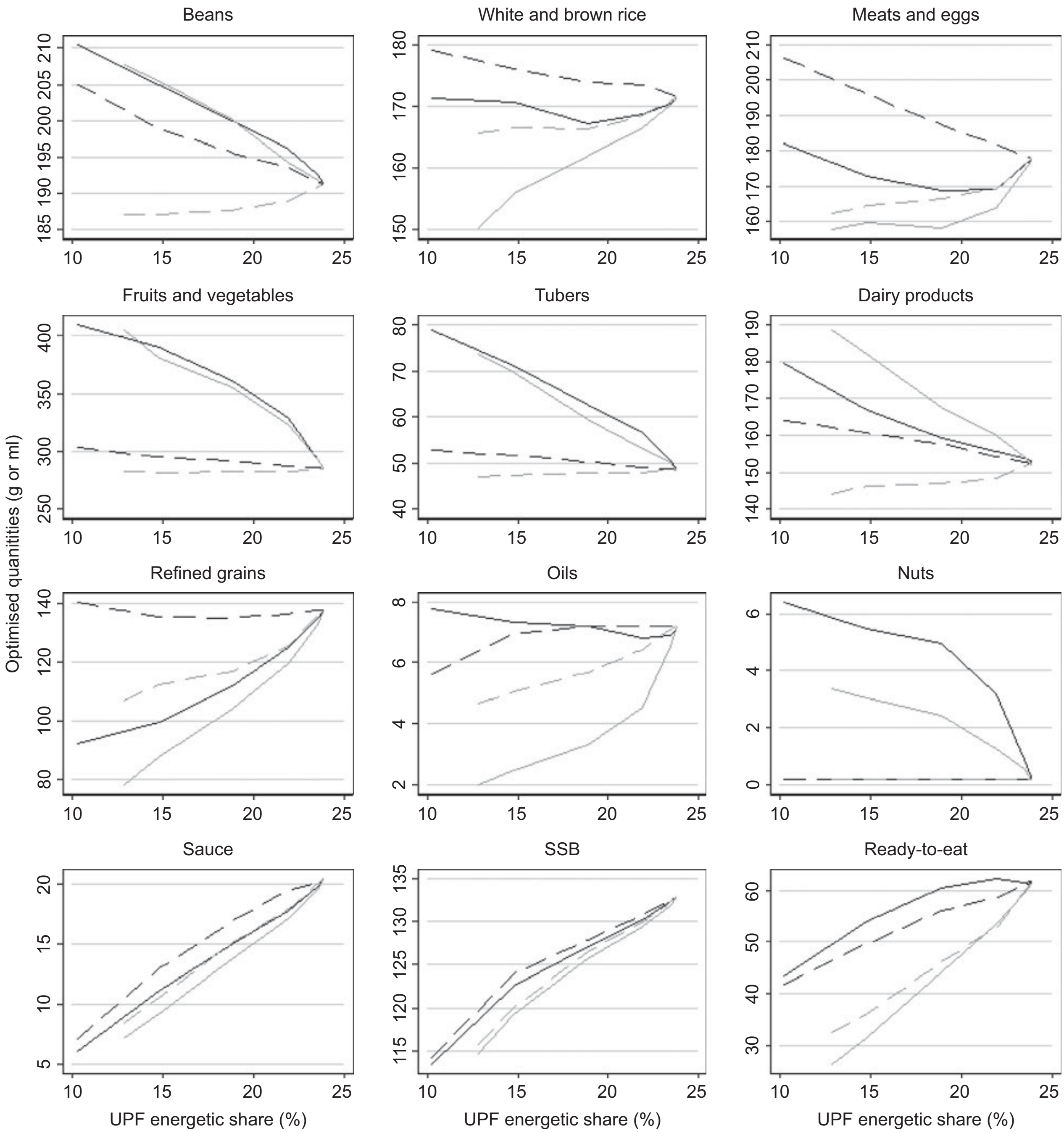

Fig. 2. Variation in the mean food group quantities in the optimised diets across the ultra-processed food (UPF) energetic share. Brazil, 2008–2009. ——, Isoenergetic nutrient-constrained models; - - - -, isoenergetic nutrient-free models; ——, UPF-energetic nutrient-constrained models; - - - -, UPF-energetic nutrient-free models. SSB, sugar-sweetened beverages.

the achieved quantities of FV (409 g in the lowest optimised UPF energetic share *v.* 285 g in the observed diets), beans (210 g *v.* 191 g), tubers (79 g *v.* 48 g), dairy products (180 g *v.* 152 g) and nuts (6 g *v.* 0·2 g). SSB (113 ml *v.* 132 ml), refined cereals (92 g *v.* 138 g), ready-to-eat foods (43 g *v.* 61 g) and sauces (6 g *v.* 20 g) were higher as the UPF energetic share increased (Fig. 2). In general, the curves of the UPF-energetic models were similar to those found in the isoenergetic models, but with disparities in the lower or upper percentages, as observed in most food groups. The exceptions were for the white and brown rice and oils content, which were stable compared with the observed consumption in the isoenergetic model and decreased in the UPF-energetic model as the UPF energetic share reduced.

Nutrient-free models

The variations in the quantities of beans, rice, meats and eggs, and dairy products went in opposite directions with the UPF reduction; these increased in the isoenergetic models and decreased in the UPF-energetic models. Refined grains

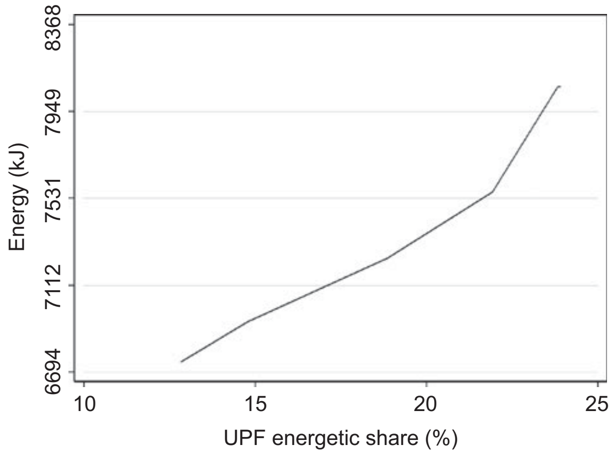

Fig. 3. Variation in the mean energy content in the optimised diets across the ultra-processed food (UPF) energetic share, UPF-energetic models. Brazil, 2008–2009.

decreased only in the UPF-energetic models. There was a reduction in the sauces, SSB and ready-to-eat foods across all models.

Energy and nutrient content in the optimised diets

The mean energy content across the UPF reduction in the optimised diets from the UPF-energetic models are presented in Fig. 3. Most nutrients in the optimised diets were stable or showed little variation across the UPF energetic share in all models. The content of fibre, K, Mg, vitamin A and vitamin C increased with the reduction of the UPF energetic share in the nutrient-constrained models. Fibre and Mg content decreased in the nutrient-free UPF-energetic models. Vitamin A was reduced in all the nutrient-free models and vitamin B_6 was reduced in all models. Added sugar and *trans*-fat content was reduced in all models. The *trans*-fat content in the mean observed UPF energetic share was approximately twice the amount of the lowest UPF energetic share. There were no marked variations in other assessed nutrients: macronutrients, mono- and polyunsaturated fats, Ca, P, Cu, Fe, Mn, niacin, vitamins B_1 and B_2, and folate. The variations of the selected nutrients (the ones with marked variation across UPF energetic share) are shown in Fig. 4. None of the optimised diets, regardless of the percentage of UPF energetic share, was adequate regarding Na and K content. However, a Na:K ratio lower than 1 was attained when the UPF energetic share was up to 20 %.

Discussion

With linear programming, we showed that it is possible to reduce the UPF energetic share without increases in the cost of the diet, which leads to an increase in diet quality. However, a further increase in diet quality can be achieved, also at no cost increment, when the UPF items are replaced by foods that comply with other nutritional goals. These results support the current Brazilian Dietary Guidelines and the FAO's recent report[25], in which the reduction of the UPF is one strategy to improve diet quality and promote health.

A previous study showed that the ready-to-eat products (processed and UPF) cost 52 % more than the average cost of other foods items in Brazil. This could explain why the consumption of UPF in Brazil is lower than in high-income countries. For example, in the UK, where the ready-to-eat products cost 13 % less than the average of other foods, the energetic share of UPF is approximately 60 %[26]. In this context, some studies have already suggested that diets composed mainly of unprocessed or minimally processed foods cost less than diets with high UPF energetic shares. These studies, however, compared the average price per kJ of the foods purchased according to the NOVA classification and did not consider individual food consumption[13,26]. In our analysis, we went further by (i) assessing away-from-home food consumption; (ii) considering the heterogeneity in the food habits, food price and diet cost across the country; (iii) assessing the feasibility of a wide reduction of UPF energetic share at no cost increment and (iv) evaluating how these changes could be consistent with international dietary recommendations to prevent chronic diseases. In doing so, we demonstrated that not only reducing the UPF energetic share but also increasing the overall diet quality is feasible at no additional cost.

The results obtained from the nutrient-free models indicate that food choices only concerning the reduction of UPF and with the least deviation from current food consumption patterns led to an increase in diet quality regarding only a few components, such as added sugar and a remarkable reduction in *trans*-fat. This means that the reduction in UPF energetic share in the diet by itself would have little impact on other dietary components, unless other diet changes are also considered. In this set of models, the reduction in the UPF was replaced mainly by an increase in beans, rice, meat, eggs and dairy products. Once our models minimised the difference, in g, between the optimised and observed food quantities, the energy-dense foods, such as those aforementioned, provide energy to compensate for the reduction in the energy from UPF at the lowest deviation from the current diets; that is why the quantities of less energy-dense foods, such as FV, were kept relatively stable across the UPF reduction. Although individuals' food choices are not based on this calculation, this set of models might be extremely informative when dietary counselling is restricted to 'avoid UPF'. Of note, the current UPF energetic share in the population is approximately 24 %, considerably lower than what has been observed in other countries, such as in the UK (60 %)[27], Canada (48 %)[28] and the USA (58 %)[29]. Perhaps the impact on diet quality of such UPF reduction in these countries would be more relevant. Moreover, the restriction of UPF could be insufficient to predict micronutrient consumption in a context of low consumption of FV and little variety related to these items[30]. Another scenario is that, when someone is willing to reduce the UPF in the diet, he/she is also open to other diet modifications, such as increasing FV consumption, limiting red meat intake and giving preference to whole cereals instead of refined grains, meaning that the concern regarding the UPF in the diet is part of a behaviour change towards overall healthier choices. However, despite this willingness, healthier food choices may be hampered by local food preferences in addition to the food budget. We attempted to reproduce this scenario by performing the nutrient-constrained

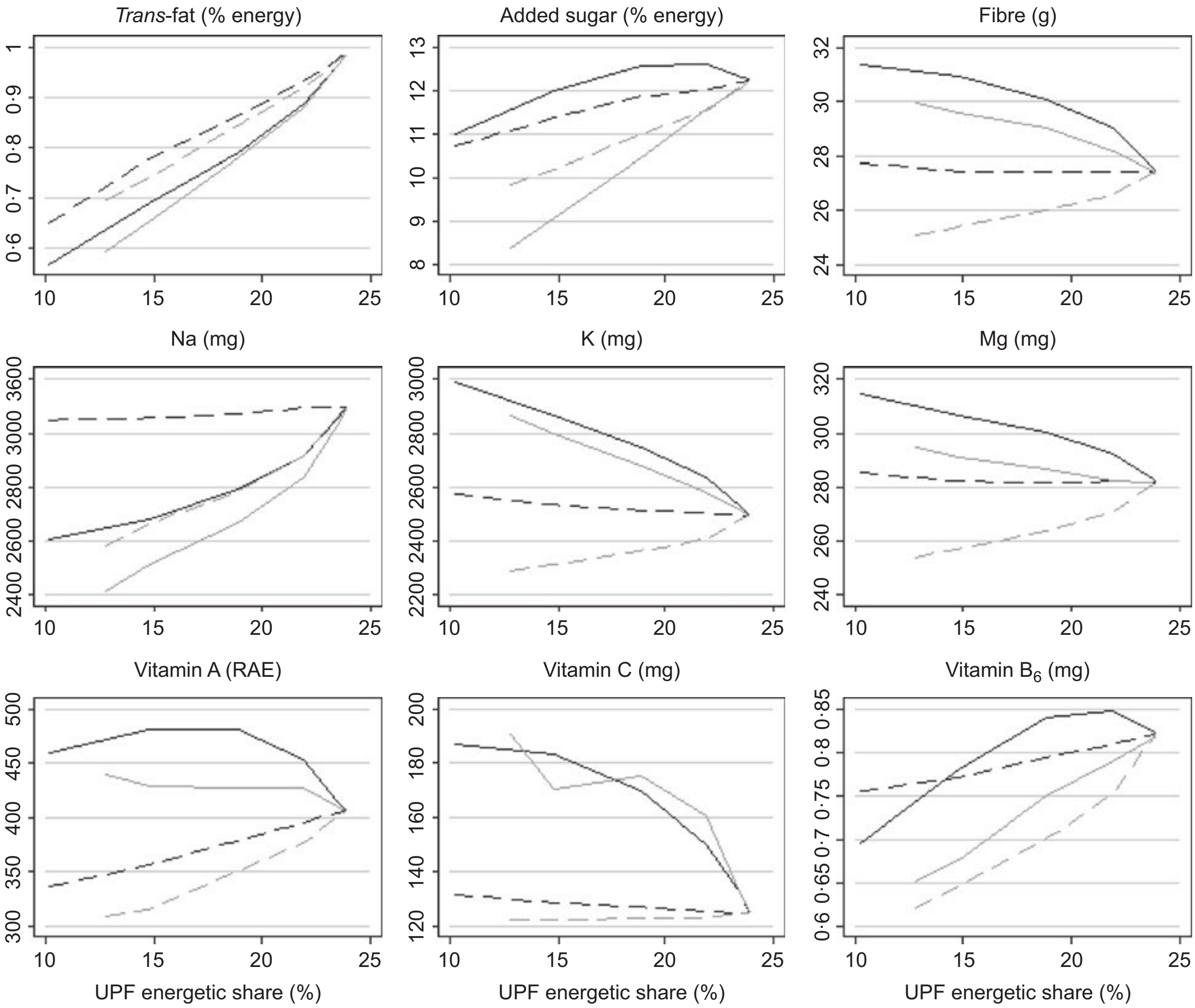

Fig. 4. Variation in the mean content of selected nutrients in the optimised diets across the ultra-processed food (UPF) energetic share. Brazil, 2008–2009. RAE, retinol activity equivalent. ——, Isoenergetic nutrient-constrained models; - - - -, isoenergetic nutrient-free models; ——, UPF-energetic nutrient-constrained models; - - - -, UPF-energetic nutrient-free models.

models, where other nutritional goals were imposed in the models while still maintaining the economic and social dimensions of the diets. When the reduction of UPF occurred simultaneously with compliance, as much as possible, to other nutritional goals, there was an additional gain in diet quality, still at no cost increment. In this set of models, the reduction in the UPF was replaced mainly by an increase in FV and tubers (in addition to a reduction in the refined grains). The implication of these results for public practice is that dietary counselling should explicitly address health and affordable choices that could replace the UPF, which is emphasised in the new Brazilian Dietary Guidelines.

The total energy in the optimised diets was constrained in two different perspectives in our models. The first, the isoenergetic model, assumes that people would maintain their energy intake regardless of the level of UPF energetic share. This implies that the energy content from UPF are replaced by other foods, according to the acceptability food constraints introduced in the models. The second, the UPF-energetic model, assumes that part of the energy content from the UPF will not be compensated for by the consumption of other foods, which is in line with the proposed mechanism that the intrinsic characteristics of UPF promote overconsumption. Therefore, people are expected to reduce their energy intake while reducing UPF consumption. Recently, a randomised controlled trial added evidence to this hypothesis[20]. Hall *et al.*[20] investigated whether UPF impacted energy intake. Adults participants were randomised to receive consume either UPF or unprocessed diets for 2 weeks *ad libitum*; the mean energy intake was higher with the UPF diets by 2125 kJ/d. The results from the UPF-energetic models also emphasise the importance of considering what foods should replace the UPF. The reduction in energy intake usually leads to a reduction in nutrient intake, as it did with vitamin B_6 in our study; thus, the choice of nutrient-dense foods is a key point when reducing UPF in diets.

The amount of some nutrients and dietary components related to chronic disease in the optimised diets varied with the reduction in the UPF energetic share. Except for Na and K, all nutritional constraints were met in the lowest UPF energetic share. The results for Na, however, should be interpreted in the light of potential bias in the estimate of Na intake since we did not have a reliable measure of added salt (table and culinary salt). Given the expected underestimation of dietary Na intake measured by short-term instruments[31], such as the used in this study, it is plausible that both observed and optimised Na contents exceed the recommended 2300 mg/d. No constraints were introduced for the other minerals and vitamins assessed in this study, but the expected impact would be of an increase in the cost of the diet. In a previous study using linear programming to find the most effective food choices for the lower-income Brazilian households to reduce nutrient inadequacy, a cost increment was necessary to increase the content of some nutrients, particularly Ca, Mg and vitamin A[32]. This finding is indeed in accordance with other studies evaluating the cost impact of nutrient adequacy[24,33].

This is a theoretical study that cannot accommodate all aspects concerning food choices and their implications. In addition to the household budget, there are other facilitators and barriers of UPF consumption. The taste is one of the strongest facilitators for consumption of these foods[34]. Moreover, more than only cost and food preferences, the changes in the optimised diets encompass other issues, including convenience[35]. One of the main changes included a substantial increase in fruit and vegetable consumption, which implies weekly visits to the market due to a shorter shelf life in comparison with other foods. Moreover, cooking hard vegetables and beans requires more time for preparation and energy (electricity or cooking gas). Therefore, these results should be interpreted as feasible diets explicitly from the food cost viewpoint.

The modifications identified in the food choices to accommodate the reduction in the UPF energetic share and to optimally approach dietary adequacy were constrained by lower and upper boundaries, named acceptability constraints. These constraints limit how much each food and food group could change in relation to the observed quantities. The definition of these constraints is a crucial aspect when designing diets with linear programming. We do not have information on food preference; thus, we derived these boundaries from the population intake distribution and used them as a proxy for food preference. The rationale is that, if people reported that they consume these items, it means that they are acceptable in the population. Nonetheless, the values from the intake distribution (in this case 10th and 90th percentiles), are arbitrary and, therefore, subject to personal judgement, and consist in a limitation in studies using linear programming to design diets (although it is commonly done in this type of study). Another limitation concerns the food prices. We assumed that all foods prices are those as purchased in markets or street vendors after using cooking factors and removing non-edible portions. As a consequence, the diet cost may be underestimated when the food price refers to a food that is assumed to be prepared at home but is purchased ready to eat, such as meals at restaurants. Conversely, the diet cost may be overestimated when the food price refers to a food that is assumed to be purchased ready to eat but is prepared at home, such as cakes and sandwiches. We cannot know, however, the extent to which these opposed scenarios balance out. It is also important to highlight that the surveys were conducted approximately 10 years ago. However, it is the most recent nationwide dietary and HBS currently available.

Despite these limitations, this study has the advantage of taking into account the population strata in diet modelling. This procedure accommodates actual food consumption and price variation in nationally representative sets of households characterised by geographic and socio-economic homogeneity within a cluster. Assessing food prices and consumption in the same households during the same period is especially important in the context of a large and heterogeneous country such as Brazil.

In conclusion, it is possible to reduce the UPF energetic share and improve diet quality while respecting local food preferences across the country in all income strata at no cost increment. The variation in the UPF energetic share alone impacted on *trans*-fat and added sugar content in diets; a higher diet quality was achieved when other nutritional goals were included in the models.

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The authors declare that they have no competing interests.

Availability of data and material

The datasets analysed during the present study are available in the Brazilian Institute of Geography and Statistics' repository (in Portuguese), (https://ww2.ibge.gov.br/home/estatistica/populacao/condicaodevida/pof/2008_2009_analise_consumo/microdados.shtm). *Code availability*: Available under request.

Supplementary material

For supplementary material referred to in this article, please visit https://doi.org/10.1017/S0007114520004365

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