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The cost of eating more sustainable diets: a nutritional and environmental diet optimisation study

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Abstract

We aim to identify the dietary changes to improve nutrition and reduce diet-related greenhouse gas emission (GHGE) simultaneously in Brazil, taking into account the heterogeneity in food habits and prices across the country. Food consumption and prices were obtained from two nationwide surveys (n=55,970 households and 34,003 individuals). Linear programming models were performed to design optimized diets most resembling the observed diets, and meeting different sets of constraints: i) nutritional, for preventing chronic diseases and meeting nutrient adequacy; ii) socio-cultural: by respecting food preferences; and iii) environmental: by reducing GHGE by steps of 10%. Moving toward a diet that meets nutritional recommendations led to a 14% to 24% cost increase and 10% to 27% GHGE reduction, depending on the stringency of the acceptability constraints. Stronger GHGE reductions were achievable (up to about 70%), with greater departure from the current diet, but not achieving calcium and potassium goals. Diet cost increment tended to be mitigated with GHGE reduction in most models, along with reductions in red meat, chicken, eggs, rice, and high-fat sugar sodium foods.

Keywords: Sustainable diet, Healthy diet, Diet cost, Greenhouse gas emissions, Linear programming

Introduction

The issue of the environmental impacts of the food system has been addressed in many studies in the last years (Aleksandrowicz et al., 2016). Studies from different parts of the world have estimated the food production and all related processes, such as land use, transport, storage, cooking and disposal of waste as an important source of environmental impact, end hence, potential effect on climate change (Clark et al., 2019). Worldwide, agriculture occupies about 40% of global land (Foley et al., 2005), and food production is responsible for up to 30% of greenhouse gas emissions (GHGE) (Vermeulen et al., 2012). In Brazil, the more recent data refer to 2018, where the major source of GHGE was the land-use change (44% of the total GHGE), followed by agriculture, accounting for 25% of the total emission. The livestock is responsible for about 70% of the agricultural emission, and about 15% of the total country emission (Climate Observatory, 2020).

Consumers play an important role as they can give preference to foods or products with lower GHGE. For example, it is consensus that the most effective way to reduce GHGE from the diet is to reduce or eliminate animal-based products (as long as the production is reduced as well (Willett et al., 2019)). However, the adoption of a meat-reduced diet may be hampered by consumer preferences, once meats are often considered as the central food of the meal. In addition, Brazilians are, along with North Americans, the world's largest consumers of meat (World Research Institute, 2019). Moreover, reducing one food item implies the substitution by another, preferably nutrient-rich and with low environmental impacts. Furthermore, animal-source foods are a valuable source of protein and bioavailable micronutrients. Plant-based foods such as fruit and vegetables, in general, have less greenhouse gas emission associated with their production than animal source foods on a per weight basis (Vieux et al., 2013).

However, fruit and vegetable consumption in Brazil is relatively low (about 270g/day per capita), for which the main barriers to increase consumption are the preference, convenience, and economical aspects (Kasprzak et al., 2020). Rice is the base of the traditional Brazilian diet, but 75% of the production is based on flood cultivation (Marrenjo et al., 2016), which leads to higher environmental impact compared with other, less common, ways of production (Miranda et al., 2015). Diets are considered ”sustainable healthy diets” when they display favorable characteristic on four dimensions (Food and Agriculture Organization of the United Nations, 2010): 1) nutritional – diets must be healthy; 2) socio-cultural – diets should be culturally acceptable; 3) environmental – diet should be protective and respectful of biodiversity and ecosystems; and 4) economic – diets must be affordable for everyone. Thus, modification in the diet needed to mitigate the environmental impacts must take into account the other three dimensions of sustainability. The economic dimension is particularly important in low- and middle-income countries, where a high percentage of the total income is already assigned to food purchases. Approximately 24% of households surveyed in Brazil within the Household Budget Survey 2017-2018 had a monthly income of less than two official minimum wages; in these households, the percentage of the total income spent on food was 22%, while this value for the whole population was 14% (Brazilian Institute of Geography and Statistic, 2019).

In parallel, in many parts of the world diets contain insufficient amounts of fruit and vegetables, nuts, and whole grains (Willett et al., 2019), which is linked to a higher risk of chronic diseases (World Health Organization, 2003). Theoretical healthy diets with reduced GHGE have been proposed in several studies (Willett et al., 2019). However, most of them have not addressed the cultural and economic aspects of the diets. For example, the EAT-Lancet commission proposed an evidence-based reference diet, healthy for both the planet and humans (Willett et al., 2019). Although clearly stated that local and regional realities need to be carefully considered, this diet consisted of a reference for the world, its economic and social aspects were barely addressed. Its affordability was assessed in another study, that concluded that EAT-Lancet reference diets are not affordable for most people living in low-income countries (Hirvonen et al., 2020). Moreover, they are often based on mean food availability at the country level and do not consider the heterogeneity in food habits and prices across and within the countries. Food and nutrition disparities are particularly important in large, socially unequal, and culturally heterogeneous countries, such as Brazil.

Linear programming is a mathematical approach that has been used to design nutritionally adequate diets considering several aspects (Gazan et al., 2018). In this study, using linear programming we aimed to identify the dietary changes able to simultaneously improve nutrition and reduce diet-related GHGE in Brazil, taking into account food preferences and food prices across the country. The impacts on diet cost and on deviation from habitual food patterns of stepwise GHGE reductions (until GHGE couldn't be reduced more) were explored.

Material and Methods

Surveys

We used data from two nationwide representative samples for the Brazilian population: The Household Budget Survey (HBS), which collected information on household food purchases, and the National Dietary Survey (NDS), which collected information on individual food consumption. The surveys took place in 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; in the second stage, households were randomly selected within census tracts. Census tracts (n=12,800) were grouped into 550 strata with geographical and socioeconomic homogeneity with the number of tracts proportional to the number of households in the stratum. The samples included 55,970 households (HBS) and 13,569 households (NDS). Data collection in each stratum were uniformly distributed throughout the four trimesters to encompass seasonal variations in both food intakes and prices. NDS was simultaneously performed in a random subsample of ~25% of the HBS, thus food consumption and purchase were collected in the same household and time frame. More information on the surveys and data collection can be found elsewhere (Oliveira et al., 2019).

Unit of analysis

The optimized diet should resemble as most as possible the current food habits in the population. However, due to the large heterogeneity in food consumption and prices throughout the country, we defined several subpopulations as follows: the 550 strata were collapsed into 26 Brazilian States and one Federal District, and further stratified into four income levels 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 MW (Minimum wage: BRL415.00 (Brazilian Reals) equivalent to US$179.65 in January 2009) totaling 108 aggregated strata (named geographic-income strata, or GIS). This rearrangement was adopted to improve the precision of the estimates by increasing the number of households by each unit of analysis.

Food variables

Dietary intake was collected from two non-consecutive food records filled by 32,746 individuals ≥10 years old (pregnant and breastfeeding women were excluded; n=1,254). Participants were asked to fill in a proper form the foods and drink they consumed, with detailed information on preparation, ingredients, and amounts. It was reported 1,103 different types of food items, which comprised similar items with distinct subtypes or preparation methods, for instance, different types of banana, or different preparation of red meat (boiled, roasted, grilled, etc.). The food subtypes were clustered (e.g., different types of cakes were categorized into 'cakes') resulting in a list varying from 87 to 102 food items according to the GIS. Non-food nutrient and energy sources from the food items list, i.e., coffee and tea (without sugar), and alcoholic beverages were not included in the analysis.

Mean food intakes were obtained for each GIS and used as starting points to design optimized diets using linear programming models. As described below, several linear programming models were run, giving rise to several optimized diets for each of the 108 GIS. The Brazilian Food Composition database was used to obtain nutrient content in both observed and optimized diets. Nutrient composition of foods clustered from food subtypes (e.g. different types of rice into 'rice') were obtained as the mean composition of the food subtypes weighted by their frequency of reporting in the NDS, also according to the GIS.

Food prices

Food prices were extracted from the HBS database, where each household registered the amount and price of each food product purchased, further converted into prices per 100g of edible portion. Considering the variation in food prices throughout the collection (12 months), all prices were deflated to the same reference date (January 31th 2009) using official inflation rates. Prices of food items was obtained as the mean price over the food subtypes (e.g., different types of oranges into 'orange') weighted by their frequency of reporting in the budget survey. In each GIS, the food prices were matched to the corresponding food item declared as consumed in the NDS; thus, the price variation over all the GIS was preserved.

Environmental impact of food

We used the "Environmental Footprints of Food and Culinary Preparations Consumed in Brazil" database to estimate the environmental impact of food items, based on an extensive review of the life cycle assessment (LCA) literature for consumed foods in the Brazilian National Dietary Survey 2008/2009 (Garzillo et al., 2019). This compilation considered greenhouse gas emission (GHGE) data estimated from farm to the point of sale processes, considering commodities produced at conventional agriculture. Garzillo et al (2019), estimated the greenhouse gas emissions based on the simple average of the LCA values found in the literature for each produced food. After that, they applied correction factors (such as peeling vegetables), cooking factors (such as adding water to cooking cereals), and adding GHGE from the gas used to cook each food. Extensive details about the development of this database have been published previously (Garzillo et al., 2019). The GHGE data was linked to consumed foods through unique food codes. For mixed dishes, the recipes were disaggregated into their ingredients and linked to the GHGE data. The indicator of the environmental impact used in this study was the GHGE expressed in kilograms of CO_2 equivalents (kgCO2eq) per day.

Linear programming models

A linear programming model is defined by an objective function that is optimized (i.e., minimized or maximized), depending on decision variables restricted by various constraints (Gazan et al., 2018). The decision variables were the foods that composed each GIS-specific diet (that is, the foods reported as consumed in each GIS). Several types of constraints were introduced into the models as described below:

Nutritional constraints

Two sets of nutritional constraints were used to ensure the amounts of nutrients and foods that optimized diets should contain: i) World Health Organization guidelines for non-communicable chronic diseases (CND) prevention (**CND** models) (World Health Organization, 2003); and ii) **CND** model plus mineral and vitamin requirements (**NUT** models). In the **NUT** models, constraints for calcium, magnesium, iron, phosphorus, copper, zinc, vitamins A, B1, B2, B6, B12, C, niacin, and folate were derived from the Estimated Average Requirement (EAR) (Murphy & Poos, 2002); as they are age-sex specific, the overall constraint for each nutrient corresponded to mean values of the requirements (i.e., mean of age-sex EAR values) weighted by the frequency of age-sex group in the population. In all the models, total energy content was constrained to be equal to the mean estimated energy requirement (EER) (Institute of Medicine, 2002) calculated using age, sex, and anthropometric information specific for each GIS (mean EER over the 108 GIS = 2,107 kcal). Due to the absence of information on the accuracy of estimates for added salt in food preparations, the ratio sodium/kcal in the optimized diets was constrained to be equal or lower than the ratio in the observed diet obtained for each GIS.

Food acceptability constraints

To avoid optimized diets from being culturally unacceptable (that is, diet changes that would potentially not be tolerated by the population), boundaries limiting changes in food quantities were introduced in the models. For individual foods, two sets of acceptability constraints were tested: i) strict boundaries, in which each food could vary between the 5th percentile and the mean observed consumption (**STRICT** models), and ii) flexible boundaries, in which each food could vary between zero and the mean observed consumption (**FLEX** models). The upper boundaries were obtained as the mean consumption among those who reported consumption greater than zero. The lower boundaries were calculated as follows: the mean food intakes were calculated for each stratum (from all 550 strata in the full sample), and the distribution of the mean food intake over the strata was obtained (excluding strata in which the food had not been reported by any individual). From this distribution, we obtained the 5th percentile.

Constraints for food groups were also introduced in the models. Mean food group intakes (31 food groups) were calculated; the GIS-specific optimized food quantities should not exceed that boundary.

Both food and food group acceptability constraints were obtained for each state of the country. They were applied as constraints in the GIS in the corresponding state. This procedure has been applied in studies with the same population (Verly-Jr et al., 2019, 2020).

Greenhouse gas emission (GHGE) constraint

This constraint limits the GHGE in the optimized diets. We first ran all the models with only nutritional and acceptability constraints to estimate the impact of moving the observed diets toward the healthy diets on GHGE and cost (first-round analysis). Afterward, in the second-round analysis, models were GHGE constrained so that the emissions were progressively reduced by steps of 10% (from the GHGE achieved in the first-round analysis) up to the maximal GHGE reduction.

The constraints described above defined four sets of models as follows:

(1) CND-STRICT: WHO guidelines for chronic disease prevention and strict diet changes;

(2) CND-FLEX: WHO guidelines for chronic disease prevention and flexible diet changes;

(3) NUT-STRICT: WHO + minerals and vitamins requirements, and strict diet changes;

(4) NUT-FLEX: WHO + minerals and vitamins requirements, and flexible diet changes.

The four sets of models were applied to each GIS. The impacts of the different models on diet cost were explored for Brazil as a whole and stratified by income levels. The sets of constraints used in different models are described in **Table 1**.

[Table 1 here]

Objective functions:

Linear programming models were developed to obtain optimized diets with food quantities at the lowest deviation from the observed diets. Objective function #1 was run for each model with the corresponding list of nutritional constraints. However, model infeasibility may occur when one or more nutritional constraints cannot be attained. Those constraints making the model infeasible are called limiting nutrients. A built-in algorithm in the PROC OPTMODEL was used to identify the limiting nutrients when performing a model with objective function #1. When limiting nutrients are identified, the corresponding constraints were removed, and the model was run with objective function #2, which includes an additional term with undesirable deviations to be also minimized. “Undesirable deviation” refers to the difference between the nutritional target and the optimized content of a nutrient (Ferguson et al., 2006). For example, for an essential nutrient with a target of ≥100mg, an undesirable negative deviation of 10 mg refers to an optimized diet having only 90 mg of the nutrient instead of 100 mg. Similarly, for harmful components such as trans-fat, in which the target is <2 g, an undesirable positive deviation of 0.5 g refers to an optimized diet having 2.5 g instead. The deviation for a given nutrient represents the least optimized difference between the target and solution if the target cannot be attained. The two objective functions are described as follows:

$$Minimize\ Y = \sum_{i=1}^{i=g} \left| \frac{Q_i^{opt} - Q_i^{obs}}{Q_i^{obs}} \right| \qquad (objective\ function\ \#1)$$

$$Minimize\ Y = \sum_{i=1}^{i=g} \left| \frac{Q_i^{opt} - Q_i^{obs}}{Q_i^{obs}} \right| + \sum_{n=1}^{n=N} \left| \frac{nut_n^{opt} - nut_n^{target}}{nut_n^{target}} \right| \qquad (objective\ function\ \#2)$$

Where Y represents the objective function to be minimized, Q_i^{opt} is the quantity of the food item *i* in the optimized diet, g is the total number of food items, Q_i^{obs} is the mean quantity of *i* in the observed diet, nut_n^{target} is the target and nut_n^{opt} is the optimized amount of the dietary component *n* (the limiting nutrients). This is a non-linear function due to the use of an absolute function, which was then linearized to include a set of linear constraints, following a similar procedure to that described elsewhere (Darmon et al., 2002).

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

Uncertainty analysis

The inherent nature of some data used as input in the models may raise questions about their reliability. For example, the GHGE was obtained mainly from international publications and applied (adapted or not) in the Brazilian products. Uncertainty analyses were performed to deal with potential variation in model output due to the possible unreliability in the model inputs. The Monte Carlo simulations were repeated 200 times, in each iteration assigning arbitrarily random variation from -50% to +50% (uniformly distributed) in the GHGE, price, and nutrient composition values for each food item. From the generated distribution with many possibilities of outputs (diet cost and food quantities), we obtained the 2.5nd and 97.5th percentile, corresponding to the lower and upper uncertainty interval.

Descriptive analysis

Results were expressed as the overall mean food contents or mean difference between optimized and observed diets and the 95% uncertainty intervals, for stepwise GHGE reductions. The overall means (cost, food, and food group amounts, in the observed and optimized diets) refer to the weighted means over the 108 GIS. Food quantities in the observed and optimized diets were presented aggregated as follow: **beans** (beans, legumes); **white and brown rice**; **fruits and vegetables** (including tubers), **nuts**; **dairy** (whole and non-fat milk, cheese, yogurt, other dairy products); **red**

meats (including processed meats)**; chicken; eggs; fish**; **refined grains** (bread, cookies, cakes, pasta); **high-fat sugar salt (HFSS) foods** (sugar-sweetened beverages, snacks, pizza, salt pastries, sweets); **added fats** (butter, margarine, oils). The term "mean observed diet" refers to the mean diet calculated over the 108 GIS.

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).

Results

Limiting nutrients in the different models (and use of objective functions #1 and #2)

In the first-round analysis, i.e. not GHGE-constrained models, the full list of nutritional constraints was achieved, and therefore the objective function #1 was kept. However, in the second-round analysis, i.e. GHGE-constrained models, limiting nutrients were identified: energy and potassium when GHGE was constrained to ≥20% reduction (in the **STRICT** models), and ≥60% reduction (in the **FLEX** models). Particularly in the models with mineral and vitamin constraints, calcium was limiting when the GHGE was constrained to ≥10% reduction (in the **STRICT** models), and ≥50% reduction (in the **FLEX** models) (**Figure 1**). Thus, the corresponding nutritional constraints were removed and the objective function #2 was used for these limiting nutrients. **Figure 1** also shows the achievable contents of these limiting nutrients through the models. For energy, for which the mean constraint was 2107kcal, the optimized contents were 2030 kcal and 1975 kcal for a 25% and 30% GHGE reduction respectively. For calcium, for which the constraint was 868mg, the optimized contents were 755mg and 670mg for a 20 and 30% GHGE reduction respectively (only **STRICT** models). For potassium, for which the constraint was 3510mg, the optimized contents were 3470mg and 3350mg for a 20% and 30% GHGE reduction respectively (only **STRICT** models).

[Figure 1 here]

Observed diets and diets optimized without constraint on GHGE (First-round analysis)

For Brazil as a whole, the mean observed per capita/day diet cost and GHGE were US$ 2.16 (BRL 4.99) and 4.40 KgCO2eq respectively. The higher the income level, the higher the observed diet cost and the observed GHGE level. Compared with the observed diets, diet cost increased and GHGE decreased systematically in the optimized diets. Overall, the cost increment and the GHGE reduction were higher with the **NUT** models than with the **CND** ones.

[Table 2 here]

Diets optimized with GHGE constraints (Second-round analysis)

Figure 2 presents the mean cost difference (optimized – observed diets) and the GHGE reduction over the 108 GIS, according to the models. In the **FLEX** models, there were feasible solutions up to about 70% GHGE reduction from the baseline emissions regardless of the set of nutritional constraints introduced. In the **STRICT** models, the strongest feasible GHGE reduction was about 30%. The diet cost increment tended to fade with GHGE reduction. However, in the **FLEX** models, this relationship was not linear: the cost tended to increase from about 50% GHGE reduction. The optimized diets were always more expensive than the observed ones regardless of the model.

[Figure 2 here]

Figure 3 shows the food changes induced by models. Beans and FV quantities were increased to reach nutritional constraints, little variation occurred over further GHGE reductions. Rice and HFSS foods contents were reduced to reach nutritional constraints and further reductions were also needed to reduce the GHGE. Red meat quantities should decrease regardless of the model, i.e. with and without imposed GHGE reductions. In the **FLEX** models, the red meat quantities reached zero gram for GHGE reduction was about 70%. After an increase in order to meet nutritional constraints, chickens and eggs decreased as the GHGE reduction strengthened, and also reached zero gram when the GHGE reduction was about 70%. Fish and seafood quantities increased with the GHGE reduction up to about 40% and then decreased to about 40 grams with stronger GHGE reductions. Refined grains increased only with the strongest GHGE reduction, and dairy increased only in the **FLEX** models.

[Figure 3 here]

Discussion

In this study, we assessed how much the GHGE from diets could be reduced in Brazil while improving nutrition and taking into account food preference across the country. The first implication of the present study is that, moving the observed diet toward a healthy diet, by itself, leads to a substantial GHGE reduction, varying between

10% in the **STRICT** to 27% in the **FLEX** models. This suggests that following dietary guidelines may induce considerable GHGE reduction, even when the reduction of environmental impacts is not explicitly mentioned in the formulation of the guidelines (Behrens et al., 2017). Overall, the reduction in the environmental impacts measured by different indicators (for instance, carbon footprint and blue water footprint) was observed when moving observed diets toward healthier theoretical and optimized diets (Aleksandrowicz et al., 2016). Overall, the adequacy for both **CND** and **NUT** diets demanded substantially more beans, FV, fish, and chicken, and a reduction in red meat, rice, HFSS foods, and oils. A higher increase in dairy was observed particularly in the **NUT** models, probably due to the higher calcium requirement used in this set of models (868mg vs. 500mg in the **CND** models). Such changes in the food content of diets are aligned to previous studies using linear programming to reduce nutrient inadequacy in Brazil (Verly-Jr et al., 2020), especially for low-income households (Verly-Jr et al., 2019).

In parallel with the GHGE reduction, moving to a healthy diet led to a cost increment of US$ 0.30-0.37 to US$ 0.43-0.51 (about 15% and 22% increase) in the **CND** and **NUT** models, respectively. In the lowest income level, however, this increment was almost twice as much the mean increment in the whole population, and about five-fold the increment in the highest income. Nonetheless, further GHGE reductions did not necessarily increase the diet cost in addition to that induced by meeting nutritional constraints. In fact, when the optimized healthy diets were constrained to stricter GHGE reduction, the cost tended to decrease as well but limited to GHGE reduction up to about 60% from the baseline emission. In this sense, although the Eat-Lancet reference diet was considered unaffordable for most of the low-income populations worldwide (Hirvonen et al., 2020), our results suggest that its predicted cost may be lowered, by taking into account local food habits (i.e., feasible food shifts in the local context). The reduction in the cost increment was associated with a progressive reduction in meats and HFSS foods in the GHGE-reduced diets. According to the last available data on food purchase, HFSS foods are 52% more expensive than the average cost per calorie of the other food items (Moubarac et al., 2013), thus the reduction in the caloric share of this food group potentially leads to a lower diet cost. This impact in the diet cost reduction may be of less magnitude in countries where *in natura* foods are more expensive, as the case of the UK (Moubarac et al., 2013).

Decreasing GHGE by more than 30% demanded dramatic changes from current food consumption. Red meat was halved in the **STRICT** models at 30% GHGE reduction, but it was almost removed in the **FLEX** models at 60% GHGE reduction. Of note, the difference between the **STRICT** and **FLEX** models, in terms of food quantities, were marked for red meat, chicken, and HFSS foods. It implies that reducing the GHGE beyond about 30%, in light of the current food preferences, is unlikely to be achievable without tolerating drastic reductions in these three food groups. A similar picture was observed in another study using linear programming to design healthy and sustainable diets for the French population (Perignon et al., 2016). They found that moderate GHGE reductions (up to 30%) did not require any dietary shifts at the food group level additional to those induced by meeting nutritional recommendations. However, further GHGE reductions increased the distance between optimized and observed food quantities until 70% GHGE reduction, which required extreme food pattern changes. Also, they found that reaching nutritional adequacy at higher GHGE reductions (>30%) would compromise acceptability. In the UK, food shifts in order to comply with the WHO guidelines led to a GHGE reduction by 17% (Green et al., 2015). Similar to our results, further reductions of about 30%-40% could be achieved within realistic modifications to the current diets. Additional reductions are still possible but at the cost of drastic changes in consumption patterns.

In general, the GHGE reduction did not impair diet quality improvement. The more problematic models were the **STRICT** ones, where the total energy content had to be reduced by about 100 kcal at 30% GHGE reduction. This difference represents the least undesirable deviation from the energy target, i.e., 2,107 kcal. Given the uncertainties in the model inputs, this small decrease observed in our study seems not to be of concern, and may help reducing overweight and obesity (Hill et al., 2009). Another study, from Spain (Sáez-Almendros et al., 2013), suggested that a shift toward the Mediterranean diet would result in a 72% in the GHGE reduction, but requiring extreme energy restrictions. Calcium, however, was the most limiting nutrient, the highest achievable content being 650mg in the **NUT-STRICT** models (26% less than the target of 868mg) when constrained to 30% GHGE reduction, i.e., there is an incompatibility between the Institute of Medicine calcium recommendation and stronger GHGE reductions from the diet. In the **FLEX** models, where higher variation in food quantities were allowed, calcium constraint was met in the GHGE reductions up to about 50%. Although the potassium constraint was not met in the **STRICT** models, the difference was low (3380mg instead of the 3510mg). Calcium and potassium were also among the most difficult nutrients to meet in nutritionally adequate diets with important GHGE reduction in France (Perignon et al., 2016). Studies in other countries should be done to confirm the incompatibility between meeting calcium intake and big reductions of GHGE. If this finding is consistent, the committees in charge to review or establish nutrient intake requirements should consider both outputs, i.e., health benefits and environmental impacts, when establishing or reviewing nutrient reference values.

The present study is not without limitations. It is important to consider that life cycle assessments are estimates and can have a significant range due to differences in food production systems, inputs, and available data. The reference for GHGE values used in this study included life cycle analyses from production inside and outside Brazil and do not specifically represent only domestic production systems. This strategy has been used for other researches to estimate GHGE from food and has been accepted overall (Heller et al., 2018). However, we dealt with this limitation by performing an uncertainty analysis that allows each food GHGE value to randomly vary up to 50%. In general, the uncertainty at this level did not impact the main findings. It is unknown, however, whether this level of uncertainty would cover the actual variation across countries.

Food consumption and prices were based on data collected approximately ten years ago, although it is the most recent nationwide data to date. On the other hand, this represents an innovative study that takes into account the heterogeneity in the eating habits and prices across the country, which is important when stratifying the results by income levels, once the prices are expected to vary according to the economic status of the neighborhood. To our best knowledge, it is the unique study assessing food prices and consumption in the same household in the same period of collection, which is particularly important in the context of a large and heterogeneous country such as Brazil.

Conclusion

Moving toward a healthy diet in Brazil would increased diet cost, but this increase is mitigated when the healthy diet becomes more sustainable. GHGE from diets can be reduced up to about 30% when considering food preferences, but further reductions are achievable (up to about 70%) when more dramatic changes in the diets are tolerated. Red and processed meats, and high-fat sugar salt foods should be reduced to increase diet quality and reduce GHGE emissions.

Competing interests: The authors declare that they have no competing interests.

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Table 1 – Constraints used in the different sets of models, by sustainability dimension

	Sets of models	
Nutrition and health	***CND***	***NUT***
Energy (kcal)	EER	EER
Carbohydrates (%EER)	55 to 75	55 to 75
Total fats (%EER)	15 to 30	15 to 30
PUFA (%EER)	6 to 10	6 to 10
Sat. fat (%EER)	< 10	< 10
Trans-fat (%EER)	< 1	< 1
Free sugars [a] (%EER)	< 5	< 5
Protein (%EER)	10 to 15	10 to 15
Cholesterol (mg)	< 300	< 300
Fruit and vegetables (g)	≥ 400	≥ 400
Fish (g)	≥ 43 [b]	≥ 43 [b]
Calcium (mg)	≥ 500	≥ 868
Sodium (mg/kcal)	≤ observed [c]	≤ observed
Potassium (mg)	≥ 3510	≥ 3510
Iron (mg)	≥ observed	≥ 6.8
Magnesium (mg)	≥ observed	≥ 303
Folate (mcg DFE)	≥ observed	≥ 322
Niacin (mg)	≥ observed	≥ 11.5
Vitamin B1 (mg)	≥ observed	≥ 0.9
Vitamin B2 (mg)	≥ observed	≥ 1

Vitamin B6 (mg)	≥ observed	≥ 1.1
Vitamin B12 (mcg)	≥ observed	≥ 2
Vitamin C (mg)	≥ observed	≥ 66.1
Vitamin A (mcg)	≥ observed	≥ 560
Copper (mg)	≥ observed	≥ 0.7
Zinc (mg)	≥ observed	≥ 8
Phosphorus (mg)	≥ observed	≥ 649
Food consumption	***FLEX***	***STRICT***
Food	≤ mean [d]	≥ 5 pctl [e]; ≤ mean
Food group	≤ mean	≤ mean
Environment		
GHGE	decrease by steps of 10%	

CND: WHO dietary recommendations for chronic disease prevention.

NUT: Minerals and vitamins recommendations. EER: Estimated Energy Requirement. GHGE: Greenhouse gas emission.

[a] The term ‘‘free sugars’’ refers to all monosaccharides and disaccharides added to foods by the manufacturer, cook or consumer, plus sugars naturally present in honey, syrups and fruit juices (World Health Organization, 2003).

[b] From the WHO recommendation of 2 portions/week: (150g x 2)/7=43g

[c] Observed mean nutrient intakes in each GIS.

[d] Mean food or food group consumption on a consumption day.

[e] 5th percentile from the mean food item intake distribution over the strata; for details, please refer to the Methods section.

Table 2 – Mean cost and mean GHGE of observed diets and diets optimized with the CND-FLEX, CND-STRICT, NUT-FLEX and NUT-STRICT models, for Brazil as a whole and stratified by income levels (n=108 GIS). Absolute and relative (%) cost and GHGE differences between optimized and observed diets.

		Optimized diets			
Diet cost (US$/d)	**Observed diets**	**CND-FLEX**	**CND-STRICT**	**NUT-FLEX**	**NUT-STRICT**
< 0.5 MW	1.84	2.35	2.39	2.55	2.55
0.5 - 1.5 MW	2.03	2.36	2.47	2.50	2.62
1.5 - 3 MW	2.29	2.51	2.58	2.62	2.72
> 3 MW	2.60	2.71	2.76	2.80	2.85
Brazil	2.16	2.46	2.53	2.59	2.67
Cost difference (US$)[a]					
< 0.5 MW	-	0.51	0.55	0.71	0.71
0.5 - 1.5 MW	-	0.33	0.43	0.47	0.59
1.5 - 3 MW	-	0.22	0.29	0.33	0.42
> 3 MW	-	0.11	0.16	0.20	0.25
Brazil	-	0.30	0.37	0.43	0.51
Cost difference (%)					
< 0.5 MW	-	28	30	39	39
0.5 - 1.5 MW	-	16	21	23	29
1.5 - 3 MW	-	10	13	14	18
> 3 MW	-	4	6	8	10

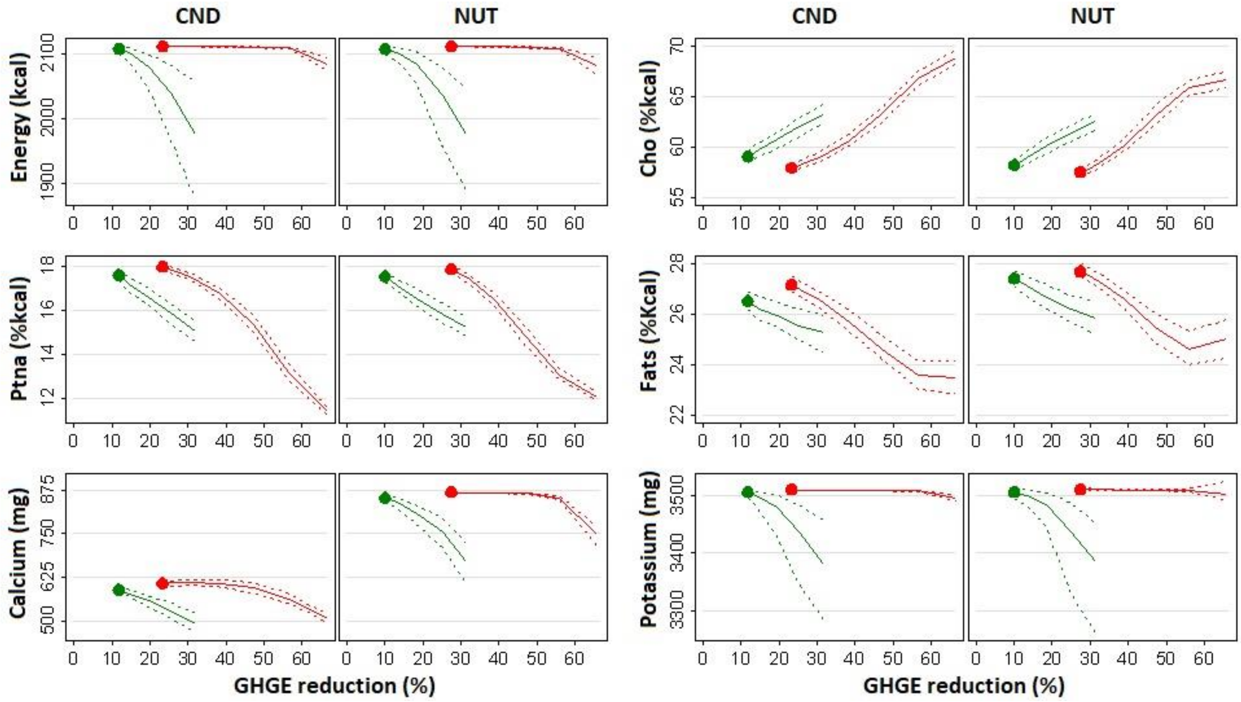
Brazil	-	14	17	20	24
GHGE (KgCO2eq/d)[b]					
< 0.5 MW	4149	3.13	3666	3079	3750
0.5 - 1.5 MW	4306	3.23	3821	3008	3913
1.5 - 3 MW	4525	3.46	3907	3153	3980
> 3 MW	4678	3.69	4015	3543	4057
Brazil	4396	3.35	3848	3150	3925
GHGE difference (%)					
< 0.5 MW	-	-23	-10	-24	-8
0.5 - 1.5 MW	-	-25	-11	-29	-9
1.5 - 3 MW	-	-23	-13	-30	-12
> 3 MW	-	-21	-14	-24	-13
Brazil	-	-23	-12	-27	-10

CND-FLEX, CND-STRICT, NUT-FLEX, and NUT-STRICT models, please refer to methods section. GHGE: greenhouse gas emission; MW: per capita minimum wage; GIS: geographic-income strata.

[a] Cost difference: optimized – observed cost, in US$.

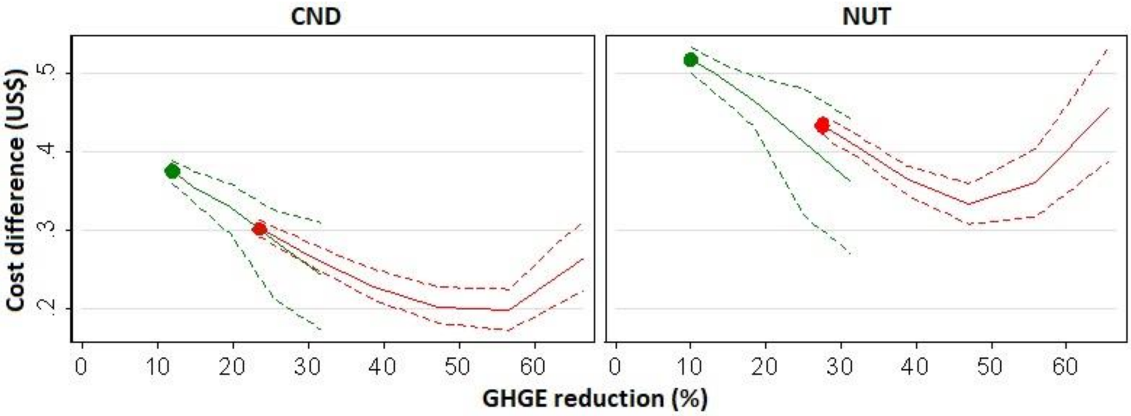
[b] GHGE difference: optimized – observed GHGE, in KgCO2eq/d.

Figure 1 – Mean energy, macronutrients, calcium, and potassium contents in the optimized diets at strengthened levels of GHGE reduction, according to the model (n=108 GIS).



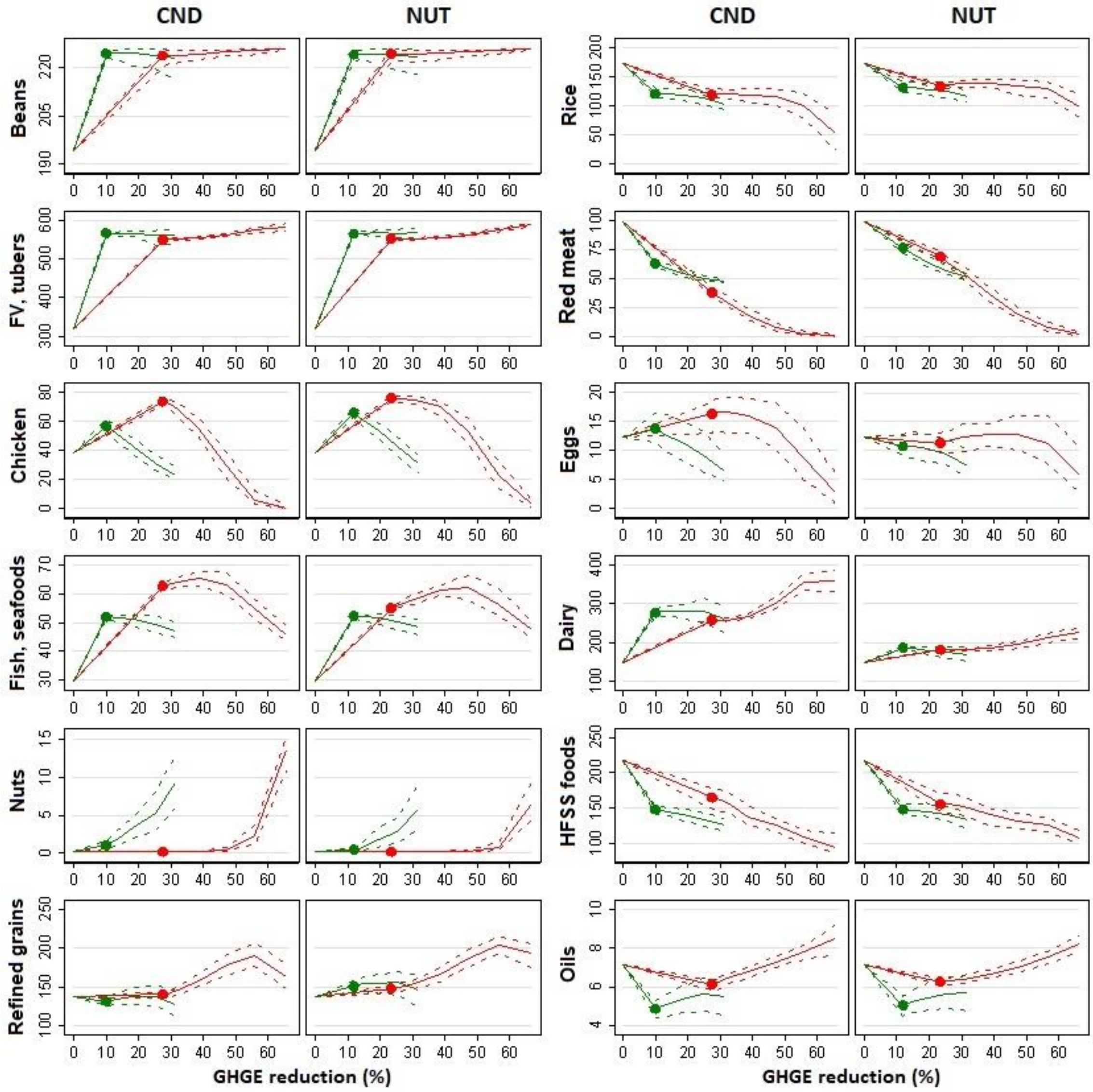
CND: models constrained for WHO dietary recommendations; NUT: models constrained for minerals and vitamins recommendations. Dots: spontaneous GHGE reduction after meeting nutritional constraints (first-round analysis) in the STRICT (green) and FLEX (red) models. Solid lines: optimized energy and nutrient contents throughout the GHGE reduction in the STRICT (green) and FLEX (red) models. Dashed lines: 95% uncertainty interval. Cho: carbohydrates; Ptna: protein.

Figure 2 – Mean diet cost difference in the optimized diets at strengthened levels of GHGE reduction, according to the model (n=108 GIS).



CND: models constrained for WHO dietary recommendations; NUT: models constrained for minerals and vitamins recommendations. Dots: cost difference to achieve the nutritional constraints (first-round analysis) in the STRICT (green) and FLEX (red) models. Solid lines: cost difference throughout the GHGE reduction in the STRICT (green) and FLEX (red) models. Dashed lines: 95% uncertainty interval. Cost difference: optimized – observed cost.

Figure 3 – Mean change in the food quantities in the optimized diets at strengthened levels of GHGE reduction, according to the model (n=108 GIS)



CND: models constrained for WHO dietary recommendations; NUT: models constrained for minerals and vitamins recommendations. The straight lines before the dots represent the food changes induced by the models in the first-round analysis, after this point, the lines show the food changes induced by the progressive GHGE-constrained models (STRICT models: green; FLEX models: red). The intake at the 0% GHGE reduction refers to the baseline consumption. Dashed lines: 95% uncertainty interval.