Greenhouse gas emissions, water footprint, and ecological footprint of food purchases according to their degree of processing in Brazilian metropolitan areas: a time-series study from 1987 to 2018

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Summary

Background The consumption of ultra-processed foods has increased worldwide and has been related to the occurrence of obesity and other non-communicable diseases. However, little is known about the environmental effects of ultra-processed foods. We aimed to assess the temporal trends in greenhouse gas emissions (GHGE), water footprint, and ecological footprint of food purchases in Brazilian metropolitan areas, and how these are affected by the amount of food processing.

Methods In this time-series study, we used data from five Brazilian Household Budget Surveys (1987–88, 1995–96, 2002–03, 2008–09, 2017–18) to calculate GHGE, water footprint, and ecological footprint per 1000 kcal of food and beverages purchased. Food items were classified into NOVA food groups: unprocessed or minimally processed foods (G1); processed culinary ingredients (G2); processed foods (G3); and ultra-processed foods (G4). We calculated the proportion each NOVA food group contributes to daily kcal per person. Linear regression was performed to evaluate trends of the environmental impacts across the years.

Findings Between 1987–88 and 2017–18, diet-related GHGE increased by 21% (from 1538·6 g CO_2 equivalent [CO_2e] per 1000 kcal [95% CI 1473·3–1604·0] to 1866·0 g CO_2e per 1000 kcal [1788·0–1944·0]; p_{trend}<0·0001), diet-related water footprint increased by 22% (from 1447·2 L/1000 kcal [95% CI 1400·7–1493·8] to 1769·1 L/1000 kcal [1714·5–1823·7]; p_{trend}<0·0001), and diet-related ecological footprint increased by 17% (from 9·69 m²/1000 kcal [95% CI 9·33–10·05] to 11·36 m²/1000 kcal [10·91–11·81]; p_{trend}<0·0001). We found that the change in the environmental indicators over time varied between NOVA food groups. We did not find evidence of a change in the environmental indicators for G1 foods over time. GHGE from G2 foods decreased by 18% (p_{trend}<0·0001), whereas GHGE from G4 foods increased by 245% (p_{trend}<0·0001). The water footprint from G2 foods decreased by 17% (p_{trend}<0·0001) whereas the water footprint from G4 foods increased by 233% (p_{trend}<0·0001). The ecological footprint from G2 foods decreased by 13% (p_{trend}<0·0001), whereas the ecological footprint from G3 foods increased by 49% (p_{trend}<0·0001) and from G4 foods increased by 183% (p_{trend}<0·0001). We found no significant change in contribution by any other NOVA food groups to any of the three environmental indicators over the study period.

Interpretation The environmental effects of the Brazilian diet have increased over the past three decades along with increased effects from ultra-processed foods. This means that dietary patterns in Brazil are becoming potentially more harmful to human and planetary health. Therefore, a shift in the current trend would be needed to enhance sustainable healthy food systems.

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For Portuguese translation of the abstract see **Online** for appendix 1

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Introduction

The pressures that food systems exert on ecosystems and human health have been widely explored. Food supply chains have been identified as one of the largest global environmental threats, and unhealthy diets are the most important risk factor for non-communicable diseases worldwide.[1,2]

There are an increasing number of studies investigating the effects of foods on climate change, most of them accounting exclusively for the greenhouse gas emissions (GHGE) from specific food groups.[3–5] Recently, not only GHGE, but a much larger set of environmental indicators have been explored. For example, studies in Brazil,[6] China,[7] India,[8] and

Research in context

Evidence before this study

We did a literature search in May, 2020, and found that there is increasing evidence of the environmental effects of diets, particularly after the publication in *The Lancet* of the EAT–*Lancet* Commission and the Global Syndemic Commission, as well as the publication of the Food and Agriculture Organization of the United Nations Sustainable Healthy Diets Guiding Principles. Since the release of the NOVA food classification system in 2010, multiple studies have explored how different levels of food processing are associated with health outcomes. However, to date, there has been no robust assessment of the trends in the environmental effects of diets, considering the degree of food processing and stage of nutrition transition.

Added value of this study

To our knowledge, this is the first study with nationally representative data assessing temporal trends in three environmental indicators (greenhouse gas emissions, water footprint, and ecological footprint) in Brazil accounting for the extent of food processing. The results show that the environmental impacts of the Brazilian diet are increasing while undergoing a dietary transition, with increased effects from ultra-processed foods. This shows that the nutrition transition through dietary change has environmental implications.

Implications of all the available evidence

This study provides new evidence to inform public policies and actions towards sustainable healthy diets and changes in the food systems. If the current dietary trends continue, Brazil might not be able to achieve international targets to mitigate climate change and reduce the burden of nutrition-related diseases. Therefore, a shift in the current trends is needed.

Australia[9] have estimated the GHGE, water footprint, and ecological footprint of various diets.

These three environmental indicators (GHGE, water footprint, and ecological footprint) have a sufficient range of primary data available in the literature, allowing for complex assessments, although not always at the country level. Each one of them is linked to a different aspect of the pressure of human activities on the planet.[10–12] For instance, GHGE is a measure of global warming potential; water footprint estimates the use of water, a valuable natural resource; and ecological footprint represents the amount of biologically productive area (eg, cropland, grazing land, fishing ground, forest, and built-up area).[10]

The relationship between multiple aspects of diet and environmental effects have been investigated, for instance, affordability,[13] regulatory frameworks,[14] and food culture.[15] There are also studies exploring the influence of diet type, for example vegetarian and vegan diets,[16] and the amount of meat consumed.[17] However, there is a need for studies investigating the trends in the environmental effects of diets, accounting for the degree of food processing and situating this narrative within a nutrition transition and wider dietary change.[18,19]

NOVA is a food classification system based on the nature and extent of food processing, which divides foods into four groups: unprocessed or minimally processed (G1); processed culinary ingredients (G2); processed foods (G3); and ultra-processed foods (G4).[20] In the past few decades, the consumption of G4 foods has increased worldwide,[21] and has been related to the occurrence of non-communicable diseases, such as obesity, heart disease, diabetes, and cancer, and all causes of mortality.[22,23]

Little is known about the environmental effects of G4 foods. Such effects probably go beyond the production of specific commodities (eg, sugar and vegetable oil), and could also be related to industrial processing, packaging, distribution, and all the stages concerning the preparation of many ingredients used exclusively in G4 food (ie, additives, preservatives, and colourants).[18,19] A study has shown that industrially made meals can have higher environmental effects than home-made equivalents, due to the increase in manufacturing stages, refrigerated storage, and the waste generated in their life cycle.[24] Another study found that discretionary food, equivalent to G4 food, represents 40% of daily energy intake in Australia, and more than a third of the total diet-related GHGE, water footprint, and ecological footprint, with this proportion being expected to double by 2050.[9]

Brazil is one of the most populated and agriculturally productive countries in the world and, as such, is responsible for a large proportion of GHGE, water use, and land occupation. At the same time, Brazil is one of the first countries to consider the extent and purpose of food processing as well as sustainability aspects in its National Dietary Guidelines. The third of the five principles underpinning the guidelines focuses on “the interdependence between healthy diets and the social and environmental sustainability of the food system”.[25]

To complement these guidelines and to provide relevant information to guide interventions and investments towards sustainable healthy diets, it is important to understand the effects of current food systems on the environment.[26] Although there are estimations of GHGE and the water and ecological footprints for the Brazilian diet for 2003,[6] these do not include how the environmental effects are changing with time, or investigate how different levels of food processing affect them. Thus, our research addresses this gap by assessing the temporal trends in GHGE, water footprints, and ecological footprints of food purchases in Brazil for more than 30 years (1987–2018), accounting for the degree of food processing.

Methods

Data sources

In this time-series study, we analysed data from five Brazilian Household Budget Surveys (1987–88, 1995–96, 2002–03, 2008–09, and 2017–18) carried out by the Brazilian Institute of Geography and Statistics (IBGE) and available at IBGE's Automatic Recovery System (SIDRA). The households were selected by a complex sampling method in two stages. Briefly, the census tracts in the studied territory were stratified by geographical area and socioeconomic level. Then, census tracts were selected by systematic sampling (stage 1) and households were selected by simple random sampling without replacement (stage 2). Additional information on the sampling and other methodological procedures is available elsewhere.[27]

The dataset recovered from SIDRA lists the annual per-person purchased amount of 334 food and beverages for household consumption in 11 metropolitan areas, grouping the households into ten classes of income, totalling 110 strata per survey.[27] IBGE obtained the annual per-person quantity of each food by estimating the ratio between the total quantities and the estimated resident population.[27] Data on the estimated population size in each income level per city per year were provided by IBGE.

For the **SIDRA data** see https://sidra.ibge.gov.br/tabela/419

Environmental footprints

To convert the purchased amounts of food into kcal, we used data from the Brazilian Food Composition Table[28] and applied correction factors to the crude amounts of food so as to exclude the inedible portion.

We assessed the environmental effects of food purchases using three indicators that were compiled in a previous publication by Garzillo and colleagues in 2020,[29] which provides data for climate change through GHGE, water footprint, and ecological footprint for individual foods consumed in Brazil. The compilation made by Garzillo and colleagues focuses on food consumption and provides a single value for GHGE, water footprint, and ecological footprint for each food item. Therefore, our analysis used the same environmental impacts for each year (ie, we assumed that 1 kg of a specific type of food had the same environmental effect in 1987–88 and 2017–18) and did not reflect changes in food production practices.

GHGE include carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), hydrofluorocarbon (HFC), perfluorocarbons (PFCs), and sulphur hexafluoride (SF_6), among others, and are directly or indirectly caused by an activity or are accumulated over the course of a product life cycle. GHGE is expressed in mass of CO_2 equivalent (g CO_2e).[30]

Water footprint measures the total amount of fresh water directly or indirectly used during the lifecycle of a product and is expressed in volume (L). The total water is the sum of surface water or groundwater (blue water), rainwater (green water), and the water needed to assimilate the pollution load of the production system and consumption (grey water).[10]

The ecological footprint accounts for how much humankind demands from the regenerative capacity of the biosphere. It measures the direct and indirect use of renewable resources and carbon assimilation, comparing them with the ecological assets of our planet, which is our biocapacity. Ecological footprint is expressed in units of the global area (m^2) that is needed to regenerate the resources used during a product lifecycle.[10]

In Garzillo and colleagues' study,[29] the environmental impacts accounted for the whole lifecycle of the product (eg, cradle-to-grave scope), hence we included the total amount of food purchased, including discarded parts (eg, peels and seeds), considering that the discarded parts generate an effect that is associated with the edible part, and must be incorporated to the estimation. The environmental footprints of the total diet, and of each NOVA group and subgroup (described in the following section) are shown per 1000 kcal.

NOVA classification system

All food items were classified into the NOVA groups and the subgroups within them.[20] Unprocessed or minimally processed foods (NOVA group G1) are directly obtained from nature and might undergo a minor processing, such as removal of parts and cleaning, fermentation, drying, or pasteurisation. This group of foods includes grains, legumes (beans), fruits, vegetables, roots and tubers, meats, eggs, milk, and others. Processed culinary ingredients (NOVA group G2) include substances extracted from foods or from nature, such as salt, table sugar, vegetable oils, and animal fat, which are added to unprocessed or minimally processed foods to create culinary preparations. Processed foods (NOVA group G3) are products manufactured by the food industry that are composed of unprocessed or minimally processed foods with added culinary ingredients such as salt, oil, and sugar. This group includes foods such as unpackaged, freshly made breads, cheeses, fermented alcoholic beverages, preserves, and salted, cured, or smoked meats. Ultra-processed foods (NOVA group G4) are industrial formulations that are characterised by a high degree of processing, the addition of substances exclusive to the food industry, and frequent application of cosmetic additives whose function is to make the final product palatable or hyperpalatable and more appealing. This group includes cookies, chocolate, snacks, sweetened beverages (eg, soda), milk-based drinks, breakfast cereals, mass-produced and packaged breads and buns, frozen meals, ultra-processed meat (poultry and fish nuggets and sticks, sausages, burgers, hot dogs, and other reconstituted meat products), among others. Ultra-processed products typically contain little or even no unprocessed or minimally processed foods. We calculated the proportion that each NOVA food group contributes to daily kcal per person.

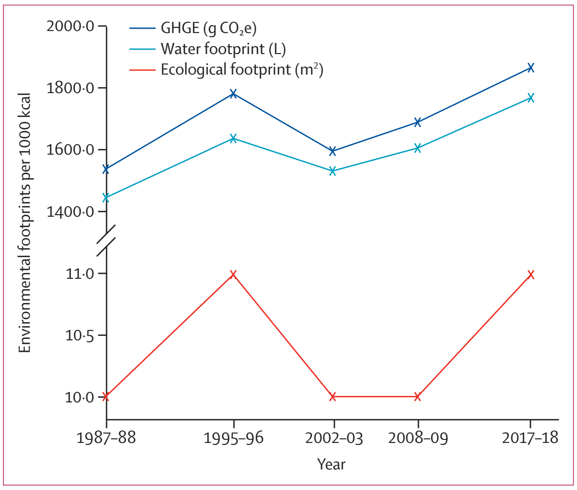

Figure 1: **Trends in the environmental impacts per 1000 kcal from food purchases in Brazilian metropolitan areas, 1987–88 to 2017–18**

CO_2e=CO_2 equivalent. GHGE=greenhouse gas emissions.

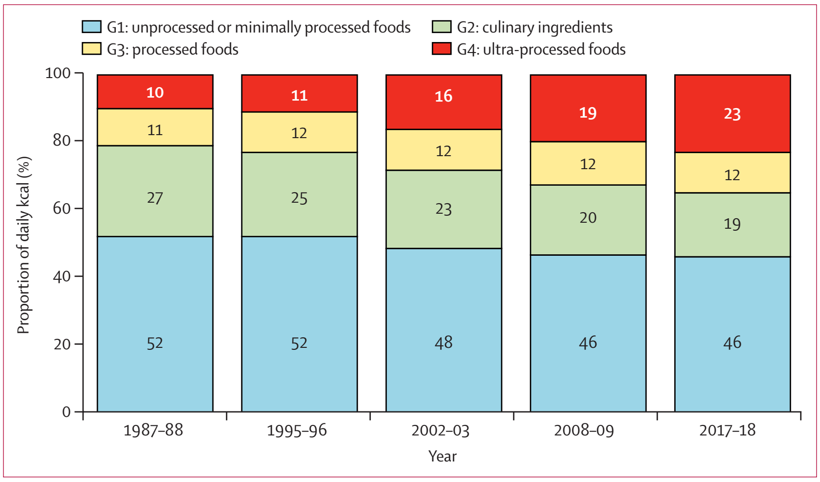

Figure 2: **Proportion of daily kcal provided by each NOVA food group based on food purchases in Brazilian metropolitan areas, 1987–88 to 2017–18**

Data analysis

The contribution of each NOVA food group to daily kcal and the environmental impacts (GHGE, water footprint, and ecological footprint) per 1000 kcal are described as population-weighted means and 95% CI for each year studied. The results are shown as relative numbers (either as the share [%] of total kcal or per 1000 kcal) to account for the progressive decrease in the caloric purchase for consumption at home over the years and possible under-reporting. Temporal trends in the environmental effects of the diet, as well as NOVA group and subgroups, were tested using linear regression. The analysis was done using the population size in each data cluster (income level, city, year) as a weighting factor. The data were analysed in R version 3.6.1 using the survey package.[31]

Role of the funding source

The funder of the study had no role in study design, data collection, data analysis, data interpretation, or writing of the report.

Results

From 1987–88 to 2017–18, the three environmental impacts increased significantly (figure 1). GHGE increased by 21% (from 1538·6 g CO_2e per 1000 kcal [95% CI 1473·3–1604·0] to 1866·0 g CO_2e per 1000 kcal [1788·0–1944·0]; p_{trend}<0·0001). Likewise, the daily water footprint increased by 22% (from 1447·2 L/1000 kcal [95% CI 1400·7–1493·8] to 1769·1 L/1000 kcal [1714·5–1823·7]; p_{trend}<0·0001). The ecological footprint also increased by 17% (from 9·69 m²/1000 kcal [95% CI 9·33–10·05] to 11·36 m²/1000 kcal [10·91–11·81]; p_{trend}<0·0001) over the study period. The trends were not uniform over the time and there was a decrease in all three impacts between 1996 and 2003.

Over the 30-year period, there were changes in dietary patterns assessed according to NOVA classification. The proportion of total energy consumption provided by G1 foods decreased from 52·1% to 45·8% (p_{trend}<0·0001), and the share provided by G2 foods decreased from 26·9% to 19·1% (p_{trend}<0·0001; figure 2). On the other hand, the dietary share of G3 foods increased by 1·1 times over 30 years (from 11·2% in 1987–88 to 12·1% in 2017–18; p_{trend}=0·0032), while the share of G4 foods increased by 2·3 times in the same period (from 9·8% to 23·0%; p_{trend}<0·0001; figure 2).

Analysing the trends of the environmental impacts over time, we note that they varied with NOVA food groups. G1 foods made the greatest contribution to GHGE (figure 3A), and this did not change significantly over the study period (increasing only from 1248·6 g CO_2e per 1000 kcal [95% CI 1197·3–1299·8] to 1295·0 g CO_2e per 1000 kcal [1245·1–1344·9]; p_{trend}=0·35; table 1). The contribution of G2 foods to GHGE significantly decreased by 18% (47·4 g CO_2e per 1000 kcal [46·2–48·6] to 38·9 g CO_2e per 1000 kcal [37·0–40·9]; p_{trend}<0·0001), while the contribution of G3 foods marginally changed (from 132·6 g CO_2e per 1000 kcal [118·2–147·0] to 152·0 g CO_2e per 1000 kcal [135·3–168·8]), but no linear trend was observed (p_{trend}=0·17). The contribution to GHGE by G4 foods significantly increased by 245% over the study period (from 110·0 g CO_2e per 1000 kcal [96·3–123·7] to 380·0 g CO_2e per 1000 kcal [336·1–424·0]; p_{trend}<0·0001).

When we analysed the NOVA subgroups (table 1), we observed that the contributions of some types of G1 foods (cereals other than rice, poultry and eggs, and other unprocessed foods) to GHGE significantly increased between 1987–88 and 2017–18, whereas the contributions of other subgroups significantly decreased (rice, milk, beans, and roots and tubers). The types of G2 foods with a significant decrease in contribution to GHGE were sugar (40% decrease) and vegetable oil (14% decrease). The contributions of some types of G3 foods to GHGE significantly increased over the period (cheese and fermented alcoholic beverages), whereas the contribution of processed meat to GHGE significantly decreased (table 1). The GHGE from all types of G4 foods significantly increased, with the emissions from all the subgroups, except margarine and other ultra-processed foods (distilled alcoholic beverages, coconut milk, industrialised sauces, and dried industrialised seasonings), at least doubling over the study period (table 1).

A similar trend was observed for the water footprint as for GHGE (figure 3B; table 2). There was no evidence that the contribution of G1 foods to the water footprint changed (1083·3 L/1000 kcal [95% CI 1048·8–1117·9] to 1146·6 L/1000 kcal [1111·8–1181·3]; p_{trend}=0·86). The contribution of G2 foods to the water footprint significantly decreased by 17% (93·4 L/1000 kcal [90·8–96·0] to 77·3 L/1000 kcal [73·3–81·3]; p_{trend}<0·0001), and the contribution of G3 foods remained the same (152·5 L/1000 kcal [139·1–165·9] to 151·8 L per 1000 kcal [137·5–166·1]; p_{trend}=0·75). The contribution of G4 foods to the water footprint significantly increased by 233% (118·0 L/1000 kcal [104·3–131·7] to 393·4 L/1000 kcal [354·7–432·1]; p_{trend}<0·0001).

Although the overall contribution of G1 foods to the water footprint was constant from 1987–88 to 2017–18, the contribution of some types of G1 foods significantly decreased (rice, milk, beans, and roots and tubers), and the contribution of other unprocessed foods (nuts, coffee, tea, and home-made meals) significantly increased (table 2). Among G2 foods, the contribution of sugar and vegetable oil to the water footprint significantly decreased. Among the G3 subgroups, we observed a significant decrease in contribution to the water footprint from processed meat and a significant increase in the water footprint from cheese, fermented alcoholic beverages, and canned or tinned fruits and vegetables. The contributions of all types of G4 food to the water footprint significantly increased, being at least twice as high in 2017–18 than in 1987–88 for all subgroups, except margarine and other ultra-processed foods.

The contribution of G1 foods to the ecological footprint remained constant between 1987–88 and 2017–18 (from 7·69 m²/1000 kcal [95% CI 7·39–7·99] to 7·83 m²/1000 kcal [7·49–8·17]; p_{trend}=0·31; table 3; figure 3C). The contribution of G2 foods to the ecological footprint significantly decreased by 13% (from 0·82 m²/1000 kcal [0·79–0·85] to 0·71 m²/1000 kcal [0·67–0·75]; p_{trend}<0·0001) over the same period, whereas the contributions of G3 foods significantly increased by 49% (from 0·41 m²/1000 kcal [0·37–0·44] to 0·61 m²/1000 kcal [0·56–0·67]; p_{trend}<0·0001) and the contribution of G4 foods significantly increased by 183% (from 0·78 m²/1000 kcal [0·71–0·84] to 2·21 m²/1000 kcal [2·02–2·40]; p_{trend}<0·0001) over the study period.

Some NOVA subgroups had a significant decrease in contribution to the ecological footprint: rice, milk, beans, and root and tubers (G1); and sugar and vegetable oil

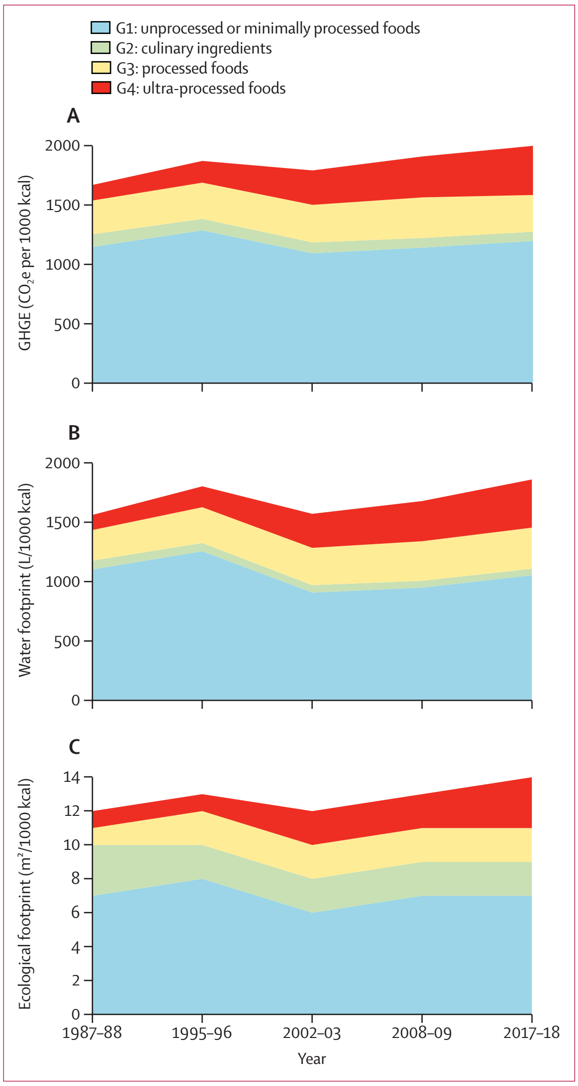

***Figure 3:* Temporal trends in the environmental impacts from food purchases according to NOVA food groups in Brazilian metropolitan areas, 1987–88 to 2017–18**

(A) GHGE. (B) Water footprint. (C) Ecological footprint. CO_2e=CO_2 equivalent. GHGE=greenhouse gas emissions.

(G2; table 3). The contribution of other subgroups to the ecological footprint significantly increased: poultry and eggs and other unprocessed foods (G1); cheese and fermented alcoholic beverages (G3); and all types of G4 except for other ultra-processed food (table 3).

The effects from ultra-processed foods on GHGE, water footprint, and ecological footprint all increased during the study period. The types of G4 foods contributing the largest proportions to the environmental impact varied across the indicators and the years, with some exceptions. For example, ultra-processed meat was the highest G4 contributor to daily GHGE and water footprint in each year of the study period (appendix 2 pp 2–5). For the ecological footprint, margarine was the highest G4 contributor in 1987, whereas ultra-processed

See Online for appendix 2

	1987–88	1995–96	2002–03	2008–09	2017–18	p_{trend} value
G1: unprocessed or minimally processed foods	1248·6 (1197·3–1299·8)	1440·1 (1348·3–1531·9)	1196·7 (1121·4–1272·0)	1235·6 (1184·3–1286·9)	1295·0 (1245·1–1344·9)	0·35
Rice	112·6 (105·7–119·5)	111·5 (101·8–121·2)	103·4 (95·7–111·1)	102·4 (92·8–112·0)	88·3 (79·7–96·9)	<0·0001
Milk	130·9 (123·5–138·3)	138·9 (126·2–151·6)	119·4 (110·5–128·4)	108·9 (102·6–115·2)	106·0 (99·4–112·5)	<0·0001
Cereals other than rice	16·4 (15·4–17·3)	17·3 (16·0–18·6)	18·1 (16·5–19·8)	18·3 (16·6–20·1)	22·2 (19·6–24·8)	<0·0001
Beans	3·9 (3·6–4·1)	3·7 (3·3–4·0)	3·7 (3·3–4·1)	3·3 (3·0–3·6)	3·1 (2·8–3·4)	<0·0001
Poultry and eggs	110·3 (106·7–113·9)	126·4 (119·1–133·8)	99·0 (91·7–106·2)	109·7 (103·9–115·6)	129·0 (120·7–137·3)	0·023
Roots and tubers	8·7 (7·6–9·9)	7·2 (6·2–8·2)	6·6 (5·5–7·7)	5·4 (4·6–6·2)	4·9 (4·3–5·4)	<0·0001
Fruits and vegetables	59·0 (54·8–63·2)	53·0 (47·4–58·6)	47·1 (43·0–51·2)	53·6 (48·8–58·3)	66·6 (59·7–73·6)	0·058
Beef	760·5 (714·6–806·3)	942·5 (865·3–1019·6)	741·0 (674·2–807·8)	769·4 (722·9–815·9)	778·3 (730·7–825·9)	0·16
Pork	15·2 (13·7–16·6)	10·2 (8·2–12·1)	10·7 (8·9–12·5)	9·8 (8·2–11·4)	17·5 (14·8–20·1)	0·15
Fish	20·7 (17·2–24·1)	18·7 (16·3–21·0)	20·5 (16·8–24·3)	22·5 (16·6–28·5)	21·5 (16·7–26·3)	0·45
Other unprocessed foods*	10·6 (7·7–13·5)	10·8 (4·4–17·3)	27·1 (20·4–33·9)	32·2 (25·2–39·3)	57·7 (44·6–70·8)	<0·0001
G2: processed culinary ingredients	47·4 (46·2–48·6)	42·7 (40·7–44·6)	41·0 (38·9–43·1)	36·5 (35·1–37·9)	38·9 (37·0–40·9)	<0·0001
Sugar	14·1 (13·3–14·8)	13·8 (12·7–14·9)	11·8 (10·8–12·7)	10·9 (10·2–11·7)	8·4 (7·6–9·1)	<0·0001
Vegetable oil	23·5 (22·2–24·7)	21·3 (20·0–22·5)	21·6 (20·0–23·3)	19·4 (18·1–20·6)	20·2 (18·7–21·6)	0·0002
Animal fat	6·3 (5·2–7·5)	4·7 (3·8–5·6)	5·1 (4·3–5·8)	3·7 (2·9–4·5)	6·7 (5·5–7·9)	0·97
Starch	1·0 (0·8–1·1)	0·6 (0·5–0·8)	0·4 (0·3–0·5)	0·4 (0·3–0·5)	1·0 (0·8–1·2)	0·61
Other culinary ingredients†	2·6 (2·4–2·8)	2·3 (2·0–2·6)	2·1 (1·8–2·4)	2·1 (1·9–2·3)	2·7 (2·4–3·1)	0·60
G3: processed foods	132·6 (118·2–147·0)	135·9 (119·6–152·2)	115·3 (101·3–129·2)	126·3 (109·3–143·4)	152·0 (135·3–168·8)	0·17
Processed bread	16·3 (15·7–17·0)	17·3 (16·0–18·5)	17·8 (16·4–19·1)	18·7 (17·3–20·2)	15·1 (13·9–16·3)	0·39
Cheese	24·4 (19·8–29·1)	30·9 (22·8–39·1)	31·8 (25·8–37·9)	37·9 (32·3–43·4)	55·4 (47·5–63·2)	<0·0001
Processed meat‡	78·3 (64·6–91·9)	69·9 (57·2–82·7)	45·5 (34·2–56·8)	48·3 (34·9–61·8)	53·1 (39·9–66·3)	0·0012
Fermented alcoholic beverages	9·4 (7·9–10·8)	14·7 (11·8–17·5)	15·2 (12·5–17·9)	17·2 (13·1–21·4)	24·4 (20·7–28·1)	<0·0001
Canned or tinned fruits and vegetables	4·2 (3·8–4·5)	3·1 (2·8–3·4)	5·0 (4·4–5·6)	4·2 (3·7–4·7)	4·1 (3·3–5·0)	0·40
G4: ultra-processed food and drinks	110·0 (96·3–123·7)	163·1 (136·8–189·5)	243·9 (217·9–270·0)	291·3 (269·8–312·8)	380·0 (336·1–424·0)	<0·0001
Cookies, crackers, cakes, and pies	11·7 (10·7–12·7)	14·3 (13·0–15·7)	18·0 (16·4–19·5)	21·9 (20·0–23·7)	25·4 (23·6–27·3)	<0·0001
Margarine	4·9 (4·6–5·3)	3·7 (3·3–4·0)	5·5 (4·7–6·3)	6·0 (5·5–6·5)	5·5 (5·0–5·9)	<0·0001
Sweets	12·1 (9·6–14·6)	9·5 (7·6–11·3)	13·6 (11·4–15·8)	17·7 (14·9–20·5)	24·7 (21·7–27·7)	<0·0001
Sweetened beverages	9·8 (8·7–11·0)	16·4 (13·3–19·5)	25·8 (22·6–29·1)	28·8 (25·9–31·8)	26·5 (23·5–29·6)	<0·0001
Ultra-processed bread	3·4 (2·9–3·9)	3·0 (2·5–3·5)	4·1 (3·4–4·8)	5·9 (5·1–6·7)	8·5 (7·3–9·8)	<0·0001
Ultra-processed meat§	36·2 (31·5–40·9)	79·0 (67·0–91·0)	120·6 (101·9–139·4)	137·6 (124·3–150·8)	147·4 (127·0–167·8)	<0·0001
Ready-to-eat meals	11·8 (8·5–15·1)	19·3 (11·2–27·5)	21·7 (17·2–26·2)	35·3 (28·5–42·1)	90·1 (68·2–112·1)	<0·0001
Milk-based products	10·1 (8·0–12·2)	10·6 (7·8–13·3)	27·4 (23·6–31·1)	28·3 (25·2–31·3)	38·0 (33·7–42·3)	<0·0001
Other ultra-processed food¶	10·1 (6·7–13·5)	7·4 (5·7–9·1)	7·2 (5·9–8·5)	9·8 (7·9–11·7)	13·8 (11·8–15·8)	0·019
Total	1538·6 (1473·3–1604·0)	1781·8 (1664·1–1899·6)	1597·0 (1502·5–1691·4)	1689·8 (1627·3–1752·2)	1866·0 (1788·0–1944·0)	<0·0001

Data are g CO_2 equivalent per 1000 kcal (95% CI). *Other unprocessed food: nuts, coffee, tea, home-made meals. †Other culinary ingredients: salt, baking powder, vinegar, honey. ‡Processed meat: salted, cured, or smoked meats. §Ultra-processed meat: chicken nuggets, sausages, burgers, hot dogs, and other reconstituted meat products. ¶Other ultra-processed food: distilled alcoholic beverages, coconut milk, industrialised sauces, and dried industrialised seasonings.

Table 1: **Greenhouse gas emissions from food purchases according to NOVA food groups and subgroups in Brazilian metropolitan areas, 1987–88 to 2017–18**

meat occupied this position from 1996 onwards (appendix 2 pp 6–7).

Another food category that contributed to the increase in the environmental impacts was cheese (G3), with the GHGE, water footprint, and ecological footprint from this subgroup doubling over the 30-year period. Processed meat (G3) had a decreasing contribution to GHGE and water footprint, remaining constant for ecological footprint (appendix 2 pp 2–5).

Discussion

To our knowledge, this is the first study reporting the temporal trends of GHGE, water footprint, and ecological footprint in the Brazilian diet considering the degree and purpose of food processing according to NOVA food classification. Over the 30-year study period, diet-related GHGE increased by 21%, the diet-related water footprint increased by 22%, and the diet-related ecological footprint increased by 17%.

	1987–88	1995–96	2002–03	2008–09	2017–18	p_{trend} value
G1: unprocessed or minimally processed foods	1083·3 (1048·8–1117·9)	1218·6 (1151·1–1286·1)	1035·2 (977·4–1092·9)	1057·8 (1021·5–1094·0)	1146·6 (1111·8–1181·3)	0·86
Rice	57·4 (53·9–60·9)	56·8 (51·9–61·8)	52·7 (48·8–56·6)	52·2 (47·3–57·1)	45·0 (40·6–49·4)	<0·0001
Milk	129·0 (120·7–137·2)	131·4 (116·8–145·9)	107·7 (98·0–117·4)	102·0 (94·2–109·8)	95·6 (88·2–103·1)	<0·0001
Cereals other than rice	30·5 (28·7–32·2)	30·6 (28·2–33·0)	29·5 (26·6–32·4)	28·6 (26·0–31·3)	30·2 (27·7–32·8)	0·56
Beans	59·4 (55·4–63·5)	56·4 (51·0–61·8)	56·8 (50·9–62·6)	50·3 (45·9–54·6)	47·5 (43·2–51·8)	<0·0001
Poultry and eggs	133·7 (129·3–138·1)	159·8 (150·4–169·1)	131·1 (121·4–140·8)	138·8 (131·1–146·4)	161·1 (150·4–171·9)	0·0063
Roots and tubers	24·5 (21·2–27·9)	20·3 (17·4–23·2)	18·9 (15·9–21·9)	15·7 (13·3–18·0)	14·6 (13·0–16·2)	<0·0001
Fruits and vegetables	63·3 (58·9–67·7)	63·4 (55·0–71·8)	54·9 (50·1–59·7)	60·6 (55·7–65·4)	76·3 (69·1–83·5)	0·013
Beef	499·8 (468·9–530·6)	624·4 (572·1–676·6)	486·8 (442·1–531·5)	510·0 (478·7–541·3)	516·3 (484·2–548·4)	0·23
Pork	27·6 (24·9–30·3)	18·4 (14·8–21·9)	19·3 (16·1–22·6)	18·1 (15·1–21·1)	31·9 (27·2–36·7)	0·15
Other unprocessed foods*	58·2 (54·3–62·1)	57·2 (51·1–63·2)	77·5 (69·1–86·0)	81·5 (74·3–88·8)	127·9 (116·0–139·8)	<0·0001
G2: processed culinary ingredients	93·4 (90·8–96·0)	84·3 (80·5–88·1)	83·0 (77·9–88·0)	74·4 (71·1–77·8)	77·3 (73·3–81·3)	<0·0001
Sugar	22·8 (21·6–24·0)	22·4 (20·5–24·2)	19·0 (17·4–20·6)	17·3 (16·2–18·4)	13·2 (12·0–14·4)	<0·0001
Vegetable oil	60·9 (57·4–64·4)	54·9 (51·7–58·0)	57·2 (52·5–62·0)	51·5 (47·9–55·0)	53·9 (50·0–57·8)	0·0057
Animal fat	4·4 (3·6–5·2)	3·3 (2·7–3·9)	3·7 (3·1–4·2)	2·7 (2·1–3·2)	4·9 (4·0–5·7)	0·69
Starch	3·5 (3·0–4·1)	2·3 (1·8–2·7)	1·5 (1·1–1·9)	1·5 (1·0–1·9)	3·3 (2·7–3·9)	0·30
Other culinary ingredients†	1·8 (1·6–1·9)	1·5 (1·3–1·7)	1·6 (1·3–1·9)	1·5 (1·4–1·7)	2·1 (1·8–2·3)	0·095
G3: processed foods	152·5 (139·1–165·9)	152·2 (138·9–165·6)	135·1 (122·5–147·7)	144·2 (128·2–160·2)	151·8 (137·5–166·1)	0·75
Processed bread	55·8 (53·5–58·0)	59·0 (54·8–63·3)	60·3 (55·7–64·9)	62·9 (58·1–67·8)	50·6 (46·3–54·9)	0·19
Cheese	16·0 (12·8–19·2)	20·3 (14·8–25·7)	21·3 (17·3–25·4)	24·7 (21·1–28·3)	36·7 (31·6–41·9)	<0·0001
Processed meat‡	76·2 (63·4–88·9)	66·8 (55·0–78·7)	44·9 (34·2–55·6)	47·4 (34·4–60·4)	52·4 (39·7–65·1)	0·0015
Fermented alcoholic beverages	3·1 (2·6–3·5)	5·0 (4·0–5·9)	5·1 (4·1–6·1)	5·6 (4·4–6·7)	8·1 (6·9–9·3)	<0·0001
Canned or tinned fruits and vegetables	1·5 (1·4–1·7)	1·2 (1·0–1·3)	3·5 (2·8–4·1)	3·6 (2·9–4·4)	3·9 (3·1–4·7)	<0·0001
G4: ultra-processed food and drinks	118·0 (104·3–131·7)	183·1 (158·2–207·9)	279·4 (249·0–309·8)	330·6 (303·5–357·7)	393·4 (354·7–432·1)	<0·0001
Cookies, crackers, cakes, and pies	14·1 (13·0–15·2)	18·4 (16·7–20·0)	23·8 (21·9–25·6)	27·4 (25·3–29·4)	31·4 (29·3–33·5)	<0·0001
Margarine	4·2 (3·9–4·5)	3·1 (2·8–3·4)	4·7 (4·0–5·3)	5·1 (4·7–5·4)	4·6 (4·3–5·0)	<0·0001
Sweets	34·4 (29·1–39·7)	32·0 (26·7–37·3)	59·7 (50·1–69·2)	70·7 (59·1–82·3)	95·3 (82·9–107·8)	<0·0001
Sweetened beverages	10·0 (8·9–11·1)	16·5 (13·5–19·6)	26·4 (23·1–29·8)	29·3 (26·3–32·2)	26·9 (23·9–29·9)	<0·0001
Ultra-processed bread	2·7 (2·3–3·1)	2·4 (2·0–2·9)	3·3 (2·8–3·9)	4·7 (4·1–5·3)	6·7 (5·7–7·6)	<0·0001
Ultra-processed meat§	38·1 (33·1–43·0)	91·7 (78·5–104·8)	132·3 (113–151·6)	153·3 (138·6–168·0)	154·1 (134·6–173·6)	<0·0001
Ready-to-eat meals	5·7 (4·2–7·2)	10·1 (6·1–14·1)	9·7 (7·5–12·0)	18·2 (13·2–23·2)	43·4 (31·3–55·4)	<0·0001
Milk-based products	6·0 (4·6–7·4)	6·9 (5·0–8·7)	16·6 (14·1–19·1)	18·3 (16·1–20·4)	26·4 (23·5–29·4)	<0·0001
Other ultra-processed food	2·9 (2·4–3·3)	2·0 (1·7–2·3)	2·9 (2·6–3·3)	3·7 (3·1–4·3)	4·6 (4·1–5·0)	<0·0001
Total	1447·2 (1400·7–1493·8)	1638·2 (1547·6–1728·9)	1532·7 (1452·7–1612·6)	1607·1 (1555·2–1658·9)	1769·1 (1714·5–1823·7)	<0·0001

Data are L/1000 kcal (95% CI). The food group fish is not shown in this table because it has a water footprint equal to zero. *Other unprocessed food: nuts, coffee, tea, home-made meals. †Other culinary ingredients: salt, baking powder, vinegar, honey. ‡Processed meat: salted, cured, or smoked meats. §Ultra-processed meat: chicken nuggets, sausages, burgers, hot dogs, and other reconstituted meat products. ¶Other ultra-processed food: distilled alcoholic beverages, coconut milk, industrialised sauces, and dried industrialised seasonings.

***Table 2:* Water footprint from food purchases according to NOVA food groups and subgroups in Brazilian metropolitan areas, 1987–88 to 2017–18**

The temporal trends differed in 2003, when the environmental impacts were lower than the preceding study year (1996). This was due to changes in animal product consumption patterns. From 1987 to 1996, the consumption of fresh meat increased from 9·1% to 10·7% of daily kcal.[32] However, from 1996 to 2003, the trends reverted, with the consumption of fresh meat decreasing to 9·5% of daily kcal.[32] The reduced consumption of meat in 2003 is explained by an economic crisis that affected South America (Argentina, Uruguay, and Brazil) in 2001–02, causing an increase in food prices in Brazil, particularly beef.

The environmental effects of Brazilian food purchases have increased due to changes in dietary patterns. The contributions of G1 foods and G2 foods to the diet have decreased, whereas the contributions of G3 foods and G4 foods have increased. Regarding animal products, the consumption of unprocessed and minimally processed red meat (beef and pork) has remained relatively constant over the observed period. On the other hand, the

	1987–88	1995–96	2002–03	2008–09	2017–18	p_{trend} value
G1: unprocessed or minimally processed foods	7·69 (7·39–7·99)	8·41 (7·95–8·86)	7·28 (6·84–7·71)	7·43 (7·09–7·77)	7·83 (7·49–8·17)	0·31
Rice	0·45 (0·42–0·48)	0·44 (0·41–0·48)	0·41 (0·38–0·44)	0·41 (0·37–0·45)	0·35 (0·32–0·39)	<0·0001
Milk	0·82 (0·76–0·87)	0·82 (0·73–0·92)	0·67 (0·60–0·73)	0·64 (0·59–0·69)	0·59 (0·54–0·64)	<0·0001
Cereals other than rice	0·17 (0·16–0·18)	0·17 (0·15–0·18)	0·16 (0·15–0·18)	0·16 (0·14–0·17)	0·17 (0·15–0·18)	0·65
Beans	0·10 (0·09–0·11)	0·09 (0·08–0·10)	0·09 (0·08–0·10)	0·08 (0·08–0·09)	0·08 (0·07–0·09)	<0·0001
Poultry and eggs	0·82 (0·79–0·85)	0·97 (0·91–1·02)	0·78 (0·72–0·84)	0·84 (0·79–0·88)	0·98 (0·91–1·04)	0·011
Roots and tubers	0·12 (0·10–0·14)	0·10 (0·09–0·12)	0·09 (0·08–0·11)	0·08 (0·06–0·09)	0·07 (0·06–0·08)	<0·0001
Fruits and vegetables	0·36 (0·34–0·39)	0·32 (0·28–0·36)	0·25 (0·23–0·28)	0·30 (0·27–0·33)	0·36 (0·32–0·40)	0·84
Beef	3·26 (3·06–3·45)	4·00 (3·68–4·32)	3·18 (2·90–3·46)	3·26 (3·07–3·46)	3·30 (3·10–3·50)	0·11
Pork	0·13 (0·12–0·14)	0·08 (0·07–0·10)	0·09 (0·07–0·10)	0·09 (0·07–0·10)	0·15 (0·13–0·17)	0·11
Fish	1·23 (1·07–1·39)	1·16 (1·02–1·31)	1·22 (1·00–1·44)	1·21 (0·93–1·50)	1·23 (1·01–1·44)	0·89
Other unprocessed foods*	0·24 (0·22–0·25)	0·24 (0·21–0·27)	0·33 (0·29–0·37)	0·36 (0·33–0·40)	0·56 (0·50–0·61)	<0·0001
G2: processed culinary ingredients	0·82 (0·79–0·85)	0·73 (0·70–0·77)	0·72 (0·68–0·76)	0·64 (0·61–0·67)	0·71 (0·67–0·75)	<0·0001
Sugar	0·13 (0·12–0·13)	0·12 (0·11–0·13)	0·10 (0·10–0·11)	0·10 (0·09–0·10)	0·07 (0·07–0·08)	<0·0001
Vegetable oil	0·53 (0·50–0·56)	0·48 (0·45–0·51)	0·49 (0·45–0·52)	0·44 (0·41–0·47)	0·46 (0·43–0·49)	0·0068
Animal fat	0·12 (0·10–0·14)	0·09 (0·07–0·11)	0·10 (0·08–0·11)	0·07 (0·06–0·09)	0·13 (0·10–0·15)	0·94
Starch	0·01 (0·01–0·02)	0·01 (0·01–0·01)	0·01 (0·00–0·01)	0·01 (0·00–0·01)	0·01 (0·01–0·02)	0·89
Other culinary ingredients†	0·03 (0·03–0·03)	0·03 (0·03–0·03)	0·03 (0·02–0·03)	0·03 (0·02–0·03)	0·03 (0·03–0·04)	0·30
G3: processed foods	0·41 (0·37–0·44)	0·47 (0·40–0·53)	0·47 (0·42–0·52)	0·53 (0·48–0·59)	0·61 (0·56–0·67)	<0·0001
Processed bread	0·15 (0·14–0·16)	0·16 (0·15–0·17)	0·16 (0·15–0·18)	0·17 (0·16–0·18)	0·14 (0·13–0·15)	0·24
Cheese	0·10 (0·08–0·12)	0·13 (0·09–0·16)	0·13 (0·11–0·16)	0·16 (0·13–0·18)	0·23 (0·20–0·26)	<0·0001
Processed meat‡	0·10 (0·09–0·12)	0·11 (0·08–0·14)	0·10 (0·08–0·12)	0·11 (0·08–0·14)	0·13 (0·10–0·15)	0·18
Fermented alcoholic beverages	0·04 (0·03–0·05)	0·06 (0·05–0·07)	0·06 (0·05–0·07)	0·08 (0·05–0·10)	0·10 (0·09–0·12)	<0·0001
Canned or tinned fruits and vegetables	0·01 (0·01–0·01)	0·01 (0·01–0·01)	0·02 (0·01–0·02)	0·01 (0·01–0·02)	0·01 (0·01–0·01)	0·23
G4: ultra-processed food and drinks	0·78 (0·71–0·84)	0·97 (0·85–1·09)	1·5 (1·36–1·63)	1·80 (1·68–1·92)	2·21 (2·02–2·40)	<0·0001
Cookies, crackers, cakes, and pies	0·08 (0·07–0·08)	0·10 (0·09–0·11)	0·12 (0·11–0·13)	0·15 (0·14–0·16)	0·17 (0·16–0·18)	<0·0001
Margarine	0·21 (0·19–0·22)	0·16 (0·14–0·17)	0·23 (0·20–0·27)	0·25 (0·23–0·27)	0·23 (0·21–0·25)	<0·0001
Sweets	0·09 (0·07–0·11)	0·09 (0·07–0·11)	0·15 (0·13–0·18)	0·18 (0·15–0·21)	0·26 (0·23–0·30)	<0·0001
Sweetened beverages	0·06 (0·05–0·06)	0·09 (0·07–0·10)	0·17 (0·15–0·20)	0·19 (0·17–0·22)	0·22 (0·19–0·24)	<0·0001
Ultra-processed bread	0·02 (0·01–0·02)	0·02 (0·01–0·02)	0·02 (0·02–0·03)	0·03 (0·03–0·03)	0·04 (0·04–0·05)	<0·0001
Ultra-processed meat§	0·13 (0·12–0·15)	0·33 (0·28–0·38)	0·48 (0·41–0·55)	0·56 (0·51–0·61)	0·55 (0·48–0·62)	<0·0001
Ready-to-eat meals	0·04 (0·03–0·05)	0·06 (0·04–0·09)	0·06 (0·05–0·08)	0·11 (0·08–0·14)	0·26 (0·19–0·33)	<0·0001
Milk-based products	0·05 (0·04–0·06)	0·05 (0·04–0·06)	0·17 (0·13–0·20)	0·22 (0·19–0·25)	0·34 (0·30–0·38)	<0·0001
Other ultra-processed food¶	0·11 (0·08–0·14)	0·07 (0·06–0·09)	0·09 (0·08–0·10)	0·10 (0·08–0·12)	0·13 (0·11–0·15)	0·065
Total	9·69 (9·33–10·05)	10·58 (10·01–11·14)	9·96 (9·44–10·48)	10·4 (10·00–10·8)	11·36 (10·91–11·81)	<0·0001

Data are m^2/1000 kcal (95% CI). *Other unprocessed food: nuts, coffee, tea, home-made meals. †Other culinary ingredients: salt, baking powder, vinegar, honey. ‡Processed meat: salted, cured, or smoked meats. §Ultra-processed meat: chicken nuggets, sausages, burgers, hot dogs, and other reconstituted meat products. ¶Other ultra-processed food: distilled alcoholic beverages, coconut milk, industrialised sauces, and dried industrialised seasonings.

***Table 3:* Ecological footprint from food purchases according to NOVA food groups and subgroups in Brazilian metropolitan areas, 1987–88 to 2017–18**

consumption of ultra-processed meat has increased; therefore, the environmental effects from this product have at least doubled over the years. In addition to ultra-processed meat, other animal products (eg, cheese and milk) contribute to the increasing environmental effects across the 30-year period.

The results suggest a shift in the quality and quantity of meat in the diet. Although the effects related to fresh meat were stable throughout the study period, the environmental effects of processed meat decreased and the effects from ultra-processed meat products increased.

Our finding that animal product purchases drove increased environmental footprints is echoed by other studies. For example, a Chinese study found that animal products cause 30% of diet-related GHGE, 44% of the diet-related water footprint, and 27% of the diet-related ecological footprint.[7] In India, where the consumption of red meat is low, dairy products are one of the main drivers of GHGE, water footprint, and ecological footprint.[8] Although the results of the Chinese and Indian studies are shown separated by food groups, there is no information on the extent of food processing, and so further direct comparison with our results is not possible. In an Australian study, ultra-processed meat was the ultra-processed food with the largest contribution to GHGE, water footprint, and ecological footprint.[9]

The relationship between food systems and climate change is complex and challenges food security. On one hand, global food systems are one of the main drivers of climate change, causing around 33% of global GHGE.[4,5] On the other hand, food systems are vulnerable to changes in the climate. There is evidence that over the past 30 years, climatic changes have reduced agricultural productivity and have caused volatility in food prices, affecting the availability and access to nutritious foods in different areas of the world, particularly areas with low-income and that are more vulnerable to food insecurity.[33] Therefore, increases in GHGE, the water footprint, and the ecological footprint while providing the same amount of kcal, as observed in this study, might reduce the stability of environmental systems and threaten food security.[1]

The availability of ultra-processed foods (G4) is increasing in many countries.[34] This food group is known to be high in energy content and low in beneficial nutrients (eg, vitamins, minerals, and fibre),[23] and its consumption has been associated with an increased risk of diet-related morbidity.[22,23] Our study found that from 1987–88 to 2017–18, the contribution of G4 foods to daily environmental impact per individual at least doubled, reaching about 20% of total diet-related footprints. This means that per-person environmental impacts from these energy-dense and nutrient-poor products are increasing, which might affect both human and planetary health. The excessive caloric intake itself is known as a driver of environmental degradation. Because ultra-processed foods are associated with the overconsumption of calories, they indirectly generate negative effects on the environment. Therefore, limiting caloric consumption from ultra-processed foods is a simple strategy to control the environmental effects of diets.[18] For example, adjusting an hypercaloric diet into a normocaloric diet through the restriction of non-core foods such as ultra-processed products can reduce GHGE by 25%.[35] In addition, ultra-processed products derive from a food system based on few agricultural species cultivated in large areas, some obtained by forest clearing, which results in the negative effects of land conversion, chemical pollution, and biodiversity loss.[18,36] In Brazil, G4 food contribution to daily kcal and diet-related environmental effects is still lower than in higher-income countries such as Australia, where ultra-processed foods are responsible for 40% of daily kcal and more than a third of the total diet-related GHGE, water footprint, and ecological footprint.[9] However, if no action is taken and G4 food consumption continues to increase, Brazil will possibly reach the numbers seen in high-income countries, who are already struggling with high obesity rates and the sustainability implications associated with this (eg, health, economic, and social costs).

Our study has many strengths. To the best of our knowledge, this is the first study that has reported the trends in environmental cts of dietary changes considering the degree and purpose of food processing, according to the NOVA food classification system.[20] The analysis includes three different environmental indicators (GHGE, water footprint, and ecological footprint), using a compilation of data developed specifically to assess the Brazilian diet.[29] Finally, the study covered a period of 30 years, using data from the Brazilian Household Budget Survey, a representative sample of the population living in metropolitan areas.

The limitations of the study should be considered. First, because the dataset includes only Brazilian metropolitan areas, the estimates might not represent the reality in rural areas where the dietary patterns are different and the consumption of G4 foods is lower.[37] Second, the Household Budget Survey captures only food purchased for consumption at home, which represented about 87% of the total food consumption in 2009[38] (and this ratio might have changed over the study period). Third, the environmental footprints were estimated for foods as they are purchased, and cooking effects have not been considered in this analysis. If the effects of cooking were considered, GHGE would probably be higher, as cooking can contribute as much as 61% of GHGE for individual foods, particularly unprocessed or minimally processed foods.[39] The effects of cooking could change the results of our study, but are beyond the scope, since this estimation would require a survey of cooking habits such as that carried out for the UK.[39] Finally, due to the limitations of the data, we assumed a static nature of environmental impacts over time. This allowed us to focus our study on the changes in dietary choices, as separate from improvements in production practices and other changes in the food systems during this period that could affect the impacts.[5] However, it is unlikely that the effects of food production have remained the same. For example, in Sweden, where historical data are available, GHGE intensity (emission per unit of product) related to the production of animal products (beef, pork, chicken, dairy, and eggs) decreased around 20% in the 15 years from 1990 to 2005.[17] However, GHGE related to the consumption of animal products increased by 16% over the same period, due to an increase in the proportion of the diet made up of animal products.[17] Another study showed that variations in production methods can mean that GHGE and water footprint from the same food can vary by 460% and 200%, respectively, between different producers.[3] However, the effects of animal products typically markedly exceed those of plant based foods.[3] Thus, even if the production processes change, due to the increasing consumption of high impact food such as meat, the trends in environmental effects are expected to be similar. Finally, the lack of available information in terms of quantities and manufacturing of industrial ingredients or food grade chemicals such as preservatives and dyes has meant that it has not been possible to account for their effects or to include them in this study. Accounting for these ingredients would mainly increase the effects of G4 products.

Our findings show an increase in GHGE, water footprint, and ecological footprint from the Brazilian diet over 30 years, particularly from ultra-processed foods. This means that dietary patterns in Brazil are becoming potentially more harmful to human and planetary health. Therefore, a shift in the current trend would be needed to enhance sustainable healthy food systems.

Increasing environmental effects of food and beverages, influenced by the increased consumption of meat and dairy products in addition to ultra-processed foods, are being observed worldwide. To a large extent, the intensive production based on monocultures and all its environmental effects are linked to a globalised food system, which promotes this change in consumption patterns. This is a concern for many countries due to the effects of G4 food consumption on public health and environmental degradation. Our study showed the increase in consumption of G4 foods in Brazil in the past 30 years and assessed the environmental effects associated with the observed dietary changes. Hence, the results of our study could be roughly applied to other countries by comparing the country's amount and type of G4 products consumed and estimating the potential effects that this could have.

Additionally, understanding the effects of dietary changes, not only on public health but on the environment, in a large country such as Brazil will serve as evidence for promoting changes in the local and global food system; what is consumed in one country might have an effect in other countries, and as such changing the food system is key to improving environmental and health protection.

Our findings also suggest that diet-related diseases, climate change, and effects on key natural resources (water and land) share an underlying driver and therefore should be addressed simultaneously. Single and isolated interventions might not be able to change the current trends in diet-related environmental effects and G4 food consumption. Multicomponent actions and policies targeting multiple areas should be considered. For instance, fiscal interventions (taxes or subsides), regulation of advertising, and improving food and menu labelling with the possible addition of information on environmental effects.[21]

Brazil has committed to reducing GHGE under the Paris Agreement. The increase in GHGE from food purchases is one indicator that Brazil is moving in the opposite direction to its commitments. Therefore, the development and implementation of policies and measures to reach the Paris Agreement targets should be integrated into the Brazilian Nationally Determined Contributions framework, as well as public health, food, and nutrition policies to jointly reduce the environmental effects and the burden of diseases from the current Brazilian diet.

Contributors

SB, CR, XSR, JTdS, and RBL wrote the main research proposal that this manuscript is part of and got funding for this research. FR, JTdS, and RBL designed the scope of this manuscript. JMFG and CAMo provided data on the environmental impacts. JTdS, GLdC, and CAMa coded the data. RBL, FR, JMFG, GLdC, and JTdS have accessed and verified the underlying data. All authors have full access to all the data in the study. JTdS did the data analysis. JTdS, AK, XSR, and CR drafted the manuscript. FR and AK worked on the data visualisation. JMFG, FR, AK, XSR, AF, CAMa, MLdCL, CAMo, CR, SB, and RBL critically revised and edited the manuscript. RBL has primary responsibility for the final content. All authors have read and approved the final manuscript. All authors accept responsibility to submit for publication.

Declaration of interests

We declare no competing interests.

Data sharing

We have used publicly available data that can be found online. Data are available from the corresponding author on reasonable request.

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References

1 Willett W, Rockström J, Loken B, et al. Food in the anthropocene: the EAT-*Lancet* Commission on healthy diets from sustainable food systems. *Lancet* 2019; **393:** 447–92.
2 Swinburn BA, Kraak VI, Allender S, et al. The global syndemic of obesity, undernutrition, and climate change: the *Lancet* Commission report. *Lancet* 2019; **393:** 791–846.
3 Poore J, Nemecek T. Reducing food's environmental impacts through producers and consumers. *Science* 2018; **360:** 987–92.
4 Crippa M, Solazzo E, Guizzardi D, Monforti-Ferrario F, Tubiello FN, Leip A. Food systems are responsible for a third of global anthropogenic GHG emissions. *Nat Food* 2021; **2:** 198–209.
5 Tubiello FN, Rosenzweig C, Conchedda G, et al. Greenhouse gas emissions from food systems: building the evidence base. *Environ Res Lett* 2021; **16:** 065007.
6 Travassos GF, da Cunha DA, Coelho AB. The environmental impact of Brazilian adult's diet. *J Clean Prod* 2020; **272:** 122622.
7 Song G, Li M, Semakula HM, Zhang S. Food consumption and waste and the embedded carbon, water and ecological footprints of households in China. *Sci Total Environ* 2015; **529:** 191–97.
8 Athare TR, Pradhan P, Kropp JP. Environmental implications and socioeconomic characterisation of Indian diets. *Sci Total Environ* 2020; **737:** 139881
9 Hadjikakou M. Trimming the excess: environmental impacts of discretionary food consumption in Australia. *Ecol Econ* 2017; **131:** 119–28.
10 Galli A, Wiedmann T, Ercin E, Knoblauch D, Ewing B, Giljum S. Integrating ecological, carbon and water footprint into a "footprint family" of indicators: definition and role in tracking human pressure on the planet. *Ecol Indic* 2012; **16:** 100–12.
11 Fang K, Heijungs R, De Snoo GR. Theoretical exploration for the combination of the ecological, energy, carbon, and water footprints: overview of a footprint family. *Ecol Indic* 2014; **36:** 508–18.
12 Kissinger M, Dickler S. Interregional bio-physical connections—a "footprint family" analysis of Israel's beef supply system. *Ecol Indic* 2016; **69:** 882–91.
13 Reynolds CJ, Horgan GW, Whybrow S, Macdiarmid JI. Healthy and sustainable diets that meet greenhouse gas emission reduction targets and are affordable for different income groups in the UK. *Public Health Nutr* 2019; **22:** 1503–17.

14 Swensson LFJ, Tartanac F. Public food procurement for sustainable diets and food systems: the role of the regulatory framework. *Glob Food Secur* 2020; **25:** 100366.

15 Yin J, Yang D, Zhang X, et al. Diet shift: considering environment, health and food culture. *Sci Total Environ* 2020; **719:** 137484.

16 Chai BC, van der Voort JR, Grofelnik K, Eliasdottir HG, Klöss I, Perez-Cueto FJA. Which diet has the least environmental impact on our planet? A systematic review of vegan, vegetarian and omnivorous diets. *Sustainability* 2019; **11:** 4110.

17 Cederberg C, Hedenus F, Wirsenius S, Sonesson U. Trends in greenhouse gas emissions from consumption and production of animal food products—implications for long-term climate targets. *Animal* 2013; **7:** 330–40.

18 Fardet A, Rock E. Ultra-processed foods and food system sustainability: what are the links? *Sustainability* 2020; **12:** 6280.

19 Seferidi P, Scrinis G, Huybrechts I, Woods J, Vineis P, Millett C. The neglected environmental impacts of ultra-processed foods. *Lancet Planet Health* 2020; **4:** e437–38.

20 Monteiro CA, Cannon G, Levy RB, et al. Ultra-processed foods: what they are and how to identify them. *Public Health Nutr* 2019; **22:** 936–41.

21 Baker P, Machado P, Santos T, et al. Ultra-processed foods and the nutrition transition: global, regional and national trends, food systems transformations and political economy drivers. *Obes Rev* 2020; **21:** e13126.

22 Pagliai G, Dinu M, Madarena MP, Bonaccio M, Iacoviello L, Sofi F. Consumption of ultra-processed foods and health status: a systematic review and meta-analysis. *Br J Nutr* 2021; **125:** 308–18.

23 Monteiro CA, Cannon G, Lawrence M, Costa Louzada ML, Machado PP. Food and Agriculture Organization of the United Nations. Ultra-processed foods, diet quality, and health using the NOVA classification system. Rome: Food and Agriculture Organization of the United Nations, 2019.

24 Schmidt Rivera XC, Espinoza Orias N, Azapagic A. Life cycle environmental impacts of convenience food: comparison of ready and home-made meals. *J Clean Prod* 2014; **73:** 294–309.

25 Ministry of Health of Brazil, Secretariat of Health Care. Dietary guidelines for the Brazilian population. http://bvsms.saude.gov.br/bvs/publicacoes/dietary_guidelines_brazilian_population.pdf (accessed Dec 7, 2020).

26 Béné C, Fanzo J, Prager SD, et al. Global drivers of food system (un) sustainability: a multi-country correlation analysis. *PLoS One* 2020; **15:** e0231071.

27 Brazilian Institute of Geography and Statistics. POF—consumer expenditure survey. https://www.ibge.gov.br/en/statistics/social/health/17387-pof-2008-2009-en.html?edicao=19559&t=sobre (accessed Aug 11, 2021).

28 Universidade de São Paulo, Food Research Center. Tabela Brasileira de composição de alimentos. Version 7.0. 2019. http://www.fcf.usp.br/tbca (accessed March 30, 2020).

29 Garzillo JMF, Machado PP, Costa Louzada ML, Levy RB, Monteiro CA. Footprints of foods and culinary preparations consumed in Brazil. https://doi.org/10.11606/9788588848405 (accessed Dec 7, 2020).

30 Intergovernmental Panel on Climate Change. AR4 climate change 2007: the physical science basis. Solomon S, Qin D, Manning M, et al, eds. https://www.ipcc.ch/report/ar4/wg1/ (accessed Dec 7, 2020).

31 R Core Team. R: a language and environment for statistical computing. 2018. https://www.r-project.org/ (accessed Dec 7, 2020).

32 Martins APB, Levy RB, Claro RM, Moubarac JC, Monteiro CA. Increased contribution of ultra-processed food products in the Brazilian diet (1987–2009). *Rev Saude Publica* 2013; **47:** 656–65.

33 Mbow C, Rosenzweig C, Barioni LG, et al. Special report on climate change and land: food security. IPCC. https://www.ipcc.ch/srccl/chapter/chapter-5/ (accessed Dec 7, 2020).

34 Vandevijvere S, Jaacks LM, Monteiro CA, et al. Global trends in ultraprocessed food and drink product sales and their association with adult body mass index trajectories. *Obes Rev* 2019; **20** (suppl 2): 10–19.

35 Hendrie GA, Baird D, Ridoutt B, Hadjikakou M, Noakes M. Overconsumption of energy and excessive discretionary food intake inflates dietary greenhouse gas emissions in Australia. *Nutrients* 2016; **8:** 690.

36 Food and Agriculture Organization of the United Nations, WHO. Sustainable healthy diets—guiding principles. 2019. https://doi.org/10.4060/CA6640EN (accessed Dec 7, 2020).

37 Khandpur N, Cediel G, Obando DA, Jaime PC, Parra DC. Sociodemographic factors associated with the consumption of ultra-processed foods in Colombia. *Rev Saude Publica* 2020; **54:** 19.

38 Andrade GC, Gombi-Vaca MF, Costa Louzada ML, Azeredo CM, Levy RB. The consumption of ultra-processed foods according to eating out occasions. *Public Health Nutr* 2020; **23:** 1041–48.

39 Frankowska A, Rivera XS, Bridle S, et al. How home cooking methods and appliances affect the GHG emissions of food. *Nat Food* 2020; **1:** 787–91.