First Measurements of a Prototype of a New Generation Pixel Readout ASIC in 65 nm CMOS for Extreme Rate HEP Detectors at HL-LHC

ENVIRONMENTAL RESEARCH
FOOD SYSTEMS

PURPOSE-LED PUBLISHING™

Part of the ENVIRONMENTAL RESEARCH SERIES

PAPER • OPEN ACCESS

High-income countries dietary trajectories diverge from the global nutrition transition

To cite this article: Vittorio Giordano *et al* 2026 *Environ. Res.: Food Syst.* **3** 015005

ENVIRONMENTAL RESEARCH
FOOD SYSTEMS

OPEN ACCESS

RECEIVED
18 April 2025

REVISED
10 January 2026

ACCEPTED FOR PUBLICATION
27 January 2026

PUBLISHED
12 February 2026

PAPER

High-income countries dietary trajectories diverge from the global nutrition transition

Vittorio Giordano*, Marta Tuninetti and Francesco Laio

Department of Environment, Land, and Infrastructure Engineering, Politecnico di Torino, Corso Duca degli Abruzzi, 24, Torino 10129, Italy

* Author to whom any correspondence should be addressed.

E-mail: vittorio.giordano@polito.it, marta.tuninetti@polito.it and francesco.laio@polito.it

Keywords: dietary trajectories, food system, nutrition transition, compositional change, calories supply

Supplementary material for this article is available online

Abstract

Countries with rising incomes typically undergo a nutrition transition, marked by increasing consumption of animal-sourced foods and declining intakes of cereals and other plant-based products. However, large-scale, data-driven assessments of how diets worldwide align with this transition remain scarce. Here, we analyse dietary regimes in 188 countries, from 1970 to 2021, covering 370 food products, and identify a nutrition transition occurring at the global scale. On average, every tenfold increase in a country's per capita gross domestic product corresponds to a 13% rise in the dietary share of calories supplied by animal products and to a 15% decline in the share supplied by cereals. Nonetheless, in several high-income countries, such as Canada, Finland, Norway, New Zealand, Switzerland, and the UK, the dietary composition diverges from global trends, exhibiting declining caloric shares from animal-sourced foods alongside rising contributions from cereals and plant-based products.

1. Introduction

Growing food demand and diet shifts towards higher calorie and protein intake intensify human pressure on the environment [1, 2]. Current global food production and consumption generate one-third of global greenhouse gas emissions [3], they are the primary cause of freshwater consumption [4], release of polluting nutrients in the environment [5], biodiversity loss and terrestrial ecosystem destruction [6]. Between 1961 and 2022 food demand (calorie intake per capita) has increased by 36% and eating habits have profoundly changed [7].

Different and complex mechanisms shape food demand, such as affluence, demographic structure, urbanisation, culture, habits and physical activity levels [8]. These factors affect access to food and the composition of diets. The intensification and the industrialisation of agriculture have dramatically lowered the prices of animal-sourced products and processed foods [2], while fresh vegetables and fruits have become more expensive and less accessible [9]. The ongoing process of dietary shift is known as nutrition transition [8] and it is rapidly transforming food systems, with widespread consequences for public health and the environment. Diets are becoming sweeter and increasingly energy-dense, accompanied by increased portion sizes, away-from-home food intake and snacking. Eating patterns are shifting towards affluent diets high in sugar, fat, animal-source foods, highly processed products and empty calories [10, 11]. Nutritionally inadequate diets and reduced physical activity rates drive the incidence of overweight and non-communicable diseases (NCDs), while increasing the burdens of food production on natural resources and the environment. Despite the enormous variability in eating habits, this pattern has been observed worldwide, in high as well as low and middle income countries (LMICs) [10].

Multiple works have proposed pathways and scientific targets for achieving sustainable, equitable and healthier food systems [9, 12–16], as this is considered the most effective demand-side option to mitigate climate change [13, 17–19]. These include regenerative production practices, reduction of food loss and waste, food taxes, food environments that promote healthier diets, with balanced intake levels and rich in a variety of plant-based foods. Nevertheless, to the best of our knowledge, a comprehensive, data-driven analysis of current and historical dietary caloric composition, which assesses the adherence of diets to the nutrition transition is still missing. While some studies have examined the relation between food demand and income [1, 2, 20], or investigate transitions in food systems from a consumption standpoint [21], they typically encompass a limited amount of countries or food items [22–24]. In addition, although some works have developed future scenarios describing potential trajectories for global food consumption [1, 2, 11, 22], the present starting point of this urgent transition to healthier diets remains unclear.

With this article, we aim to address this knowledge gap by conducting a global analysis of the current state of food systems from the demand side. We examine the evolution of energy intake within food demand data series. Household income significantly influences the composition of food consumed and dietary change is closely correlated with variations in commodity prices [21, 25]. In countries undergoing economic development, income drives diet diversification, through the inclusion of new foods, typically non-starchy and energy-dense, such as vegetables, dairy, meat and oils, and the decline of dietary staples [2, 26]. Therefore, we investigate coupled trajectories of dietary caloric shares and per capita gross domestic product (GDP) over time, both at global and country scale. The shift towards unbalanced diets, along with rising obesity rates and NCDs, is only the most recent pattern in the nutrition transition [8]. Currently, most of the global diets align with the third pattern of receding famine or the fourth pattern, characterised by the spread of degenerative diseases [10, 22]. Nevertheless, a fifth pattern was theorised, where behavioural change encourages healthier eating habits [8, 20], but it has never been observed [11]. We develop a statistical framework to describe global dietary regimes, identify past and present transitions in countries' food demand, and highlight heterogeneities in the global trend. We show ever increasing animal-sourced products dietary share and declining caloric supply from cereals and plant-based products, depicting the nutrition transition as a globally emerging process. Nonetheless, several high-income countries, such as Canada, Finland, Norway, New Zealand, Switzerland, and the UK exhibit compositional changes opposed to global trends, reducing the caloric share derived from animal products in their diets and increasing the share of calories provided by cereals and plant-based foods, possibly indicating the onset of a new phase in the nutrition transition.

2. Methods

2.1. Dietary energy supply (DES) data

Per capita food supply data has been sourced from the FAOSTAT [7] database through Countries' Food Balances. The FAO food balance sheets (FBS) provide openly-accessible, nation-specific dietary estimates with global coverage, and yearly resolution spanning the period 1961–2021 (at the time of analysis). FBS provide the sources of supply and utilisation for each food item, both primary and processed commodities available for human consumption. A country's food supply consists of the total quantity of foodstuffs produced, added to the total quantity imported and adjusted to changes in stocks that may have occurred since the beginning of the reference period. The supply is then split into quantities exported, fed to livestock, used for seed, put to manufacture for food use and non-food uses, losses during storage and transportation and food supplies available for human consumption. The latter is then converted in per capita supply and expressed in terms of quantity and caloric value. In this work we have used the (DES, Kcal/capita/day) of 17 food items: Animal fats, Bovine Meat, Pig-meat, Poultry Meat, Eggs, Milk—Excluding Butter, Fish, Seafood, Cereals—Excluding Beer, Pulses, Soybeans and Groundnuts, Fruits—Excluding Wine, Starchy Roots, Nuts and products (Tree-nuts), Vegetables, Vegetable Oils, Sugar & Sweeteners. The selected food items match the 15 food groups available in the EAT-Lancet report [14, 16]—pulses, soybeans and groundnuts are aggregated into the Legumes item (supplementary table 1)—and account for 370 food products. We use the Healthy Reference Intake thresholds (table 1) from the EAT-Lancet report [14] as benchmarks to interpret the DES values presented in this study. These thresholds are expressed as shares of the total caloric supply of a reference diet of 2503 kcal/cap/day. They are intended as single, static benchmark values, not to evaluate national diets, but to indicate where an ideal healthy diet would fall in terms of caloric intake, introduced here for ease of interpretation, and should not be compared to more elaborate indices, such as the planetary health diet index [27], which adopts a flexible scoring approach. The FBS data set is divided in two parts, which cover the reference periods from 1961 to 2013 and 2010–2021, respectively, and compute food balances with different methodologies: the old methodology (1961–2013) and the new methodology (2010–2021). The main distinction between the two versions of the database lies in the absence of a balancer variable in the most recent version, which employs a balancing mechanism that proportionally distributes any imbalances across all components of the food balance. Conversely, in the old methodology, the unbalanced amounts are attributed to one component of the FBS (often stocks or feed), which inherits all statistical errors. This methodological difference introduces discrepancies between the old and the new DES time series, which we address as described in the following paragraph. The uncertainty associated with FBS data is another limitation of this data source. Comparisons with more accurate data from individual dietary surveys or household budget surveys suggested that FAO estimates can overestimate national dietary consumption [28]. The choice of expressing DES as shares limits the magnitude of the error, as the uncertainty is present in both terms of the ratio calculation. Finally, FAO estimates do not account for losses and waste that occur at the household level [16]. These quantities are present both in the total food supply data of a country and in any food-specific supply data; therefore, they do not affect the share of the DES, which we obtain by dividing food-specific DES by the total national DES.

2.2. Aggregation of food items and methodologies

We aggregate the individual FAO food items into four comprehensive categories: Animal products, Cereals (excluding beer), Sugars and sweeteners, and Plant-based products. Because commodities differ in energy yield per unit weight, aggregation is performed using their caloric content. The process of aggregation enhances statistical robustness, as the resulting categories exhibit higher DES shares with lower dispersion compared to individual food items. It also mitigates the uncertainty introduced by the two methodologies in the FAOSTAT dataset [7]. Moreover, this approach improves interpretability and readability by synthesising results while limiting the number of panels per figure. The analysis is carried out for 189 countries (encompassing 99.5% of the world population) and covers the period from 1961 to 2021 (last year available when the analysis was carried out). Since the study period encompasses both methodologies present in the FAOSTAT database [7], we assess the continuity between the two reference periods. Due to inconsistencies between the two methodologies, which occur for multiple food groups and countries, we establish maximum acceptability thresholds to determine whether to include or exclude entire countries' time series of DES data relative to a food category. This prevents us from joining time series that are inconsistent with each other and ensures the accuracy of our analysis. We compute the average percentage error across the four years covered by both methodologies (2010–2013), relative to the old methodology, and we exclude those time series with an error greater than 20%. In addition, we normalise the average residual across the four years with the standard deviation of the old methodology data, and we exclude the time series where this value exceeds twice the standard deviation of the old methodology data (supplementary figure S1 and S2). The first threshold ensures the gap between the time series is narrow, and the second ensures that this gap is comparable with previous oscillations in the data. Only those time series which comply with both thresholds are included in this analysis. This process reduces the coverage of our analysis, but the share of the population encompassed remains high: 95% for Animal products, 93% for Cereals, 91% for Plant-based products, 90% for Sugars & sweeteners. Once the selection process is complete, we join the old and new data series for all the food categories and countries. This join is performed by computing a weighted average over the overlapping four years, which assigns progressively higher weights (20% 2010, 40% 2011, 60% 2012, 80% 2013) to the new data and lower weights (80% 2010, 60% 2011, 40% 2012, 20% 2013) to the old (supplementary figure S1), creating a smooth transition from one to the other. We finally express the DES time series as a share of total DES. The same analysis is carried out for each of the 15 disaggregated food items matching the food groups of the EAT Lancet report—the results are shown in the Supplementary Material (supplementary figure S3–S17)—and for absolute caloric supply distributions of both aggregated and disaggregated food items (supplementary figure S18–S34).

2.3. Relationship between food consumption and GDP

We determine the dependence of global DES on per capita (GDP/cap) using GDP data of 189 countries, ranging from 1970 to 2021, sourced from the FAOSTAT Database. GDP is measured at constant 2015 US dollars, since 2015 is the base year for Macroeconomic Indicators series at constant prices from 1970 to 2023, to account for inflation and allow cross-country comparisons. As a measure that captures different economic realities, GDP is available across the spatial and temporal coverage of this study and, once adjusted for inflation, is frequently employed as an indirect indicator of per capita income. We employ 2nd order linear regression models to interpolate DES—GDP relations for the four food categories included in the analysis. Each of the four models contains an intercept, a linear and a squared term for the predictor, which we choose as the $\log_{10}$ of GDP, to limit the spread of per capita GDP, and uses ordinary least-square to fit the response variable. In addition, we perform quantile regressions of the 2nd order between $\log_{10}$(GDP) and DES, at different quantiles of the response variable probability distribution, using the R package 'quantreg' [29]. Quantile regression is a robust statistical method that estimates the conditional quantile function as a linear combination of the predictors [30]. We obtain models that estimate the predictive effect of GDP on 19 quantiles of global DES—from $Q_5(\text{DES}|\text{GDP})$ to $Q_{95}(\text{DES}|\text{GDP})$. We plot quantile regressions on $\log_{10}(\text{GDP})$ vs DES scatter plots (figure 2 and 3), where each point represents one year in a single country's DES data. We also show the healthy reference intake amount proposed by the EAT-Lancet dietary commission for individual food items, and in an aggregated form to match our composite food categories [14]. The healthy reference intake (expressed as share of kcal per capita per day) defines the global benchmark diet, it is reported for each food group and is the share of an average intake of 2500 kCal per day.

2.4. Identify single countries trajectories across quantile regressions

We look for cases of deviation from the nutrition transition we describe, namely trajectories that move across the quantiles of the DES probability distributions, rather then parallel to them. This indicates that a specific country has experienced a dietary transition over the years that contrasts the global DES-GDP relation. We estimate each country's quantile level in the DES distributions over the years. The quantile levels sequence from 1970 to 2021 is then fitted with a 1st order linear regression model (figure 4, insets (a)–(d)). The quantile level τ is the probability $P[\text{DES} \leqslant Q_\tau(\text{DES}|\text{GDP})|\text{GDP}]$, and corresponds to the value of DES below which the proportion of the conditional response population is τ, for a given GDP. In other words, it represents the proportion of the DES distribution associated with a quantile at a given GDP level. Therefore, the slope of the 1st degree polynomial shows the yearly rate of change of each country's trajectory across the global DES distributions. We then use the slope value to map each country on a global map and identify cases of deviation from the global trend, or those countries whose evolution follows closely the global nutrition transition.

3. Results

We analyse historical data of food-item specific DES (Kcal/capita/day), expressed as a share of the total energy supply (%, DES), relative to four main food groups: animal products, plant-based products, cereals and sugars (table 1, disaggregated food items are listed in supplementary table (1). DES reflects the food supply available for human consumption, converted to per capita energy supply and expressed in terms of caloric content. It represents the supply of food per person within a household, thus not its intake, as part of it is not eaten, but rather wasted [16, 31, 32]. DES shares illustrate the relative contribution of food groups to a country's diet, and are well suited to analysing changes in the predominance of different caloric sources and their substitution over time. By expressing DES in relative shares, we emphasise the study's focus on dietary composition and compositional changes, which may display distinct temporal dynamics compared to caloric supply expressed in absolute quantities (available in the supplementary material, supplementary figures S18–S34).

Our analysis documents a major and coherent shift occurring in dietary patterns since 1970. This is known as the nutrition transition [8] and is formally described by Bennett's Law [2, 33]. As per-capita GDP rises, the caloric share provided by starchy staple foods—such as cereals and tubers—declines and is replaced by nutrient-dense meats, oils, sweeteners, fruits, and vegetables. The ternary plots in figure 1 show the DES composition of multiple countries for 1970 to 2021 as barycentres in a three variables space. These are the DES of animal products, plant-based foods and the aggregation of cereals and sugars. By combining to 100% of the DES, they show the joint contribution of the food groups to dietary regimes. The DES of grains and plant-based foods has declined since 1970 in multiple countries, while the caloric supply of animal-based foods has increased globally. Both China and India, for example, were primarily relying on cereals as a source of calories in 1970, whereas in 2021 they have significantly increased the share of animal products in their diets. Countries whose diet was consisting mainly of plant based-foods (specifically tubers, blue area in figure 1) in 1970, show a progressive introduction of cereals in their diets, such as Tanzania. Bennett's theory suggests that the caloric fraction freed by the reduction in starchy staples is filled by energy-dense foods, rich in high-quality proteins, vitamins and minerals [26]. However, this caloric share is often taken up by highly processed foods, cheap animal products, fats, refined carbohydrates and vegetable oils. Fruits and vegetables are relegated to a smaller share of the diet and their availability tends to decrease [9].

3.1. The nutrition transition emerges in the global food regime

To unravel the nature of the nutrition transition, we investigate the global dependence of DES on GDP, for each of the four food categories, by modelling it with 2nd order linear regression models and quantile regressions. Figure 2 illustrates that the nutrition transition is not merely a country-specific trend, but a global phenomenon. It reflects systemic changes in the global food system and appears in the distributions of DES shares as an emergent property of a complex, interconnected system [34].

Table 1. Food groups aggregation and the respective healthy reference intake.

Food groups	FAO items included	Healthy reference intake	[%]
Animal-sourced food	Animal fats, bovine meat, eggs, fish, seafood, milk (excluding butter), pig meat, poultry meat	340	13.6
Cereals	Cereals (excluding beer)	811	32.4
Plant-based food	Fruits (excluding wine), legumes, starchy roots, treenuts, vegetables, vegetable oils	1232	49.2
Sugars & sweeteners	Sugars and sweeteners	120	4.8
Total		2503	100

Association between the food groups used in the analysis and the individual FAO [7] food items included in each group. The healthy reference intake (expressed in kcal per capita per day) defines the global benchmark proposed by the EAT Lancet commission [14] and is referred to an average intake of 2500 kcal per day.

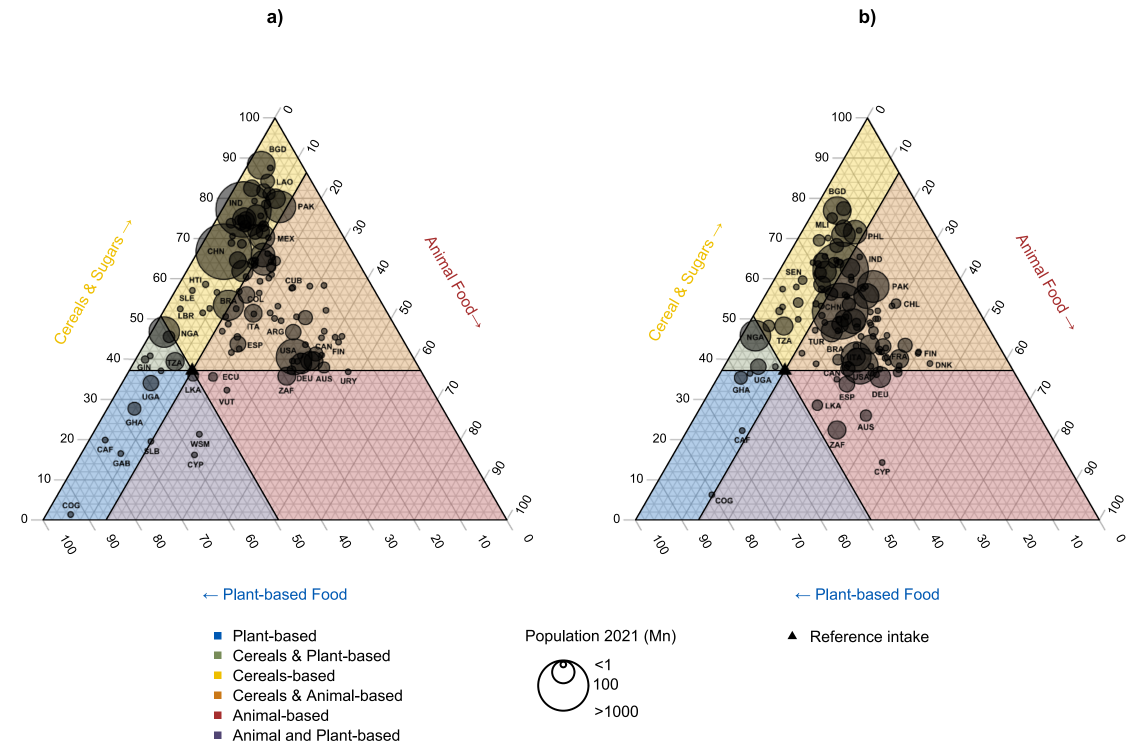

Figure 1. Ternary plots of dietary composition. The ternary plots show the dietary composition of each country as their barycentre in a three variable space, for (a) 1970 and (b) 2021. The three variables are DES of animal foods, plant-based foods and the aggregation of cereals and sugars. Black lines indicate the EAT-Lancet healthy reference intake (table 1), relative to the three food groups and cross in the black triangle which represents the barycentre of the EAT-Lancet healthy reference diet [14]. They indicate, respectively, recommended intakes and the recommended composition of a balanced diet, and offer a reference for comparison for countries' barycentres. The coloured regions are defined by the intersections of the black lines and define areas where one or two food groups dominate the dietary composition, by supplying the major share of calories. The size of the bubbles represents each country's population in 2021.

Animal-source foods DES ranges from dietary shares lower than 5% to over 40%. Our findings extend previous analyses [1, 2, 20, 22] to a global scope, revealing a significant correlation between animal products caloric share and GDP within the global food system, evident in both linear and quantile regressions (figure 2(a), suppl. table 2). This relation is consistent across multiple quantiles of the animal products DES probability distribution (suppl. table 3). The horizontal dashed line in figure 2 is the healthy reference intake (expressed as a share of kcal per capita per day), indicated by the EAT-Lancet commission [14]. It defines the global benchmark diet and it is specified for each food item, based on an average total intake of 2500 kcal per capita per day. Here, it is obtained by aggregating the reference intakes of the food items included in the animal-sourced food category and it sets at 14% (table 1). It is surpassed at relatively low GDP levels, with 56% of the distribution exceeding it, and 57% of countries reporting a higher DES in 2021. The global increase in animal-source caloric supply share is mainly driven by poultry meat, pig meat, milk and animal fats, while bovine meat, fish and seafood DES slowly grows with rising GDP and plateaus in high-income countries (supplementary figure S3–S9); very similar patterns are shown in the absolute caloric supply distributions (supplementary figure S18a, S20–S26)

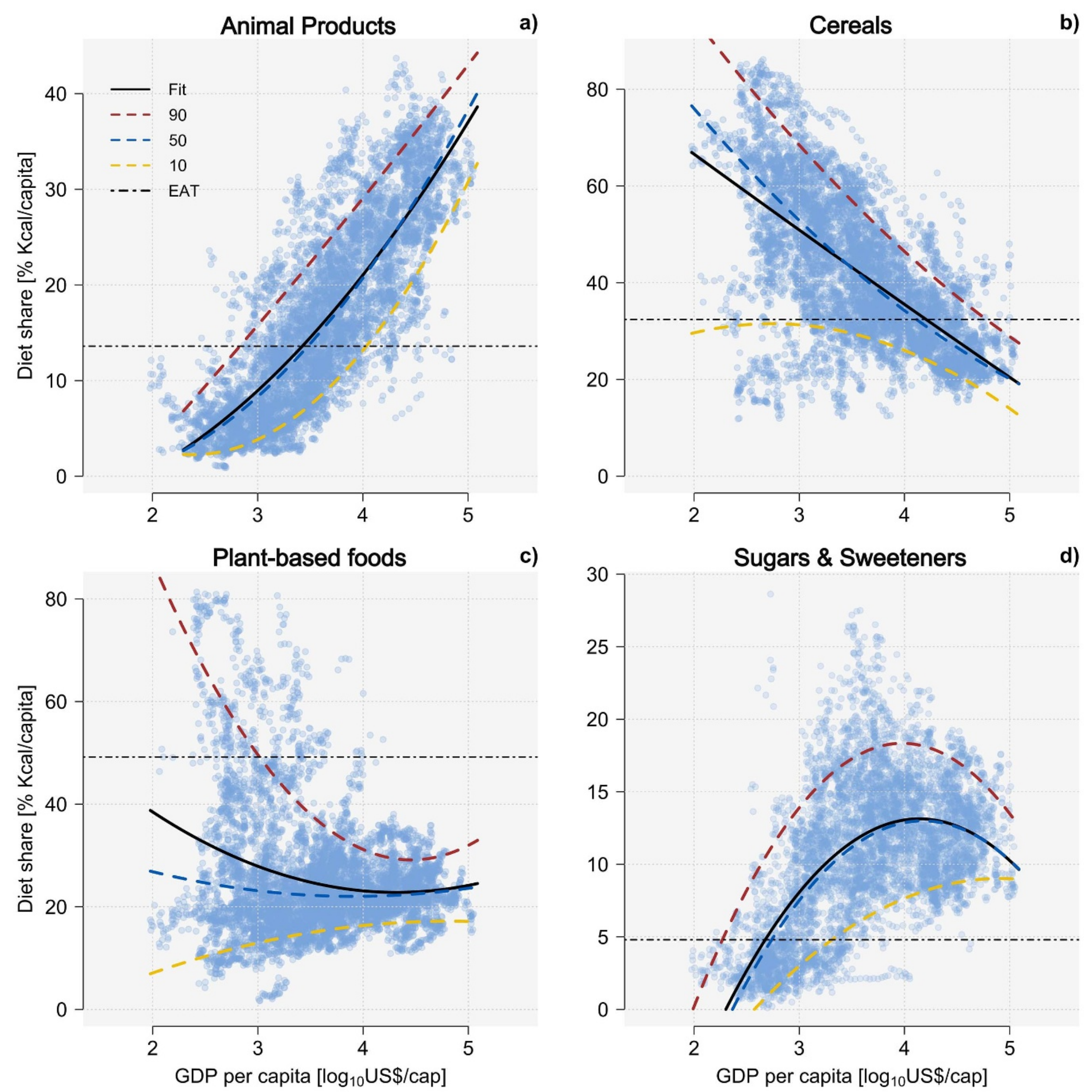

Figure 2. Scatter plots of global dietary energy supply shares and GDP for four main food groups. Each point represents a country-year observation of dietary energy supply (DES), expressed as the share of kcal per capita, plotted against the logarithm of per capita GDP in US dollars, with purchasing power parity at 2015. The black line shows the distribution fitting by a second degree polynomial linear regression, while the red, blue and yellow dashed lines indicate, respectively, the 90th, 50th (median) and 10th quantile regressions (The terms of the linear and quantile regressions are available in supplementary tables 2 and 3, with their statistical significance). Horizontal black dashed lines show the healthy reference intake amount suggested by the EAT-Lancet dietary commission [14]. (a) Animal foods. (b) Cereals (c) plant-based foods, (d) sugars & sweeteners.

Contrarily to animal products, the relative caloric supply from cereals decreases markedly with rising GDP (figure 2(b). Although low cereal DES can be observed at low GDP levels below the 10th quantile, on average, cereals DES declines from 70% to 20% of the total diet across the GDP range. In absolute terms (supplementary figure S18(b)), however, the reduction in calories provided by cereals is less pronounced, particularly in upper-middle- and high-income countries. While cereals remain a global dietary staple, they show diminishing caloric shares in diets where total caloric intake is increasing. This reflects a compositional change towards other sources of calories, such as animal-sourced foods, which fill the dietary gap created by declining cereal consumption [33]. Plant-based foods (figure 2(c)) and cereals DES shares distributions exhibit heterogeneous values at low GDP levels, while their inter-quantile ranges narrow at higher GDP levels. This reduction in the dispersion indicates a convergence towards low cereal and plant-based foods DES [26, 33] and a global homogenisation of diets, that become more similar and westernised [10, 21]. Only 6% of plant-based foods distribution exceeds the reference intake, and just 5% of countries achieve a healthy DES in 2021, all of which are African countries (Angola, Burundi, Central African Republic, Congo, Democratic Republic of the Congo, Ghana, Nigeria, Rwanda, Uganda). The decline in plant-based products caloric supply is primarily driven by the significant reduction in starchy roots and legumes DES, both in relative and absolute terms, for high-GDP levels (supplementary figures S10–S17 and S28–S33). Although high-income countries exhibit a rise in the total calories supplied by plant-based foods (supplementary figure S18(c)), this increase is not visible in the distribution of DES shares, because it is outweighed by a larger rise in total caloric intake. As a result, the increase in plant-based calories does not reflect a compositional dietary change, nor does it indicate substitution of other calories sources. These results contrast markedly with the recommended intake and with the urgency of a protein transition away from animal sourced-proteins [35]. Sugars DES share regressions show a maximum around 10^4 US$/capita GDP, followed by a notable decline in both the 90th and 50th quantile regressions, as well as in the linear regression (−27%), at higher GDP per capita levels (figure 2(d)). Despite this decline, 82% of the DES distribution remains above the reference intake. In 2021, 61% of countries record a proportion of energy supplied by sugar that exceeds the recommended level. The linear regression of absolute caloric supply by sugars shows a less marked reduction and a peak at higher GDP levels (supplementary figure S18(d)). Even in high-income countries, both in absolute and relative terms, sugar DES remains more than double the recommended intake.

3.2. Country-scale divergences from the global pattern contrast the nutrition transition

Despite the global trends depicted in figure 2, individual countries DES exhibit considerable heterogeneity, at times contrasting with the global pattern. We highlight specific trajectories that deviate from the global DES-GDP relationship. Several high-income countries show a reduction in the dietary share of animal products since 1970, such as Canada and Norway, which exhibit, respectively, a reduction of 12.3 and 7.9 percentage points (pp) (figure 3(a), figure S19). This correspond to an average decline of 154.8 and 104.2 Kcal/capita/day, respectively, or a 15.4% and 9.4% reduction in animal food absolute caloric supply (supplementary figure S19(a), supplementary table 4). Furthermore, over the past 50 years, these countries have transitioned from having the highest DES share from animal products in 1970, within their GDP group, to the lowest in 2021. Their trajectories move across the entire quantile range, shifting from the 95th and 90th quantiles, respectively, to the 10th. Beyond reducing their animal food dietary share, these countries experienced dietary transitions which show a dynamic that is orthogonal to the global quantile regressions. However, their animal foods DES remains well above the healthy reference intake recommended by the EAT Commission [14]. In both cases, the main food items contributing to the decline are dairies and animal fats; bovine meat DES also decreases in Canada, while it slightly rises in Norway; poultry meat shows rising trends in relative as well as in absolute terms (supplementary figures S3–S9, supplementary table 5). In contrast, Brazil and Portugal exhibit a pronounced increase in their animal-sourced food DES-GDP relationship, which amounts to 13.0 and 15.1 pp in their DES share, respectively (+175.6% and +144.6% in their absolute caloric supply), coherent among individual animal-based food items and which exceeds the global trend slope (figure 3). The same countries show reversed patterns in their cereal DES (figure 3(b), figure S19). Both Brazil and Portugal record a decline in their dietary share (−7.6 and −11.8 pp) as GDP increases, Portugal's absolute caloric supply from cereals decreases as well (−214.0 Kcal/capita/day), while Brazil's remains stable. These results indicate a compositional change in these countries' diets: the caloric fraction freed by the decline in cereals DES share is replaced by animal-sourced calories. Conversely, Canada and Norway show rising cereal DES shares (+4.3 and +5.6 pp) and growing cereal caloric supplies (+56.6% and +43.2%), which reflect a shift in their diet composition opposed to the typical pattern described by Bennett's Law. In the case of Canada, this is further supported by a 117.9% increase in its absolute DES from plant-based foods (+689.1 Kcal/capita/day), primarily driven by vegetable oils caloric supply, but also by fruits, vegetables and treenuts (supplementary figures S16, S19–S33, supplementary table 5).

Figure 4 illustrates how the diet composition has evolved across countries relative to the global DES share pattern, between 1970 and 2021. The figure maps each country by the slope of the polynomial interpolating its trajectory across the distribution (figure 4, insets (a)–(d); see Methods). The slope represents the yearly rate of change of DES, relative to the global distribution, since 1970. The analysis reveals distinct trends among various countries and food categories. For animal-sourced foods, several countries including Canada, Norway, the United Kingdom, Germany, Austria, Switzerland, Slovenia, the United States, Cuba, Uruguay, Mali, Ethiopia, Yemen, Azerbaijan, Nepal, and New Zealand exhibit significant negative rates in animal foods DES. This indicates that diets in these countries include a declining share of animal sourced calories over time, relative to the global trend. In contrast, Central African Republic, Croatia, Brazil and Portugal exhibit positive rates, indicating a more pronounced increase in animal-sourced products DES than the global average. Nevertheless, a predominance of countries with negative rates can be seen for animal foods, as well as for Sugar & sweeteners (figure 4(d)), while in the case of plant-based foods positive rates dominate (figure 4(c). This shows that the plant-based foods DES of most countries is shifting towards higher quantiles in the global distribution, which means that, over time, a growing share of calories is being supplied by plant-based foods.

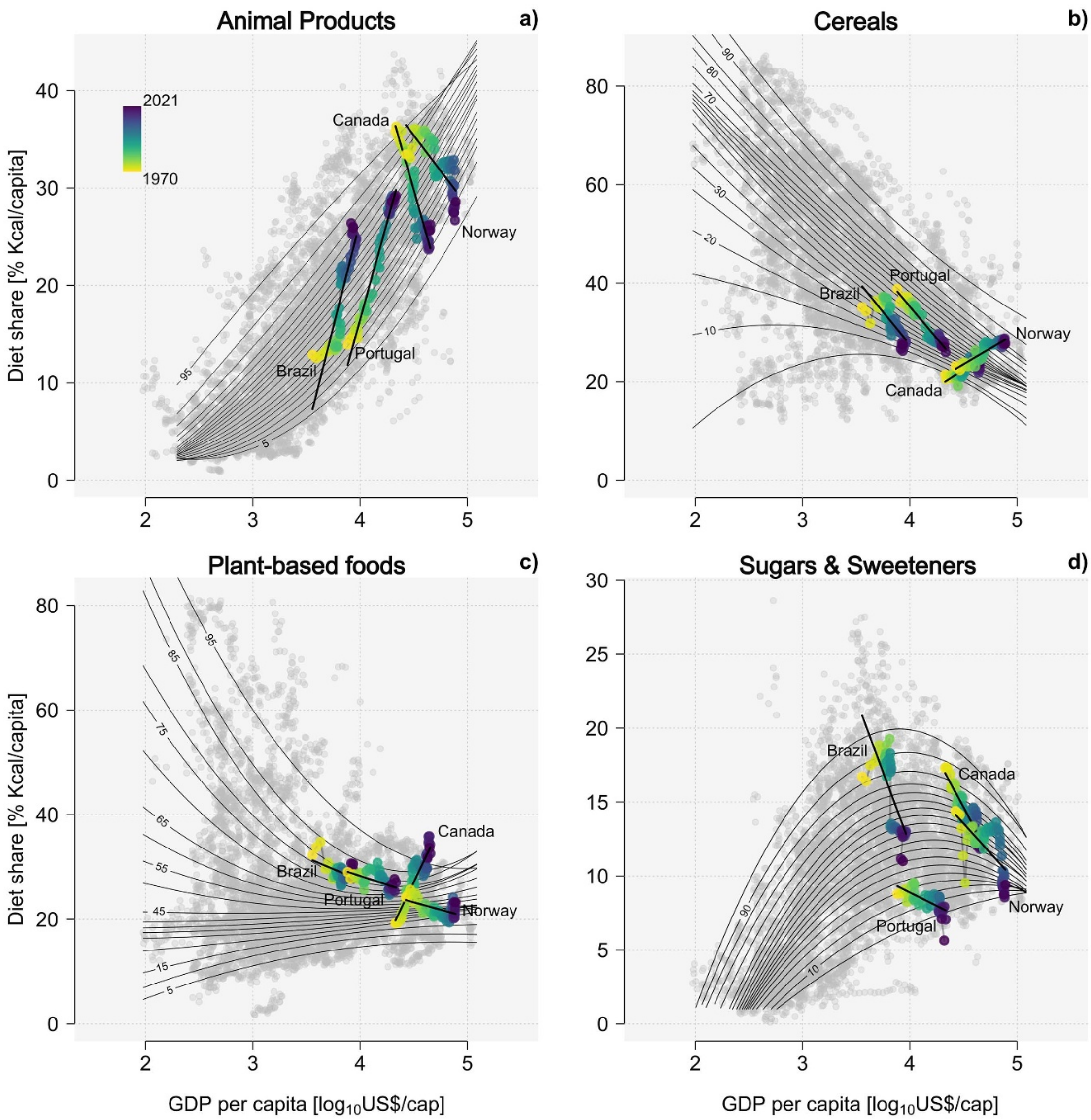

Figure 3. Individual countries transitions. Brazil, Canada, Norway and Portugal DES-GDP relations for (a) Animal-sourced foods (b) Cereals (c) Plant-based foods, (d) Sugars & sweeteners. Colour indicate time, from 1970 in yellow to 2021 in purple. National data are highlighted against the global DES-GDP distributions (grey dots) of the four main food groups and their quantile regressions (black lines).

4. Discussion

This work examines the evolution of relative caloric intake in food demand time series and assesses its consistency with the nutrition transition pattern. We develop a statistical framework to identify the occurrence of the nutrition transition at the national and global scale. Our results provide data-driven evidence of past and ongoing shifts in national food demand, revealing the global scope of the nutrition transition, and highlighting heterogeneities across countries. Countries moving from lower to higher income levels experience rapid changes in their dietary habits, driven by urbanisation, motorised transportation, sedentary lifestyles and the availability of cheap, ultra-processed foods and beverages [10]. Globalisation, large-scale agricultural production, long-haul transportation and the availability of cheap energy from fossil fuels, have shaped this process worldwide [9, 25]. We show ever increasing animal-sourced products caloric supply with rising GDP, globally, driven by increasing dietary shares and intakes of animal fats, dairy foods, poultry meat and pig meat. This dramatic increase in livestock production has been driven by the 'livestock revolution', a productive system dependent on concentrated animal feed operations that shifted caloric provision from cereals to animal-sourced foods, and increased the dependency of emerging economies on feed imports [2, 36, 37]. The decline in animal products prices is another key driver of overconsumption, which results from agricultural policies that prioritise cheaper, energy-rich grains and animal-source foods, along with trade liberalisation [9].

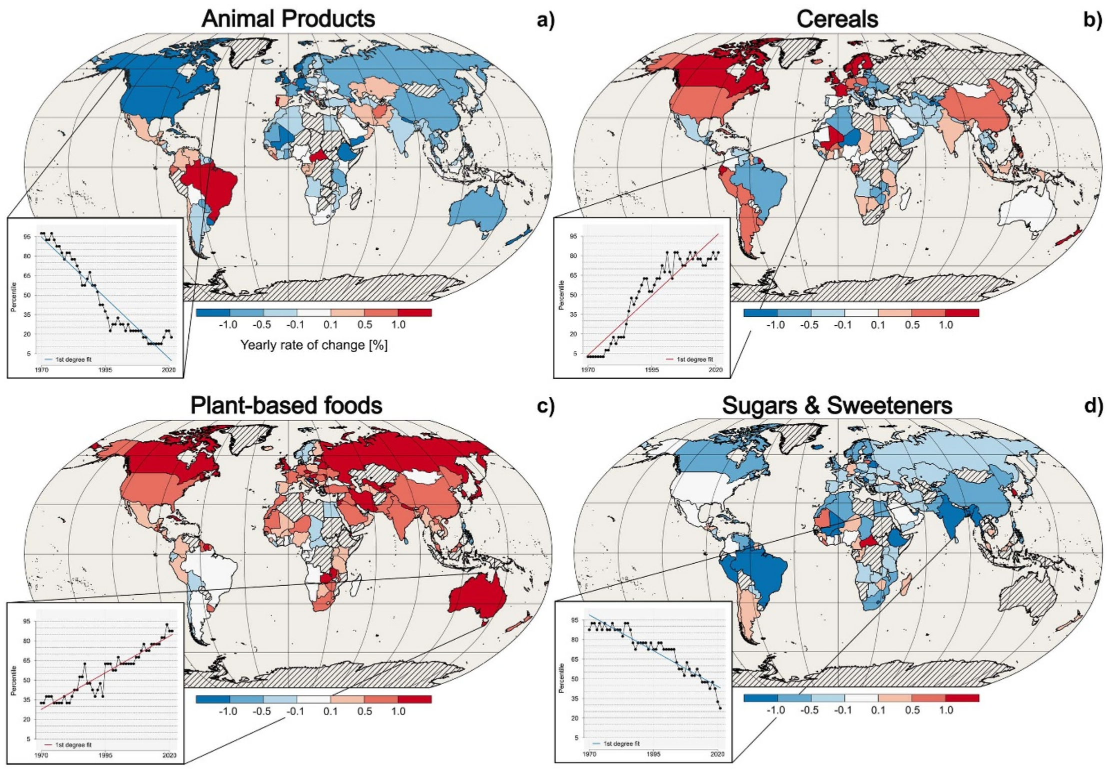

Figure 4. Global maps of countries' trajectories slopes. Each country is shown on the map based on how its DES has changed over time compared to the global trend. The slope of the linear regression fitting a country yearly position among the quantiles of the global distribution defines the colour associated to each country. A blue colour indicates that the country's share of calories supplied by a food group has decreased since 1970, compared to the global average (negative slope), while red denotes an increase in the DES compared to the global average (positive slope). Countries represented in white have shifted their DES coherently with the global pattern, since 1970. The four insets on the map exemplify the association of a colour to a country, based on the slope of the linear regression, which indicates the yearly rate of change of a country's trajectory across the quantiles of the global distribution. (a) Canada—animal foods. Canada has shifted its position in the global distribution from being above the 95th quantile in 1970, to being below the 20th in 2021, relative to its GDP. This results in a rate of change lower than −1% per year and the respective blue colour associated to Canada in the map. (b) Mali—cereals, (c) Australia—plant-based foods, (d) India—sugars and sweeteners. Countries with missing or unreliable data are shown with dashed patterns.

We show how the share of energy derived from cereals and plant-based foods, as well as the dispersion in their distributions, decrease with increasing GDP. The caloric supply of staples, such as cereals and tubers, vegetables, fruits and legumes converges to lower shares, approaching those of western diets. The 'retail revolution' has led to the rapid spread of supermarkets, while improvements in technology, logistics and supply chains have allowed large retailers to compete with local outlets, thus replacing the fresh market as the primary source of food supply [8]. This process made cheap, processed food high in fat, added-sugar and salt a convenient, inexpensive and ready to eat food choice whose demand is on the rise, especially in LMICs [9]. Indeed, our results show an increase in Sugar DES regressions up to a GDP of approximately 10^4 US$/capita, after which this tendency inverts, and Sugar DES shares notably decline at higher GDP levels. This shows that, consistently across upper-middle- and high-income countries, such as Canada, the United States, European countries, China, Brazil, Peru, and especially where food taxes, healthcare recommendations, and public health initiatives have targeted sugar and sweeteners, their presence in diets has shrunk [38–40]. The trend inversion we show emerges coherently across multiple countries and reflects a global tendency towards reduced dietary shares of sugars and sweeteners. Nevertheless, the absolute caloric supply distribution shows a more protracted increase towards high GDP levels, where a peak can be identified in the regressions, followed only by a slight decrease. This implies continued sugar intakes, which stagnates at high income levels, remaining well above the recommended intake.

Although our results, at the global scale, align with nutrition transition theory and Bennett's Law, which suggests that countries shift their caloric provision from cereals to animal products as GDP rises, we find instances of high-income countries in which an opposite compositional change occurs. Between 1970 and 2021, Canada, Finland, Norway, New Zealand, Switzerland and the UK show declining DES by animal products and increasing DES derived from cereals (stable in Switzerland), both in absolute and relative terms, as shown in Supplementary table 4. These shifts are mainly driven by declining animal fats, beef (except in Norway and New Zealand) and milk (stable in Finland) DES , while poultry meat caloric supply increases both in absolute and relative terms, for all countries mentioned above (supplementary table 5). We argue that such coherent trends in both total caloric supplies and caloric fractions constitute compositional changes towards diets less reliant on animal products and more on cereals for daily energy supply, although it must be noted that animal-based food intakes remain above recommended levels. In contrast to global trends, this compositional changes in high-income countries occur within a narrow GDP range, suggesting that its underlying drivers are not solely economic but also linked to shifting societal norms and consumer behaviours [21]. Indeed, In Europe and North America, per capita consumption of fresh dairy products and animal fats is declining, and consumer preferences are shifting from beef and pork toward poultry, which remains the primary driver of growth in protein supply from meat [41]. In addition, growing attention to animal welfare, environmental sustainability, and health has led to stagnating or even decreasing per capita meat consumption [41]. Concurrently, plant-based substitutes for dairy and meat are becoming increasingly established and competitive in the market [41]. Indeed, our results show that the substitution of animal calories is complemented by an increase in plant-based foods DES, both relative and absolute, led by vegetable oil consumption, but also legumes, fruits, nuts and vegetables in Canada, Finland, New Zealand, Switzerland and the UK (supplementary tables 4 and 5). In Austria, Germany and the USA, while animal-sourced food DES remains stable, increases in absolute and relative DES by cereals and plant-based food can be observed, which also indicate compositional dietary changes. In countries where we observe compositional shifts away from animal-based calories, previous studies show that dietary changes aligned with the EAT-Lancet recommendations can reduce water footprints and greenhouse gas emissions [16, 42]. Lowering intakes of red meat and fats also provides health benefits while reducing nutrient pollution, land use, land clearing and habitat disturbance, freshwater use, and biodiversity loss [1, 43]. However, the magnitude and nature of these benefits depend strongly on the type of compositional change and the calorie sources involved: whether the shift occurs within animal products (e.g. from beef to poultry or fish) or from animal products toward cereals and plant-based sources.

At the global scale, we do not observe any compositional shift toward cereal- or plant-based calories, nor toward pulses specifically, which would reveal the occurrence of a protein transition [35]. Instead, legumes DES continues to decline in both absolute and relative terms, reaching levels far below recommended intakes. Cereals and starchy roots also decline, but approach their respective healthy reference intake. Treenuts DES increases, but remains below one-third of the recommended level, while the caloric shares of fruits and vegetables approach recommended intake levels (supplementary figures S3–S17, S20–S34). In contrast, the absolute caloric supply of animal fats, bovine meat, dairy products, pig meat, and poultry continues to rise and exceeds recommended intakes.

This study examines historical data on (DES, kcal/capita/day), expressed as a share of total energy supply, at both national and global levels. Absolute and relative caloric intakes provide different yet complementary perspectives on dietary patterns and transitions. In this work, we focus primarily on DES shares, as they more accurately capture diet composition and the relative contributions of multiple food products to daily energy supply, and are particularly well suited to identifying compositional changes and investigating the nutrition transition. The aggregated categories of animal-sourced and plant-based foods used for synthesis include items with diverse health and environmental implications. This also applies to the aggregated reference intakes, which combine several distinct food items for consistency. For providing the interested reader with a more complete information, we show all the relevant analyses for each individual food item in the Supplementary material. While calories quantify the energy provided by food, they are not the sole indicator of diet quality. Future analyses should incorporate macronutrients (proteins, carbohydrates, fats) and micronutrients. Integrating individual dietary surveys or household budget surveys would also allow the inclusion of additional explanatory variables, such as age, sex, urban or rural residence, and education level, thereby capturing within-country inequalities, wealth distribution and enabling sub-national assessments. Finally, limitations arise from uncertainties in the source data, which require extensive preprocessing due to the coexistence of two different FAOSTAT methodologies. Future research could further investigate the drivers underlying the dietary transitions identified in this study.

5. Conclusions

In this work, we provide clear evidence of a global nutrition transition by examining the distributions of DES shares in relation to per capita GDP for four major food categories and their constituent food items. We show that rising GDP is consistently associated with higher caloric shares from animal-sourced foods, declining shares from cereals and plant-based products, and a peak in sugars for intermediate

GDP levels, followed by a decline; patterns that align with trends observed in absolute caloric supply. At the country level, however, we identify substantial heterogeneity, including cases that diverge from the global transition trajectory. Notably, our results reveal emerging compositional shifts in certain high-income countries, where both absolute and relative DES from animal products decrease while cereals and plant-based foods gain prominence as sources of calories. Yet, despite these reductions, animal-sourced foods still contribute caloric shares that exceed recommended intake levels. Reducing the dietary share of animal-based products holds significant potential for environmental mitigation [13, 15]; however, such a change must be considered in light of regional nutritional contexts to ensure that efforts to promote healthier and more sustainable diets also support equitable food access and nutritional adequacy worldwide.

Data availability statement

The data that support the findings of this study are openly available at the following URL/DOI: https://github.com/vittorio-giordano/High-income-countries-dietary-trajectories-diverge-from-the-global-nutrition-transition [44].

Supplementary data available at https://doi.org/10.1088/2976-601X/ae3ded/data1.

Code Availability

All scripts developed for the analyses and for generating the results are available on GitHub: https://github.com/vittorio-giordano/Country-level-dietary-trajectories-unexplained-by-affluence-amidst-a-global-nutrition-transition.

Acknowledgment

The authors acknowledge funding support provided by the European Research Council (ERC) through the project 'Social Tipping Point in the Food System for Freshwater Sustainability' (ERC-2025 StG, project 101161244).

Conflcts of interest

The authors declare no competing interests.

Author contributions

Vittorio Giordano 0009-0005-5613-8177
Conceptualization (equal), Data curation (lead), Formal analysis (lead), Investigation (equal), Methodology (equal), Visualization (lead), Writing – original draft (lead), Writing – review & editing (lead)

Marta Tuninetti 0000-0003-2619-8783
Conceptualization (equal), Formal analysis (equal), Funding acquisition (equal), Investigation (equal), Methodology (equal), Supervision (lead), Visualization (supporting), Writing – original draft (supporting), Writing – review & editing (supporting)

Francesco Laio 0000-0003-3931-1482
Conceptualization (equal), Formal analysis (equal), Funding acquisition (lead), Investigation (equal), Methodology (equal), Supervision (lead), Visualization (supporting), Writing – review & editing (supporting)

References

[1] Tilman D and Clark M 2014 Global diets link environmental sustainability and human health *Nature* **515** 518–522
[2] D'Odorico P *et al* 2018 The global food-energy-water nexus *Rev. Geophys.* **56** 456–531
[3] Crippa M, Solazzo E, Guizzardi D, Monforti-Ferrario F, Tubiello F N and Leip A 2021 Food systems are responsible for a third of global anthropogenic GHG emissions *Nat. Food* **2** 198–209
[4] Hoekstra A Y , Mekonnen M M 2012 The water footprint of humanity *Proc. Natl Acad. Sci. USA* **109** 3232–72
[5] Peñuelas J *et al* Human-induced nitrogen-phosphorus imbalances alter natural and managed ecosystems across the globe *Nat. Commun.* **4** 2934
[6] Boakes E H, Dalin C, Etard A and Newbold T 2024 Impacts of the global food system on terrestrial biodiversity from land use and climate change *Nat. Commun.* **15** 5750

[7] FAOSTAT Food and Agriculture organization (available at: http://faostat.fao.org)
[8] Popkin B 2006 M Global nutrition dynamics: the world is shifting rapidly toward a diet linked with noncommunicable diseases *Am. J. Clin. Nutr.* **84** 289–98
[9] Swinburn B A *et al* 2019 The global syndemic of obesity, undernutrition and climate change: the lancet commission report *Lancet* **393** 791–846
[10] Popkin B M, Corvalan C and Grummer-Strawn L M 2020 Dynamics of the double burden of malnutrition and the changing nutrition reality *Lancet* **395** 65–74
[11] Bodirsky B L *et al* 2020 The ongoing nutrition transition thwarts long-term targets for food security, public health and environmental protection *Sci. Rep.* **10** 19778
[12] Rockström J, Edenhofer O, Gaertner J and DeClerck F 2020 *Planet-proofing the global food system Nat. Food* **1** 3–5
[13] Humpenöder F *et al* 2024 Food matters: dietary shifts increase the feasibility of 1.5°c pathways in line with the paris agreement *Sci. Adv.* **10** eadj3832
[14] Willett W *et al* 2019 Food in the Anthropocene: the EAT-*Lancet* Commission on healthy diets from sustainable food systems *Lancet* **393** 447–492
[15] Springmann M *et al* 2018 Options for keeping the food system within environmental limits *Nature* **562** 519–525
[16] Tuninetti M, Ridolfi L and Laio F 2022 Compliance with eat-lancet dietary guidelines would reduce global water footprint but increase it for 40% of the world population *Nat. Food* **3** 143–151
[17] Shukla P *et al* 2022 Climate change 2022: mitigation of climate change *Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* (Cambridge University Press)
[18] Clark M A, Domingo N G G, Colgan K, Thakrar S K, Tilman D, Lynch J, Azevedo I L and Hill J D 2020 Global food system emissions could preclude achieving the 1.5° and 2°C climate change targets *Science* **370** 705–708
[19] Li Y, He P, Shan Y, Li Y, Hang Y, Shao S, Ruzzenenti F and Hubacek K 2024 Reducing climate change impacts from the global food system through diet shifts *Nat. Clim. Change* **14** 943–953
[20] Vranken L, Avermaete T, Petalios D and Mathijs E 2014 Curbing global meat consumption: emerging evidence of a second nutrition transition *Environ. Sci. Policy* **39** 95–106
[21] Moberg E *et al* 2021 Combined innovations in public policy, the private sector and culture can drive sustainability transitions in food systems *Nat. Food* **2** 282–290
[22] Mathijs E 2015 Exploring future patterns of meat consumption *Meat Sci.* **109** 112–116
[23] Clifford Astbury C, Aguirre E, Cullerton K, Monsivais P and Penney T L 2021 How supportive is the global food supply of food-based dietary guidelines? a descriptive time series analysis of food supply alignment from 1961 to 2013 *SSM - Populat. Health* **15** 100866
[24] Kastner T, Rivas M J I, Koch W and Nonhebel S 2012 Global changes in diets and the consequences for land requirements for food *Proc. Natl Acad. Sci. USA* **109** 6868–68722012
[25] D'Odorico P, Carr J A, Laio F, Ridolfi L and Vandoni S 2014 Feeding humanity through global food trade *Earth's Future* **2** 458–469
[26] Bennett M K 1941 International contrasts in food consumption *Geogr. Rev.* **31** 365–376
[27] Gu X *et al* 2024 Global adherence to a healthy and sustainable diet and potential reduction in premature death *Proc. Natl Acad. Sci. USA* 121
[28] Del Gobbo L C , Khatibzadeh S, Imamura F, Micha R, Shi P, Smith M, Myers S S and Mozaffarian D 2015 Assessing global dietary habits: a comparison of national estimates from the FAO and the Global Dietary Database23 *Am. J. Clin. Nutr.* **101** 1038–10462015
[29] Koenker R 2023 Quantreg: quantile regression (available at: https://CRAN.R-project.org/package = quantreg R package version 5.97)
[30] Koenker R 2005 *Quantile Regression* (Cambridge University Press)
[31] Semeria F, Ridolfi L and Tuninetti M 2024 A multi-level network tool to trace wasted water from farm to fork and backwards *Environ. Res. Lett.*
[32] Godfray H C J *et al* 2010 Food security: the challenge of feeding 9 billion people *Science* **327** 812–818
[33] Bennett M K 1941 *Wheat Studies of the Food Research Institute* vol 12 (Stanford University)
[34] Leeuwis C, Boogaard B K and Atta-Krah K 2021 How food systems change (or not): governance implications for system transformation processes *Food Sec.* **13** 761–780
[35] Duluins O and Baret P V 2024 A systematic review of the definitions, narratives and paths forwards for a protein transition in high-income countries *Nat. Food* **5** 28–36
[36] De Petrillo E, Tuninetti M, Ridolfi L and Laio F 2023 International corporations trading Brazilian soy are keystone actors for water stewardship *Commun. Earth Environ.* **4** 1–12
[37] Davis K F *et al* 2015 Historical trade-offs of livestock's environmental impacts *Environ. Res. Lett.* **10** 125013
[38] Hawkes C, Jewell J and Allen K 2013 A food policy package for healthy diets and the prevention of obesity and diet-related non-communicable diseases: the NOURISHING framework *Obes. Rev.* **14** 159–168
[39] 2024 NOURISHING nutrition policy framework | World Cancer Research Fund (available at: https://www.wcrf.org/research-policy/policy/nutrition-policy/nourishing-framework) (Accessed 16 January 2025)
[40] Bucher Della Torre S, Moullet C and Chaparro J C 2022 Impact of Measures Aiming to Reduce Sugars Intake in the General Population and their implementation in Europe: a scoping review *Int. J. Public Health* **66** 1604108
[41] 2025 OECD/FAO Oecd-fao agricultural outlook 2025-2034 *Technical Report* OECD Publishing, Paris/FAO (https://doi.org/10.1787/601276cd-en)
[42] Semba R D, de Pee S, Kim B, McKenzie S, Nachman K, Bloem M W 2020 Adoption of the 'planetary health diet' has different impacts on countries' greenhouse gas emissions *Nat. Food* **1** 481–484
[43] Halpern B S *et al* 2022 The environmental footprint of global food production *Nat. Sustain.* **5** 1027–1039
[44] Giordano V 2026 High-income countries dietary trajectories diverge from the global nutrition transition github *repository* (available at: https://github.com/vittorio-giordano/High-income-countries-dietary-trajectories-diverge-from-the-global-nutrition-transition)