Multi-dimensional characterisation of global food supply from 1961-2013

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Food systems are increasingly globalized and interdependent and diets around the world are changing. Characterising national food supplies and how they have changed can inform food policies that ensure national food security, support access to healthy diets and enhance environmental sustainability. Here, we analysed data for 171 countries on availability of 18 food groups from the United Nations Food and Agriculture Organization to identify and track multi-dimensional food supply patterns from 1961 to 2013. Four predominant food group combinations were identified that explained almost 90% of cross-country variance in food supply: animal source and sugar; vegetable; starchy root and fruit; and seafood and oilcrops. South Korea, China and Taiwan experienced the largest changes in food supply over the past five decades, with animal source foods and sugar, vegetables, and seafood and oilcrops all becoming more abundant components of food supply. In contrast, in many Western countries, the supply of animal source foods and sugar declined. Meanwhile, there was remarkably little change in food supply in countries in the sub-Saharan Africa region. These changes have led to a partial global convergence in national supply of animal source foods and sugar, and a divergence in vegetables, and seafood and oilcrops. Our analysis has generated a novel characterisation of food supply that highlights the interdependence of multiple food types in national food systems. A better understanding of how these patterns have evolved and will continue to change is needed to support the delivery of healthy and sustainable food system policies.

The past half-century has seen economic growth, urbanization, advances in technologies for agriculture and food production, food processing and storage, and an increasingly powerful and globalized food industry - all of which have led to profound changes in national and regional food systems.[1-3] A number of studies have reported trends over time in the global supply and/or consumption of individual foods and nutrients and in the diversity of foods supplied at national, regional and global levels.[4-14] Few of these studies have, however, represented the totality of food supply patterns; those that considered multiple foods[7,11,12,15,16] have not accounted formally for the interdependencies between the demand for and supply of different foods. This is an important omission because national food supplies are modified simultaneously by a mix of socioeconomic, ecological, technological and commercial factors, with complex impacts on the availability of different foods due to these interdependencies, creating multiple possible trajectories for food systems. For example, different patterns and speeds of urbanization, rising national income, or more widespread use food processing and restaurant sales alter the variety of food types available or demanded, their sources, and the price of food (partly through infrastructural changes).[9]

There is, therefore, a need for a coherent multi-dimensional measure of food supply that can be tracked over time, as has been argued previously for individual consumption.[17,18] Here we develop a novel data-driven approach for defining characterising national food supplies that quantifies multi-dimensional patterns over time. We apply this method to a global database of food supply, and demonstrate how patterns of food supply changed from 1961 to 2013 across the world. These novel characterisations will be valuable for tracking country-level food systems and their different trajectories, in order to identify common drivers of healthier and/or more sustainable food systems. This will in turn enable the development of national and regional food production and trade policies to maximise health and minimise negative impacts on the environment.

Results

Food supply scores

We summarized the availability of 18 food groups into numerical scores that characterize food systems in different countries and years. Figure 1 and Supplementary Figure 1 show how the scores relate to the availability of specific foods, characterized by the proportion of total energy available for human consumption from each food group; Supplementary Table 1 lists the individual food items in each group. The first score represents food systems characterized by *animal source and sugar*-based foods, and is higher where meat, milk, animal fats, eggs, offals, and sugar and sweeteners are a more abundant part of food supply, and lower where cereals make up a larger share of the food supply. The *vegetable score* is higher in food systems characterized by an abundance of vegetables, vegetable oils, treenuts and eggs. The *starchy root and fruit score* is higher in food systems with an abundance of those two foods, and decreases with abundance of cereals. Finally, the *seafood and oilcrops score* is higher in food systems which have an abundance of those foods. Almost 90% of the cross-country variation in food availability from 1961 to 2013 is explained by these four scores, demonstrating their ability to characterize national food supply parsimoniously and coherently.

Current food supply patterns and change over time

Figure 2 and Supplementary Table 2 present mean food supply scores by country for the period 2009-2013, and change from 1961-1965 to 2009-2013. Although a food system characterized by a high supply of animal source foods and sugar is viewed as representing a typical affluent Western population,[17,19] and the highest scores for this pattern in 2009-2013 were seen in Iceland and Denmark, the scores were also high elsewhere, e.g. in Argentina, Kazakhstan and Mongolia. The animal source and sugar score was low in most countries in sub-Saharan Africa and south Asia, with the lowest values seen in Burundi and Rwanda, while Latin American countries had a mix of low and high scores. The animal source and sugar score increased most over the half-century in China, followed by countries in southern and eastern Europe, east Asia and parts of central Asia. Meanwhile, six of the nine largest decreases took place in high-income English-speaking countries (i.e. Australia, Canada, Ireland, New Zealand, UK and USA). The cross-country variation in the score was similar in 1961-1965 and 2009-2013 (Supplementary Table 3).

The vegetable score was highest in the "Silk Road" band stretching from east Asia (China and South Korea), through west Asia (Iran) to the Mediterranean (Lebanon and Greece). The lowest vegetable scores were seen in parts of sub-Saharan Africa, e.g. Chad and Lesotho, and some Pacific islands, e.g. Solomon Islands; the scores were also consistently low across Latin America. The largest increases in the vegetable score over the last half-century occurred in east Asia and parts of the Middle East, with a change of +75 in South Korea. Decreases in the score were typically small, and occurred largely in sub-Saharan African countries, including Guinea and Sierra Leone. The cross-country variation of this score increased between 1961-1965 and 2009-2013 (Supplementary Table 3).

The starchy root and fruit score was highest in tropical sub-Saharan Africa, with the seven highest scores appearing in this area. It was lowest in east and south Asia, particularly in South Korea. In contrast to the animal source and sugar and vegetable scores, there was little change in starchy root and fruit scores over time, while their variation decreased. Finally, the seafood and oilcrops score was high in South Korea and Japan, and in diverse island nations in the Pacific, Indian and Atlantic Oceans (e.g. Kiribati, Seychelles, Iceland and Bermuda); it was lowest in landlocked Burundi and Mongolia. Over time, the share of seafood and oilcrops in the food supply increased in parts of east Asia, particularly in South Korea (+62) and China.

Relationships between changes in scores

Correlations between changes in the food supply scores from 1961-1965 to 2009-2013 ranged from close to zero to moderately positive (Table 1). The moderate correlations between changes in vegetable scores and both animal source and sugar, and seafood and oilcrops scores, were driven by heterogeneous changes in different food groups across countries (Supplementary Figures 2 and 3). For example, the vegetable score increased in both east Asia and high-income Western countries. However, while east Asia also experienced a large rise in the animal source and sugar score, many Western countries, especially high-income English-speaking countries, experienced declines.

Overall change in national food supply

The index of overall change in food supply, which combines changes in the four scores, shows clear regional patterns (see Figure 3). The greatest changes in food supply from 1961-1965 to 2009-2013 occurred in east and southeast Asia, especially in South Korea, China and Taiwan, and in parts of the former Soviet Union and the Middle East. In high-income Western countries, the largest changes took place in six southern European countries (Cyprus, Portugal, Greece, Spain, Malta and Italy), and in some high-income English-speaking countries (e.g., Australia and Canada). The countries with the smallest changes in their food supply were in sub-Saharan Africa (e.g. Mali, Chad and Senegal), Latin America (e.g. Argentina) and south Asia (e.g. Bangladesh).

The main strength of our work is its novel scope of developing data-driven scores that characterize national food systems and have clear interpretations. Furthermore, we used a comprehensive open-source dataset with global coverage over a long time period. However, our analysis also has some limitations. The FAO Food Balance Sheet data are estimates of food availability, which may be substantially different from food consumption,[20] and do not capture food waste or subsistence production, nor do they account for food processing, which may have health consequences above and beyond differences in availability of food groups.[21] The FAO Food Balance Sheet data are provided at national level, and therefore do not account for within-country heterogeneity. Additionally, there were no data available for some countries and territories, including a number of Pacific islands (e.g. American Samoa and Nauru) where major changes to dietary patterns have consequences such as obesity and diabetes that are of particular concern.[22-25] Where data are available, the FAO acknowledges that data quality varies among countries and items, and over time.[26]

Discussion

We found that four data-driven scores characterize major patterns in national food supply across the world, and explain approximately 90% of the variation in worldwide food supplies over a period of nearly half a century. With the notable exception of countries in sub-Saharan Africa, there have been substantial changes in national food supply patterns over the past 50 years. South Korea, China and Taiwan have experienced the largest changes, with animal source foods and sugar, vegetables, and seafood and oilcrops all becoming a more abundant component of food supply. This contrasts with high-income English-speaking countries, where the animal source and sugar score has declined substantially.

FAO food balance data have been used previously to investigate various features and implications of food systems at the global level, including food and nutrient supply,[11,13] dietary adequacy,[15] human trophic levels (i.e., the position of humans in the food chain),[16] and food trade.[14] However, these studies either used data on individual foods, or constructed scores that were pre-defined, based on criteria such as the mean of the trophic level of food items in the diet,[16] or the ratio of energy available from Mediterranean and non-Mediterranean food groups.[15] In comparison, our data-driven approach used the internal structure and interrelationships of different food groups, identifying coherent food supply patterns that are present in all 171 countries over 53 years, but with widely varying scores. Despite differing approaches, some commonalities in findings appear, such as increasing trophic levels over time,[16] as populations (especially in Asia) increase their consumption of animal source foods, and an overall increase over time in global food supply diversity.[11]

Our findings highlight the importance of examining entire national food systems and accounting for internal interdependencies, rather than changes in supply of individual foods and food groups. This will allow us to understand better how factors such as increasing income affect multiple food groups simultaneously, and how food systems act collectively as potential determinants of nutritional status and health. Major shifts towards more diverse food supplies in emerging economies, especially in east and southeast Asia, may be partly responsible for substantial improvements in nutritional status (e.g., reductions in stunting, anaemia and other micronutrient deficiencies) in this region.[27-30]. For example, we assessed the strength of crude association of food supply scores in 2009-2013 with national data from the same years on adult body-mass index (BMI) and adult height.[23,27] We identified a strong positive association of animal source and sugar scores with BMI and height, and a moderate positive association of vegetable scores with BMI and height (Supplementary Table 4).

We also highlighted the relatively small scale of changes in food supply in south Asia and sub-Saharan Africa, which was in clear contrast to the large changes in east and southeast Asia. Low values of food supply scores other than starchy roots and fruit in much of sub-Saharan Africa suggest that food systems in the region are failing to deliver diverse diets and may be particularly low in animal source foods.[31] This food insecurity and poor dietary quality may help to explain the co-existence of undernutrition and overweight in many African countries.[23,25,27-30] Parallel to trends in low- and middle-income countries, in many high-income countries, declines in animal source and sugar supply and commensurate increases in vegetable supply indicate a possible trend towards more balanced and healthier diet composition. There is a need to understand the technical, economic, political and social determinants of these trends, and to develop policies that will make them healthier and more sustainable.

Food production and trade also affect the local, regional and global environment, through their impact on soil nutrient and biotic properties, water systems, and emissions of greenhouse gases.[31-40] Our multi-dimensional characterisation of food supply will allow a more comprehensive assessment to be made of environmental impacts at a global scale. However, detailed data on the country of origin and international trade of foods, and how these interact with the food supply scores is needed to investigate these impacts in specific countries, as has been done for air pollution.[41]

Multi-dimensional descriptions of national food systems can both illustrate concurrent trends in food supplies, and identify interdependencies between different constituents of population-level diets. Such data provide novel information, which can be used to underpin agricultural and trade policies for a sustainable and healthy future.

Methods

Data

We downloaded food balance data from the website of the FAO (http://faostat3.fao.org/home/E), which were updated on 12th December 2017. Food balance sheets have been published by the FAO since 1949 and describe availability of different foods for human consumption. As described in detail in the Food Balance Sheets Handbook,[26] the FAO has used official and unofficial data, its own technical knowledge, and feedback from national governments to create the series of food balance sheets; further details are available in the FAO archives (http://www.fao.org/library/fao-archives/about-the-archives/en/). The current data were assembled from a variety of sources, including national statistics, farmer stock surveys and industrial censuses. For each food item, domestic supply quantity comprises production and imports, less exports, and adjusted for variations in stocks (e.g. food stored by governments). The quantity of food is domestic supply quantity, less food losses and food used for feed and seed. The quantity of food is then used to calculate food supply in kcal/capita/day, which are the data used in our analyses.[26]

We used data from 18 food groups for the years 1961 to 2013: cereals, starchy roots (e.g. potatoes), sugar and sweeteners, pulses (e.g. beans and peas), treenuts, oilcrops, vegetable oils, vegetables, fruits, stimulants, spices, meat, offals, animal fats, eggs, milk, fish and seafood, and aquatic products including aquatic mammals and plants (Supplementary Table 1). We excluded the miscellaneous category (which includes infant food and other unspecified items), sugar crops and alcoholic beverages.

Data for Burundi, Comoros, Eritrea, Libya, Seychelles, Somalia and Syria were not available in the most recent version of the food balance sheets. For Libya, Somalia and Syria, we used data from the previous version, which provided data for the period 1961-2011. For Burundi, Comoros, Eritrea and Seychelles, we used data from the next most recent version, which provided data for the period 1961-2009.

Cleaning and imputation

We examined time series for all country-food type pairs and identified outliers and countries with implausible data. We removed data for the Occupied Palestinian Territory, as there were large discontinuities in the data, likely because governance and reporting systems changed over time. We also removed data for Maldives, which were implausibly low for many food type-year combinations, causing discontinuities in the time series. Data for the current Sudan were only available for 2012 and 2013, and no data were available for South Sudan, so we report estimates for former Sudan. Finally, we removed all data for the former Yugoslavia, owing to large and inconsistent discontinuities between Yugoslavia and its successors, and Serbia and Montenegro and its successors.

Three other countries for which data were available ceased to exist during the period of analysis: the USSR, Ethiopia PDR (modern Ethiopia and Eritrea) and Czechoslovakia. Furthermore, data for Belgium and Luxembourg were combined by the FAO from 1961 to 1999. We created complete time series for successor countries based on the time series for the original countries as follows. Firstly, in the three years after dissolution, we calculated availability for each food type in the original countries by weighting availability in their successor countries by population share. We then calculated the ratio of mean per-capita availability in the successor country in those three years to availability in the original country. We multiplied per-capita availability in the original country by this ratio to create pre-dissolution time series for successor countries. Finally, these estimates were rescaled, so that for each country-year-food type combination, the sum of availability in the successor countries was equal to availability in the original country.

The final dataset comprised each combination of 18 food groups, 171 countries and 53 years. After cleaning, 3,714 data points (2.3% of the data) were missing. The item with the largest missingness was aquatic products, with 1,191 missing data points (13% of the total for that item). We imputed missing values using statistical models with a hierarchical structure, fitted using the integrated nested Laplace approximation (INLA) method.[42] Separate models were fitted for each food type and region, with sub-regions and countries forming the two levels of the hierarchy for each model (see Supplementary Table 5). Estimates for each country and year were informed by data from other years in the same country, and from other countries, especially those in the same sub-region with data for similar time periods. The model incorporated non-linear time trends comprising a combination of linear terms and a first-order random walk, all modelled hierarchically.

Statistical analysis

The data for the 18 food groups were provided in units of kcal/capita/day. To characterize food supply patterns independently of the total energy from these 18 food groups available in each country, we divided each data point by the total sum of calories for that country, in units of kilocalories per person per day. Data on energy available from each food group for each country-year were therefore expressed as a proportion of energy available from all 18 food groups, i.e. the values for each country-year summed to one.

We carried out principal component analysis (PCA) on the food supply composition data;[43] PCA identifies patterns by finding weighted sums of variables that explain as much of the variance in the data as possible. The first four principal components explained 89.2% of the variance in the data. We applied a varimax rotation to the loadings of the four principal components.[44] This rotation aids interpretation by producing a small number of coefficients with large values, and many coefficients close to zero. For presentation, we scaled each varimax-rotated component score linearly to lie in the range 0 to 100, i.e. the country-year with the lowest score was scaled to 0, and the highest score to 100.

We calculated an overall index of change in national food supply. The absolute values of the changes in the scores were each weighted by the proportion of the total variance explained by its varimax-rotated principal component, normalized to add to one (0.46, 0.21, 0.18 and 0.15 respectively). These values were then summed to give the value of the index, i.e.,

Index of change = *0.46* x *Absolute change in animal source and sugar score +*
0.21 x *Absolute change in vegetable score +*
0.18 x *Absolute change in starchy root and fruit score +*
0.15 x *Absolute change in seafood and oilcrops score*

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Author contributions

ME and GD developed the study concept. JB, GMS and JKL obtained data, conducted analyses and prepared results. RG, GAS, FF, JEB, MDC and ADD contributed to data, analyses and interpretation. JB and ME wrote the first draft of the paper with input from other authors.

Competing financial interests

ME reports a charitable grant from the AstraZeneca Young Health Programme, and personal fees from Prudential, Scor and Third Bridge, outside the submitted work. The other authors declare no competing interests.

Data availability statement

The data analysed in this study are published by the Food and Agriculture Organization of the United Nations, and are available from http://www.fao.org/faostat/en/#data/FBS. The results of this study (i.e., the scores and change index) are available from the website of the NCD Risk Factor Collaboration at http://ncdrisc.org/publications.html.

Figure legends

Figure 1. Loadings of each food group for the four food supply scores. Warm colours indicate that abundance of a food type as a component of total energy from food supply increases the scores and absence decreases the scores; cold colours indicate that absence increases the scores and abundance decreases the scores.

Figure 2. Mean food supply scores by country. Scores by country for the period 2009-2013 (panel A) and change from 1961-1965 to 2009-2013 (panel B). Countries shown in grey had no data. As described in Methods, the scores are presented on a scale of 0 to 100, with 0 representing the lowest value observed in any country from 1961 to 2013, and 100 the highest.

Figure 3. Overall change in national food supply from 1961-1965 to 2009-2013. This index is a weighted sum of the absolute values of change in the four food supply scores. The weights

are the proportion of the total variance explained by each score, normalized to add to one. Countries shown in grey had no data.

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Table 1. Correlations between changes in food scores from 1961-1965 to 2009-2013.

Score	**Animal source and sugar**	**Vegetable**	**Starchy root and fruit**	**Seafood and oilcrops**
Animal source and sugar	1	0.32	-0.06	0.01
Vegetable		1	0.17	0.41
Starchy root and fruit			1	0.01
Seafood and oilcrops				1