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

2

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

49

50 The past half-century has seen economic growth, urbanization, advances in technologies for  
51 agriculture and food production, food processing and storage, and an increasingly powerful  
52 and globalized food industry - all of which have led to profound changes in national and  
53 regional food systems.<sup>1-3</sup> A number of studies have reported trends over time in the global  
54 supply and/or consumption of individual foods and nutrients and in the diversity of foods

55 supplied at national, regional and global levels.<sup>4-14</sup> Few of these studies have, however,  
56 represented the totality of food supply patterns; those that considered multiple foods<sup>7,11,12,15,16</sup>  
57 have not accounted formally for the interdependencies between the demand for and supply of  
58 different foods. This is an important omission because national food supplies are modified  
59 simultaneously by a mix of socioeconomic, ecological, technological and commercial factors,  
60 with complex impacts on the availability of different foods due to these interdependencies,  
61 creating multiple possible trajectories for food systems. For example, different patterns and  
62 speeds of urbanization, rising national income, or more widespread use food processing and  
63 restaurant sales alter the variety of food types available or demanded, their sources, and the  
64 price of food (partly through infrastructural changes).<sup>9</sup>

65

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

76

## 77 **Results**

78 *Food supply scores*

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

93

#### 94 *Current food supply patterns and change over time*

95 Figure 2 and Supplementary Table 2 present mean food supply scores by country for the period  
96 2009-2013, and change from 1961-1965 to 2009-2013. Although a food system characterized  
97 by a high supply of animal source foods and sugar is viewed as representing a typical affluent  
98 Western population,<sup>17,19</sup> and the highest scores for this pattern in 2009-2013 were seen in  
99 Iceland and Denmark, the scores were also high elsewhere, e.g. in Argentina, Kazakhstan and  
100 Mongolia. The animal source and sugar score was low in most countries in sub-Saharan Africa  
101 and south Asia, with the lowest values seen in Burundi and Rwanda, while Latin American  
102 countries had a mix of low and high scores. The animal source and sugar score increased most  
103 over the half-century in China, followed by countries in southern and eastern Europe, east Asia

104 and parts of central Asia. Meanwhile, six of the nine largest decreases took place in high-  
105 income English-speaking countries (i.e. Australia, Canada, Ireland, New Zealand, UK and  
106 USA). The cross-country variation in the score was similar in 1961-1965 and 2009-2013  
107 (Supplementary Table 3).

108

109 The vegetable score was highest in the “Silk Road” band stretching from east Asia (China and  
110 South Korea), through west Asia (Iran) to the Mediterranean (Lebanon and Greece). The lowest  
111 vegetable scores were seen in parts of sub-Saharan Africa, e.g. Chad and Lesotho, and some  
112 Pacific islands, e.g. Solomon Islands; the scores were also consistently low across Latin  
113 America. The largest increases in the vegetable score over the last half-century occurred in east  
114 Asia and parts of the Middle East, with a change of +75 in South Korea. Decreases in the score  
115 were typically small, and occurred largely in sub-Saharan African countries, including Guinea  
116 and Sierra Leone. The cross-country variation of this score increased between 1961-1965 and  
117 2009-2013 (Supplementary Table 3).

118

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

127

128 *Relationships between changes in scores*

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

137

#### 138 *Overall change in national food supply*

139 The index of overall change in food supply, which combines changes in the four scores, shows  
140 clear regional patterns (see Figure 3). The greatest changes in food supply from 1961-1965 to  
141 2009-2013 occurred in east and southeast Asia, especially in South Korea, China and Taiwan,  
142 and in parts of the former Soviet Union and the Middle East. In high-income Western countries,  
143 the largest changes took place in six southern European countries (Cyprus, Portugal, Greece,  
144 Spain, Malta and Italy), and in some high-income English-speaking countries (e.g., Australia  
145 and Canada). The countries with the smallest changes in their food supply were in sub-Saharan  
146 Africa (e.g. Mali, Chad and Senegal), Latin America (e.g. Argentina) and south Asia (e.g.  
147 Bangladesh).

148

149 The main strength of our work is its novel scope of developing data-driven scores that  
150 characterize national food systems and have clear interpretations. Furthermore, we used a  
151 comprehensive open-source dataset with global coverage over a long time period. However,  
152 our analysis also has some limitations. The FAO Food Balance Sheet data are estimates of food  
153 availability, which may be substantially different from food consumption,<sup>20</sup> and do not capture



154 food waste or subsistence production, nor do they account for food processing, which may have  
155 health consequences above and beyond differences in availability of food groups.<sup>21</sup> The FAO  
156 Food Balance Sheet data are provided at national level, and therefore do not account for within-  
157 country heterogeneity. Additionally, there were no data available for some countries and  
158 territories, including a number of Pacific islands (e.g. American Samoa and Nauru) where  
159 major changes to dietary patterns have consequences such as obesity and diabetes that are of  
160 particular concern.<sup>22-25</sup> Where data are available, the FAO acknowledges that data quality  
161 varies among countries and items, and over time.<sup>26</sup>

162

## 163 **Discussion**

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

172

173 FAO food balance data have been used previously to investigate various features and  
174 implications of food systems at the global level, including food and nutrient supply,<sup>11,13</sup> dietary  
175 adequacy,<sup>15</sup> human trophic levels (i.e., the position of humans in the food chain),<sup>16</sup> and food  
176 trade.<sup>14</sup> However, these studies either used data on individual foods, or constructed scores that  
177 were pre-defined, based on criteria such as the mean of the trophic level of food items in the  
178 diet,<sup>16</sup> or the ratio of energy available from Mediterranean and non-Mediterranean food

179 groups.<sup>15</sup> In comparison, our data-driven approach used the internal structure and  
180 interrelationships of different food groups, identifying coherent food supply patterns that are  
181 present in all 171 countries over 53 years, but with widely varying scores. Despite differing  
182 approaches, some commonalities in findings appear, such as increasing trophic levels over  
183 time,<sup>16</sup> as populations (especially in Asia) increase their consumption of animal source foods,  
184 and an overall increase over time in global food supply diversity.<sup>11</sup>

185

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

198

199 We also highlighted the relatively small scale of changes in food supply in south Asia and sub-  
200 Saharan Africa, which was in clear contrast to the large changes in east and southeast Asia.  
201 Low values of food supply scores other than starchy roots and fruit in much of sub-Saharan  
202 Africa suggest that food systems in the region are failing to deliver diverse diets and may be  
203 particularly low in animal source foods.<sup>31</sup> This food insecurity and poor dietary quality may

204 help to explain the co-existence of undernutrition and overweight in many African  
205 countries.<sup>23,25,27-30</sup> Parallel to trends in low- and middle-income countries, in many high-income  
206 countries, declines in animal source and sugar supply and commensurate increases in vegetable  
207 supply indicate a possible trend towards more balanced and healthier diet composition. There  
208 is a need to understand the technical, economic, political and social determinants of these  
209 trends, and to develop policies that will make them healthier and more sustainable.

210

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

218

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

223

## 224 **Methods**

### 225 *Data*

226 We downloaded food balance data from the website of the FAO  
227 (<http://faostat3.fao.org/home/E>), which were updated on 12<sup>th</sup> December 2017. Food balance  
228 sheets have been published by the FAO since 1949 and describe availability of different foods

229 for human consumption. As described in detail in the Food Balance Sheets Handbook,<sup>26</sup> the  
230 FAO has used official and unofficial data, its own technical knowledge, and feedback from  
231 national governments to create the series of food balance sheets; further details are available in  
232 the FAO archives (<http://www.fao.org/library/fao-archives/about-the-archives/en/>). The  
233 current data were assembled from a variety of sources, including national statistics, farmer  
234 stock surveys and industrial censuses. For each food item, domestic supply quantity comprises  
235 production and imports, less exports, and adjusted for variations in stocks (e.g. food stored by  
236 governments). The quantity of food is domestic supply quantity, less food losses and food used  
237 for feed and seed. The quantity of food is then used to calculate food supply in kcal/capita/day,  
238 which are the data used in our analyses.<sup>26</sup>

239

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

246

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

252

253 *Cleaning and imputation*

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

263

264 Three other countries for which data were available ceased to exist during the period of  
265 analysis: the USSR, Ethiopia PDR (modern Ethiopia and Eritrea) and Czechoslovakia.  
266 Furthermore, data for Belgium and Luxembourg were combined by the FAO from 1961 to  
267 1999. We created complete time series for successor countries based on the time series for the  
268 original countries as follows. Firstly, in the three years after dissolution, we calculated  
269 availability for each food type in the original countries by weighting availability in their  
270 successor countries by population share. We then calculated the ratio of mean per-capita  
271 availability in the successor country in those three years to availability in the original country.  
272 We multiplied per-capita availability in the original country by this ratio to create pre-  
273 dissolution time series for successor countries. Finally, these estimates were rescaled, so that  
274 for each country-year-food type combination, the sum of availability in the successor countries  
275 was equal to availability in the original country.

276

277 The final dataset comprised each combination of 18 food groups, 171 countries and 53 years.  
278 After cleaning, 3,714 data points (2.3% of the data) were missing. The item with the largest

279 missingness was aquatic products, with 1,191 missing data points (13% of the total for that  
280 item). We imputed missing values using statistical models with a hierarchical structure, fitted  
281 using the integrated nested Laplace approximation (INLA) method.<sup>42</sup> Separate models were  
282 fitted for each food type and region, with sub-regions and countries forming the two levels of  
283 the hierarchy for each model (see Supplementary Table 5). Estimates for each country and year  
284 were informed by data from other years in the same country, and from other countries,  
285 especially those in the same sub-region with data for similar time periods. The model  
286 incorporated non-linear time trends comprising a combination of linear terms and a first-order  
287 random walk, all modelled hierarchically.

288

### 289 *Statistical analysis*

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

296

297 We carried out principal component analysis (PCA) on the food supply composition data;<sup>43</sup>  
298 PCA identifies patterns by finding weighted sums of variables that explain as much of the  
299 variance in the data as possible. The first four principal components explained 89.2% of the  
300 variance in the data. We applied a varimax rotation to the loadings of the four principal  
301 components.<sup>44</sup> This rotation aids interpretation by producing a small number of coefficients  
302 with large values, and many coefficients close to zero. For presentation, we scaled each

303 varimax-rotated component score linearly to lie in the range 0 to 100, i.e. the country-year with  
304 the lowest score was scaled to 0, and the highest score to 100.

305

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

$$\begin{aligned} 310 \text{ Index of change} = & 0.46 \times \text{Absolute change in animal source and sugar score} + \\ 311 & 0.21 \times \text{Absolute change in vegetable score} + \\ 312 & 0.18 \times \text{Absolute change in starchy root and fruit score} + \\ 313 & 0.15 \times \text{Absolute change in seafood and oilcrops score} \end{aligned}$$

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320

#### 321 **Author contributions**

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

325

#### 326 **Competing financial interests**

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

330

### 331 **Data availability statement**

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

336

### 337 **Figure legends**

338

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

343

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

348

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



351 are the proportion of the total variance explained by each score, normalized to add to one.

352 Countries shown in grey had no data.

353

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462

463 **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

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