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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.¹⁻³ 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.⁴⁻¹⁴ Few of these studies have, however,
56 represented the totality of food supply patterns; those that considered multiple foods^{7,11,12,15,16}
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).⁹

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.^{17,18} 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,^{17,19} 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,²⁰ 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.²¹ 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.²²⁻²⁵ Where data are available, the FAO acknowledges that data quality
161 varies among countries and items, and over time.²⁶

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,^{11,13} dietary
175 adequacy,¹⁵ human trophic levels (i.e., the position of humans in the food chain),¹⁶ and food
176 trade.¹⁴ 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,¹⁶ or the ratio of energy available from Mediterranean and non-Mediterranean food

179 groups.¹⁵ 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,¹⁶ as populations (especially in Asia) increase their consumption of animal source foods,
184 and an overall increase over time in global food supply diversity.¹¹

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.²⁷⁻³⁰ 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.^{23,27} 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.³¹ This food insecurity and poor dietary quality may

204 help to explain the co-existence of undernutrition and overweight in many African
205 countries.^{23,25,27-30} 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.³¹⁻⁴⁰ 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.⁴¹

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 12th 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,²⁶ 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.²⁶

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.⁴² 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;⁴³
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.⁴⁴ 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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