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RESEARCH ARTICLE

Can economic development be a driver of food system sustainability? Empirical evidence from a global sustainability index and a multi-country analysis

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Abstract

Despite representing a growing element of the international community's discourse, the sustainability of food systems and the challenge of its empirical measurement are still highly debated. In this paper, we propose to address this gap by computing a global food system sustainability index which we then use in a cross-country analysis covering 94 countries in low-, middle- and high-income regions. The analysis reveals a strong non-linear but positive correlation between the food system sustainability index and countries' individual GDP per capita. This relationship suggests some possible degree of endogeneity between food system sustainability and economic development. We then use the Shared Socioeconomic Pathways framework and Individual Conditional Expectations modeling techniques to explore how the sustainability of food systems is projected to evolve in the future as countries move up the economic development ladder. The projections indicate that for lower income countries, the change is usually more significant than for higher income countries. The analysis also reveals that the different dimensions of sustainability will not all contribute equally to future improvements in food system sustainability. In particular, investments targeting social and food security & nutrition dimensions are projected to have a greater effect on the sustainability of food systems than investment/interventions aiming at the environment or economic domains. For countries located at the lower end of the economic development spectrum, this would imply that, even with limited resources, policy-makers could substantially improve the sustainability of countries' food systems by prioritizing (sub) national policies and interventions focused on social and food security & nutrition domains.

Author summary

How sustainable are our food systems? Answering this question is important from both a research and a policy perspective. Without a better understanding of how sustainable (or unsustainable) our current food systems are, and what drives this (un)sustainability, decision-makers are left with little information on what to do -or what to prioritize- to

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overcome malnutrition and hunger while at the same time reducing the environmental or social impacts of our food systems' economic activities. In this paper we aim to address those questions. For this purpose, we build a global food system index that "gauges" how sustainable food systems are, and we apply this index to a set of low-, middle- and higher-income countries across the globe. We then use modeling techniques to predict how the sustainability of food systems as we observe them today may evolve in the future as lower income countries move up the economic development ladder. We conclude with specific reflections on the importance of this work for policy prioritization amongst the trade-offs that characterize food system interventions.

Introduction

Now more than ever the question of the sustainability of our food systems is at the core of the international development discourse. Sustainable food systems are increasingly central to the United Nations' 2030 Sustainable Development Goals (SDGs), with the achievement of many SDGs tied closely to the performance of local and global food systems [1–3]. This link between SDGs and the sustainability of food systems was restated more recently through the vision of the UN Food System Summit where there were promises to make "progress on all 17 Sustainable Development Goals (SDGs), each of which [relying] on healthier, more sustainable and more equitable food systems" [4].

Yet, despite representing a growing part of the international community's discourse, 'sustainable food systems' are still a contested concept debated by a multitude of actors using different—and sometimes substantially divergent—views and frameworks [5–7]. Although some elements of consensus are emerging on what a sustainable food system should look like [2,8], researchers and analysts still struggle with one basic question: How can we define and empirically measure food systems' sustainability?

This question of defining and measuring food systems' sustainability is critical [9]. In a global environment with increasing calls for food system transformation, e.g., [10–12], one needs to know not just the meaning of transformation [13–15] but also the direction and outcomes one should be aiming at [16]. Without a good understanding of what exactly food system sustainability entails and how to measure or to monitor progress towards it, it will be difficult for decision-makers to make appropriate decisions or to design suitable policies to nudge food systems in the direction of a more sustainable global outcome for all [9].

Along with this question of measuring sustainability lie many other key challenges, including the identification and prioritization of relevant intervention areas for transformation. Indeed, if food system sustainability depends on so many dimensions—nutrition, food security, environment, e.g., [17,11], but also economic development, social/equity [18–20] or even cultural dimensions [21]—then how can we help decision-makers navigate those different outcomes and their trade-offs? For countries with scarce resources and capacities, this question is even more critical as it is not just about better understanding of what drives the sustainability of their food systems, e.g., [2,18,22], but also about how to make choices, sequence, and (re) direct limited resources toward the most judicious interventions. In this context, the role of economic development in contributing to the sustainability (or unsustainability) of food system is of central importance. Can countries simply rely on industrial modernization of food and agricultural sectors to expect to see their food systems become more sustainable, or should they instead invest in more specific interventions?

Building on some of the most recent food system sustainability frameworks [3,17,23–26], the objective of this paper is to address these important questions. To tackle this challenge, the paper starts by unpacking some of the elements and dimensions of food systems, looking in particular at the potential key determinants of their sustainability, and then explores more thoroughly the respective contributions that each of those different dimensions makes in relation to the system's holistic outcomes. The analysis, however, does not just revisit and expand the many theoretical frameworks that have been proposed recently, e.g., [8,27]. Instead, it aims to ground the discussion more empirically into the real world. For this, it uses data from a cross-country database covering 94 countries and expands an existing global food system sustainability index. Following this analysis, we critically discuss our assumptions and explore some of the policy implications that emerge from our findings, with the objective to contribute to the rapidly growing body of literature that discusses the challenging task of linking food systems with sustainability.

Empirical food system sustainability indices–a rapid review

A large and rapidly growing body of literature is now available which proposes various frameworks and/or metrics aiming at defining or measuring food systems' sustainability, e.g., [8,27–30]. The majority of these frameworks reflects a holistic approach and embraces the multi-sectoral and multi-outcome nature of food systems. Yet, while several of those frameworks are based on empirical data, e.g., [31], a larger number of them remain essentially conceptual or theoretical, e.g., [8,27], and as such do not provide the empirical elements which are necessary to measure concretely food systems' sustainability.

Within this literature, a smaller number of papers propose to tackle the measure of food system sustainability more concretely. Chaudhary and his colleagues [25], for instance, build on several years of collaboration with other experts—see, e.g., [17,32,33]—to develop a framework that combines several dimensions and their associated indicators aimed at quantifying empirically food system sustainability. Expanding Gustafson et al. [17]'s earlier work beyond the original nine countries for which the metrics had been initially computed, Chaudhary et al. [25] proposed to measure the sustainability of food systems in 156 countries. The lack of data in several of those countries forced these authors, however, to rely on regional extrapolations for several of their proposed indicators.

The Food Sustainability Index (FSI) developed by the Economist's Intelligence Unit is another attempt to advance empirical research on food system sustainability measurement based on three specific dimensions: food loss and waste; sustainable agriculture; and malnutrition [24]. The ambition of the FSI has been limited however by the low data availability that characterizes many regions of the world. As a consequence, the FSI has so far been computed only for 67 countries—essentially high-income countries for which data availability is generally better than in lower income countries. Beyond this issue of representativeness, some would also argue that the three domains included in the FSI (food loss and waste, sustainable agriculture and malnutrition) capture only partially food system sustainability and that other dimensions such as social or economic considerations should also be considered [21,34].

In parallel to those endeavors, Fanzo and her colleagues recently developed a new tool, the Food System Dashboard [35] with the objective to offer a holistic overview of the key components of countries' food systems. For this purpose, the Dashboard includes over 215 indicators covering most food system components. It does not provide, however, any clear or explicit normative element leading toward food systems' sustainability (it simply provides a snapshot of the current situation); nor does it attempt to combine the different indicators it collates into a single combined index.

A few other papers explore alternative approaches to measure food system sustainability. Most of these studies, however, offer indices that don't cover well the entire food system. Zhang et al. [31] for instance develop a multi-dimensional sustainability index that focuses on the agricultural sector only, thus, overlooking the other components of food system (processing, storage, distribution, etc.). Other studies propose to work at the local or subnational scales, e.g., [30,36], and, as such, are not suitable for global multi-country assessments. In some other cases, while offering an international dimension, the proposed indices don't embrace the multi-dimensional nature of the concept of sustainability. Fridman and his colleagues [37], for instance, integrate four food staples (wheat, rice, maize, and soybeans) but they consider only the inter-country trade impact of those four staples on the environment (measured in terms of land and water usage). Their framework therefore only accounts for one dimension of sustainability (the environment), subsequently missing other key dimensions as well as a significant number of other commodities beyond the four staples considered.

In this paper, we propose to build on Béné and his colleagues' global sustainability index. Béné et al. [26]'s index considers four dimensions of food system sustainability (food security & nutrition, environment, economic and social dimensions) and covers 97 countries from low, middle and high-income regions. As such, it offers one of the most systemic indices of food system sustainability. One limitation of this index, however, is that the four dimensions are not equally represented, with both the economic and social dimensions depending on a limited number of indicators. In the present paper, we propose to build an extended version of Béné's sustainability index by adding several indicators to the two dimensions where the representativity was weak: the social and economic dimensions. We then use the newly created extended index to explore some of the key questions raised earlier in the introduction. In particular, we investigate whether all four dimensions of the index contribute equally to the change observed in the sustainability of food systems across countries, or whether some dimensions are more important than others, and if so, which dimension(s) and for which (group of) countries.

As part of this research, the question of the relationship between food system sustainability and economic development will receive a particular attention. Until recently, policy debates have often raised the question of whether positive changes in societies could 'naturally' follow economic development. A first example of this is the Kuznets curve where it was posited that, after an initial increase, inequality in societies would progressively decline as countries' economies develop further [38]. Expending this initial idea beyond income inequality, an environmental Kuznets curve hypothesis was later proposed, e.g., [39,40], whereby environmental health indicators would also follow a U-shaped curve and eventually improve as per capita income and GDP rise. Although those assumptions have not been confirmed empirically, see, e.g., [41], a question rises as whether a similar pattern could be observed with food systems sustainability. Is it indeed possible to envisage that countries within the high-income group (e.g., OECD countries) perform better in terms of aggregated food system sustainability than countries in the lower-income country group, especially if the social or economic dimensions of food system sustainability are considered? Or, is it possible that higher-income countries have a much more unsustainable food systems than lower-income countries, especially when one considers consumption of ultra-processed food per capita or even, perhaps, the environmental food print of their respective food systems?

To explore those different questions, the paper will follow a two-step approach. First, a series of descriptive analyses built around the computation of the 'extended' global food system sustainability index (GFSSI) will be presented. We will use this part of the analysis to also highlight some of the strengths of the GFSSI. Then, in a second part, we will use modeling techniques to explore how the sustainability of food systems is likely to evolve in the future as countries move up the economic development ladder. Underlying these analyses is our desire to better understand the determinants and dynamics of food systems, in the hopes that answers to these interrogations can provide useful and policy-relevant insights into decisions made regarding the transformation of food systems toward sustainability [9,12,16].

Methods

GFSSI computation

The starting point of our approach was to build on and expand the global food system sustainability index (GFSSI) developed by Béné et al. [26]. In its original version, the GFSSI employed a clear and rigorous inclusion/exclusion process based on 10 criteria (**Table 1**) to select indicators. These included conventional criteria such as 'clear methodology' and 'conceptual relevance' (see detailed definition in Table 1), but also other, more specific, criteria that were deemed to be instrumental to build the GFSSI such as 'global scale'—reflecting the fact that the indicators needed to be available for at least 70 countries to be considered as 'global'—or the

Table 1. The 10 exclusion criteria use for the choice of sustainability indicators.

▪ **Cross correlation**. Indicators which are closely cross-correlated to other indicator(s) already considered in the list were excluded. For instance, "proportion of population under global poverty line" and "percentage of population living under the poverty threshold" are closely correlated. We would only keep one of those two indicators.
▪ **Conceptual relevance**. Indicators that could not be related to one of the four dimensions of the metric (that is: ecological, economic, social and food & nutrition dimensions) were excluded – see also composite indicator criterion below.
▪ **Global scale**. Indicators for which databases cover fewer than 70 countries were excluded. The threshold 70 corresponds to about 1/3 of the total number of countries and territories recognized by the UN, which was consider as the bare minimum for a global index.
▪ **Global validity**. Indicators that refer to processes that are specific to limited regions of the world were excluded. For instance, "Percentage of agricultural land lost yearly to desertification" was excluded, as desertification is a phenomenon that by definition can only occur in some specific regions of the world.
▪ **Time period**. Indicators for which the database had information only prior to the year 2000 were excluded. The main reason for this exclusion is to ensure that only the most recent trends in indicators are considered.
▪ **Latent variables**. Indicators based on latent variables were excluded. For instance, indicators of "resilience" or "economic vulnerability" were not considered as there is no agreed measure/unit for resilience or economic vulnerability.
▪ **Clear methodology**. Indicators for which the methodology used to construct the database was not clearly detailed in the original database were excluded.
▪ **Non-composite indicators**. Indicators based on composite indices that fall into two different dimensions of the metric were excluded. For instance, the ratio "natural capital used / GDP" which is sometimes proposed in the literature as an indicator of sustainability would not be included as it clearly lies at the interface between the environmental and economic dimensions of food systems.
▪ **Comparability**. Indicators that were based on absolute numbers that do not allow for comparison between countries were excluded – for instance, the total km of paved roads would not be included. Instead, the road density – that is, the total number of km of paved road per 100 square km of land area – would be considered.
▪ **Directionality** – Indicators that do not have a clear directionality (positive or negative) within the dimension to which they were associated were excluded – for instance indicators reflecting food trade were excluded because the impact of food trade on the different dimension of sustainability is not clear. A clear directionality (also referred to as 'monotonicity' in the relevant literature -see e.g., [31]) is critical to build the basis for the sustainability of the index. Using directionality (as opposed to ranges of 'ideal' values or specific thresholds beyond which indicators would be expected to show levels of 'sustainability') is a more appropriate approach since it provides a generic framework that can be applied to different cases -in particular to cases when no consensus exists or uncertainty remains on what the 'ideal' range or sustainable threshold is, but where a 'direction' is easy to agree upon (for instance, less GHG emission is preferable regardless of the fact that the threshold below which we can consider sustainability with respect to GHG is not yet agreed).

Source: modified from [26].

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'cross-correlation' criterion where only one indicator amongst a group of indicators known to be cross-correlated (e.g. wasting and stunting) would be included in the index, in order to avoid misspecification. Those inclusion/exclusion criteria were initially compiled by Béné et al. [26] to address some of the most common and important issues encountered in the literature on food system sustainability indices, including: (i) lack of representativeness (that is, the fact that, because of data availability issues, a large proportion of the countries included in those analyses are often high-income countries -as in, e.g., [24]; (ii) lack of conceptual clarity on how the different dimensions of food system sustainability are constructed and delimited, see, e.g., [25,31,37]; and (iii) replication and/or strong cross-correlation amongst indicators, see, e.g., [24,32].

One of the important advantages of using such a set of inclusion/exclusion criteria is that all the indicators that were eventually included in the index are global and tractable, meaning they have measurable values that are publicly available for all countries included in the GFSSI. Another important consideration was the directionality of these indicators. Were excluded indicators that do not have a clear directionality (positive or negative) within the dimension to which they were associated. The objective was to ensure the coherence of the aggregated GFSSI. Here, 'coherence' does not refer to conceptual coherence, but to the statistical property of the aggregated index, in the sense described in [42]: if two or more of the dimensions were negatively correlated with each other, this would mean that a change in the aggregated index in one direction (increase or decrease) could happen while some of the dimensions within the index are moving in the opposite direction. This would indicate a flaw in the construction of the GFSSI [42].

Finally, a central property of the GFSSI was the explicit ambition to offer a true, systemic, framework and, in doing so, to embrace a holistic interpretation of sustainability. As such, the GFSSI does not consider only trade-offs between the need to produce more healthy/nutritious food and the urgency to reduce the environmental impacts of such activities, e.g., [11,43]. Rather the GFSSI comprises the four key dimensions that are more generally recognized to constitute food system sustainability, namely food security & nutrition, environmental, social and economic dimensions.

Each of four dimensions was then disaggregated into individual sets of sub-dimensions included to ensure the conceptual comprehensiveness of the indicators. For instance, for the environmental dimensions, the sub-dimensions considered include quality of air, water, soil & land, and level of biodiversity, while for the food security & nutrition dimension, the sub-dimensions include indicators that reflect the four pillars of food security (availability, access, utilization and stability–[44], complemented by key indicators capturing the other dimensions central to this dimension of sustainability: food safety, food waste and losses, diet quality, obesity and micro-nutrient deficiency [45–48]. Those dimensions and sub-dimensions are presented in **Table 2** and their details are provided in **S1 Table in Supporting material**.

At the same time, some of the GFSSI strengths (such as the inclusion of those four dimensions of sustainability) also constitute its main weakness, at least in the original version proposed by Béné and his colleagues [26]. In that initial version, both the social and economic dimensions were represented through one indicator only. We addressed this by adding nine new indicators to increase the representativity of these two dimensions. This raises the total number of indicators in the expanded version of the GFSSI to 29, thus achieving a more 'balanced' representation between the four dimensions: six indicators for the environmental dimension; seven indicators for the economic dimensions; four indicators for the social dimension; and 12 indicators for the food security and nutrition dimension.

Expanding the number of indicators to 29, however, means we had to drop three countries for which some of those new indicators' datasets were not available. The new GFSSI proposes

Table 2. List of 29 indicators included in the global food system sustainability index (GFSSI). The * symbols indicate indicators that have been 'flipped' to ensure the coherence of the GFSSI (see details in text). Source of the individual datasets indicated in S1 Table.

Dimension	Sub-dimension	Category	Indicators	Period	Nber countries
Environment	Air	Quality	Greenhouse gas emissions in total agriculture (gigagrams)*	2000–2010	222
	Water	Use	Agricultural water withdrawal as percentage of total renewable water (%)*	2000–2016	174
	Soil and land	Quality	Soil carbon content (as percentage in weight)	2008	202
		Use	Agricultural land as % of arable land*	2000–2014	217
	Biodiversity	Wildlife (plants, animals)	Benefits of biodiversity index (0 = no biodiversity potential to 100 = maximum)	2008	192
			Crop diversity (calories diversity measured by Shannon index)	2009–2011	177
Economic		Performance	Agriculture value-added per worker (constant 2010 US$)	2000–2015	181
			Retail value of ultra-processed food sales per capita*	2017	201
		Effectiveness	Cost of nutrient adequacy (at purchasing price parity)*	2011	159
		Efficiency	Relative caloric price of milk, eggs, white meat and fish*	2011	176
			Relative caloric price of Vit A rich vegetables and fruits*	2011	176
			Relative caloric price pulses*	2011	174
			Relative caloric price of junk food	2011	176
Social and Policy		Gender equity	Labor force participation rate, female (% of female population ages 15+)	2000–2016	184
		Supporting regulations	Existence of national food-based dietary guidelines	1991–2019	248
			Existence of any policies on marketing of junk foods to children	2015–2019	248
			Existence of any policies on mandatory nutrition labeling	1999–2017	248
Food and Nutrition	Food Security	Availability	Per capita food available for human consumption (kcal/capita/day)	2016	113
		Access	Food consumption as share of total income (% of total household expenditure)*	2016	113
			Estimated travel time to the nearest city of 50,000 or more people*	2015	245
		Utilization	Access to improved water resource (% of total population)	2000–2014	198
			Access to electricity (%)	2000–2014	211
		Stability	Price volatility index*	2011–2017	194
			Per capita food supply variability (kcal/capita/day)*	2000–2011	162
	Food Safety		Burden of foodborne illness (number of cases)*	2010	194
	Food waste and Use		Food loss as % of total food produced*	2016	113
	Nutrition	Diet	Diet diversification	2001–2010	165
		Overweight & obesity	Prevalence of obesity (% of the population, over 18 years of age)*	2000–2014	191
		Hidden hunger	Serum retinol deficiency*	1995–2005	193

Source: expanded from [26].

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therefore a sustainability index covering 94 countries (instead of the initial 97) across the range of low (N = 17), middle (N = 49) and high-income countries (N = 28). Importantly the process was designed so that the GFSSI is calculated with the exact same set of 29 individual indicators for every country, making those 94 countries strictly comparable in terms of their individual index. The datasets used to build the GFSSI were retrieved from the Harvard Dataverse [49] where they are stored, to which we added the datasets for the nine new indicators. The six new economic indicators focus essentially on the economic performances and efficiency of food systems to produce nutritious (and non-nutritious) foods. This speaks directly to the recent attention paid in the international community to the issue of 'affordability of healthy diets' [50]. The three new indicators added to the social dimension of the GFSSI refer to the existence of particular policies assumed to contribute positively to the sustainability of the index's social dimension. For those, we did not, however, simply use a binary value (absence = 0; presence = 1) but used instead the number of years since these policies were first implemented (thus, the earlier the beginning of the implementation in a country, the higher the indicator values for that country).

A Box Cox transformation was applied to the most skewed indicators–i.e., those with a $|\text{Skew}(x) - 0| > 2$ –to improve the normality of distribution and avoid potential issues related to heteroskedastic dataset distributions. Once transformed, the indicators were normalized using a standard (rescaling) min-max transformation with a [0, 1] range. Indicators expected to have a negative effect on sustainability within their own dimension were then 'flipped' (i.e., inverted) so that all indicators had the same directionality–a critical condition to ensure the coherence of the approach in the case of a composite index (test of internal consistency–see [42]). For the few indicators for which a 'middle value' is considered optimum (e.g., water pH around 7), data were transformed to measure the distance away from that optimum value in both directions.

Finally, the computation of the aggregated index combining the 29 indicators was done following standard approach suggested in the literature on composite indicators [51,52]. The formula for the aggregated index GFSSI is displayed in Eq (1). It is based on a combination of geometrical and arithmetic means in which each indicator had an equal weight within its own dimension and the four dimensions also received equal weight so as to avoiding overemphasizing particular indicators and/or dimensions over others:

$$\text{GFSSI} = (\text{ENV}_G;\ \text{SOC}_A;\ \text{ECON}_G;\ \text{F\&Nutr}_A)_G \quad (1)$$

where ENV, SOC, ECON, and F&Nutr represent the arithmetic or geometric means of each dimension, and the subscript *A* and *G* indicates the nature of the computation; A = arithmetic; G = geometric means.

Modeling sustainability of food systems and Gross Domestic Product

The modeling analysis aimed to explore the possible association between sustainability of food systems and Gross Domestic Product (GDP) per capita (used as a proxy for economic development). To explore this possibility, we developed a two-step modeling approach, building on some of the results obtained in the first part of the paper, and used the 'Middle of the Road' scenario (SSP2) from the Shared Socioeconomic Pathway [53] to assess how changes in GDP per capita may affect countries' food system sustainability in the future.

The Shared Socioeconomic Pathways (SSPs) framework provides narratives describing alternative socio-economic developments up to 2100, based on projected changes in world population, urbanization, and GDP per capita [54]. The Middle of the Road scenario (i.e., SSP2 in the SSP five-scenario framework) was chosen as it is equivalent to assuming a continuation of current economic development path (i.e., a business-as-usual scenario) in the future. We used the change in GDP per capita as projected between 2015 and 2050 by the SSP2 as input in our modeling analysis.

The two-step modeling approach included a first step where the effects of change in GDP per capita on the individual dimensions of the GFSSI were estimated using a series of Generalized Additive Models (GAM) run between the GDP per capita and the four dimensions of the GFSSI considered separately. GAM were initially chosen because they allow semi-parametric fits with relaxed assumptions on the actual relationship between dependent and explanatory variables, thus providing potential for better fits to data than purely parametric models (potentially with some loss of interpretability -see [55,56]). For three of the four models this approach turned out to be effective and the GAM provided the best fitted model. The Akaike information criterion (AIC) was used to confirm this against a whole set of other parametric models (see **S2 Table**). For the food security and nutrition dimension, however, a fitted log-model generated a better fit. That log-model was therefore used in the rest of the analysis for the food security and nutrition dimension along with the GAM models used for the three other dimensions.

Once those different models were estimated, we used them in the second step of the modeling analysis to compute the effects of the changes in each dimension on the GFSSI aggregated value, using Individual Conditional Expectations (ICE) computations [57,58]. The one-dimensional profiles constructed with those ICE models was used to estimate the dependence of the conditional expectation of the dependent variable (the aggregated GFSSI) on the values of the particular explanatory variables (the four dimensions of the GFSSI) taken individually. The idea was to determine the respective contribution of each dimension of the GFSSI (*ceteris paribus*) to the overall change in its aggregated value over time. The computations were made using the command DALEX in R (version 4.0.2). Underlying this analysis was the key assumption that the relationship as we observe it today between food system sustainability and GDP per capita across countries (used in step 1) is a reasonable proxy for the way it will evolve over time at country level (used in step 2). In other terms, we assumed that lower income countries will continue to evolve in the future along a path which is not too different from the path that higher income countries have followed so far.

Results

Descriptive analysis

The first step in the analysis was to check the statistical coherence of the aggregated GFSSI by confirming that the four dimensions of the index all vary in the same direction [42]. **Fig 1** shows the cross-correlation matrix between the four dimensions of the GFSSI. It indicates that the four dimensions positively correlate with each other (with values varying from +0.11 to +0.69), confirming the coherence of the index, thus allowing us to continue the analysis.

Fig 2 shows the GFSSI for the 94 countries for which data were available. Several key observations emerge from this global map. First, the index ranges from very low values (dark red) in some countries (e.g., Egypt, Mali, Pakistan, Myanmar) to middle range values (orange) in countries such as Brazil, India, Indonesia, to high or very high values (light beige) in others (e.g., Canada, France, Spain), suggesting a heterogeneity in terms of the level of food system sustainability across the world. Second, although the GFSSI could not be calculated for several countries in Africa and West Asia, a clear trend emerges, with low- and middle-income countries displaying, on average, lower sustainable values than countries belonging to the higher-income country group.

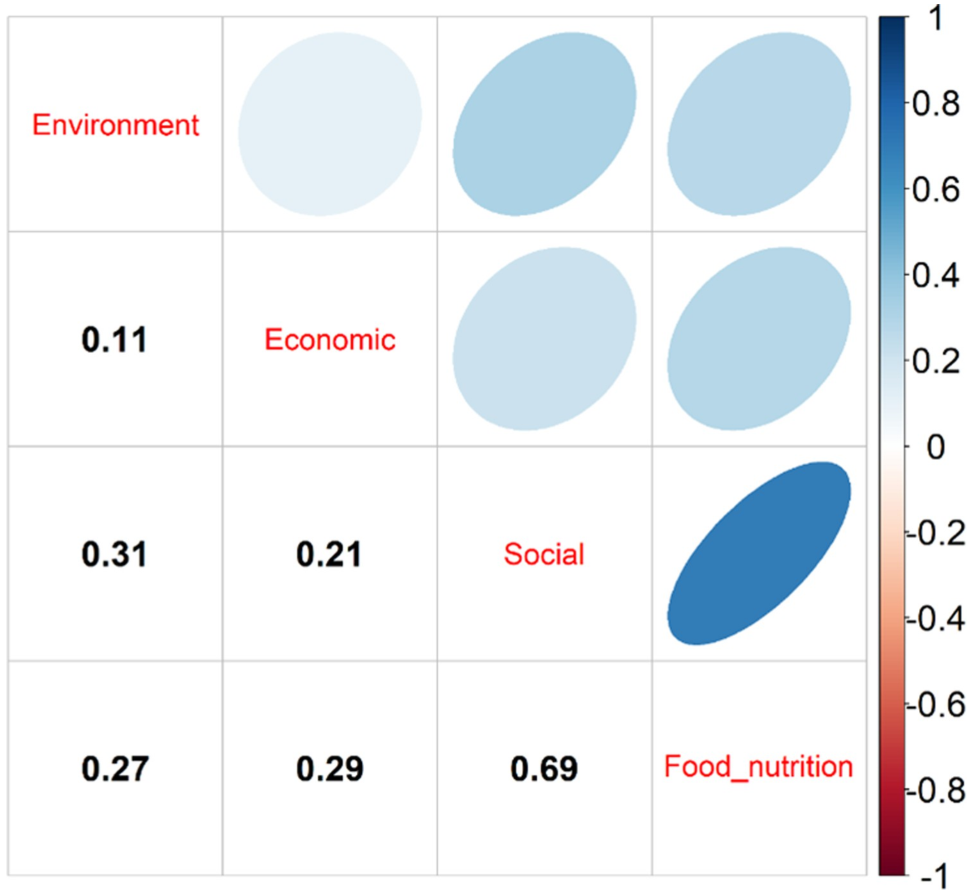

Fig 1. Cross correlation matrix showing the different correlations between the four dimensions of the GFSSI. Numbers represent Pearson correlation coefficients; ellipses represent the strength and direction of the correlation.

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This apparent trend is also observable in **Fig 3** in the form of a clear positive relationship between the GFSSI (Y-axis) and the GDP per capita (X-axis). The correlation is highly significant (Spearman coefficient $\rho = 0.81$, $p<0.001$) and considered "very strong" ($\rho \geq 0.8$) [59]. The relationship does not appear strictly linear, however, but log-shaped, indicating that, while countries' food system sustainability scores increase very rapidly with GDP per capita amongst the 'poorest' countries, the relationship then plateaus and countries with higher GDP per capita are characterized by a much flatter relationship.

Categorizing the countries using either the World Bank's low-, middle-, and high-income categories or grouping them by income terciles confirms the positive relationship between food system sustainability and GDP per capita: countries with higher GDP per capita are, on average, characterized by higher food system sustainability scores (see **Fig 4**). Non-parametric Kruskal-Wallis tests confirm that the differences are statistically significant for both World Bank ($\chi^2_{(0.95,2)} = 44.2$; $p< 0.001$) and tercile groupings ($\chi^2_{(0.95,2)} = 57.79$; $p< 0.001$) despite some relatively large variances, especially for middle-income and tercile 2 groups respectively. For the World Bank grouping, note also that the proportions of low, middle, and high-income countries amongst the 94 countries are 18% (L), 52% (M), and 30% (H), which is remarkably close to the proportions observed for the 218 countries and other regions listed in the World Bank 2019 list, respectively: 14% (L); 49% (M); 37% (H), thus suggesting that, if any, the risk of selection bias affecting our findings is relatively low.

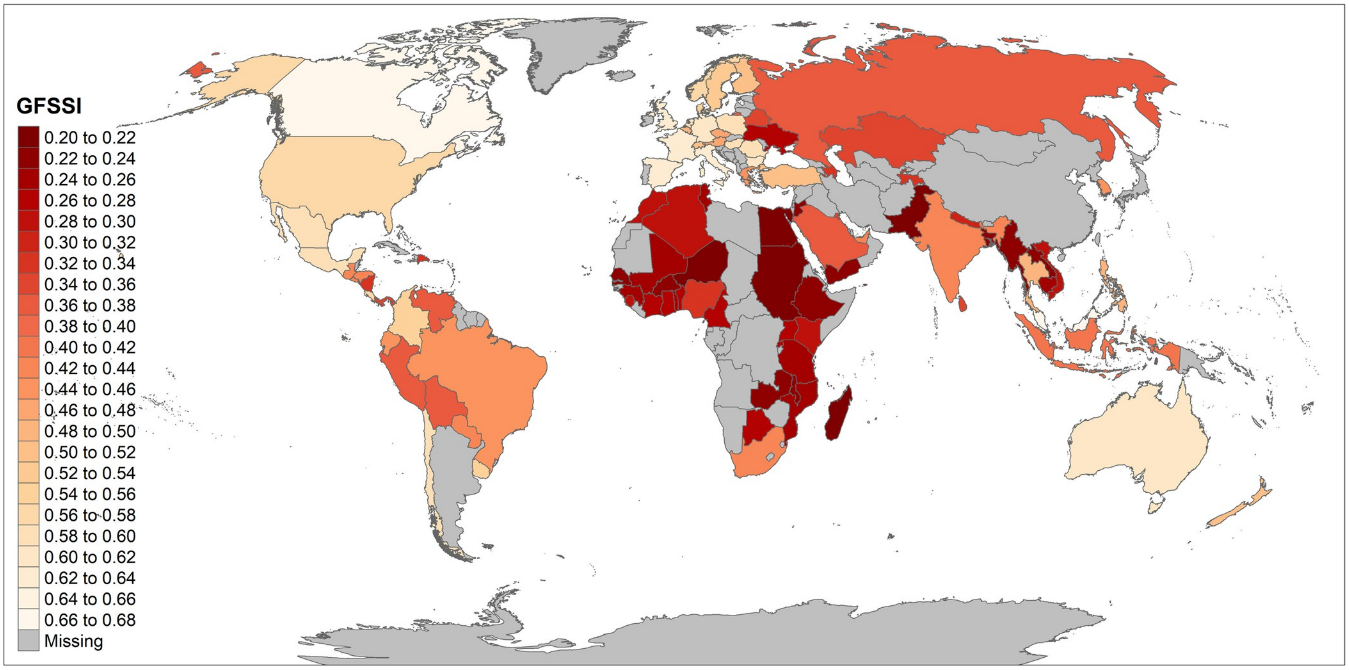

Fig 2. Global map showing the GFSSI computed for 94 countries, based on 29 indicators covering four dimensions: food security & nutrition; environment, economic, and social/policy. Red = lower level of sustainability, beige higher level of sustainability (map source: https://gadm.org/).

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Fig 5 examines the contribution of each of the 29 individual indicators to the aggregated GFSSI. Since the 29 indicators had been transformed and, when necessary, 'flipped' to ensure an appropriate directionality (that is, an increase in any of those indicators would theoretically be associated with a higher sustainability score in their own dimension), we would have expected the correlation coefficients between all 29 indicators and the aggregated index to be positive. The results indicate however that three indicators display negative coefficients: (*i*) the (flipped) retail value of ultra-processed food sales per capita; (*ii*) the relative caloric price of salt-rich foods and soft drinks and (*iii*) the (flipped) prevalence of obesity. What this indicates is that, as countries' overall sustainability indexes improve (essentially as countries move up the economic development ladder and increase their GDP per capita), these three indicators are moving in the opposite direction, suggesting that they are not improving with the aggregated sustainability index. This means that the changes in these three indicators (ultra-processed food sales; consumption of salt-rich foods and soft drinks; and obesity prevalence) are negative (i.e., getting worse) as countries' GDPs per capita increase and the countries' overall GFSSIs improve.

Dynamic analysis

The next step in the analysis was to revisit some of those results from a dynamic perspective. For this, we used the two-step modeling approach described in the methodology section. First, the effects of change in GDP per capita on each of the four individual dimensions of the index were estimated using Generalized Additive Models (S1 Fig). The results were then used in the second step to calculate the effects of future changes in each of those dimensions on the aggregate index for the period 2015–2050 under a 'business-as-usual' SSP2 scenario. Fig 6 shows the results of the SSP2 projection. The four graphs display the projected changes in countries' sustainable index, broken down by dimensions (food security & nutrition, environment, economic and social dimensions) between 2015 and 2050. To facilitate the analysis, countries

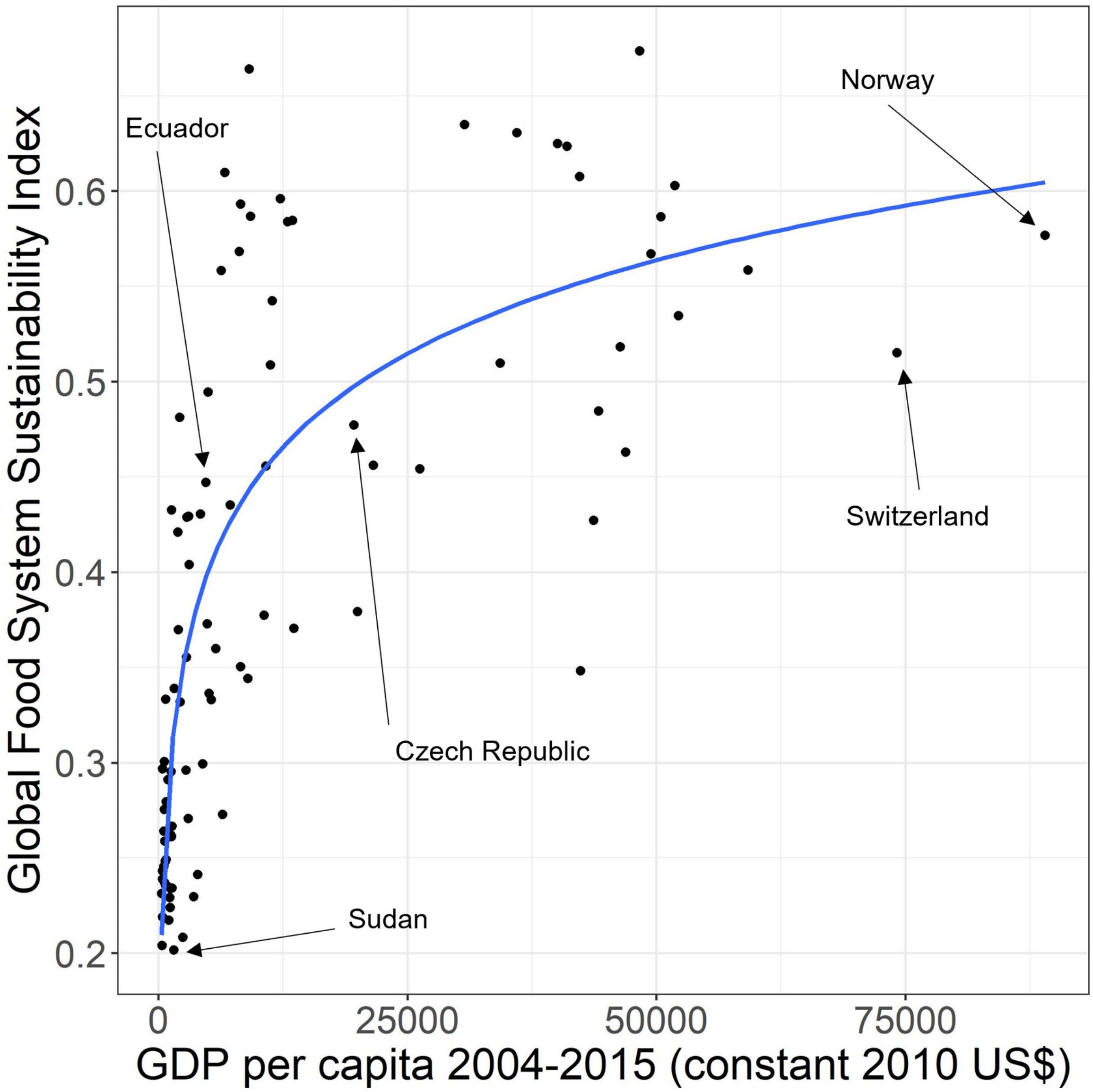

Fig 3. Relationship between countries' food system sustainability index and level of GDP per capita. The correlation is highly significant (Spearman coefficient ρ = 0.81, $p<0.001$) and 'very strong' (as per [59]'s 5-scale system). The blue line corresponds to the fit of a logarithmic regression model (adjusted $R^2 = 0.6391$). Five countries (Sudan, Ecuador, Czech Republic, Switzerland, Norway) have been highlighted for illustration purpose.

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have been grouped into geographical regions: South Asia, sub-Sahara Africa, East Asia and the Pacific, Latin America and the Caribbean, Europe and central Asia, Arab states, and a group of 'developed' countries (Individual countries results are displayed in **S2 Fig**).

Fig 6 shows that amongst the four dimensions of the index, social dimension and food security & nutrition are the two dimensions for which a larger number of countries across the different regions/groups show significant improvements in their individual sustainability scores. This suggests that the projected increase in GDP per capita under the SSP2 scenario is associated with the largest changes in the GFSSI through the improvements induced in the social and food security & nutrition dimensions. In comparison, the projected changes on environment and economic dimensions are much more modest across all countries' regional groups.

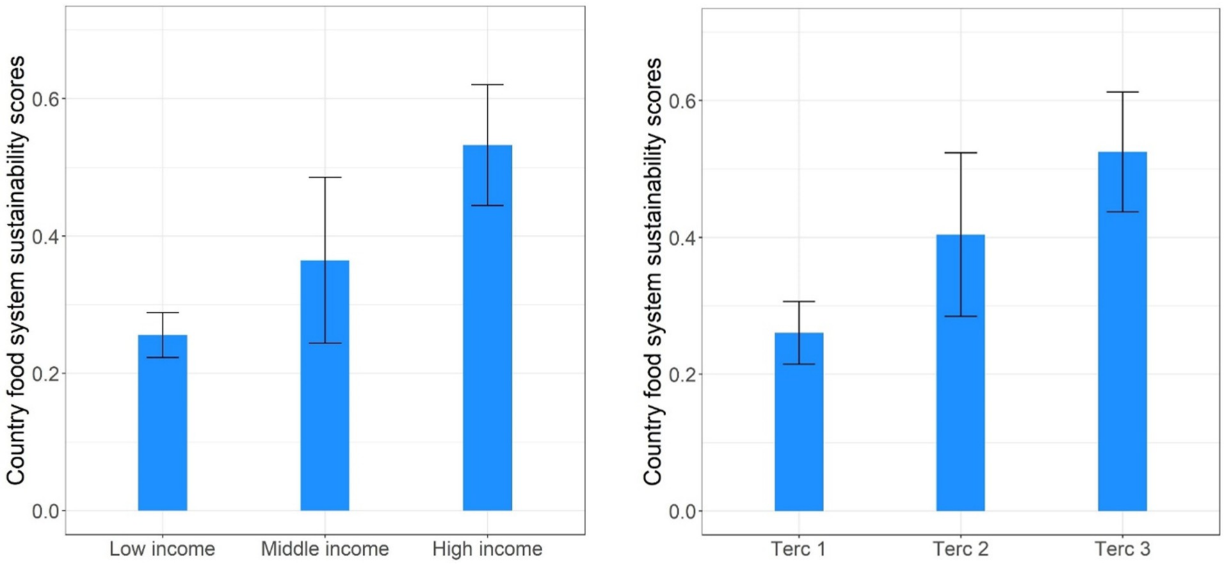

Fig 4. Level of countries' food system sustainability scores (means and 95% confidence intervals) for countries grouped according to (a) the World Bank's low, middle, high-income groups (left) or (b) by terciles (right). (World Bank groups: N = 17, 49, and 28 for low, middle, and high-income countries respectively. Terciles: N = 31 for terc_1 and terc_2; and N = 32 for Terc_3). Non-parametric Kruskal-Wallis tests conducted on both World Bank and tercile groupings confirm that the differences are statistically significant for both groupings: $\chi^2_{(0.95,2)} = 44.2$; $p< 0.001$ for World Bank; and $\chi^2_{(0.95,2)} = 57.79$; $p< 0.001$ for tercile grouping.

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More specifically, Sub-Sahara Africa, South Asian, and East Asia and the Pacific are the regions for which the improvements in the food security & nutrition and social dimensions are projected to be the largest. The group of Arab States is also projected to show significant improvement in their social dimension. In contrast, the group of developed countries display almost no improvement in their individual sustainability index for all four dimensions. In fact, for the economic dimension, they even show a slight decline in the GFSSI (top-left quadrant).

Discussion

In this paper, we explore the empirical question of the sustainability of food systems and its measurement, and how this sustainability may evolve as countries move along their economic development paths. Several approaches have been proposed recently in the literature to measure or to assess food systems' sustainability at a global, multi-country level, see e.g., [3,17,24–26]. A review of those analyses reveals, however, a number of methodological or conceptual challenges that impede or slow down progress. Several of those challenges relate to the fact that those analyses often adopt a relatively narrow interpretation of sustainability and/or of food systems, either by focusing only on the trade-offs between the need to produce and consume more nutritious food and the resulting environmental impacts (thus overlooking the more social and economic/policy-related aspects e.g., [11]), or by considering 'sustainable diets', e.g. [23,60,61], as opposed to 'sustainable food systems', e.g. [25,26,35]. Some comprehensive frameworks exist, e.g., [8,27], but those are mostly theoretical or conceptual and many of their proposed indicators don't have associated (publicly) available datasets, making these frameworks non-operational and of lower relevance for decision-makers [7].

In this context, one of the ambitions of this analysis was to show it is possible to build a holistic index that embraces the multi-dimensional nature of food systems' sustainability, yet remains representative not just of a few (higher-income) countries but more globally of a number of low-, middle- and high-income countries. To do so, we expanded Béné et al. [26]'s initial

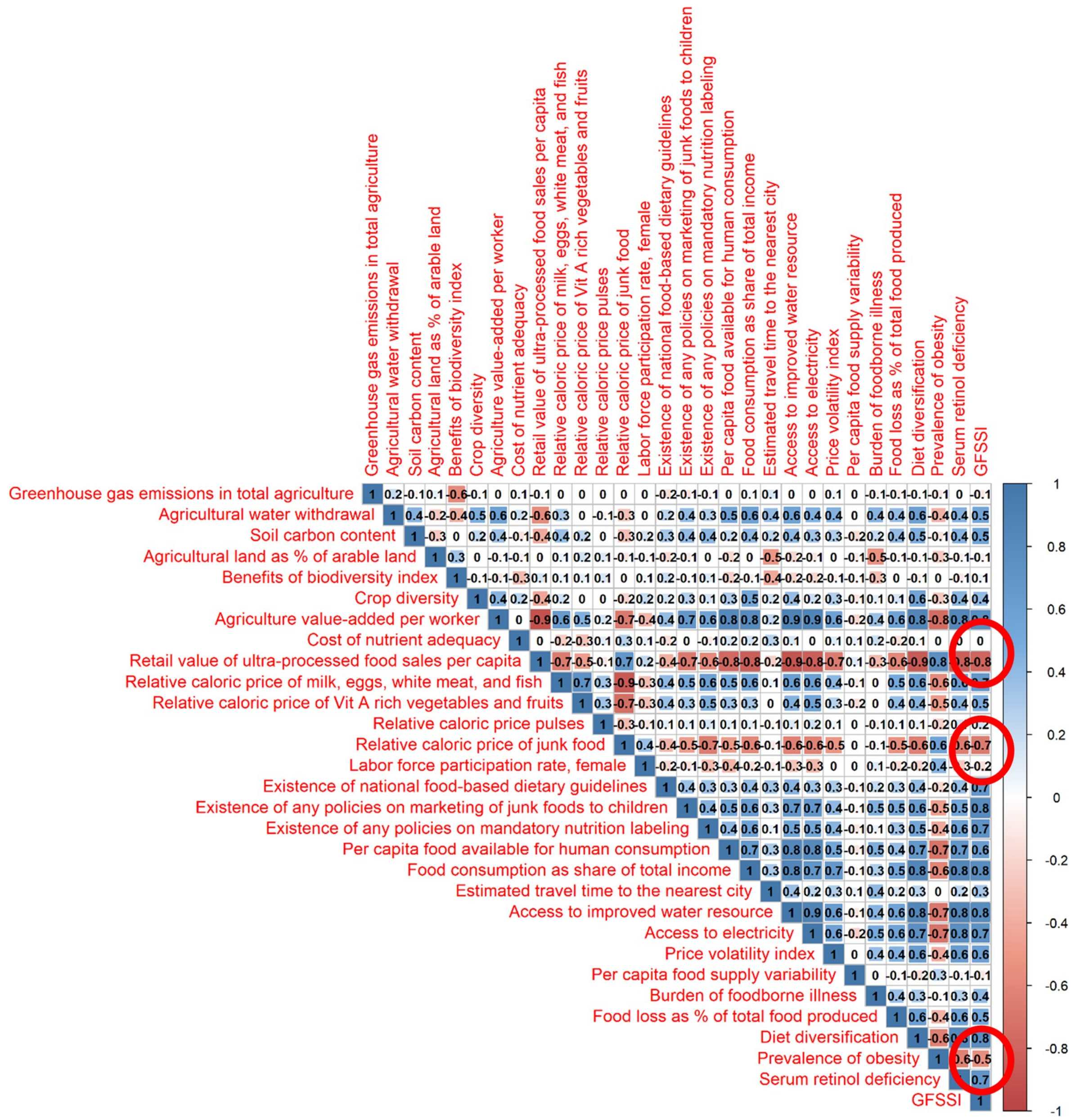

Fig 5. Cross-correlation matrix of the 29 indicators and the GFSSI (last column one on the right). Note the only three negative (and relatively strong) correlations observed between the GFSSI and (1) the retail value of ultra-processed food sales per capita; (2) the relative caloric price of salt-rich foods and soft drinks and (3) the prevalence of obesity.

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framework by adding nine new indicators to the two dimensions of their global index for which the number of indicators was the lowest (social and economic dimensions), while managing to retain 94 of their initial 97 countries. We argue that those different features make the GFSSI comprehensive *yet* operational. It is comprehensive in the sense that four different dimensions of sustainability are considered (food security & nutrition; environmental, social/policy and economic dimensions), each of them broken down further into a combination of sub-dimensions that ensure the conceptual coherency of the indicators. At the same time, the GFSSI remains operational and tractable as all those indicators have measurable values that are

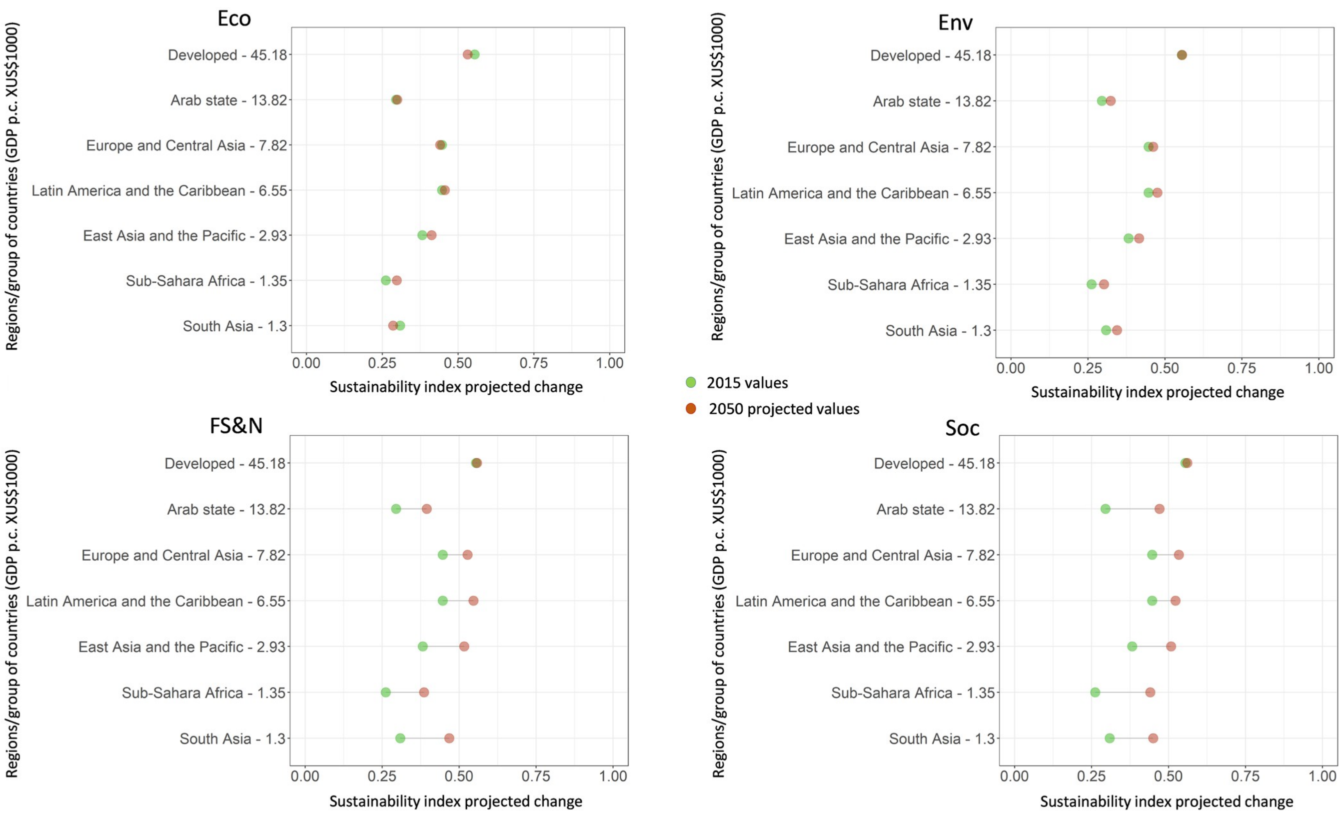

Fig 6. Projected changes in country sustainability index under a SSP2 scenario. Green dots: 2015 values, red dots: 2050 projected values. Eco = economic dimension; Env = environmental dimension; FS&N = food security & nutrition; Soc = social/policy dimension.

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publicly available for all 94 countries -70% of those 94 countries being low- or middle-income countries. Finally, the selection of these indicators relied on a rigorous and transparent protocol based on a set of ten clear inclusion/exclusion criteria.

Some caveats need to be kept in mind before discussing the results. First, this analysis presents data at the global aggregate level. Disaggregated data at the sub-national level is scant, and there is a need for more data granularity by geographic location at sub-national levels [62]. Second, and most importantly, correlation does not mean causality. In this context, the relationship observed between countries' level of food system sustainability and GDPs per capita remains at this stage an empirical correlation. In other terms, we do not claim that GDP per capita is a driver of food system sustainability (and we paid attention throughout the paper not to make this confounding statement). In fact, like in the case of the environment, e.g. [41], there is growing evidence that economic growth does not necessarily result in beneficial outcomes from a food system perspective. In particular, in some high-income countries, obesity and diet-related non-communicable diseases, and environmental sustainability remain significant issues [63–65].

Our analysis, however, also indicates that, when the sustainability of the food system is conceptualized not just based on food security/nutrition and environment outcomes but with a more holistic framework that also encompasses social and economic considerations, countries characterized by high economic development levels (measured through GDP per capita) are also amongst the group of countries with higher food system sustainability scores. In contrast, countries at the 'bottom' of the food system sustainability ranking also appear to belong to the low-income country group (Fig 1). Furthermore, because this result is based on a large but relatively balanced number of indicators between the four dimensions of the index, it indicates that this cross-country pattern is relatively 'robust' and not just an artifact of the composition of the index.

Sustainability and GDP

It is not the first time that the question of the sustainability of food system and its correlation to GDP is raised. Chaudhary et al. [25] for instance discuss this relationship in their food systems' multi-indicator sustainability analysis (see in particular their Table 1 p.2). These authors however only consider the correlations between GDP per capita and the 25 *individual* indicators included in their analysis. They find that several of those indicators are strongly correlated to GDP per capita (either positively, e.g., Food Availability Score or Food Safety Score, or negatively, e.g., per-capita GHG emissions); but they do not attempt to extrapolate what this would mean for an *aggregated* sustainability index.

The empirical correlation observed in our analysis between GDP per capita and the aggregate GFSSI suggests some possible degree of endogeneity between food system sustainability and economic development. From a macro-economic perspective, the presence of this potential endogeneity is an important result. It does not imply any form of direct causality (see above); but it suggests that some of the internal processes and variables driving GDP per capita may also be driving food system sustainability. To some extent, this result is not completely unexpected given that some of the key variables known to be important drivers of GDP per capita -such as income or foreign investments- have also been shown to be important drivers of food system transition [2,18]. What was unclear until now, however, was how the *combination of all those different variables* influence the overarching, emerging sustainability of food systems. Taken individually, some economic, social or environmental variables that are generally observed (or expected) to improve with economic development (such as gender and social equity, decency of jobs, reduction in undernutrition) are also assumed to contribute positively to the sustainability of food systems, e.g., [25,66]. Other processes, however, which also increase with economic development are known to contribute negatively to the sustainability of food systems (e.g., GHG emission, deforestation, prevalence of obesity) [43,67]. What our study shows is that the overarching sustainability of food systems that *emerges* from this combination of 29 different indicators is eventually positively aligned with economic development. In essence, our analysis suggests that food system sustainability and economic development *coevolve* over time. The term coevolution is used here purposively to refer to the empirical observation by which both processes appear interrelated and are moving simultaneously in the same direction as time passes.

The data revealed, however, that this coevolution is not a strict linear relationship. Although higher-income countries do have on average higher food system sustainability scores than countries in the lower-income groups (Fig 4), the positive trend observed between GDP per capita and food system sustainability flattens relatively rapidly (Fig 3) and the sustainability of food systems eventually stops improving for the economically more advanced countries.

Beyond the non-linearity of this relationship, the data also reveals that the coevolution of food system sustainability and economic development is not 'infallible'. Some countries appear as 'outliers' and fall well outside the trend. In particular, a certain number of countries display a much higher GFSSI than one would have predicted based on their level of GDP per capita; this is the case of Malaysia in the middle-income country group and Canada in the high-income countries (**Fig 7**). In contrast, some countries are doing worse than would be expected: Saudi Arabia and Kuwait are two examples amongst the high-income country group. Because

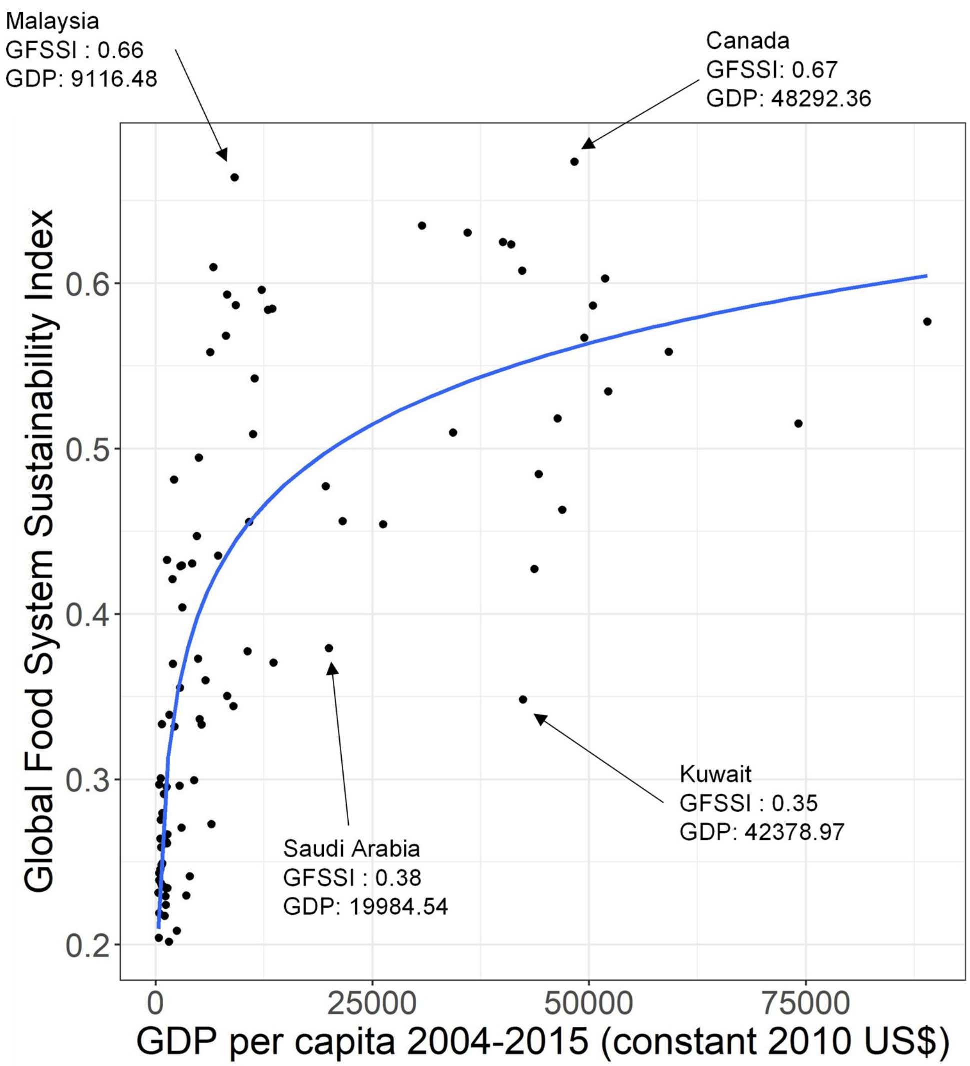

Fig 7. Examples of countries for which the 'coevolution' between GFSSI and GDP per capita is not particular strong.

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each indicator and each dimension has been weighted equally in the computation of the aggregated GFSSI (see methodology section), the large divergence observed for those particular countries cannot simply be explained by the effect of one or two 'outlying' indicators; it suggests instead an overall difference (either positive or negative) across the 29 indicators. Exploring more thoroughly why particular countries fall well aside the general trend would require country-specific analyses and, as such, is beyond the scope of this initial analysis. Studying positive or negative deviants could, however, unveil important information.

The data also revealed that some particular indicators can diverge from the positive trend linking global food system sustainability and economic development. In our case, the retail value of ultra-processed food sales per capita, the relative caloric price of salt-rich foods and soft drinks, and the prevalence of obesity all show negative correlations with their aggregate GFSSI (Fig 5). These results suggest that the respective contributions of those three indicators to food system sustainability are negative, and eventually that these indicators move in the opposite directions as countries move up the economic development ladder. This observation is in line with the rest of the literature where sales of ultra-processed food, consumption of salt-rich foods and soft drinks, and prevalence of obesity are usually observed to increase in high-income countries -even though those global trends are being increasingly observed in low- and middle-income countries as well [68,69].

Dynamics of food system sustainability

Building on those various empirical results, Individual Conditional Expectations (ICE) models were then used to explore further the dynamics of food system sustainability. Through this modeling we were especially interested in determining how the sustainability of food systems will evolve in the future as lower-income countries continue their economic development, and whether all dimensions of their GFSSI (food security & nutrition; environment; social; and economic dimensions) would contribute equally to the projected changes in these countries' food systems sustainability. Underlying all those different interrogations was the quest for a better understanding of the determinants and dynamics of food systems sustainability.

Our results are contingent on some strong assumptions—especially the hypothesis that food systems in lower income countries will continue to evolve in the future along a transitional path relatively similar to the path that food systems have followed in higher income countries. Looked at from close range, this assumption is somewhat questionable if we agree that countries' food systems generally follow distinct and individual transitional paths that are unique and specific to each country, reflecting the strong cultural, historical and socially-defined identity associated with food [70,71]. But we also know that beyond those specificities, food systems are all moving in similar directions and showing disturbing similarities/convergences across countries, including the "Westernalization of diets" [72], the "homogenization of crops" [73], the increased dependence on Genetically Modified Organisms [74], the general increase in consumption of ready-to-eat, convenient, cheap, and often ultra-processed foods [75,76] or the quasi-universal increase in demand/consumption of animal-based protein triggered by income rise [77]. The assumption of food system future transition perpetuating (or reproducing) the current trends is therefore not totally unrealistic and in the absence of any alternative grounded theory, this assumption can be seen as a reasonable starting point to (better) understand what will drive food system (un)sustainability in the future,—even if we stress that this interpretation needs to be made with caution.

The ICE models show that countries are not projected to improve their food system sustainability in an identical manner. For lower income countries, the improvement is usually more significant than for higher income countries (Fig 6). For those higher income countries, the extent to which food system sustainability is projected to improve appears relatively limited. The analysis also reveals that the different dimensions of food system sustainability will not all contribute the same way to the change in GFSSI. Investments and interventions targeting social and food security & nutrition dimensions are projected to have a greater effect on the sustainability of food systems than investment/interventions aiming at the environment or economic domains (Fig 6). In sum, despite the fact that the sustainability of food systems appears to coevolve with countries' GDP per capita (a variable generally assumed to be closely related to economic dynamism), social and food security & nutrition are the dimensions where the effects of interventions are projected to be the largest.

Policy relevance

If our results are confirmed by other similar analyses, they will point at important policy implications. In particular, for countries located at the lower end of the economic development spectrum, this would imply that, even with limited resources, policy-makers would still be able to substantially improve the sustainability of their countries' food systems by prioritizing (sub) national policies and interventions focused on social and food security & nutrition domains. These could include restricting marketing and advertising of ultra-processed foods to children [78,79], improving governance, policies and planning to support the role of informal actors in urban poor population's food security, e.g. [19,80], or instituting labeling and fiscal policies such as taxation [81–83].

The locus of action for prioritizing, investing, and implementing improved food system performances falls therefore on national and sub-national actors engaged directly in food system governance. These actors are best positioned to identify, prioritize, and sequence interventions based on the needs of their food systems. Nonetheless, these domestic processes require support from a global architecture to identify common information gaps and promote efforts to fill these, facilitate knowledge exchange on the impacts of policies / interventions across diverse contexts, promote global compacts to hold multinational non-state actors accountable to common standards and ensure access to necessary financial support to implement these approaches particularly in lower-income countries [9]. Parts of this architecture exist and other components are under discussion in the aftermath of the UN Food System Summit. Moving from paper to practice, however, requires concerted effort from multiple parties over an extended period of time.

Within the wider literature, there is already a recognition that it will be difficult to achieve SDGs without food system sustainability [1,3,22,84,85]. All 17 SDGs are important but with less than ten years to achieve them, a mounting sense of urgency is emerging. In that regard, our work suggests that in order to achieve *both* the SDGs and the sustainability of food systems, focusing on particular SDGs may be especially important. Beyond (the obvious) Goal 2 devoted to ending hunger and malnutrition or Goal 12 encouraging responsible consumption and production, improvements in social dimensions seems to be key to increase sustainability. This suggests that the synergy between food system sustainability and SDGs will also depend on those other SDGs with specific emphasis on social objectives, such as, e.g., Goal 3 on health and well-being, Goal 5 on gender equality, Goal 8 on decent work, or Goal 10 on inequalities. Without investing in those objectives, countries will struggle to meet not only food system sustainability but their SDGs as well.

Beyond these specific reflections, this work demonstrates the necessity to rapidly develop analyses and tools that can allow exploring more dynamically and comprehensively food systems, investigating what drives them and how the different elements of those systems interact with each other and evolve over time [9,86]. At present, our ability to do so and to assess more holistically the consequences of food systems' rapid transformations on different outcomes (food security, nutrition, environment, or social dimensions) is limited [87]. Part of this limitation derives from the generally incomplete, fragmented and static datasets that we have at our disposal at present. More effort and investments will have to be made in the coming years at (sub)national and international levels to address this gap [7,16]. Understanding the dynamics of food systems, how those dynamics affect trajectories toward sustainability, and how to measure this sustainability at the system level is indeed critical if we want to support policy-makers in designing and implementing appropriate policy and interventions.

Conclusion

In this paper, we develop a global food system sustainability index (GFSSI) built on 29 indicators and structured into four dimensions: food security & nutrition, environment, economic and social dimensions. We use this holistic index to assess the sustainability of national food systems across a set of 94 countries covering low, middle and high-income regions. The analysis revealed a strong positive correlation between countries' food system sustainability and economic development, suggesting that, in general, countries characterized by higher (lower) economic development are also characterized by higher (lower) level of food sustainability. This coevolution is not a strictly linear and perfect one however, and some countries fall well outside (either above or below) the trend, thus emphasizing the need for more data granularity by geographic location at national or even subnational level -especially for large countries. Relying on modeling techniques, we then explore how this relationship is likely to evolve in the coming decades as countries move up the economic development ladder. The analysis reveals that countries are not projected to improve their food system sustainability in an identical manner. For lower income countries in particular, the changes are usually more significant/rapid than for higher income countries. The analysis also reveals that the different dimensions of sustainability considered in the GFSSI will not all contribute equally to future improvements in countries' food system sustainability. Especially, investments targeting social and food security & nutrition dimensions are projected to have a greater effect on the sustainability of food systems than investment/interventions aiming at the environment or economic domains.

These different results and analyses are part of the emerging body of literature that discusses how to assess and measure food systems sustainability across countries. This literature generally aims at capturing the holistic nature of food systems while embracing the complex set of outcomes, driver metrics and trade-offs that characterize these food systems. Achieving consistent measurements of food system sustainability at a global scale remains challenging due to data limitations, methodological concerns and our nascent understanding of how different components interact with each other to deliver (or not) sustainable outcomes. Despite these challenges, the need for policy-relevant tools continues to grow as the recent UN Food System Summit highlighted. Governments still need to develop food system upgrading strategies -even with imperfect or decontextualized information- that can help them move towards greater sustainability while accounting for difficult trade-offs, specific development needs and limited investment capacities in the context of the SDGs. Tools that embrace the holistic nature of this challenge, based on consistent indicators and improved understanding of how components of the food system interact can help decision-makers see around the corner and design policies that are more effective. No one tool delivers all that is needed, but the global food system sustainability index (GFSSI) presented here, hopefully, takes an important step in this direction.

Supporting information

S1 Fig. Step 1 of the modeling: the four Generalized Additive Models run between the GDP per capita and the four dimensions of the GFSSI. 95% confidence intervals highlighted in grey. Social dimension adjusted R-squared: 0.4518; Food & nutrition adjusted R-squared: 0.81; Environment adjusted R-squared: 0.1448; Economic adjusted R-squared: 0.0953.
(TIF)

S2 Fig. Step 2 of the modeling: Projected changes in country sustainability index under a SSP2 scenario (Individual country's results). Green dots: 2015 values, red dots: 2050 projected values. Eco = economic dimension; Env = environmental dimension; Fnt = food security & nutrition; Soc = social/policy dimension.
(TIF)

S1 Table. The 29 indicators and their sources.
(DOCX)

S2 Table. Akaike information criterion (AIC) (and adjusted R2 and level of significance in brackets) for the different models tested as part of step 1 of the modeling analysis. In shade gray the models which were retained based on their AIC scores.
(DOCX)

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Writing – review & editing: Christophe Béné, Jessica Fanzo, Mark Lundy.

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