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Specialization in food production, global food security and sustainability

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Specialization in food production, global food security and sustainability

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Abstract

Understanding specialization patterns of countries in food production can provide relevant insights for the evaluation and design of policies seeking to achieve food security and sustainability, which are key to reach several Sustainable Development Goals (SDGs). In this paper, we use production data from FAO for the period 1993 to 2013 to build bipartite networks of food products and food producing countries. We use methods from complex systems analysis to rank countries according to their capabilities or competitiveness and products according to their sophistication or need of capabilities. Competitiveness is quantified by the fitness of countries, which measures the quality and how diversified are their food production baskets. We observe two well-defined communities of food producing countries, one clustering countries with relatively developed agricultural systems, and the other one grouping only developing countries. We use network statistics on food production and specialization patterns, and we perform an econometric analysis to study whether and how specialization patterns affect food supply, food security, and sustainability of food systems. We show that concentrating agricultural production decreases food supply, food security, and sustainability of food systems. The competitiveness or fitness of countries as well as the coherence of diversification patterns, both increase per capita food supply and food security (SDGs: Targets 2.1 and 2.2) but might have a negative effect on sustainability (SDGs: Target 2.4). This reflects the trade-off between achieving food security while simultaneously improving sustainability, which needs to be considered when developing or implementing policies seeking to reach SDGs. Given that the position of countries in food trade dynamics also affects their decisions in food production specialization, the analysis opens the ground for trade policy considerations (SDGs: Target 2.b).

Keywords: Specialization; Food supply; Food security; Sustainability; Complex networks; Bipartite networks
JEL Codes: Q01; Q18; F63

1 Introduction

Achieving global food security and sustainability of food systems has become a growing challenge at the international policy level. The relevance of the global food system is reflected in the fact that it appears as a key element for a great number of the 17 Sustainable Development Goals (SDGs). This reflects the broad scope of the SDGs, which require holistic approaches, integrating food sustainability assessments (Chaudhary et al., 2018; Blesh et al., 2019). Although the concept of food system has gained prominence in recent years among both scholars and policymakers, Béné et al. (2019) show that the related studies tend to be framed within distinctive disciplinary narratives. Likewise, the concept of sustainability remains poorly defined, and applied in different ways. The trade-offs between different dimensions of food systems sustainability are unavoidable and, therefore, need to be addressed when developing or implementing sustainable food system initiatives.

The global food system can be regarded as an evolving, complex, dynamic, and highly interconnected network of activities, including production, processing, transport, and consumption of food. In addition, the food system involves a high number of heterogeneous stakeholders (Timmer, 2009; Lowder et al., 2016), with multiple issues shaping and affecting it, including the governance of food production and trade (Oosterveer, 2007), food standards (Hansen and Trifković, 2014), intellectual property rights (Campi and Nuvolari, 2015; Campi and Dueñas, 2016; Campi, 2017), food supply and distribution (Validi et al., 2014; Distefano et al., 2018), sustainability (Chaudhary et al., 2018; Béné et al., 2019), food waste (Parfitt et al., 2010), biodiversity (Khoury et al., 2016), and the impact of climate change and food quality on population health (Patz et al., 2005).

Although our understanding of the global food system is still recent and incomplete (Puma, 2019), several efforts have been made in analyzing it as an evolving complex network. While there has been progress in the understanding of how countries are interconnected in the food system through international-trade linkages, there is less evidence on how countries, given their capabilities, specialize in food production, and on the effects of their specialization patterns.

This paper starts filling this gap by studying the global food production system from a complex network perspective. We provide evidence on how specialization in food production at the country level affects food supply, food security, and food system sustainability at the country level. This evidence can help improving our understanding of agricultural production at the country level, which is crucial to achieve food security and sustainable food systems, and to address the trade-offs that might emerge in pursuing both.

In a recent paper, Campi et al. (2019) analyze the global food system as a bipartite network, using production data from FAO for the period 1993-2013. They show that the network exhibits well-defined communities of countries and products, i.e. the network is characterized by groups of countries that are similar in their agricultural capabilities and production baskets, as well as by groups of products that are close to each other because they share the need of similar capabilities. Furthermore, despite food systems have been undergoing unprecedented pressure in recent years and that they have suffered changes in terms of demand and dietary quality, specialization patterns are very stable over time. Interestingly, the communities of countries are not only defined by agro-ecological conditions but also by economic and technological factors, which are shaped by the development levels of countries.

Building on this evidence, we analyze whether and how food specialization patterns of countries, which arise from the network analysis, have an impact on food supply, multidimensional aspects of food security (SDGs: Targets 2.1 and 2.2), and sustainability of food systems (SDGs: Target 2.4), which are key for achieving the second SDG, Zero Hunger, that seeks to simultaneously address global environmental sustainability and food security challenges. Understanding food systems from an evolving complex network perspective can provide relevant elements to reach the SDGs. In addition, this analysis opens the ground for trade policy considerations (SDGs: Target 2.b), given that the position of countries in food trade dynamics also affects their decisions in food production specialization.

Using production data of 219 agricultural products for 169 countries, we analyze food specialization patterns and how countries diversify their production baskets. Countries can diversify their production in products that are close to the set of capabilities they already have (measured by the degree of similarity of products) or they can instead diversify in products for which they need to acquire new capabilities. In addition, we estimate indicators of concentration of agricultural production at the country level.

Following the recent literature that studies how capabilities shape production of different types of products and how this, in turn, helps economic development (Hidalgo et al., 2007; Hidalgo and Hausmann, 2009; Cristelli et al., 2013; Zaccaria et al., 2014), we employ a method to rank countries according to their capabilities or competitiveness, and products according to their need of capabilities or their sophistication. We use network-based indicators: competitiveness or "fitness" of countries, which considers the type of goods produced by them, and the sophistication or "complexity" of products, which is determined by whether agricultural products are commonly produced or if, on the contrary, particular or scarce capabilities are required for their production. In the case of food production, the fitness of a country is an extensive variable with respect to the number of goods produced. Thus, the larger is the fitness of a country, the more diversified is its production basket and the larger is the quality of the goods produced (Tacchella et al., 2012). In this sense, we use the measure of fitness as an indicator of the competitiveness of countries in food production.

The networks of agricultural products and food producing countries are both stable over the period and although they are very dense, they display well-defined communities. The networks of products are featured by four communities of closely related products, i.e. that require similar capabilities for their production. In the network of food producing countries, we observe that countries cluster in two stable and well-defined communities, which implies that countries within a community are characterized by similar endowments of natural conditions and capabilities for agricultural production. One community includes all developed countries and countries with relatively developed agricultural systems. Instead, the other community only includes developing countries. The community with developed countries produces higher shares of food, and imports and exports more food per capita, although the shares of population are similar in both communities.

The indicator used to classify countries by their competitiveness or fitness shows positive correlations with different macro indicators, such as agricultural gross production values, gross domestic product, and agricultural exports. Moreover, it also correlates positively with food supply, and with multidimensional indicators of food security and sustainability of food systems.

Combining network-based statistics and other indicators characterizing food production baskets of countries, we perform an econometric analysis, controlling for omitted variables bias and endogeneity, to evaluate how competitiveness or fitness, coherence of diversification patterns, and concentration of food production affect per capita food supply, food security, and sustainability of food systems. The data on per capita food supply at the country level is provided by FAO (2019). The indicators of food security and food systems sustainability consider multidimensional aspects. The recent composite index of food security, built by Caccavale and Giuffrida (2020), weights 21 selected indicators distributed in the four pillars of food security: availability, access, utilization, and stability. The composite indicator of sustainability of food systems, from Béné et al. (2019), aggregates 27 indicators grouped in four dimensions: Environmental, Economic, Social, and Food & Nutrition.

Our results show that concentrating production decreases food supply, food security, and sustainability levels of countries. We find a positive relation between competitiveness in agricultural production with both food supply and food security. Given that the indicator of competitiveness is closely related to the variety of products, the evidence indicates that promoting diversification of agricultural production, rather than specialization, reduces the risk of facing a food deficit. Moreover, we estimate an additional gain when diversification is coherent, which implies that countries benefit by exploiting their existing capabilities. The effect on sustainability is more ambiguous, but, in some cases, we find that more competitive agricultural systems that follow a coherent diversification pattern negatively affect sustainability of food systems. This reflects the trade-off between achieving food security while simultaneously improving sustainability, which needs to be considered when developing or implementing policies seeking to reach SDGs. Finally, we also observe different effects when we consider the two detected communities of countries.

Generally, the evidence suggests that country specialization in food production could be a key pillar affecting countries food supply, food security, and sustainability of food systems. Thus, understanding agricultural specialization patterns can provide relevant insights for the evaluation and design of policies seeking to achieve both food security and food systems sustainability.

The remaining of the paper is organized as follows. In Section 2, we present a brief literature review. In Section 3, we describe the data. In section 4, we explain the methodology. In Section 5, we present the main results. Finally, Section 6 concludes.

2 Literature review

The analysis of multiple aspects of the global food system has derived in a broad number of studies. In this section, we revise different analysis that are useful for characterizing food production and its relationship with food security and sustainability.

Several features shaping food systems have developed relatively quickly and are rapidly evolving. Multiple factors have been placing unprecedented pressure on food systems: population growth (Godfray et al., 2010), dietary changes (Finaret and Masters, 2019), rising food prices and agricultural production shocks (Tanaka and Hosoe, 2011), over-exploitation of natural resources (Hazell and Wood, 2007; Cassidy et al., 2013), climate change (Battisti and Naylor, 2009; Gornall et al., 2010; Coumou and Rahmstorf, 2012), and increasing biofuels and biomass use (Woods et al., 2010; Nonhebel and Kastner, 2011). In this context, meeting an increasing and more sophisticated demand while moving towards more sustainable food systems has become a growing challenge at the international policy level.

Countries have been recently going through dietary changes towards more diverse foods, different nutrient composition, sustainability, and a variety of credence attributes (Finaret and Masters, 2019; Barabási et al., 2020). Accordingly, agricultural production has diversified but has also become more similar in composition. Khoury et al. (2014) analyze changes in the relative importance of different crop plants in national food supplies worldwide for 50 years. They show that within a global trend of increased overall quantities of food calories, protein, fat, and weight, national food supplies have diversified. Simultaneously, they have become increasingly similar in composition, based upon a suite of truly global crop plants. The growth in reliance worldwide on these crops heightens interdependence among countries regarding availability and access to these food sources and plant genetic resources. Similarly, Bentham et al. (2020) show that four predominant food-group combinations explain almost 90% of the cross-country variance in food supply.

Therefore, most countries now consume more homogeneous food, despite not all countries have natural conditions to produce these generic products that constitute their food baskets. Khoury et al. (2016) show that countries are highly interconnected regarding primary regions of diversity of the crops they cultivate and/or consume. They show that foreign crop usage has increased significantly over the past 50 years, including in countries with high indigenous crop diversity.

Food availability is also determined by food international trade, which has been also increasing, shaping, and homogenizing the variety of available food at the country level. Thus, several studies have analyzed and characterized food trade networks (for example: Ercsey-Ravasz et al., 2012; Shutters and Muneepeerakul, 2012; Puma et al., 2015). From a multi-network perspective, Torreggiani et al. (2018) show that the individual crop-specific layers of the multi-network have densely connected trading groups consistently over 2001–2011. The multi-network is characterized by low variability but with substantial heterogeneity across layers in each year. The layers are mostly assortative, which implies that more intensively connected countries tend to import from and export to countries that are themselves more connected. This evidence is valuable to understand past and emerging dynamics in the global food system, especially to examine potential shocks to global food trade, which has also been addressed from a complex network perspective (see, for example Fair et al., 2017; Burkholz and Schweitzer, 2019).

All these studies have shed light on the behavior of a more interconnect world and on possible implications and vulnerabilities for agricultural production, sustainability, and food security. Thus, the evidence calls for the analysis of food systems as a complex system. In fact, substantial progress in the understanding of the features and evolution of food systems has been recently made employing a complex network approach (Schweitzer et al., 2009; Puma, 2019).

However, despite its relevance for food security and sustainability, the production side of food systems has been much less studied. Campi et al. (2019) started filling this gap by analyzing the networks of food producing countries, their specialization patterns in food production, and how they diversify their production baskets. This study builds on the idea that different products are jointly produced because they require similar capabilities (Teece et al., 1994).

The employment of network analysis for empirically developing these ideas in the pioneering analysis of Hidalgo et al. (2007) was followed by a great number of studies showing that the possibilities of diversification into new products are strongly determined by the capabilities revealed in the products currently produced (for example: Hidalgo and Hausmann, 2009; Caldarelli et al., 2012; Tacchella et al., 2012; Cristelli et al., 2013; Hausmann et al., 2014; Zaccaria et al., 2014; Balland and Rigby, 2017). Thus, although the set of capabilities necessary for production cannot be directly observed, the fact that different countries produce identical products may indicate that these countries share capabilities that are needed to produce these products.

In brief, these studies develop a methodology to analyze how countries manage to produce goods that demand different capabilities, and to build the world product space network, where more sophisticated products are located in a densely connected core, whereas less sophisticated products occupy a less connected periphery. Empirically, countries move through the product space by developing goods close to those they currently produce. Poorest countries tend to be located in the periphery, where moving toward new products is harder to achieve.

Although several products in the periphery of the world production space are agricultural products and, therefore, could be regarded as not relevant to reach sectors in the core, agricultural production is undoubtedly relevant for achieving food security and sustainable food systems. Moreover, considering that agricultural production has been frequently affected by shocks that give place to fluctuations (see, for example, Gornall et al., 2010; Coumou and Rahmstorf, 2012), we could expect that certain specialization patterns and concentration of production might make countries more vulnerable to production shocks endangering their food security and their sustainability.

In brief, food systems are increasingly globalized, complex, and interdependent, while diets worldwide are changing, and pressure over natural resources is increasing. In this context, a better understanding of diets and food systems, and how they evolve is necessary to support the delivery of healthy and sustainable food system policies and, in particular, to achieve the second SDG, which seeks to simultaneously address global environmental sustainability and food security challenges. In this task, trade-offs between different dimensions of food system sustainability are unavoidable and need to be addressed (Béné et al., 2019).

3 Data and definitions

We use data from FAO (2019) on food production for the period 1993-2013, for 169 countries that are detailed in Table A.1 of the Appendix, and of 219 agricultural goods, which are presented in Table A.2 of the Appendix.

We define an agricultural or food product as any product or commodity, raw or processed, that is marketed for human consumption (excluding water, salt, and additives) or animal feed. Agricultural products are classified in four main groups: crops, crops processed, livestock primary, and livestock processed.[1] All data are in tonnes and we also transform them to kilocalories (Kcal), using the data provided by FAO (2001).

In addition, we use food balance sheets to obtain data on food supply at the country level (FAO, 2019). For a given country, its food supply is determined by total production, plus imports, minus exports, stock variation, and the use of agricultural products for utilization different from food –for example, animal feed, seeds, and others. We also consider imports of food given its relevant role for determining food supply together with

[1] We exclude production of live animals, which is in stocks of animal heads and cannot be compared with the rest of agricultural production. We also exclude fibers for textiles and other products for non-food uses.

the production side. Both food supply and imports data are given in Kcal per capita per day, after applying appropriate food composition factors for all primary and processed products in terms of dietary energy value content.

In order to study how different specialization patterns of food production impact on food security and sustainability of food systems, we use two additional indicators. Firstly, we employ a new composite index, built by Caccavale and Giuffrida (2020), that measures the multidimensional concept of food security and covers 185 countries between 1990 and 2017. The index weights 21 selected indicators distributed in the four pillars of food security: availability, access, utilization, and stability. It ranges between 0 and 1, with lower values indicating greater food security. We redefine the index in order to obtain a measure that indicates that an increase in the index implies an improvement in food security (1 - index). Secondly, we use an indicator of sustainability of food systems from Béné et al. (2019), which is computed for 97 countries, every three years between 2000 and 2017. We use values for 2000, 2004, 2007, 2010 and 2013. The metric is a composite indicator that aggregates 27 indicators grouped in four dimensions: Environmental, Economic, Social, and Food & Nutrition. The data and metadata are available at Achicanoy et al. (2019).

Finally, we use a set of indicators for quantifying the status of national food systems performance of 156 countries in 2011, which includes 25 sustainability indicators across 7 domains: nutrition, environment, food affordability and availability, socio-cultural well-being, resilience, food safety, and food waste (Chaudhary et al., 2018). The indicator shows that different countries have widely varying patterns of performance and unique priorities for improvement.

4 Methodology

4.1 Agricultural product space and agricultural country space networks

In order to obtain the Agricultural Product Space Network (APSN) and the Agricultural Country Space Network (ACSN), we build the world agricultural products network using a bipartite matrix: rows represented by countries and columns by products. The entries of this matrix take the value of one when a given country is considered a relevant producer of a given product, which is determined by the revealed comparative advantages (RCA) of countries (Balassa, 1965). This approach has been commonly used to measure different types of capabilities (see, for example: Petralia et al., 2017; Hidalgo et al., 2007; Ferrarini and Scaramozzino, 2016; Bruno et al., 2018).

Given that agricultural production is in tonnes, we weight production using the agricultural gross production value (GPV), which is built by multiplying gross production in physical terms by output prices at farm gate (in constant 2004-2006 million dollars)

(FAO, 2019). Thus, we compute the indicator of RCA as:

$$RCA_{ikt} = \frac{Q_{ikt}/\sum_j Q_{jkt}}{GPV_{it}/\sum_j GPV_{jt}} \tag{1}$$

where Q is production of product k, i is a country, and t is a given year. We assume that a $RCA_{ikt} \geq 1$ reveals that country i is a relevant producer of product k at time t.

Therefore, suppressing time subscripts for simplicity, the elements of the agricultural products bipartite matrix M are defined as:

$$m_{ik} = \begin{cases} 0 \text{ if } RCA_{ik} < 1, \\ 1 \text{ if } RCA_{ik} \geq 1. \end{cases} \tag{2}$$

We build the bipartite matrix M for every year between 1993 and 2013 in order to observe its evolution.

We define the agricultural production space as a network-based representation of global agricultural production, where nodes represent agricultural products and ties among them indicate their degree of relatedness. Relatedness between a pair of products derives from the fact that these two products are commonly produced together, and relatedness between a couple of countries implies that those countries share similar capabilities that derive in similar production baskets.

It is important to highlight that agricultural production requires not only technology, capital, institutions, and skills, which are certainly difficult to be quantified, but it also depends on natural conditions necessary to produce agricultural products. As any other type of capabilities, it is not easy to determine their presence for each country. Thus, like in the world product space, a measure of relatedness allows to quantify the existence of a set of natural characteristics and capabilities that shape diversification patterns.

Several possibilities have been proposed to measure product and country relatedness or similarity (for a discussion, see: Leydesdorff, 2008; Eck and Waltman, 2009). We employ a widely used measure of relatedness based on the Jaccard index. In the product case, similarity P between products (k, k') reads:

$$P_{kk'} = \frac{V_{kk'}}{V_k + V_{k'} - V_{kk'}}, \tag{3}$$

where $V_{kk'} = \sum_i m_{ik} m_{ik'}$ is the number of times two different countries produce products k and k' together, and $V_k = \sum_i m_{ik}$ is the total number of countries that produce k. The resulting matrix P is used to define the APSN, where nodes are products and weighted links $P_{kk'}$ measure similarity between them.

Following the same strategy, we define the ACSN, where nodes are countries and a link between countries i and i' is weighted by the corresponding Jaccard index $C_{ii'}$, which measures similarity between country production baskets. To compute the Jaccard index between countries, we simply replace $V_{kk'}$ and V_k in Eq. (3) by $\Lambda_{ii'} = \sum_k m_{ik}m_{i'k}$ (the number of goods that are produced by countries i and i' together) and $\Lambda_i = \sum_k m_{ik}$ (the total number of products produced by country i).

In these space networks, it is possible to observe that both products and countries tend to cluster, giving raise to communities of products that are similar because many countries are producing them together, and to communities of countries that are similar because they have similar production baskets. Then, in order to detect communities in the APSN and the ACSN, we use the Louvain algorithm, which is a widely employed community-detection algorithm for large graphs (Blondel et al., 2008). The algorithm optimizes a function known as "modularity" over the possible partitions (or communities) of a network. Modularity aims to capture the degree to which a network can be partitioned in groups of nodes, with higher interaction within groups than between them. The algorithm incorporates a statistical null model (known as the configuration model) to compare the existence of a link with its theoretical probability of existence, which depends on structural attributes of the network itself. The modularity function compares the within communities share of links in the observed network with the share of such links that would be expected on the basis of the null model (i.e. occurring by chance provided that some structural constraints given by the observed network are satisfied on average). We use the weighted version of the Louvain algorithm to consider link weights in both the APSN and the ACSN.

4.2 Fitness and complexity

The bipartite matrix gathers valuable information on the capabilities of countries to produce diverse products. A simple way of measuring these capabilities is to count the total number of items produced. This strategy, however, ignores that the production of some products requires endowments and skills that may be unevenly distributed among countries because, in essence, some products are more or less complex to produce, i.e. they require more or less capabilities, in a broad sense.

Tacchella et al. (2012) provide an algorithm to reduce the multidimensional problem at analyzing the bipartite matrix, achieving a measure of the competitiveness of a country, which they call *Fitness*, and of the difficulty –in terms of required capabilities– of producing a given product, which they call *Complexity*. This method, known as the Fitness and Complexity Algorithm (FiCo), rewards countries according to the variety and complexity of their production baskets.[2]

[2]This methodology builds on the measure proposed by Hidalgo and Hausmann (2009). Both measures have drawbacks that will be addressed when necessary in the analysis of the results.

5 Results

5.1 The agricultural product space and the agricultural country space networks

The Agricultural Product Space Network (APSN) and the Agricultural Country Space Network (ACSN) are shown in Figures 1 and 2, respectively, for the years 1993 and 2013. An interesting evidence is that both networks are very stable between 1993 and 2013, despite that global food systems have suffered unprecedented pressure and changes during this period.

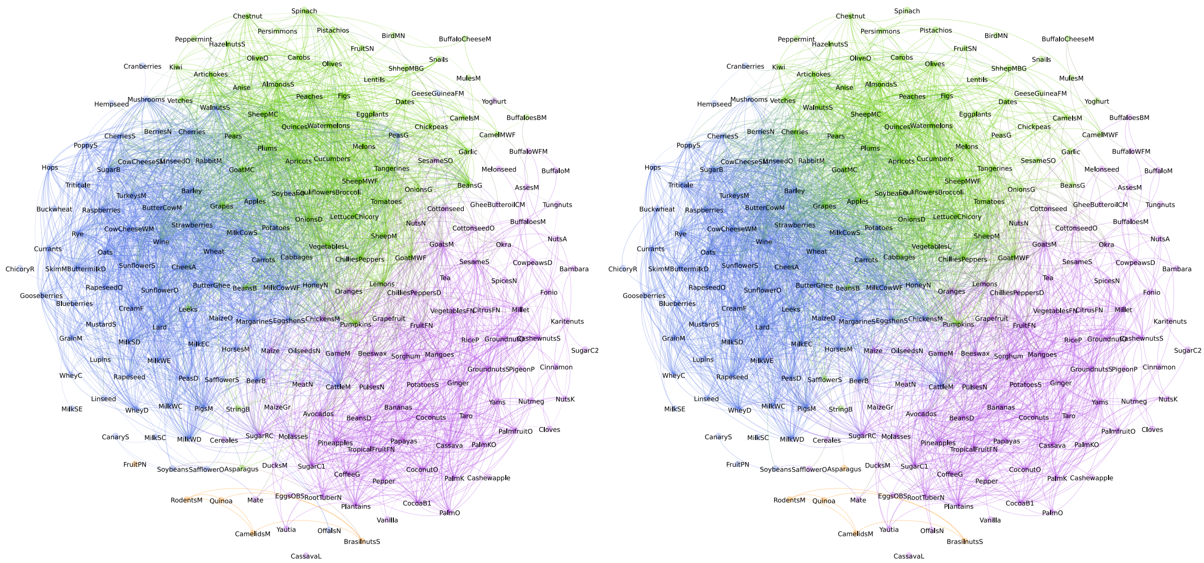

Figure 1: Agricultural Product Space Network (APSN). Colors represent different detected communities using the Louvain algorithm in the corresponding year. Weakest link weights ($P_{kk'}$ <0.2) are removed to improve the visualization of the network. Node positions are fixed in order to facilitate the comparison between years. Left: 1993. Right: 2013.

In the APSN, nodes are products and links represent the projection of the RCA-based bipartite country-product matrix into a between-product similarity measure computed with the Jaccard index. Similarly, in the ACSN, nodes are countries and links represent the projection of the RCA-based bipartite country-product matrix into a between-country similarity measure computed with the Jaccard index.

Both networks are very dense, meaning that many products are jointly produced, in the APSN, and that many countries are able to produce a relatively large number of similar products, in the ACSN. This is because most countries share capabilities to produce a basket of common food products, including, for example, eggs, some types of meat, dairy products, and even some crops and fruits.

Both networks are fully-connected, but despite their high density, products and countries

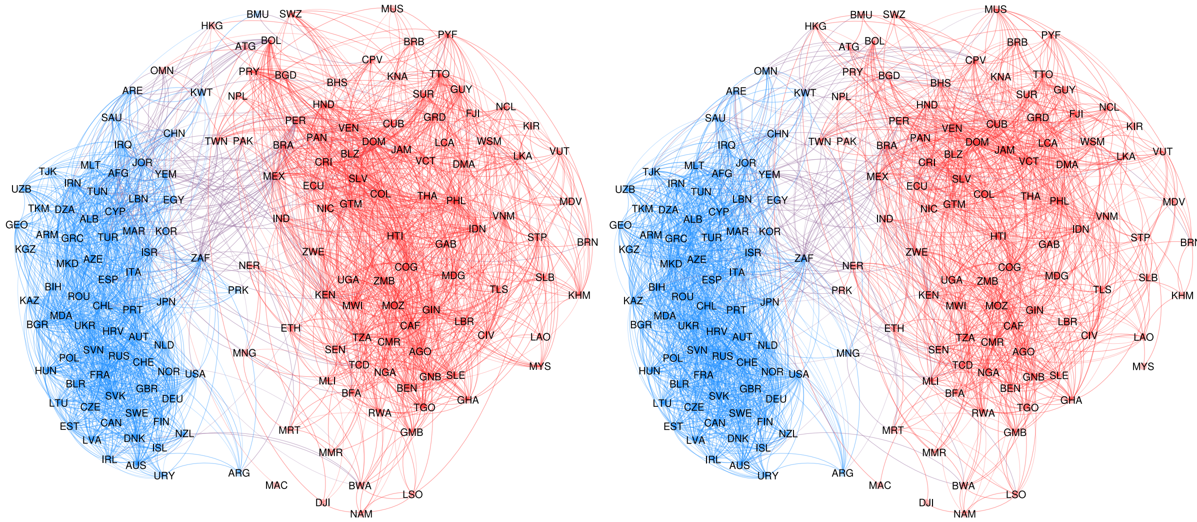

Figure 2: Agricultural Country Space Network (ACSN). Colors represent different detected communities using the Louvain algorithm in the corresponding year. Weakest link weights ($C_{ii'}$ <0.25) are removed to improve the visualization of the network. Node positions are fixed in order to facilitate the comparison between years. ISO codes are defined in Table A.1 of the Appendix. Left: 1993. Right: 2013.

cluster in well-defined communities, detected with the Louvain algorithm.[3] In the APSN, this implies that products that belong to a given community share the need of similar capabilities for their production. In the ACSN, this implies that countries within a community are characterized by similar endowments of natural conditions and capabilities for agricultural production. Both products and countries within a community have higher interaction within them than with countries in other communities.

In the APSN, we observe four well-defined communities, which connect highly related products, portrayed in different colors in Figure 1. The community in purple contains mostly tropical fruits and crops, such as mangoes, bananas, coconuts, avocados, and coffee. In blue, we observe crops, such as wheat and barley, processed crops, and processed livestock products, such as butter and cheese. In the community in green, most products are vegetables, nuts, and fruits from Mediterranean or sub-tropical regions. The community in orange mostly groups certain products with a low relevance in global food production, such as, quinoa, Brazil nuts, safflower seeds and oil, camelids and rodents meat, and mate.

In the ACSN, we detect two well-defined communities of great size. Interestingly, one community (in blue) groups all developed countries and a group of developing countries that have relatively developed agricultural systems, such as Uruguay, Argentina, and several Eastern European countries. Instead, the other community (in red) only groups developing countries.[4] For the analysis, we name these communities as: "Developed

[3]There are several ways of filtering links that could lead to the definition of more or different communities (see: Campi et al., 2019). In this paper, we keep the unfiltered links to detect the main communities.

[4]Except in 2013, when one developed country in the border of the communities (Bermuda) changes

Community" (blue) and "Developing Community" (red). Table 1 shows several statistics of the two communities detected in the ACSN for 1993, 2003, and 2013.

Table 1: Summary statistics of the communities detected in the ACSN. 1993, 2003, and 2013

	1993		2003		2013	
	Developed	Developing	Developed	Developing	Developed	Developing
Number of countries	75	94	75	94	73	96
Number of developed countries	36	0	36	0	35	1
Number of developing countries	39	94	39	94	38	95
Share of total population	0.56	0.44	0.51	0.49	0.48	0.52
Share of total production in calories	0.67	0.33	0.60	0.40	0.57	0.43
Share of total production in proteins	0.75	0.25	0.69	0.31	0.67	0.33
Share of total production in fats	0.63	0.37	0.56	0.44	0.51	0.49
Share of total food exports	0.79	0.21	0.69	0.31	0.62	0.38
Share of total food imports	0.77	0.23	0.70	0.30	0.72	0.28

We observe that, although the shares of total population are similar in both communities, the share of total production in calories, proteins, and fats are clearly lower in the developing community (red). Instead, the developed community (blue), which includes countries with more developed agricultural systems, has higher shares of production in all the measures considered. Moreover, the developed community concentrates much higher shares of both total food exports and imports.

5.2 Fitness and complexity

Next, we apply the Fitness and Complexity (FiCO) algorithm to the bipartite matrix of world agricultural production. Figure 3 shows a plot of the bipartite matrix, as defined in Eq. (2), for 2013. In this graphical representation, countries are ordered by their competitiveness and products by their sophistication, which means that we have organized the rows in ascending order according to countries fitness, and the columns, from left to right, in ascending order of product complexity. Organized by FiCo, the matrix reveals a triangular form, which might indicate nestedness in agricultural production.

As expected, given the stability of the bipartite networks, the pattern depicted in Figure 3 is very stable, i.e. we do not observe remarkable changes in the bipartite matrix between 1993 and 2013.

Interestingly, but to some degree expected, the complexity or sophistication of products is not only related to the availability of technology, institutions, capital, and skills, but also to the presence of specific natural conditions. For example, products such as camelids and quinoa are classified as highly complex or more sophisticated, which is not surprising considering that they are produced in the "Puna", an ecosystem that is present in a few South American countries, Argentina, Bolivia, Ecuador, and Peru. Actually, camelids

from the blue towards the red community, although it appears in the community blue in most years.

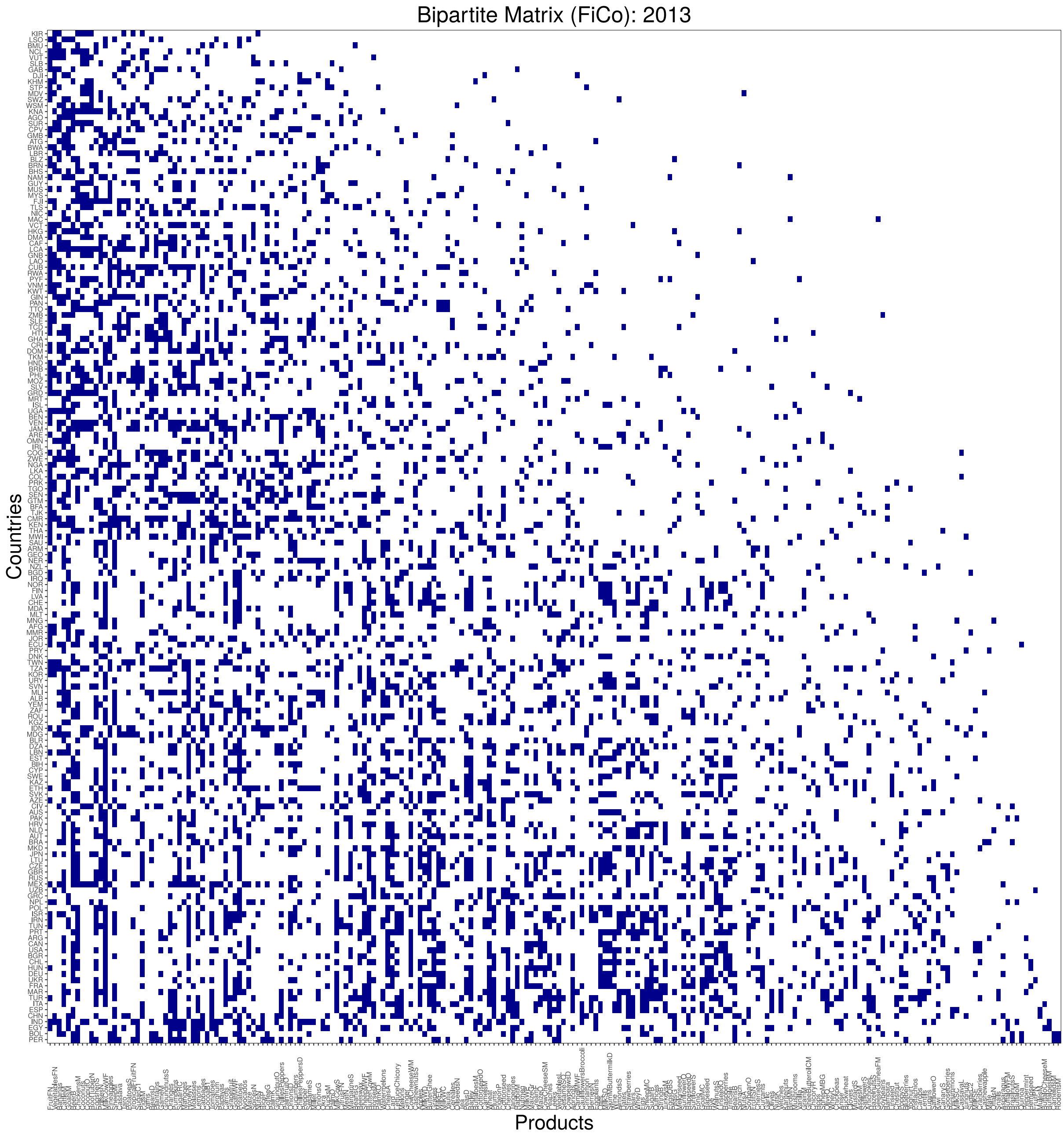

Figure 3: Country-product bipartite matrix in 2013 (y-axis: countries, x-axis: products). Each pixel is an $RCA \geq 1$, rows and columns are organized by FiCo.

meat is only produced by Bolivia and Peru, and quinoa by Bolivia, Ecuador, and Peru. A similar argument might apply for some other products classified as complex.

This evidence highlights the relevance of considering the role of agro-ecological conditions in addition to other types of capabilities as determinants of RCA in agricultural production. But also, this calls the attention on a feature of the indicator of fitness and complexity, pointed out by Morrison et al. (2017), who show that this measure often highlights economies that are producing "exclusive niche products", which are not necessarily the most complex or more sophisticated (in terms of required capabilities). The authors show that, in the case of exports, products that are classified as the most complex tend often to be sufficiently irrelevant to be exported by only a few countries. Thus, they argue that, at the micro level of products, complexity is often difficult to interpret, which suggests that the indicators are difficult to compare across different levels of aggregation.

In the world agricultural production space, we observe that there are some products that appear as complex and some countries that have a high fitness, which are not relevant in terms of global agricultural production. This might be caused by the existence of some exclusive niche products. Thus, we re-estimated the indicators of fitness and complexity excluding the products that can be considered as exclusive niche products and, as expected, the fitness of countries producing those products decreases, but the scores and positions of the remaining countries are similar, indicating that the measure of fitness is robust to changes in the set of products considered.[5]

Given that scarce natural conditions can be also considered within the set of capabilities necessary for agricultural production, we keep these probable exclusive niche products that turn out as sophisticated, because they reflect that only a few countries have the natural conditions necessary to produce them.

Given that fitness can be regarded as an indicator of competitiveness in food production, it is expected to be positively correlated with other macro indicators of competitiveness. Figure 4 shows the dispersion diagram between fitness and: Gross Domestic Product (GDP), Agricultural Gross Production Value (GPV), and Agricultural Exports, for 2013.

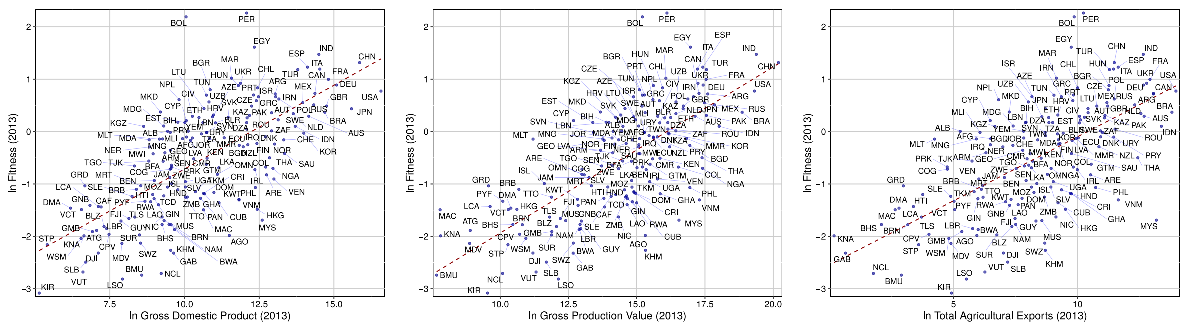

Figure 4: Fitness and macro variables: Gross Domestic Product, Agricultural Gross Production Value, and Total Agricultural Exports. 2013

As expected, fitness correlates positively with the selected macro variables. The correlations are statistically significant and positive: 0.686 with GDP, 0.713 with GPV, and 0.639 with agricultural exports. In addition, the correlations are quite stable, very low variations are observed through all the cross sections (1993 to 2013). Interestingly, we observe that those countries that might be classified as highly competitive because they produce what can be considered exclusive niche products, such as Peru, Bolivia, and Egypt, appear as outliers in the dispersion diagrams.

[5]The results are available upon request.

Overall, this evidence suggests that the presence of niche products at the micro level, does not undermine the behavior of fitness at the macro level. The measure seems able to reasonably capture the set of capabilities and natural endowments that are needed for agricultural production. We further explore this in the econometric estimations.

In addition, by capturing capabilities and natural endowments for food production, fitness is expected to have a positive relation with food security. The correlation with sustainability of food systems is expected to be both positive or negative because it depends on the result of the trade-off that frequently emerges between improving both food security and sustainability. In addition, both food security and sustainability are multidimensional concepts that might mask complex effects and, therefore, relations. Figure 5 shows the correlations between fitness and several dimensions of food security and of sustainability of food systems from Chaudhary et al. (2018) for 2011.

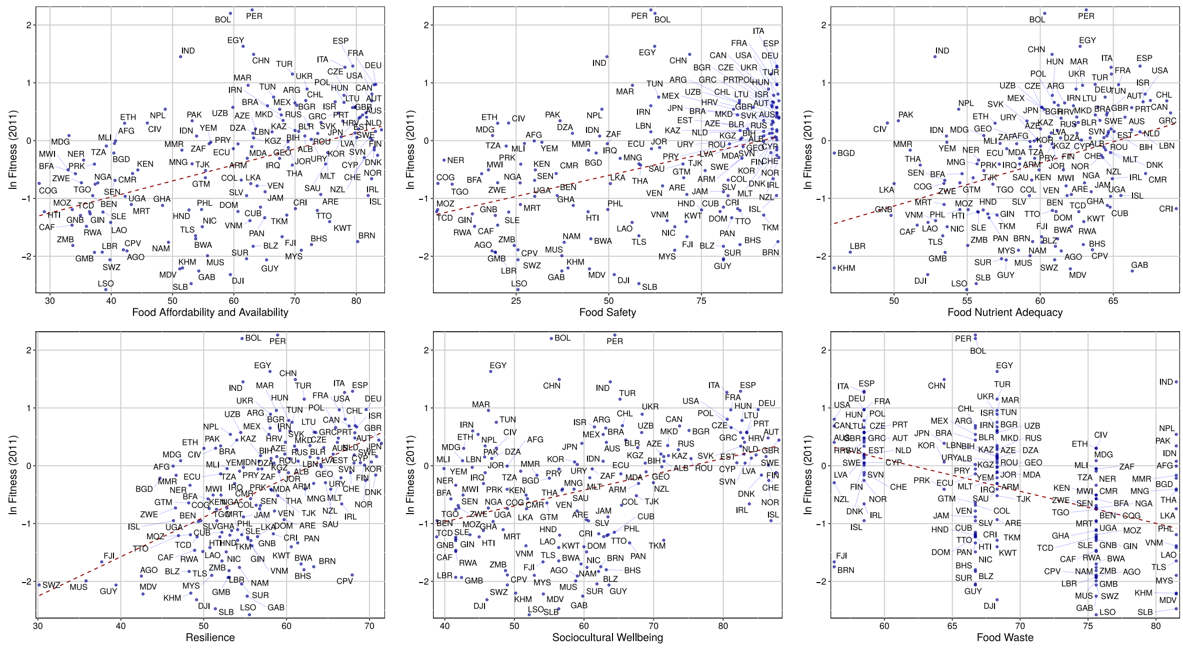

Figure 5: Fitness and indicators of different dimensions of food security and sustainability: Affordability and Food Availability, Food Safety, Food Nutrient Adequacy, Resilience, Sociocultural Well-being, and Food Waste. 2011

We observe a positive correlation between fitness and food availability and affordability, food safety, food nutrient adequacy, resilience, and sociocultural well-being. Instead, we observe a negative correlation between fitness and food waste.

Finally, in Figure 6 we present the correlations between the measure of fitness and the three dependent variables that we use in the econometric estimations: food supply, and two multidimensional measures of food security and sustainability of food systems, from Béné et al. (2019) and Caccavale and Giuffrida (2020), respectively. We observe that fitness is positively correlated with all these variables.

Despite there is a great dispersion in some of the measures considered, the correlations

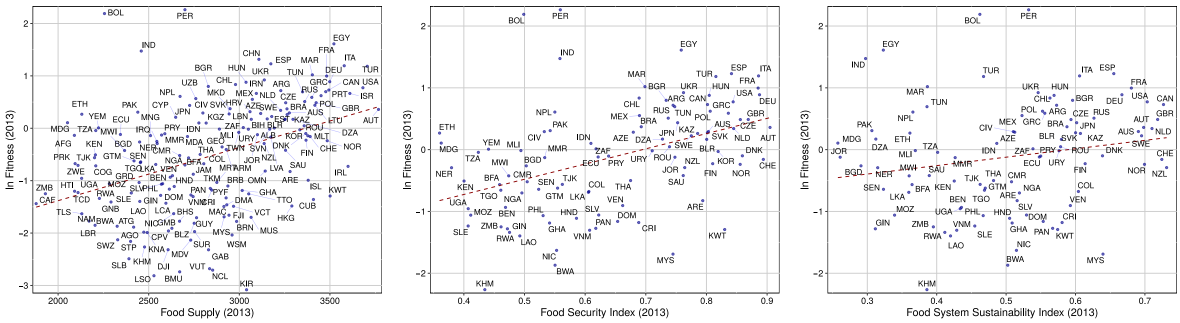

Figure 6: Fitness and: food supply, food security, and sustainability of food systems. 2013

suggest that countries with higher fitness are better in terms of food security and sustainability of their food systems. The fact that the measure of competitiveness in food production is positively correlated with both indicators of food security and sustainability is an interesting piece of evidence because food security and the environmental dimension of sustainable development are characterized by a trade-off. While a healthy environment is a precondition for sustaining food systems, food systems clearly impact on the environment.

5.3 The impact of country specialization patterns

Next, we use network statistics derived from our previous analysis and we perform an econometric analysis. We are interested in the effects of competitiveness (measured by fitness), concentration of production, and the coherence of diversification patterns of food production. Our interest lies in how different features of the production side of agriculture affect food supply, food security, and sustainability of food systems at the country level. Therefore, we perform regressions using different dependent variables and the same set of explanatory variables to facilitate comparisons.

In order to estimate concentration of production at the country level, we firstly transform the production of each good from tonnes into Kcal to obtain a comparable measure, using the data on food supply, which are reported in Kcal. Afterwards, we compute for every country, the production in Kcal and, then, we estimate the concentration of their production baskets.

For a country i with a production basket of agricultural goods Ω_{it} in a given time t, the Herfindal-Hirschman index is defined as $HH_{it} = \sum_{k\in\Omega_{it}} s_{ikt}^2$, where s_{ikt} is the share of the k variety in the production basket. As an alternative indicator of concentration, we use the Shannon entropy index, which is defined as $S_{it} = -\sum_{k\in\Omega_{it}} s_{ikt} \ln s_{ikt}$.

In addition, we define a variable that measures the overall similarity of the production baskets of countries. The fact that a country produces several products does not necessarily mean that all those products are strongly connected in the APSN because diversification can occur in different ways. Most likely, diversification is expected in products close to those already produced, although countries may also build capabilities to develop new products that are far from their current products. Thus, an indicator of the "coherence" of the diversification process would allow us to explore whether countries diversify in products that are close to their set of current capabilities (measured by the degree of similarity of products) or if, conversely, they diversify in products that are far from their capabilities. We define the coherence of the production basket of a country as the total strength of the products in the APSN:

$$Coherence_{it} = \sum_{k \in \Omega^*_{it}} \sum_{k' \in \Omega^*_{it}} P_{kk't}, \quad (4)$$

where Ω^*_{it} is the production basket of country i restricted to those products k with $RCA_{ikt} \geq 1$ at time t. Given that the APSN is very dense, the measure of coherence has very large values, therefore, we express it in thousands.

Figure A.1 in the Appendix shows the distribution of the estimated measures of concentration (HH Index and Entropy Index) and coherence of diversification patterns, which show no important changes between 1993 and 2013.

In addition to the variables related to specialization patterns in food production, we include a set of control variables that aim to capture countries characteristics in terms of development, geography, and agricultural development. In some specifications, we analyze possible different effects for the two detected communities in the ACSN. In these estimations, we fix community membership for each country the whole time period by the mode, i.e. we assign to each country the community in which it was most frequently detected. The reason is that a very low number of countries, in general, those in the border of the communities, are detected in different communities in different years. Table A.3 in the Appendix describes the variables and their sources, and Table A.4 reports the summary statistics of the alternative dependent variables and the independent variables.

We estimate the following benchmark model:

$$y_{it} = \beta_0 + \beta_1 Z_{it} + \beta_2 X_{it} + \alpha_i + \tau_t + \mu_{it}, \quad (5)$$

where y is either (i) food supply per capita per day in calories, (ii) an indicator of food security, or (iii) an index of sustainability of food systems, in a given year t, Z are different variables related to specialization patterns in food production: two alternative indexes of concentration of agricultural production, the Herfindal-Hirschman index ($HHIndex$) and the Shannon entropy index ($Entropy$), an indicator of the coherence of the agricultural production basket ($Coherence$), and fitness, the indicator of countries capabilities or competitiveness ($Fitness$), X includes the following control variables: agricultural total factor productivity ($Agr.TFP$), human capital, as an indicator of the development level of countries ($HumanCapital$), imports per capita per day in calories ($Imports$), the latitude of countries in absolute values (*Latitude*), as an indicator of climatic characteristics, a dummy indicating whether countries belong to the community that includes mostly developed countries (*Community*), and a set of dummies indicating the geographical regions of countries. Finally, α_i are country fixed effects, τ_t are time dummies, and μ are the residuals.

We use different strategies to estimate Eq. (5). Firstly, we take advantage of the panel structure of the data and we use a panel data fixed effects estimation method, which allows a better control of unobserved heterogeneity and omitted variables bias. Secondly, we also use a pooled OLS estimation method because the dependent variables are relatively invariant over the years considered and have a relatively low variation across countries. As a consequence, including countries fixed effects reduces the possibility of observing the effect of the variables of interest, because fixed effects can explain by themselves most of the relatively small variations in the dependent variables.[6] In addition, pooled OLS estimations allows us to consider the effect of time invariant variables related to geographical conditions, which are also relevant to characterize specialization patterns. Finally, we implement an instrumental variables approach in both the panel and the pooled data in order to deal with possible endogeneity problems. All models include robust standard errors.

Table 2 shows the estimation results of Eq. (5) using panel data fixed effects. We estimate that increasing concentration in agricultural production has a negative effect on daily per capita food supply, food security (although not statistically significant), and sustainability of food systems, which is observed with both measures of concentration (models 1-2, 5-6, and 9-10).

A coherent diversification of the product baskets has a positive effect on per capita food supply (model 3). This evidence indicates that countries exploit economies of scope to contribute to their food supply. Therefore, this also implies that diversifying in products that need capabilities that are close to those that countries already have increases food supply. Although not statistically significant, the estimated coefficients are also positive, in the models that use food security and sustainability as dependent variables (models 7 and 11). The indicator of fitness, that reflects the capabilities of countries for food production, has a positive effect on food supply (model 4), but a negative effect on sustainability of food systems (model 12). This might be explained by the trade-off that appears in improving agricultural production and achieving a more sustainable food system.

The control variables have the expected signs and turn out significant in most cases. Agricultural total factor productivity, human capital, and per capita imports of food all have positive effects in the alternative dependent variables considered. This implies that countries that are more developed, with more productive agricultural systems, and that

[6]This is also observed in other types of dependent variables, for example, see: Chinn and Prasad (2003); Behringer and Van Treeck (2018); Grechyna et al. (2019), for the case of the current account.

Table 2: The effect of country specialization patterns on per capita food supply, food security, and sustainability. 1993 to 2013. Panel data fixed effects estimations

Dependent variable	Food Supply				Food Security				Sustainability			
Model	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
HH Index	-0.438***				-0.078				-0.054*			
	(0.159)				(0.053)				(0.032)			
Entropy		0.110***				0.013				0.017*		
		(0.041)				(0.010)				(0.010)		
Coherence			0.220***				0.019				0.015	
			(0.057)				(0.015)				(0.012)	
Fitness (ln)				0.095***				0.006				-0.016**
				(0.030)				(0.006)				(0.008)
Agr. TFP (ln)	0.341***	0.350***	0.344***	0.347***	0.059***	0.060***	0.059***	0.058***	0.055***	0.057***	0.054***	0.053***
	(0.057)	(0.059)	(0.058)	(0.058)	(0.013)	(0.013)	(0.013)	(0.013)	(0.013)	(0.014)	(0.013)	(0.013)
Human Capital	0.202***	0.198***	0.198***	0.203***	0.081***	0.081***	0.082***	0.082***	0.039***	0.039***	0.042***	0.043***
	(0.053)	(0.054)	(0.053)	(0.052)	(0.013)	(0.013)	(0.013)	(0.013)	(0.014)	(0.014)	(0.013)	(0.014)
Imports (ln)	0.104***	0.104***	0.102***	0.105***	0.008**	0.008**	0.008**	0.008**	0.006	0.006	0.007*	0.007*
	(0.016)	(0.016)	(0.015)	(0.015)	(0.004)	(0.004)	(0.004)	(0.004)	(0.004)	(0.004)	(0.004)	(0.004)
Constant	0.750***	0.370	0.462**	0.682***	0.169***	0.119**	0.138**	0.157***	0.160***	0.096	0.129**	0.145**
	(0.214)	(0.265)	(0.229)	(0.219)	(0.050)	(0.059)	(0.053)	(0.051)	(0.054)	(0.075)	(0.061)	(0.057)
Observations	2,728	2,728	2,728	2,728	2,707	2,707	2,707	2,707	448	448	448	448
Countries	130	130	130	130	129	129	129	129	92	92	92	92
R-squared	0.499	0.499	0.501	0.500	0.429	0.425	0.423	0.422	0.307	0.310	0.301	0.312

Notes: The dependent variables are food supply in calories per capita per day (average for each year) (models 1-4), an index of food security (models 5-8), and an index of sustainability of food systems (models 9-12). The index of food systems sustainability is available for 2000, 2004, 2007, 2010 and 2013. Robust standard errors are in parentheses. Significance level: *** p<0.01, ** p<0.05, * p<0.10.

can import more food per capita, have higher per capita food supply, are better in terms of food security, and have more sustainable systems.

Table 3 presents the estimations results of Eq. (5) using pooled OLS with time dummies. Again, we estimate that concentrating production has a negative effect on food supply (models 1-2), food security (models 5-6), and sustainability of food systems (model 9-10). Diversifying in a coherent way, this is, in products that are close the capabilities of countries, has a positive effect on food supply (model 3) and food security (model 7). Instead, a coherent diversification has a negative impact on food systems sustainability (model 9). The indicator of fitness has a positive impact on food supply (model 4) and food security (model 8), but a negative, although not statistically significant impact on food system sustainability. The dummy indicating if a country belongs to the community with more developed countries turns out positive and statistically significant in all the models, indicating that countries in this community are relatively better in terms of food supply, food security, and sustainability, compared to countries in the community with only developing countries.

The control variables have the expected signs when they turn out statistically significant and their effects are similar to those estimated using panel data fixed effects. The variable indicating the latitude of countries in absolute values is significant in the case of food supply, indicating a significant effect of agro-ecological and climatic conditions necessary for agricultural production. The dummy variables for geographical regions are in most cases statistically significant. Using East Asia & Pacific as the base, we observe that

Table 3: The effect of country specialization patterns on per capita food supply, food security, and sustainability. 1993 to 2013. Pooled OLS estimations with time dummies

Dependent variable	Food Supply				Food Security				Sustainability			
Model	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
HH Index	-0.452***				-0.117***				-0.065**			
	(0.045)				(0.014)				(0.027)			
Entropy		0.117***				0.025***				0.007		
		(0.012)				(0.004)				(0.007)		
Coherence			0.292***				0.064***				-0.035***	
			(0.024)				(0.006)				(0.013)	
Fitness (ln)				0.109***				0.022***				-0.005
				(0.010)				(0.003)				(0.004)
Community	0.229***	0.199***	0.119***	0.108***	0.047***	0.042***	0.023**	0.023**	0.037**	0.037**	0.056***	0.044***
	(0.033)	(0.035)	(0.035)	(0.038)	(0.008)	(0.009)	(0.010)	(0.010)	(0.015)	(0.015)	(0.016)	(0.016)
Agr. TFP (ln)	0.274***	0.278***	0.281***	0.242***	0.063***	0.065***	0.065***	0.057***	-0.037	-0.038	-0.034	-0.037
	(0.052)	(0.052)	(0.050)	(0.050)	(0.014)	(0.014)	(0.013)	(0.013)	(0.033)	(0.033)	(0.031)	(0.032)
Human Capital	0.084***	0.089***	0.097***	0.098***	0.080***	0.082***	0.083***	0.083***	0.074***	0.075***	0.072***	0.075***
	(0.018)	(0.018)	(0.017)	(0.017)	(0.004)	(0.004)	(0.004)	(0.004)	(0.008)	(0.008)	(0.008)	(0.008)
Imports (ln)	0.129***	0.133***	0.148***	0.166***	0.042***	0.043***	0.047***	0.050***	0.029***	0.029***	0.030***	0.029***
	(0.007)	(0.007)	(0.007)	(0.007)	(0.002)	(0.002)	(0.002)	(0.002)	(0.004)	(0.004)	(0.003)	(0.004)
Latitude (Abs. Value)	0.003***	0.004***	0.004***	0.003***	0.000	0.000	0.000	0.000	-0.000	-0.000	-0.001	-0.000
	(0.001)	(0.001)	(0.001)	(0.001)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
Europe & Central Asia	0.039	0.031	-0.021	0.048*	0.034***	0.034***	0.022***	0.037***	-0.008	-0.006	0.011	-0.000
	(0.031)	(0.031)	(0.030)	(0.028)	(0.009)	(0.008)	(0.008)	(0.008)	(0.016)	(0.016)	(0.017)	(0.016)
Latin America & Caribbean	-0.095***	-0.101***	-0.084***	-0.086***	-0.026***	-0.025***	-0.023***	-0.022***	0.010	0.015*	0.027***	0.023***
	(0.019)	(0.020)	(0.020)	(0.018)	(0.006)	(0.006)	(0.006)	(0.005)	(0.009)	(0.009)	(0.008)	(0.008)
Middle East & North Africa	0.048	0.043	0.007	0.051	0.032***	0.032***	0.023***	0.033***	-0.212***	-0.210***	-0.204***	-0.207***
	(0.034)	(0.034)	(0.033)	(0.032)	(0.008)	(0.008)	(0.008)	(0.008)	(0.023)	(0.023)	(0.022)	(0.023)
North America	0.526***	0.529***	0.449***	0.449***	0.060***	0.061***	0.043***	0.044***	0.077***	0.077***	0.088***	0.081***
	(0.045)	(0.044)	(0.041)	(0.043)	(0.010)	(0.009)	(0.009)	(0.009)	(0.013)	(0.013)	(0.013)	(0.014)
South Asia	-0.052***	-0.073***	-0.100***	-0.159***	0.008	0.003	-0.004	-0.015*	-0.121***	-0.122***	-0.115***	-0.116***
	(0.019)	(0.019)	(0.019)	(0.022)	(0.007)	(0.007)	(0.007)	(0.008)	(0.012)	(0.013)	(0.015)	(0.015)
Sub-Saharan Africa	-0.173***	-0.164***	-0.108***	-0.094***	-0.070***	-0.066***	-0.055***	-0.052***	-0.029***	-0.023**	-0.018**	-0.018**
	(0.021)	(0.021)	(0.018)	(0.019)	(0.006)	(0.006)	(0.006)	(0.006)	(0.009)	(0.009)	(0.008)	(0.008)
Constant	1.141***	0.740***	0.782***	1.268***	0.144**	0.050	0.058	0.161***	0.520***	0.490***	0.517***	0.495***
	(0.238)	(0.236)	(0.227)	(0.230)	(0.062)	(0.062)	(0.060)	(0.060)	(0.152)	(0.150)	(0.141)	(0.147)
Observations	2,728	2,728	2,728	2,728	2,707	2,707	2,707	2,707	448	448	448	448
R-squared	0.667	0.669	0.686	0.685	0.813	0.813	0.821	0.819	0.803	0.801	0.805	0.801

Notes: The dependent variables are food supply in calories per capita per day (average for each year) (models 1-4), an index of food security (models 5-8), and an index of sustainability of food systems (models 9-12). The index of food systems sustainability is available for 2000, 2004, 2007, 2010 and 2013. The community that includes only developing countries (red) is used as the base. The region East Asia & Pacific is used as the base of the dummies for geographical regions. All estimations include time dummies (not reported). Robust standard errors are in parentheses. Significance level: *** $p<0.01$, ** $p<0.05$, * $p<0.10$.

regions that include richer countries, compared to the base region (see Table A.1 in the Appendix), have positive impacts on food supply and food security (North America and Europe & Central Asia); and the opposite is observed for regions that have on average a lower GDP per capita (South Asia and Sub-Saharan Africa). The estimated effect for regions with GDP per capita close to the base regions are positive for the Middle East & North Africa and negative for Latin American & the Caribbean. Similarly, in the case of sustainability of food systems, the effect of geographical regions also seems to be related with their average GDP per capita. The estimated effect is negative for Middle East & North Africa, South Asia, Sub-Saharan Africa, which have lower average GDP per capita than the base region, and it is positive for Latin American & the Caribbean and North America, with higher average GDP per capita than the base.

A possible problem of these estimations is that they might be affected by endogeneity of the measures related to specialization of food production, which could lead to biased results. It may be indeed the case that fitness, concentration, and coherence could be correlated with the error term due to unobserved or omitted variables, which confound both independent and dependent variables. As to food supply and food security, countries could implement policies driving to different specialization patterns if their levels of food supply or food security are not satisfactory. However, it should also be noted that these policies might take a considerable time to have an effect, given that specialization patterns are very difficult to change in the short time.

To deal with a possible problem of endogeneity, we included in the previous estimations a set of control variables characterizing countries and panel data fixed effects estimations, which might reduce the problem of omitted variables bias. As a robustness check, we econometrically test the presence of endogeneity, using commonly employed instrumental variable techniques, on both the panel and the pooled data. In both cases, we use as instruments the one-year lags of the potentially endogenous variables: HH index, entropy, coherence, and fitness. In addition, we use the same set of the corresponding control variables in the pooled and the panel data. Due to space constraints, we present the results of these estimations in Tables A.5 and A.6 in the Appendix.

In the instrumental variables fixed effects estimations (Table A.5), when we use food supply or food security as dependent variables, the partial F-tests confirm in all cases that the instruments are strong. In addition, the endogeneity tests suggest that all potentially endogenous variables are in fact exogenous, except for fitness in the regressions with food supply as the dependent variable. In this case, the instrumental variables estimation provides more reliable results. However, the significance and magnitude of the estimated coefficient is similar to that estimated with panel data fixed effects. In the case of sustainability, the partial F-tests for instrumental variables report that some instruments are weak, which is probably related to the fact that the index is only available for 5 years and for a lower number of countries. Despite this, the endogeneity tests conclude that potentially endogenous variables are exogenous, except in the case of fitness. This is the only case in which the estimated coefficient is not similar to that obtained with fixed effects in Table 2. However, this is also the only case in which the instrument turns out to be very weak (partial F-test = 0.68).

In the instrumental variables pooled OLS estimations (Table A.6), the partial F-tests confirm in all cases that the instruments are strong. Moreover, the potentially endogenous variables can be considered exogenous, for which pooled OLS provide better estimations, except in the case of entropy when using sustainability as the dependent variable. In this case, the estimated coefficient is similar to that obtained with pooled OLS in Table 3.

Therefore, in most cases, we can conclude that the variables related to specialization patterns are not endogenous and, consequently, pooled OLS or panel data fixed effects provide better estimations. In the cases in which an instrumental variables approach is better, the estimated coefficients are in line with what we previously discussed, and the conclusions of the econometric analysis do not change.

In sum, despite endogeneity could be an issue, we should consider that the measure of fitness does not result directly from individual decisions of countries, but it is instead the result of the empirical ranking that derives from the ACSN. For this reason, fitness could be assumed to be exogenous. The variables measuring concentration and coherence of diversification, instead, result from individual production decisions of countries, although these variables are also likely to be affected by events that take place at the international level. For example, a country can decide to concentrate food production in a product that had suffered a sudden price increase at the international market, which in the case of food are not usually affected by the decision of an individual country. However, there exist severe restrictions to increase production and to change specialization patterns in the short run in response to a sudden event. Agricultural production depends on natural conditions that impose additional restrictions on those that exist in any kind of economic activities. Therefore, also these variables could be exogenous in the short and medium term and the result of processes that are the consequence of the interaction of food producing countries at the international level. The results of our econometric analysis point towards this direction.

In general, the estimated effects of the control variables allow us to conclude that different types of capabilities as well as geographical conditions influence food supply, food security, and food system sustainability. In addition, the variables related with specialization patterns of countries in food production have a significant effect on food supply, food security, and, to a lesser extent, on sustainability of food systems, even after controlling for variables characterizing the development of countries, and for geographical and technological characteristics.

Finally, given that we observe differences between the two detected communities, we now explore if the estimated effects of specialization are also different for the countries in those communities. We could also expect control variables to have different effects, therefore, we split the sample according to the two communities detected in the ACSN and re-estimate the models using panel data fixed effects, which allows a better control of omitted variables bias. Table 4 presents the estimation results.

We observe that concentration has a negative effect for all the dependent variables considered for the sample of countries in the developed community. This effect is also negative but only statistically significant in the case of food supply for the sample of countries in the developing community. Similarly, we estimate that a coherent diversification pattern has a positive effect on food supply, food security, and sustainability for the developed community. In the case of the developing community, this positive effect is only statistically significant for food supply. Finally, fitness has a positive effect on food supply of both communities on the three alternative dependent variables. Conversely, the effect of fitness is negative for sustainability of food systems in the case of the developing community.

The control variables have the expected signs for both communities. But we observe differences in the significance of some of them. Agricultural total factor productivity and

Table 4: The effect of country specialization patterns on per capita food supply, food security, and sustainability. 1993 to 2013. Panel data fixed effects estimations for the communities detected in the ACSN

Dependent variable	Food Supply				Food Security				Sustainability			
Model	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
						Developed Community (blue)						
HH Index	-0.283				-0.049				-0.068			
	(0.193)				(0.040)				(0.041)			
Entropy Index		0.100**				0.020**				0.019**		
		(0.048)				(0.009)				(0.009)		
Coherence			0.256***				0.034**				0.021*	
			(0.066)				(0.015)				(0.011)	
Fitness (ln)				0.092*				-0.002				-0.010
				(0.051)				(0.009)				(0.008)
Agr. TFP (ln)	0.307***	0.308***	0.306***	0.317***	0.053***	0.053***	0.053***	0.054***	0.057**	0.058**	0.054**	0.055**
	(0.080)	(0.079)	(0.078)	(0.079)	(0.015)	(0.015)	(0.015)	(0.016)	(0.024)	(0.024)	(0.022)	(0.024)
Human Capital	0.148*	0.144*	0.118	0.155**	0.057***	0.056***	0.053***	0.056***	0.058**	0.058**	0.065***	0.061**
	(0.081)	(0.082)	(0.077)	(0.077)	(0.018)	(0.017)	(0.018)	(0.018)	(0.025)	(0.025)	(0.024)	(0.025)
Imports (ln)	0.092***	0.091***	0.092***	0.095***	0.016***	0.015***	0.016***	0.016***	0.005	0.005	0.006	0.007
	(0.023)	(0.022)	(0.021)	(0.023)	(0.005)	(0.005)	(0.005)	(0.005)	(0.007)	(0.006)	(0.006)	(0.006)
Constant	1.259***	0.958***	0.988***	1.121***	0.335***	0.276***	0.297***	0.328***	0.131	0.066	0.086	0.125
	(0.279)	(0.357)	(0.297)	(0.296)	(0.048)	(0.060)	(0.052)	(0.053)	(0.097)	(0.122)	(0.105)	(0.106)
Observations	1,300	1,300	1,300	1,300	1,300	1,300	1,300	1,300	207	207	207	207
R-squared	0.418	0.427	0.442	0.427	0.489	0.499	0.498	0.485	0.435	0.440	0.425	0.424
Countries	62	62	62	62	62	62	62	62	43	43	43	43
						Developing Community (red)						
HH Index	-0.553***				-0.101				-0.036			
	(0.207)				(0.093)				(0.048)			
Entropy Index		0.133**				0.003				0.009		
		(0.061)				(0.022)				(0.023)		
Coherence			0.230*				0.003				0.010	
			(0.117)				(0.033)				(0.028)	
Fitness (ln)				0.068*				0.010				-0.018*
				(0.036)				(0.010)				(0.011)
Agr. TFP (ln)	0.390***	0.405***	0.394***	0.380***	0.068***	0.065***	0.065***	0.066***	0.051***	0.053***	0.052***	0.050***
	(0.081)	(0.086)	(0.089)	(0.088)	(0.020)	(0.021)	(0.021)	(0.021)	(0.012)	(0.013)	(0.013)	(0.013)
Human Capital	0.253***	0.254***	0.277***	0.262***	0.100***	0.105***	0.106***	0.103***	0.027*	0.028*	0.028*	0.033**
	(0.068)	(0.071)	(0.073)	(0.073)	(0.020)	(0.020)	(0.019)	(0.019)	(0.016)	(0.016)	(0.016)	(0.015)
Imports (ln)	0.112***	0.112***	0.109***	0.114***	0.002	0.003	0.003	0.002	0.007	0.006	0.007	0.007
	(0.020)	(0.021)	(0.020)	(0.020)	(0.005)	(0.005)	(0.005)	(0.005)	(0.005)	(0.005)	(0.005)	(0.005)
Constant	0.258	-0.237	-0.074	0.245	0.018	-0.004	0.000	0.013	0.165***	0.126	0.144*	0.141***
	(0.336)	(0.372)	(0.360)	(0.356)	(0.084)	(0.107)	(0.095)	(0.086)	(0.055)	(0.095)	(0.072)	(0.048)
Observations	1,428	1,428	1,428	1,428	1,407	1,407	1,407	1,407	241	241	241	241
R-squared	0.583	0.578	0.574	0.572	0.414	0.404	0.404	0.406	0.223	0.221	0.220	0.236
Countries	68	68	68	68	67	67	67	67	49	49	49	49

Notes: The dependent variables are food supply in calories per capita per day (average for each year) (models 1-4), an index of food security (models 5-8), and an index of sustainability of food systems (models 9-12). The index of food systems sustainability is available for 2000, 2004, 2007, 2010 and 2013. The upper part of the Table presents estimations for the developed community, while the lower part presents estimations for the developing community detected in the ACSN. Robust standard errors are in parentheses. Significance level: *** p<0.01, ** p<0.05, * p<0.10.

human capital have a positive effect in all cases. Per capita per day imports of food has a positive effect on food supply and food security of the developed community and a positive effect on sustainability of the developing community.

Overall, the econometric estimations allow us to conclude that more competitive and more diversified countries, with coherent diversification patterns, have higher food supplies and are better in terms of food security. The effect of specialization patterns on food systems sustainability is more ambiguous. We find that concentrating food production also decreases sustainability, but the way in which diversification takes place has a negative effect on sustainability. However, when we split the sample between the developed and the developing communities, we observe that a coherent diversification has a positive effect on food supply, food security, and sustainability of the developed community, while it has a positive effect on food supply but a negative effect on sustainability of the developing community. Likewise, increasing competitiveness of countries (as measured by fitness) derives in less sustainable systems, for all countries, particularly for the developing community. This calls the attention on a possible consequence of the way in which countries diversify their production baskets and on how they become more competitive. Despite more competitive countries that follow a coherent diversification pattern might be able to increase their food supplies and improve their food security, this might generate a negative impact on food systems sustainability.

6 Concluding remarks

We analyze specialization patterns of countries in agricultural production, their global competitiveness, and the coherence of their production baskets, using methodologies from complex network analysis and the theoretical framework that studies how capabilities are revealed in products and countries. We analyze the bipartite network of agricultural products and countries, obtaining the product-product and country-country projected networks based on node similarity to detect the structure of their communities.

We find that the agricultural product space network is very dense, and that product relatedness depends on similar needs of natural conditions and other set of capabilities. Despite the high density of the network, we detect that these products cluster in communities of similar products. Similarly, the countries product space network is very dense but characterized by two stable and well-defined communities, which means that given the agricultural capabilities of countries, it is possible to consistently classify them by their specialization patterns. Interestingly, one of the communities groups countries with relatively developed agricultural production systems, while the other only clusters developing countries. The more developed community produces a higher share of food, and exports and imports more food per capita, although both communities have similar shares of total population. Despite the recent unprecedented pressure on global food system and the changes in terms of demand and dietary quality and composition, we observe that the agricultural product space and the agricultural countries space networks are very stable over the period 1993-2013.

Using network-based statistics and other indicators characterizing food production systems, we study how specialization patterns affect per capita food supply, food security, and sustainability of food systems. We use several estimation methods and we control for potential endogeneity of the variables related to specialization patterns of production.

We find that concentrating production has a negative effect on food supply, food security, and food systems sustainability. We find that fitness has a positive effect on food supply and food security, which means that most competitive countries, with more diverse production baskets, have a better food supply and more food security. Instead, we find that fitness has a low but negative effect on sustainability of food systems, in particular for countries in the developing community, which reflects the trade-off between increasing food supply while simultaneously improving sustainability. Finally, we find that a coherent diversification increases food supply and food security, but it seems to have a low but negative effect on sustainability of food systems. This implies that diversifying in products that are close to the current capabilities of countries helps increasing food supply and improving food security, but it also implies that for some countries probably a different type of diversification, generating changes in production systems, is necessary to improve the sustainability of food systems.

In brief, the evidence indicates that promoting diversification of agricultural production in a coherent way, rather than specialization, increases available food supply, contributing positively to minimize the risk of facing a food deficit. In addition, the evidence suggests that in order to increase overall sustainability of food systems, countries should reduce concentration, but it might be also necessary to follow a different diversification pattern.

This evidence indicates that how and what countries produce in agriculture affect their available food supply, their food security, and their sustainability. Thus, our analysis can contribute to policies seeking to achieve global food security and a more sustainable development of agriculture by providing inputs to understand specialization patterns of agricultural production and its dynamics, which might be particularly relevant for the second SDG that simultaneously seeks to end hunger and improve sustainability of food systems.

This is an interesting evidence because food security and the environmental dimension of sustainable development are linked by bidirectional interconnections that can lead to a trade-off between increasing food supply and improving sustainability of food systems. Increasing competitiveness, production, or productivity can certainly have an impact on the environment. But the improvement and sustainability of production requires a healthy environment. Our findings indicate that there might be certain production patterns that could help improving food security and reducing the risk of facing a food deficit (Targets 2.1 and 2.2) and simultaneously help increasing the sustainability of food systems (Target 2.4). Of course, food supply, food security, and sustainability are affected by agricultural exports and imports. Therefore, our analysis opens the ground for trade policy considerations (Target 2.b). Overall, the analysis highlights the importance of studying food systems as a complex, dynamic, and highly interconnected network of activities.

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Appendix

Table A.1: List of countries, ISO codes, geographical regions, and communities

Country	ISO	Reg.	Country	ISO	Reg.	Country	ISO	Reg.
			Developed Community (Blue)					
Afghanistan	AFG	SAS	Finland*	FIN	ECA	Malta*	MLT	MNA
Albania	ALB	ECA	France*	FRA	ECA	Mongolia	MNG	EAP
United Arab Emirates	ARE	MNA	United Kingdom*	GBR	ECA	Netherlands*	NLD	ECA
Argentina	ARG	LAC	Georgia	GEO	ECA	Norway*	NOR	ECA
Armenia	ARM	ECA	Greece*	GRC	ECA	New Zealand*	NZL	EAP
Antigua and Barbuda	ATG	LAC	Croatia*	HRV	ECA	Oman	OMN	MNA
Australia*	AUS	EAP	Hungary*	HUN	ECA	Poland*	POL	ECA
Austria*	AUT	ECA	Ireland*	IRL	ECA	Korea, DPR	PRK	EAP
Azerbaijan	AZE	ECA	Iran (Islamic Rep. of)	IRN	MNA	Portugal*	PRT	ECA
Bulgaria*	BGR	ECA	Iraq	IRQ	MNA	Romania*	ROU	ECA
Bosnia and Herzegovina	BIH	ECA	Iceland*	ISL	ECA	Russian Federation	RUS	ECA
Belarus	BLR	ECA	Israel*	ISR	MNA	Saudi Arabia	SAU	MNA
Bermuda*	BMU	NAM	Italy*	ITA	ECA	Slovakia*	SVK	ECA
Canada*	CAN	NAM	Jordan	JOR	MNA	Slovenia*	SVN	ECA
Switzerland*	CHE	ECA	Japan*	JPN	EAP	Sweden*	SWE	ECA
Chile	CHL	LAC	Kazakhstan	KAZ	ECA	Tajikistan	TJK	ECA
China	CHN	EAP	Kyrgyzstan	KGZ	ECA	Turkmenistan	TKM	ECA
Cyprus*	CYP	ECA	Rep. of Korea	KOR	EAP	Tunisia	TUN	MNA
Czech Rep.*	CZE	ECA	Kuwait	KWT	MNA	Turkey	TUR	ECA
Germany*	DEU	ECA	Lebanon	LBN	MNA	Ukraine	UKR	ECA
Denmark*	DNK	ECA	Lithuania*	LTU	ECA	Uruguay	URY	LAC
Algeria	DZA	MNA	Latvia*	LVA	ECA	United States of America*	USA	NAM
Egypt	EGY	MNA	Morocco	MAR	MNA	Uzbekistan	UZB	ECA
Spain*	ESP	ECA	Rep. of Moldova	MDA	ECA	Yemen	YEM	MNA
Estonia*	EST	ECA	North Macedonia	MKD	ECA	South Africa	ZAF	SSA
			Developing Community (Red)					
Angola	AGO	SSA	Guyana	GUY	LAC	Nepal	NPL	SAS
Benin	BEN	SSA	China, Hong Kong SAR	HKG	EAP	Pakistan	PAK	SAS
Burkina Faso	BFA	SSA	Honduras	HND	LAC	Panama	PAN	LAC
Bangladesh	BGD	SAS	Haiti	HTI	LAC	Peru	PER	LAC
Bahamas	BHS	LAC	Indonesia	IDN	EAP	Philippines	PHL	EAP
Belize	BLZ	LAC	India	IND	SAS	Paraguay	PRY	LAC
Bolivia	BOL	LAC	Jamaica	JAM	LAC	French Polynesia	PYF	EAP
Brazil	BRA	LAC	Kenya	KEN	SSA	Rwanda	RWA	SSA
Barbados	BRB	LAC	Cambodia	KHM	EAP	Senegal	SEN	SSA
Brunei Darussalam	BRN	EAP	Kiribati	KIR	EAP	Solomon Islands	SLB	EAP
Botswana	BWA	SSA	Saint Kitts and Nevis	KNA	LAC	Sierra Leone	SLE	SSA
Central African Rep.	CAF	SSA	Lao P.D.Rep.	LAO	EAP	El Salvador	SLV	LAC
Côte d'Ivoire	CIV	SSA	Liberia	LBR	SSA	Sao Tome and Principe	STP	SSA
Cameroon	CMR	SSA	Saint Lucia	LCA	LAC	Suriname	SUR	LAC
Congo, Rep.	COG	SSA	Sri Lanka	LKA	SAS	Swaziland	SWZ	SSA
Colombia	COL	LAC	Lesotho	LSO	SSA	Chad	TCD	SSA
Cape Verde	CPV	SSA	China, Macao SAR	MAC	EAP	Togo	TGO	SSA
Costa Rica	CRI	LAC	Madagascar	MDG	SSA	Thailand	THA	EAP
Cuba	CUB	LAC	Maldives	MDV	SAS	Timor-Leste	TLS	EAP
Djibouti	DJI	MNA	Mexico	MEX	LAC	Trinidad and Tobago	TTO	LAC
Dominica	DMA	LAC	Mali	MLI	SSA	Taiwan (China)	TWN	EAP
Dominican Rep.	DOM	LAC	Myanmar	MMR	EAP	United Rep. of Tanzania	TZA	SSA
Ecuador	ECU	LAC	Mozambique	MOZ	SSA	Uganda	UGA	SSA
Ethiopia	ETH	SSA	Mauritania	MRT	SSA	St. Vincent & Grenadines	VCT	LAC
Fiji	FJI	EAP	Mauritius	MUS	SSA	Venezuela	VEN	LAC
Gabon	GAB	SSA	Malawi	MWI	SSA	Viet Nam	VNM	EAP
Ghana	GHA	SSA	Malaysia	MYS	EAP	Vanuatu	VUT	EAP
Guinea	GIN	SSA	Namibia	NAM	SSA	Samoa	WSM	EAP
Gambia	GMB	SSA	New Caledonia (France)	NCL	EAP	Zambia	ZMB	SSA
Guinea-Bissau	GNB	SSA	Niger	NER	SSA	Zimbabwe	ZWE	SSA
Grenada	GRD	LAC	Nigeria	NGA	SSA			
Guatemala	GTM	LAC	Nicaragua	NIC	LAC			

Notes: Countries with an asterisk (*) are classified as developed and the remaining countries as developing. Geographical regions with average GDP per capita in constant 2010 US$ and decreasing order, for 2013, are as follows, North America: NAM (50,090.48), Europe & Central Asia: ECA (24,167.07), Latin America & the Caribbean: LAC (9,662.72), East Asia & Pacific: EAP (8,626.25), Middle East & North Africa: MNA (7,469.91), Sub-Saharan Africa: SSA (1,659.56), South Asia: SAS (1,421.68). Development levels and geographical regions are from World Bank (2019).

Table A.2: List of agricultural products

Crops
Almonds, with shell; Anise, badian, fennel, coriander; Apples; Apricots; Artichokes; Asparagus; Avocados; Bambara beans; Bananas; Barley; Broad beans, horse beans, dry; Beans, dry; Beans, green; Berries nes; Blueberries; Brazil nuts, with shell; Buckwheat; Cabbages and other brassicas; Canary seed; Carobs; Carrots and turnips; Cashewapple; Cashew nuts, with shell; Cassava; Cassava leaves; Cauliflowers and broccoli; Cereals, nes; Cherries; Cherries, sour; Chestnut; Chick peas; Chicory roots; Chillies and peppers, green; Chillies and peppers, dry; Cinnamon (canella); Fruit, citrus nes; Cloves; Cocoa, beans; Coconuts; Coffee, green; Cottonseed; Cow peas, dry; Cranberries; Cucumbers and gherkins; Currants Dates; Eggplants (aubergines); Figs; Fonio; Fruit, fresh nes; Fruit, pome nes; Fruit, stone nes; Garlic; Ginger; Gooseberries; Grain, mixed; Grapefruit (inc. pomelos); Grapes; Groundnuts, with shell; Hazelnuts, with shell; Hempseed; Hops; Karite nuts (sheanuts); Kiwi fruit; Leeks, other alliaceous vegetables; Lemons and limes; Lentils; Lettuce and chicory; Linseed; Lupins; Maize; Maize, green; Mangoes, mangosteens, guavas; Mate; Melons, other (inc.cantaloupes); Melonseed; Millet; Mushrooms and truffles; Mustard seed; Nutmeg, mace and cardamoms; Areca nuts; Kola nuts; Nuts, nes; Oats; Oilseeds nes; Okra; Olives; Onions, dry; Onions, shallots, green; Oranges; Oil palm fruit; Palm kernels; Oil, palm; Papayas; Peaches and nectarines; Pears; Peas, dry; Peas, green; Pepper (piper spp.); Peppermint; Persimmons; Pigeon peas; Pineapples; Pistachios; Plantains and others; Plums and sloes; Poppy seed; Potatoes; Sweet potatoes; Pulses, nes; Pumpkins, squash and gourds; Quinces; Quinoa; Rapeseed; Raspberries; Rice, paddy; Roots and tubers, nes; Rye; Safflower seed; Sesame seed; Sorghum; Soybeans; Spices, nes; Spinach; Strawberries; String beans; Sugar beet; Sugar cane; Sugar crops, nes; Sunflower seed; Tangerines, mandarins, clementines, satsumas; Taro (cocoyam); Tea; Tomatoes; Triticale; Fruit, tropical fresh nes; Tung nuts; Vanilla; Vegetables, fresh nes; Vegetables, leguminous nes; Vetches; Walnuts, with shell; Watermelons; Wheat; Yams; Yautia (cocoyam)
Crops processed
Beer of barley; Oil, coconut (copra); Cottonseed; Oil, cottonseed; Oil, groundnut; Oil, linseed; Oil, maize; Margarine, short; Molasses; Oil, olive, virgin; Palm kernels; Oil, palm kernel; Oil, palm; Oil, rapeseed; Oil, safflower; Oil, sesame; Oil, soybean; Sugar Raw Centrifugal; Oil, sunflower; Wine
Livestock Primary
Meat, ass; Beeswax; Meat, bird nes; Meat, buffalo; Milk, whole fresh buffalo; Meat, other camelids; Milk, whole fresh camel; Meat, camel; Meat, cattle; Meat, chicken; Meat, duck; Eggs, hen, in shell; Eggs, other bird, in shell; Meat, game; Meat, goose and guinea fowl; Milk, whole fresh goat; Meat, goat; Honey, natural; Meat, horse; Meat, nes; Milk, whole fresh cow; Meat, mule; Offals, nes; Meat, pig; Meat, rabbit; Meat, other rodents; Meat, sheep; Milk, whole fresh sheep; Snails, not sea; Meat, turkey
Livestock Processed
Cheese, buffalo milk; Ghee, of buffalo milk; Butter, cow milk; Butter and Ghee; Cheese (All Kinds); Cheese, skimmed cow milk; Cheese, whole cow milk; Cream fresh; Ghee, butteroil of cow milk; Cheese of goat milk; Lard; Milk, skimmed cow; Evaporat & Condensed Milk; Milk, skimmed condensed; Milk, skimmed dried; Milk, skimmed evaporated; Milk, whole condensed; Milk, whole dried; Milk, whole evaporated; Cheese, sheep milk; Butter and ghee, sheep milk; Skim Milk & Buttermilk, dry; Whey, condensed; Whey, dry; Yoghurt

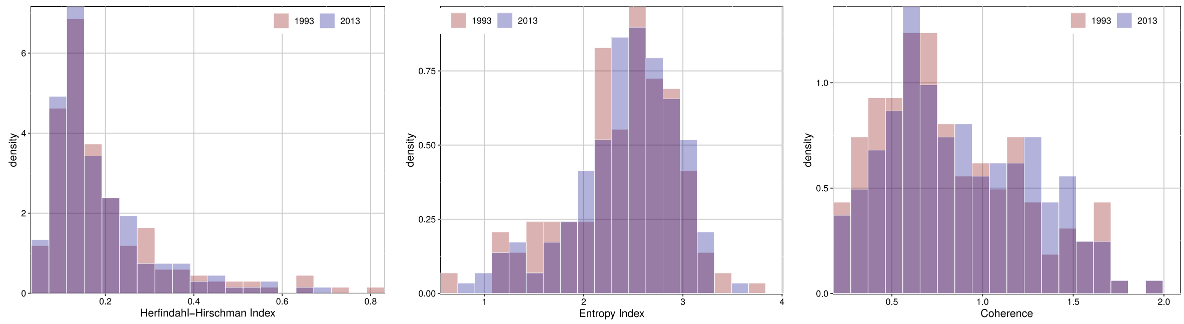

Figure A.1: Distributions of Herfindal-Hirschman index, Entropy index, and Coherence. 1993 and 2013.

Table A.3: Variables: description and sources

Variables	Description	Source
Food Supply per capita per day	Total production, plus imports, minus exports, stock variation, and the use of agricultural products for utilization different from food, in calories per capita per day, in log	FAO (2019)
Food Security Index	Composite index that measures the multidimensional concept of food security	Caccavale and Giuffrida (2020)
Sustainability Index	Composite indicator that aggregates 27 indicators grouped in four dimensions aiming to characterize the sustainability of food systems	Béné et al. (2019)
Agr. TFP (ln)	Agricultural total factor productivity index (base year 2005=100) in log	Fuglie (2012)
Human capital	Index of human capital: average years of schooling and the returns to education	Feenstra et al. (2015)
Imports per capita per day (ln)	Imports of agricultural products per capita per day in calories in log	FAO (2019)
Latitude in absolute values	Countries latitudes in absolute values in log	BACI-CEPII (2019)
Geographical regions	Variable that indicates if countries belong to a geographical region: East Asia & Pacific, Europe & Central Asia, Latin America & Caribbean, Middle East & North Africa, North America, South Asia, and Sub-Saharan Africa	World Bank (2019)

Table A.4: Summary statistics of dependent and independent variables. 1993-2013

Variable	Obs.	Mean	Std. Dev.	Min	Max
Food Supply per capita per day	3,549	2.706	0.474	1.508	3.828
Food Security Index	3,402	0.614	0.155	0.203	0.938
Sustainability Index	1292	0.495	0.128	0.149	0.740
HH Index	3,549	0.190	0.127	0.032	0.828
Entropy	3,549	2.407	0.540	0.475	3.816
Coherence	3,549	0.868	0.409	0.147	2.005
Fitness (ln)	3,549	-0.621	1.141	-3.628	2.927
Agr. TFP (ln)	3,252	4.574	0.154	3.957	5.188
Human capital	2,814	2.386	0.691	1.041	3.726
Imports per capita per day (ln)	3,549	0.263	1.049	-3.992	3.135
Latitude in absolute values	3,549	26.096	16.578	0.200	64.150

Table A.5: The effect of country specialization patterns on per capita food supply, food security, and sustainability. 1993 to 2013. Panel data fixed effects with instrumental variables

Dependent variable	Food Supply				Food Security				Sustainability			
Model	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
HH Index	-0.460***				-0.081***				-0.266*			
	(0.104)				(0.029)				(0.160)			
Entropy Index		0.129***				0.013*				0.130		
		(0.029)				(0.007)				(0.108)		
Coherence			0.264***				0.024***				0.192*	
			(0.042)				(0.009)				(0.112)	
Fitness (ln)				0.132***				0.006				0.014
				(0.019)				(0.005)				(0.106)
Agr. TFP (ln)	0.329***	0.340***	0.331***	0.336***	0.058***	0.059***	0.058***	0.057***	0.050***	0.080**	0.079***	0.045***
	(0.022)	(0.023)	(0.021)	(0.022)	(0.005)	(0.005)	(0.005)	(0.005)	(0.013)	(0.037)	(0.026)	(0.011)
Human Capital	0.207***	0.202***	0.208***	0.208***	0.083***	0.084***	0.084***	0.085***	0.052***	0.040	0.055***	0.058*
	(0.022)	(0.022)	(0.021)	(0.021)	(0.005)	(0.005)	(0.005)	(0.005)	(0.017)	(0.026)	(0.020)	(0.033)
Imports (ln)	0.106***	0.104***	0.102***	0.107***	0.007***	0.007***	0.007***	0.008***	0.006	0.002	0.008	0.010*
	(0.007)	(0.007)	(0.007)	(0.007)	(0.002)	(0.002)	(0.002)	(0.002)	(0.006)	(0.010)	(0.006)	(0.005)
Observations	2,600	2,600	2,600	2,600	2,580	2,580	2,580	2,580	362	362	362	362
R-squared	0.497	0.496	0.500	0.494	0.419	0.414	0.412	0.411	0.149	-0.302	0.060	0.249
Countries	130	130	130	130	129	129	129	129	92	92	92	92
Dependent variables	First stage											
HH Index	0.647***				0.647***				0.307***			
	(0.015)				(0.015)				(0.056)			
Entropy Index		0.556***				0.556***				0.171***		
		(0.016)				(0.017)				(0.064)		
Coherence			0.681***				0.681***				0.180***	
			(0.014)				(0.014)				(0.054)	
Fitness (ln)				0.675***				0.675***				-0.057
				(0.014)				(0.014)				(0.069)
Partial F-test of IVs	1819.85	1137.22	2224.7	2318.03	1804.01	1127.46	2210.37	2300.38	30.6	7.17	11.19	0.68
p-value	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.008	0.010	0.410
Endogeneity test	1.248	2.199	3.582	16.103	0.005	0.008	0.692	0.143	6.751	6.332	3.923	0.077
p-value	0.264	0.138	0.058	0.000	0.943	0.929	0.405	0.705	0.010	0.012	0.048	0.789

Notes: The dependent variables are food supply in calories per capita per day (average for each year) (models 1-4), an index of food security (models 5-8), and an index of sustainability of food systems (models 9-12). The index of food systems sustainability is available for 2000, 2004, 2007, 2010 and 2013. We treat variables related to specialization patterns as potentially endogenous. Instrumental variables are the first-year lags of these potentially endogenous variables. Other covariates in the first-stage regressions are not reported but are included in the estimations. Robust standard errors are in parentheses. Significance level: *** p<0.01, ** p<0.05, * p<0.10.

Table A.6: The effect of country specialization patterns on per capita food supply, food security, and sustainability. 1993 to 2013. Pooled OLS with instrumental variables

Dependent variable	Food Supply				Food Security				Sustainability			
Model	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
HH Index	-0.437***				-0.117***				-0.095***			
	(0.048)				(0.015)				(0.031)			
Entropy		0.115***				0.025***				0.014*		
		(0.013)				(0.004)				(0.008)		
Coherence			0.289***				0.063***				-0.035**	
			(0.024)				(0.006)				(0.015)	
Fitness (ln)				0.110***				0.022***				-0.005
				(0.011)				(0.003)				(0.004)
Agr. TFP (ln)	0.358***	0.356***	0.335***	0.303***	0.044***	0.044***	0.039***	0.033***	-0.034	-0.035	-0.030	-0.033
	(0.042)	(0.042)	(0.039)	(0.040)	(0.011)	(0.011)	(0.011)	(0.011)	(0.027)	(0.027)	(0.026)	(0.026)
Human Capital	0.090***	0.095***	0.100***	0.101***	0.078***	0.079***	0.081***	0.081***	0.073***	0.074***	0.071***	0.074***
	(0.018)	(0.018)	(0.017)	(0.017)	(0.004)	(0.004)	(0.004)	(0.004)	(0.009)	(0.009)	(0.008)	(0.009)
Imports (ln)	0.133***	0.136***	0.151***	0.169***	0.042***	0.043***	0.047***	0.050***	0.030***	0.031***	0.032***	0.031***
	(0.007)	(0.007)	(0.007)	(0.008)	(0.002)	(0.002)	(0.002)	(0.002)	(0.004)	(0.004)	(0.004)	(0.004)
Latitude (Abs. Value)	0.003***	0.004***	0.004***	0.003***	0.000	0.000	0.000	0.000	-0.000	-0.000	-0.000	-0.000
	(0.001)	(0.001)	(0.001)	(0.001)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
Community	0.227***	0.197***	0.118***	0.105***	0.046***	0.041***	0.022**	0.022**	0.034**	0.032**	0.052***	0.041**
	(0.034)	(0.035)	(0.036)	(0.039)	(0.008)	(0.009)	(0.010)	(0.011)	(0.016)	(0.016)	(0.018)	(0.017)
Europe & Central Asia	0.040	0.030	-0.022	0.047*	0.035***	0.035***	0.023***	0.038***	-0.016	-0.014	0.006	-0.005
	(0.032)	(0.031)	(0.030)	(0.029)	(0.009)	(0.008)	(0.008)	(0.008)	(0.017)	(0.018)	(0.019)	(0.018)
Latin America & Caribbean	-0.094***	-0.101***	-0.085***	-0.087***	-0.026***	-0.025***	-0.023***	-0.022***	0.007	0.011	0.027***	0.023**
	(0.020)	(0.021)	(0.020)	(0.018)	(0.006)	(0.006)	(0.006)	(0.005)	(0.010)	(0.010)	(0.009)	(0.009)
Middle East & North Africa	0.057*	0.050	0.013	0.057*	0.030***	0.030***	0.021***	0.031***	-0.211***	-0.209***	-0.202***	-0.205***
	(0.035)	(0.034)	(0.033)	(0.033)	(0.008)	(0.008)	(0.008)	(0.008)	(0.024)	(0.024)	(0.023)	(0.024)
North America	0.531***	0.534***	0.454***	0.454***	0.062***	0.062***	0.044***	0.046***	0.076***	0.076***	0.086***	0.080***
	(0.045)	(0.044)	(0.041)	(0.042)	(0.010)	(0.010)	(0.009)	(0.010)	(0.015)	(0.015)	(0.015)	(0.015)
South Asia	-0.045**	-0.066***	-0.095***	-0.154***	0.006	0.001	-0.006	-0.017**	-0.123***	-0.126***	-0.118***	-0.119***
	(0.020)	(0.020)	(0.020)	(0.023)	(0.007)	(0.007)	(0.007)	(0.008)	(0.013)	(0.013)	(0.015)	(0.016)
Sub-Saharan Africa	-0.163***	-0.156***	-0.102***	-0.087***	-0.072***	-0.068***	-0.057***	-0.054***	-0.031***	-0.026***	-0.018**	-0.018**
	(0.021)	(0.021)	(0.019)	(0.019)	(0.006)	(0.006)	(0.006)	(0.006)	(0.010)	(0.010)	(0.009)	(0.009)
Constant	0.776***	0.408**	0.544***	1.010***	0.227***	0.141***	0.171***	0.267***	0.519***	0.464***	0.502***	0.480***
	(0.197)	(0.194)	(0.184)	(0.188)	(0.051)	(0.051)	(0.049)	(0.050)	(0.126)	(0.131)	(0.121)	(0.124)
Observations	2,600	2,600	2,600	2,600	2,580	2,580	2,580	2,580	362	362	362	362
R-squared	0.667	0.669	0.687	0.686	0.814	0.813	0.821	0.819	0.805	0.802	0.807	0.803
Dependent variables	First stage											
HH Index	0.953***				0.953***				0.887***			
	(0.006)				(0.006)				(0.017)			
Entropy Index		0.958***				0.957***				0.932***		
		(0.006)				(0.006)				(0.018)		
Coherence			0.978***				0.978***				0.957***	
			(0.004)				(0.004)				(0.014)	
Fitness (ln)				0.982***				0.981***				0.966***
				(0.003)				(0.003)				(0.013)
Partial F-test of IVs	29674.57	28540.13	67717.46	94198.93	28895.2	27449.57	65458.87	90550.83	2706.98	2651.22	4827.85	5758.39
p-value	0.000	0.000	0.000	0.000	0.001	0.002	0.003	0.004	0.005	0.006	0.007	0.008
Endogeneity test	0.634	1.464	0.568	3.837	0.704	1.483	1.416	2.061	2.793	6.739	0.080	0.176
p-value	0.426	0.226	0.451	0.050	0.402	0.223	0.234	0.151	0.095	0.009	0.777	0.675

Notes: The dependent variables are food supply in calories per capita per day (average for each year) (models 1-4), an index of food security (models 5-8), and an index of sustainability of food systems (models 9-12). The index of food systems sustainability is available for 2000, 2004, 2007, 2010 and 2013. The community that includes only developing countries (red) is used as the base. The region East Asia & Pacific is used as the base of the dummies for geographical regions. We treat variables related to specialization patterns as potentially endogenous. Instrumental variables are the first-year lags of these potentially endogenous variables. Other covariates in the first-stage regressions are not reported but are included in the estimations. Robust standard errors are in parentheses. Significance level: *** p<0.01, ** p<0.05, * p<0.10.