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Specialization in food production and global food security: a bipartite network analysis

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Abstract

Several recent events have risen concerns about global food security, which has become a growing challenge at the international policy level. Understanding the specialization patterns of countries in food production can provide relevant insights for the evaluation and policy design seeking to achieve food security. In this paper, we analyze world agricultural production using bipartite networks and data from FAO for the period 1993 to 2013. We obtain product-product and country-country projected networks based on node similarity to detect the structure of their communities. We use different methods derived from complex system analysis that allows us to rank countries according to their capabilities and products according to their need of capabilities. We observe networks with well-defined communities of countries and products, which are very stable during the period of analysis. Interestingly, the communities of countries are not only defined by agro-ecological conditions but also by economic and technological factors. We combine network statistics on the patterns of production and specialization with data on food supply per capita per day, and we perform an econometric analysis to study how specialization patterns affect food supply. We show that concentrating agricultural production decreases food supply, while countries' competitiveness in agricultural production and the coherence of their diversification patterns both increase per capita food supply.

Keywords: Specialization; Food supply; Food security; Complex networks; Community structure detection; Bipartite networks
JEL Codes: Q18; F63

1 Introduction

Food demand has been steadily growing over the last decades as a result of an increasing global population that pressures on the limited land and water resources of the planet. In addition, shocks arising from fluctuations derived from climate change, as well as trade policies, and market volatility also threaten food security.

Multiple factors such as population growth (Godfray et al., 2010), dietary changes (Davis et al., 2014; Khoury et al., 2014; Finaret and Masters, 2019), rising food prices and agricultural production shocks (Headey, 2011; Tanaka and Hosoe, 2011; Sartori and Schiavo, 2015), over-exploitation of natural resources (Hazell and Wood, 2007; Hanjra and Qureshi, 2010; Tilman et al., 2011; Cassidy et al., 2013), climate change (Schmidhuber and Tubiello, 2007; Battisti and Naylor, 2009; Gornall et al., 2010; Coumou and Rahmstorf, 2012), regional conflicts and epidemics (McCloskey et al., 2014), and increasing biofuels and biomass use (Woods et al., 2010; Tilman et al., 2011; Nonhebel and Kastner, 2011) are placing unprecedented pressure on the global food system. The answer to this increasing demand cannot derive from extending agricultural land but through attaining higher yields and a more efficient and sustainable food production. In this context, achieving international food security has become one of the greatest challenges of economic policy worldwide (Barrett, 2010; Porkka et al., 2013).

Food security not only depends on food availability, but also on access and distribution of food in a way that allows people to have physical, social, and economic access to sufficient safe and nutritious food that meets their dietary needs and food preferences for an active and healthy life.[1]

Therefore, achieving food security depends on multiple interrelated sources. One of them is food production, which is obviously a relevant aspect to address the complex problem of food security. But also, different countries have been able to change access to food by increasing imports. Food trade, which has more than doubled in the last 30 years, has become a way to deal with production shortfalls and to access new channels to meet increasing food demand (D'Odorico et al., 2014; Torreggiani et al., 2018). However, this more opened and interconnected world might be subject to more frequent and stronger production shocks (Tanaka and Hosoe, 2011; Headey, 2011). These trends in international food trade can also affect food production leading to specialization of food systems.

In addition, countries have been going through dietary transformations towards more diverse foods (Finaret and Masters, 2019). And, accordingly, agricultural production also did become more diversified but also more similar in composition (Khoury et al., 2014). Last, but not least, increasing use of agricultural production for biomass and biofuels compete with food production and can lead to specific specialization patterns in food

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[1] There exists a high number of definitions of food security and, accordingly, of measuring it. In this paper, we define food security as a measure of availability of food and access to it by every individual.

production (Tilman et al., 2009).

Overall, the multiple aspects that can affect food security as well as the multiple sources that can improve countries' food supply constitute a complex problem that deserves different analysis from multidisciplinary perspectives.

In this paper, we focus on how countries specialize in agricultural production, their global competitiveness, and the coherence of specialization patterns of their production baskets, which are processes that are likely to affect their food supply. We claim that understanding specialization patterns of countries in food production can provide relevant insights for the evaluation and policy design seeking to achieve food security.

We borrow methodologies from network analysis and the theoretical background from recent research that has made a great advance in understanding how capabilities shape production of different types of products and how this, in turn, helps economic development (Hausmann et al., 2014; Zaccaria et al., 2014). This literature has shown that what countries produce and how they use their production capabilities to diversify production are relevant aspects shaping their development process. Different studies have proven that the "product space" conditions the development of countries because economies grow by upgrading the products they produce and export (Hidalgo et al., 2007; Hidalgo and Hausmann, 2009). In this view, technology, capital, institutions, and skills needed to make newer products are more easily adapted from some products than from others. 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, which may help explaining why they find difficulties in developing.

Interestingly, several products in the periphery of the world product space are agricultural products. Therefore, the literature has not devoted great attention to them because they are not relevant to reach sectors in the core. However, while this may be true, agricultural production is relevant to ensure food security. In addition, the agricultural product space of each country is likely to affect their food supply and, therefore, global food security.

This paper has two main objectives. Firstly, we aim to understand the agricultural product space and the specialization patterns of countries in agricultural production and their evolution between 1993 and 2013, analyzing the emerging communities of products and countries. Secondly, using the findings of this analysis, we aim to study whether specialization patterns of agricultural production affect food security.

We analyze the bipartite network of countries and agricultural products using data from FAO for the period 1993 to 2013. We obtain the product-product and country-country projected networks based on node similarity to detect the structure of their communities. We use different methods derived from complex system analysis that allows us to rank countries according to their capabilities and products according to their need of capabilities.

We use an indicator of country's competitiveness "fitness", which considers the type of goods produced by countries, and an indicator of "complexity" of products, which is determined by whether they are commonly produced or if, on the contrary, particular or scarce capabilities are required for their production.

We find that the agricultural product space is very dense meaning that many products are produced by a high number of countries. We observe that different products are jointly produced because they share the need of similar capabilities, including natural conditions, for their production. Interestingly, despite the high density of the network, it is possible to detect that these products cluster in well defined communities.

In the same way, we find that the network of countries is very dense but characterized by a small number of communities, which means that given the agricultural capabilities of countries, it is possible to consistently classify them by their specialization patterns. Using an econometric model, we show that the similarity between countries is not only determined by their endowments of natural resources, but also by other economic and political features of countries. Overall, the set of countries' capabilities are revealed by the measure of fitness, which is reflected in the positive correlation between fitness, agricultural production, GDP, and food supply.

Finally, despite dietary quality, such as nutrient composition, sustainability, and a variety of credence attributes has been changing over the years (Finaret and Masters, 2019), we observe that the agricultural product space and the network of agricultural countries are very stable over the period of twenty one years.

We combine network statistics characterizing patterns of product specialization with available per capita food supply at the country level derived from the food balance sheets from FAO, and we perform an econometric analysis to study how competitiveness of countries, depicted by fitness, coherence of diversification patterns of production baskets, and concentration of production affect food supply.

Our results show that there is a positive relation between fitness and food supply. Given that fitness 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. In addition, a coherent diversification pattern of production baskets also increases food supply. This implies that an additional contribution to food supply derives from diversifying in products related to existing capabilities of countries. Conversely, concentrating production decreases food supply.

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 and the methodology. In Section 4, we present the main results. Finally, Section 5 concludes.

2 Literature review

In this paper, we depart from the literature that considers that there exist a set of capabilities that allows countries to produce a set of related products. The pioneering analysis of Hidalgo et al. (2007) was followed by a great number of studies looking at diversification patterns of countries (for example: Caldarelli et al., 2012; Hausmann et al., 2014; Zaccaria et al., 2014). In brief, these studies develop a methodology that allows to analyze how countries manage to produce goods that demand different capabilities, including technology, capital, institutions, and skills.

This methodology has not been yet used to study agricultural production systems. Probably because several products in the periphery of the world product space are agricultural products, which implies that they are not relevant to reach sectors in the core. However, agricultural production and different related specialization patterns are undoubtedly relevant for achieving food security. In particular, considering that agricultural production has been more affected by shocks that give place to fluctuations (see, for example, Gornall et al., 2010; Coumou and Rahmstorf, 2012), we argue that certain specialization patterns and concentration of production might make countries more vulnerable to production shocks endangering their food security.

Agricultural production has indeed changed in composition in the last 60 years. Khoury et al. (2014) analyze changes in the relative importance of different crop plants in national food supplies worldwide. They show that within a global trend of increased overall quantities of food calories, protein, fat, and weight, national food supplies diversified in regard to contributing measured crop commodities. In addition, national food supplies 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.

In addition, other sources have created more interdependence between countries' food production. For example, using network analysis Khoury et al. (2016) have studied the relative contributions of different regions in the context of current food systems. The authors determine the origins of crops comprising the food supplies and agricultural production of countries worldwide. They estimate the degree to which countries use crops from regions of diversity other than their own. They show that countries are highly interconnected with regard to primary regions of diversity of the crops they cultivate and/or consume. They conclude that foreign crop usage has increased significantly over the past 50 years, including in countries with high indigenous crop diversity.

In addition, food availability is also determined by an increase in the international exchange of food production adding an extra source of interdependence among countries. Thus, achieving international food security requires not only an improved understanding of how and what countries produce, but also of how countries connect through international trade networks, and other sources that determine the food balances of each country.

In recent years, several studies have analyzed food trade networks, considering food trade layers separately (for example: Ercsey-Ravasz et al., 2012; Shutters and Muneepeerakul, 2012; Puma et al., 2015; Burkholz, 2016). From a multi-network perspective, Torreggiani et al. (2018) analyze the properties of international food trade networks. They find 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, i.e. more intensively connected countries tend to import from and export to countries that are themselves more connected. They also show that the probability of country pairs belonging to the same food trade community depends more on geopolitical and economic factors than on country economic size and income. These findings are valuable to understand past and emerging dynamics in the global food system, especially to examine potential shocks to global food trade.

In this sense, network analysis has also been applied to study how food trade networks will react to shocks that are expected to increase in the following decades. Fair et al. (2017) develop a preferential attachment network model of the global wheat trade network and are able to predict the response of wheat trade network metrics to shocks of several length and severity. They show that the network will become less vulnerable to attacks but will continue to exhibit low resilience until 2050. Even short-term shocks strongly increase link diversity and cause long-term structural changes that influence the network's response to subsequent shocks. In a recent work, Burkholz and Schweitzer (2019) analyze the international trade of maize, rice, soy, and wheat and they show that they become more prone to failure cascades caused by exogenous shocks. Instead, Sartori and Schiavo (2015) analyze the link between the flows of water embodied in the international trade of agricultural goods, and vulnerability to external shocks. They show that the increased globalization witnessed in the last three decades is not associated with the increased frequency of adverse shocks in food production.

In brief, the use of network analysis and other methods derived from complex systems analysis have been increasingly used to study multiple aspects of food systems, such as production, biodiversity, shocks, and international trade. These studies have shed light on the behaviour of a more interconnect world and on possible implication and vulnerabilities for agricultural production and food security.

3 Data and Methodology

In this section, we firstly describe the data sources and variables that we will use in our analysis. Then, we explain the methodological approach.

3.1 Data and definitions

We use data on production and food balance sheets at the country level for the period 1993-2013 from FAO.[2] We consider 169 countries that are detailed in Table SI.1 of the Supplementary Information.

In order to build the agricultural product space, we use production data of 219 different agricultural products. For the purpose of our work, an agricultural product means 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 (see list of products in Table SI.2 of the Supplementary Information).[3] All data are in tonnes, but in order to have comparable and relevant measures for food supply, we also transform them to kilocalories, fat, and protein content, using the data provided by FAO (2001).

In addition, we use data on food balance sheets to have a picture of the pattern of countries' food supply. 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. This simple calculation provides the national food supply available during a given period. Food supply data are given in kilocalories, and grams of fat and protein, per capita per day, after applying appropriate food composition factors for all primary and processed products in terms of dietary energy value, protein, and fat content.

3.2 Methodology

Next, we define several useful concepts for our analysis and we discuss the methodology, aimed at characterizing the diversification patterns of agricultural production at the country level according to their natural endowments and unobserved capabilities.

Bipartite networks

Relevant contributions have been recently made in the analysis and understanding of product diversification (for example: Hidalgo et al., 2007; Hidalgo and Hausmann, 2009; Balland and Rigby, 2017). These studies have shown that the possibilities of diversification into new products are strongly determined by the capabilities revealed in the products currently produced. Thus, although the set of capabilities necessary for production cannot be directly observed, the fact that different countries produce identical products may

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[2] FAOSTAT: `http://www.fao.org/faostat/en`

[3] We excluded production of live animals because data are given in stocks of animal heads, which is not comparable with the rest of agricultural production. In addition, we excluded fibers for textiles and other products for non-food uses.

indicate that these countries share capabilities that are needed to produce these products.

In the case of agriculture, production requires not only technology, capital, institutions, and skills, which are certainly difficult to be quantified, but it also depends on natural conditions necessary for the production of agricultural products. As any other type of capabilities, it is not simple to determine their presence for each country. Natural, environmental, and climatic conditions can be very heterogeneous within countries allowing them to diversify their agricultural baskets. It is unlikely that a country's natural resources endowment is evenly distributed throughout its territory. Thus, a measure of relatedness allows to quantify the presence of a set of natural characteristics and capabilities that determine diversification patterns.

A complex product in the product space of the universe of products is one that is produced by only a few high competitive countries. Similarly, a complex product in the case of the agricultural product space is a product that only a few countries can produce (i.e. non ubiquitous). Countries with high capabilities in agriculture are those that can produce a wide set of products, but also that have capabilities to produce goods that only a few countries can produce. It is important to highlight that, in the case of agriculture, the set of capabilities also include natural resources.

The world agricultural products network can be represented by a bipartite matrix: rows represented by countries and columns by products. The entries of this matrix take the value of one when a country is considered a relevant producer of a given product. One possible way of detecting relevant producers is to look at the revealed comparative advantages (RCA) of countries. Thus, we measure patterns of specialization by computing countries' RCA for each agricultural product.[4] This approach has been widely used to measure production capabilities (Ferrarini and Scaramozzino, 2016), technological capabilities (Petralia et al., 2017), and export capabilities (Hidalgo et al., 2007; Bruno et al., 2018) at the country and firm levels.

Given that agricultural production is in tonnes, we adopt an indicator that weights production in order to build the indicator of RCA. For this aim, we use the agricultural gross production value (GPV), which is built by multiplying gross production in physical terms by output prices at farm gate (from FAO). The variable is in constant 2004-2006 million dollars.

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, t is a given year, and GPV is the

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[4] This measure has been mostly used for international trade. In the case of production, the measure is also considering domestic consumption and it might give relevance to products that are not relevant for international consumption.

agricultural gross production value. We adopt the convention that $RCA_{ikt} \geq 1$ reveals that country i is a relevant producer of product k at time t.[5]

Consequently, the elements of the agricultural products bipartite matrix M can be defined as:

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

We study how the bipartite matrix M evolves over the period 1993 to 2013.

Product and country relatedness

We define the agricultural product space as a network-based representation of global agricultural production, where nodes represent agricultural products and ties among them indicate their degree of relatedness. The fact that different products are jointly produced by a set of countries allows us to entail that some capabilities are common for those countries and for a couple of products. Thus, relatedness between a pair of products derives from the fact that these two products are commonly produced together.

There are several possibilities of measuring product relatedness or similarity (see, for example: Zhou et al., 2007; Hidalgo et al., 2007; Caldarelli et al., 2012; Zaccaria et al., 2014). Our measure of relatedness is based on the Jaccard index:

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

where $V_{kk'} = \sum_i m_{ik} m_{ik'}$ is the number of co-occurrences in which two different countries produce products k and k', and $V_k = \sum_i m_{ik}$ is the total number of countries that produce k, and similarly for $V_{k'}$. Products are coded using the classification of FAO that disaggregates agricultural production into 219 products (after excluding non-food products).

Matrix P can be seen as the network of world agricultural products or the agricultural product space, in which nodes are represented by products and links by the degree of relatedness between them, i.e. the elements $P_{kk'}$. Therefore, the coherence of a production basket is due to the relatedness strength within products, in the sense that there are certain technological, natural, and market characteristics common to each one of the products.

Following the same strategy, we can obtain the network of countries producing agricultural goods where nodes are countries and ties represent the degree of similarity of countries' production baskets. Thus, country relatedness is defined as follows:

$$C_{ii'} = \frac{\Lambda_{ii'}}{\Lambda_i + \Lambda_{i'} - \Lambda_{ii'}}, \tag{4}$$

where $\Lambda_{ii'} = \sum_k m_{ik} m_{i'k}$ is the number of products that are produced by countries i and

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[5] We also performed robustness checks using other thresholds of RCA. Given that the results hold, we keep this convention that is commonly used in this type of analysis.

i', $\Lambda_i = \sum_k m_{ik}$ is the total number of products produced by i, and similarly for $\Lambda_{i'}$.

Community detection

In order to detect communities in matrices P and C, we use the Louvain algorithm, which is a method to extract communities from large networks. We obtain a measure of modularity that ranges between zero and one and aims to capture the degree to which a network can be separated in groups of products or countries (communities), with higher interaction within them than outside them (see: Blondel et al., 2008).

Fitness and complexity

The bipartite matrix gathers valuable information on countries' abilities 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 called *Fitness*, and of the difficulty –in terms of required capabilities– of producing a given product, which they call the *Complexity* of a product. This method is known as the Fitness and Complexity Algorithm (FiCo) and rewards countries according to the variety and complexity of their production baskets.[6]

4 Results

In this section, we present the results of the network analysis and we estimate the impact of the specialization patterns of countries on food supply.

4.1 The agricultural product space

We observe that the agricultural product space is very dense, meaning that many products are produced by a high number of countries. Figure 1 shows the network representation of matrix P, which formally is the projection of the bipartite matrix M in the agricultural product space using the Jaccard index, for the years 1993 and 2013.

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[6] 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. However, we use the FiCo algorithm because it has been shown to have a better performance, providing a measure that is more highly correlated with GDP and GDP per capita.

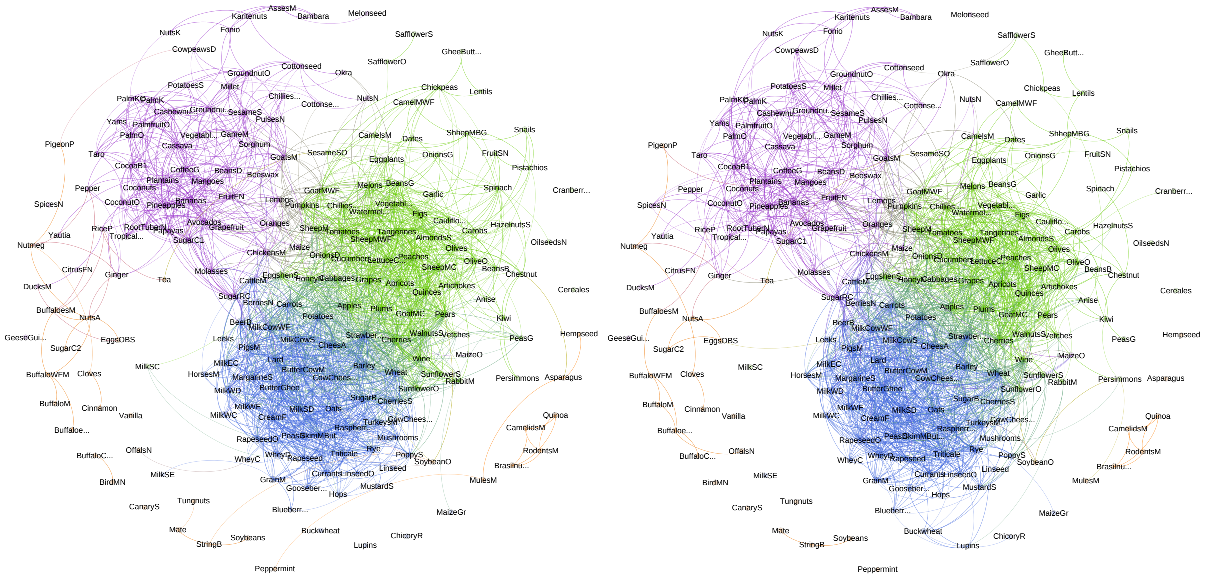

Figure 1: Agricultural product space. Product relatedness. Links are filtered by $P_{kk'} > 0.23$. Different colors represent different detected communities (Louvain algorithm): in blue "Crops and livestock", in green "Vegetables and fruits", in purple "Tropical fruits and crops", and in orange "Periphery". Left: 1993. Right: 2013

The Jaccard index allows to measure the degree of relatedness between products in order to understand which products are more connected. Figure 1 shows the strongest links, i.e. keeping links above the 0.9 quantile of the distribution of $P_{kk'} > 0$, which allows us to detect that different products are jointly produced indicating that they share the need of similar natural conditions and capabilities for their production.

Table 1 summarizes network statistics of the full network and the link filtered network of agricultural products. The network statistics reveal a very stable network architecture between 1993 and 2013. The agricultural product space is highly connected with 218 and 219 products (nodes), in 1993 and 2013, respectively.

Table 1: Network statistics of the agricultural product space

Year	1993			
	Nodes	Density	Modularity	Communities
Full network	218	0.76	0.22	4
Link filtered network*	218	0.08	0.49	28
Year	2013			
	Nodes	Density	Modularity	Communities
Full network	219	0.77	0.21	4
Link filtered network*	219	0.08	0.48	30

Notes: * Links are filtered by high relatedness with a threshold at the 0.9 quantile.

A remarkable feature of these networks is that, even without filtering links, they have four very well defined communities, which are clearly observed even when the weakest links have been removed. This process gives raise to a larger number of additional small communities, reaching a total of 28 in 1993 and of 30 in 2013. However, the structure of the network remains after filtering the weakest links. The four main communities loose size but they remain strongly connected and they concentrate a great extent of the density. An evidence in favor of the latter is that the network's architecture reveals high modularity after links that reveal low relatedness have been removed.

Table 2 reports some additional basic statistics of the full network of agricultural products for: (i) the link weight ($P_{kk'} > 0$); (ii) node degree, which is the number of products connected to a given product k, this is $ND_k = \sum_{k'} A_{kk'}$, with $A_{kk'} = 1$ if $P_{kk'} > 0$, and zero otherwise; and, (iii) node strength, which measures the cohesion of a product in the network, this is $NS_k = \sum_{k'} P_{kk'}$.

Table 2: Link weight, node degree and node strength. Full network of agricultural products

Year	1993			
	Mean	Std. Dev.	Min.	Max.
Link Weight	0.12	0.10	0.01	1.00
Node Degree	163.95	38.08	46.00	214.00
Node Strength	19.48	8.18	1.74	36.64
Year	2013			
	Mean	Std. Dev.	Min.	Max.
Link Weight	0.12	0.10	0.09	1.00
Node Degree	168.69	37.47	49.00	215.00
Node Strength	19.73	8.33	1.88	35.56

Although on average the number of connections of a node is very high (163.95 in 1993 and 168.69 in 2013), they are not necessarily strongly connected in the network. The presence of a relatively low cohesion level in the average (19.48 in 1993 and 19.73 in 2013) is due to the fact that the link weight distribution is strongly right-skewed: very few products have a high relatedness and most of them are weakly related (see Figure SI.1 in the Supplementary Information). However, the presence of modularity implies that within the communities the products are much more cohesive.

As we already mentioned, despite the high density of the full network, we detect that agricultural products cluster in four well defined communities, portrayed in different colors in Figure 1 and named for illustrative purposes as: "Crops and livestock" (in blue), "Vegetables and fruits" (in green), "Tropical fruits and crops" (in purple), and "Periphery" (in orange). These four communities of the full network connect highly related products. For example, mangoes, bananas, papayas, coconuts, plantains, avocados, and coffee, which are mostly tropical fruits and crops, appear very highly connected in a single community (in purple). In blue, we observe crops such as wheat and barley, as well as processed crops, and 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. Finally, in orange, camelids, quinoa, soybeans, and some nuts, are clustered in one smaller community.

It is interesting to note that this forth community is much smaller in size and shrinks during the period of analysis, mainly because two of its most relevant products at the beginning of the period, soybeans and soybeans oil, move to a different community. In fact, this community has a different composition in every year, although a group of products appear regularly, while the three other communities maintain their main products during the whole period (see Table SI.3 in the Supplementary Information). Thus, in 2013, the periphery refers to a community that is composed by very specific products with a low relevance in global food production: quinoa, Brazil nuts, safflower seed and oil, asparagus, mate, and camelids and rodents meat.

Given that filtering the weakest links creates a few additional communities of very small size, the following analysis is performed for the four communities detected in the full network. The contribution of these communities to global food production for 1993 and 2013, measured in kilocalories, proteins, and fat content can be observed in Table 3.

Table 3: Production shares by community in total production, measured in kilocalories, proteins, and fat. 1993 and 2013

Year		1993		
Community	N. of products	Kilocalories	Proteins	Fats
Crops and livestock	67	0.41	0.49	0.43
Tropical fruits and crops	82	0.51	0.34	0.41
Vegetables and fruits	60	0.03	0.04	0.04
Periphery	9	0.05	0.12	0.12
Year		2013		
Community	N. of products	Kilocalories	Proteins	Fats
Crops and livestock	67	0.38	0.59	0.43
Tropical fruits and crops	82	0.57	0.37	0.47
Vegetables and fruits	65	0.05	0.03	0.10
Periphery	5	0.00	0.00	0.00

An interesting thing to notice is that a community might be highly diversified in products but at the same time contribute relatively low to food production, in all the measures considered. The community based on crops and livestock includes 67 different products and has a share (in 1993 and 2013) in kilocalories of 41% and 38%, 49% and 59% in proteins, and 43% in fats. The community of tropical fruits and crops groups 82 products and contributes with 51% and 57% of total kilocalories, 34% and 27% in proteins, and 41% and 47% in fats, in 1993 and 2013, respectively. The community based on vegetables and fruits includes 60 products in 1993 and increases to 65 products in 2013. It contributes with only 3% and 5% of total kilocalories, 4% and 3% in proteins, and 4% and 10% in fats, in 1993 and 2013, respectively. Finally, the smaller and less stable community, which we call periphery, includes 9 products in 1993, contributing with 5% of total kilocalories, 12% of proteins, and 12% of fats. Interestingly, it reduces its size to 5 products in 2013 with a negligible contribution in all the measures considered.

It is important to note that the differences in the contributions to total food production using the different measures are related with the composition of the communities in terms of products' characteristics. Not surprisingly, the community based on vegetables and fruits has a lower contribution compared to communities that include meat, diary products, or oil crops.

Overall, the three larger communities are quite stable in terms of quantity of products and contribution to food production between 1993 and 2013. The main change is observed in the smaller community that includes products that can be considered as "niche products" in the sense that their consumption is not relevant at a global level. The difference between 1993 and 2013 in this community is mainly driven by the migration of soybean and soybeans oil from the periphery to other communities. The case of soybeans is particularly interesting because its world production increased more than three times between 1993 and 2013. In addition, it became one of the most important crops for some individual countries such as Brazil and Argentina. In brief, soybean production has suffered significant changes during these years, which helps explaining why soybeans and oil of soybeans are among the few products that appear in different communities depending on the year.

The geographical distributions of agricultural production of these communities can be observed in Figure 2, where each map shows the production shares of countries' total production –in kilocalories– in each of the four detected communities of products for 1993 and 2013.[7]

Typically, most countries have higher shares in one specific community, i.e. they specialize in the production of closely related products within a community. Several countries concentrate almost all their production in one single community. For example, Malaysia and Ghana with 99%, and Indonesia with 98%, of their production in the community of tropical fruits and crops (in purple). Also, we observe highly concentrated production shares in the community based on crops and livestock (in green), such as Estonia, Latvia, and Ireland, with 99% of their total production in that community, and Norway and Finland, with 98%. In contrast, other countries appear to have more diversified production baskets, distributing their production in products that belong to different communities. For example, Italy, Greece, Spain, and to a lesser extent, Argentina

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[7] The geographical distribution of food production measured in proteins and fats can be seen in Figures SI.2 and SI.3 of the Supplementary Information.

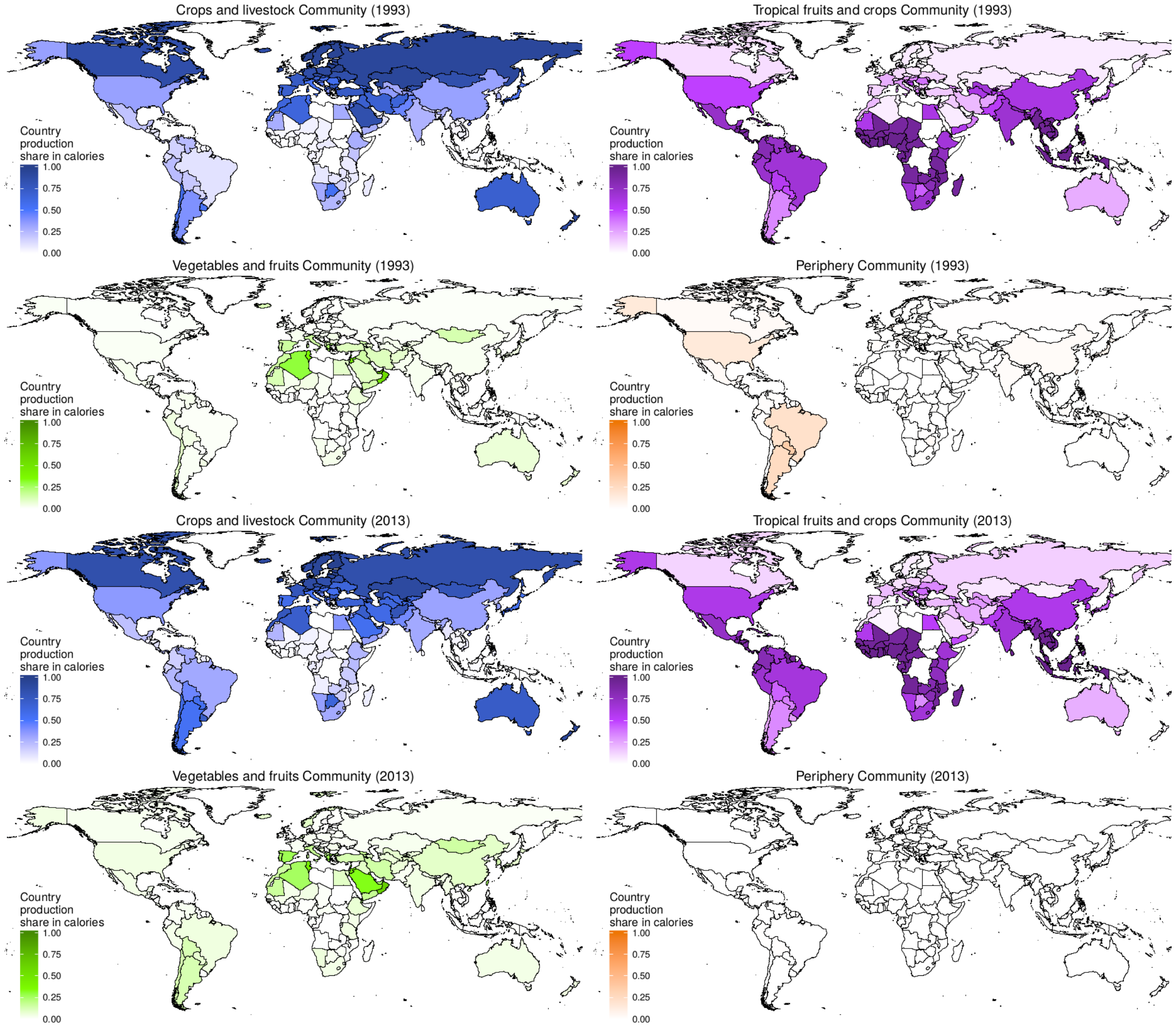

Figure 2: Production shares in kilocalories of countries in each community. 1993 and 2013. Colors represent communities as in the networks of Figure 1. Color intensity represents the share of a country's total production in the production of the community.

and the United States.

4.2 The network of countries

Next, we analyze how countries are related given their agricultural production baskets. Figure 3 shows the network representation of matrix C, for the years 1993 and 2013.

Table 4 presents statistics for the full network and the link filtered network of countries, which reveal a very stable network between 1993 and 2013. The network is highly connected with 169 countries (nodes). Filtering links by high relatedness, the number of communities increases from 2 to 5 and to 7, in 1993 and 2013, respectively.

Table 5 additional statistics of the full network. The average number of connections of a node is very high, 161.91 in 1993 and 164.78 in 2013, which implies that most countries are endowed with a similar number of capabilities and/or natural resources that allows

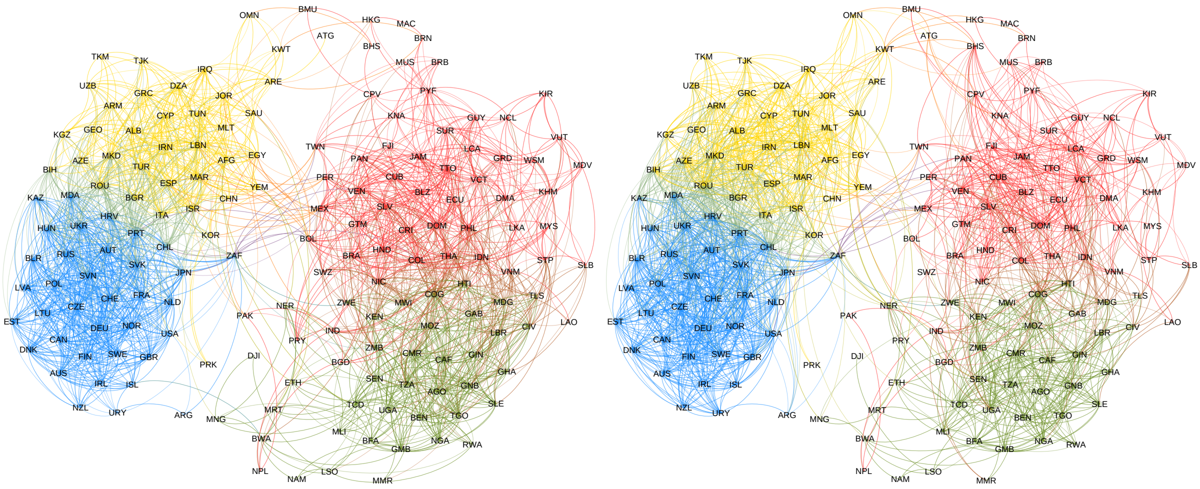

Figure 3: Countries relatedness. Links are filtered by $C_{kk'} > 0.25$. Different colors represent different detected communities (Louvain algorithm): in red “Tropical I”, in green “Tropical II”, in yellow “Subtropical”, and in blue “Tempered”. Left: 1993. Right: 2013. ISO codes are defined in Table SI.1 of the Supplementary Information.

Table 4: Network statistics of countries’ production similarities

Year	1993			
	Nodes	Density	Modularity	Communities
Full network	169	0.96	0.21	2
Link filtered network*	169	0.10	0.90	5
Year	**2013**			
	Nodes	Density	Modularity	Communities
Full network	169	0.98	0.20	2
Link filtered network*	169	0.10	0.59	7

Notes: * Links are filtered by high relatedness with a threshold at the 0.9 quantile.

them to simultaneously produce different products. However, despite the high node degree, we observe a relatively low level of cohesion, in the average the node strength is 21.46 in 1993 and 22.68 in 2013, which derives from the fact that the link weight distribution is strongly right-skewed (see Figure SI.1 in the Supplementary Information).

The network is fully-connected and it also reveals the presence of communities, where members seem to be related by their geographical closeness, understood as their environmental characteristics, which determine their natural production capabilities. For the same reason, it is not surprising to observe that there are no remarkable differences between the networks in 1993 and 2013.

Like in the agricultural product space, the communities of countries are very well defined even without filtering links. Although a lower number of communities is detected,

Table 5: Link weight, node degree and node strength. Full network of countries' production similarities

Year	1993			
	Mean	Std. Dev.	Min.	Max.
Link Weight	0.13	0.10	0.01	0.66
Node Degree	161.91	7.61	123	168
Node Strength	21.46	3.76	9.15	30.77
Year	**2013**			
	Mean	Std. Dev.	Min.	Max.
Link Weight	0.14	0.10	0.01	0.74
Node Degree	164.78	5.76	119	168
Node Strength	22.68	3.93	11.61	29.93

there are several well distinguished communities of great size, which can be clearly observed once the weaker links have been removed. The process of link filtering generates a few additional communities of smaller size, which are detached from the main communities. Therefore, the network's modularity increases when links with low relatedness are removed.

For the analysis of the network of countries, we use the communities that are defined after filtering the weakest links. We keep four communities in both 1993 and 2013 given that the remaining communities (one in 1993 and three in 2013) include only one country each. Thus, we attach those countries to the nearer community and we keep these four main communities for the remaining of the analysis.

Table 6: Production shares by community in total production, measured in kilocalories, proteins, and fat. 1993 and 2013

Year		1993		
		Share		
Community	N. of countries	Kilocalories	Proteins	Fats
Tempered	32	0.37	0.44	0.36
Subtropical	38	0.26	0.26	0.23
Tropical I	46	0.12	0.12	0.11
Tropical II	53	0.24	0.18	0.30
Year		**2013**		
		Share		
Community	N. of countries	Kilocalories	Proteins	Fats
Tempered	37	0.34	0.43	0.32
Subtropical	35	0.23	0.23	0.20
Tropical I	56	0.25	0.17	0.35
Tropical II	41	0.18	0.17	0.14

The contribution of these four detected communities of countries to world food production, measured in kilocalories, proteins, and fat content can be observed in Table 6 for 1993 and 2013. We observe that production is more evenly distributed across the communities of countries, compared to what we observed in the communities of products. However, clearly the Tempered community produces a high share of food in all kilocalories, proteins, and fats. This community is followed by the Subtropical and the Tropical I communities depending on the year and measure considered. While the Tropical II community has a lower share of food production in most of the cases.

These four main communities of countries seem to be clustered mainly by geographical factors. Figure 4 shows the geographical distribution of countries that belong to the main four detected communities after filtering.

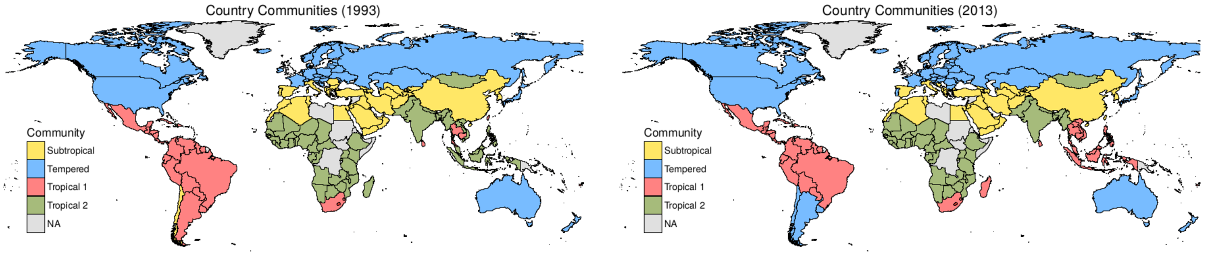

Figure 4: Geographical distribution of countries in each community. 1993 and 2013. Colors represent communities as in the networks of Figure 3.

For example, countries with tropical weather appear in two main communities. In green, the detected community clusters mainly economies from Africa and Asia, such as India, Tanzania, Zambia, Angola, which are located in the tropics. Another group of mostly tropical countries, like Colombia, Panama, and Jamaica, appear in a different community (in red). Countries from Mediterranean or warm subtropical regions are grouped in a community in yellow. In blue, most countries are those with tempered climate that mainly have extensive agricultural production systems, such as Australia, Argentina, Canada, United States, and Eastern European countries. For illustrative purposes, we name these four communities as: "Tropical I" (in red), "Tropical II"'(in green), "Subtropical" (in yellow), and "Tempered" (in blue).[8]

Interestingly, two of these communities include mostly developed countries (blue and yellow), and two other communities cluster mainly developing countries (red and green). This might indicate that not only geographical, climatic, and environmental conditions are relevant determinants of the communities but also other capabilities –including technological, economic, political, and institutional capabilities–, which can be proxied by the income or development levels of countries.

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[8] We are aware of the fact that each of these communities may include countries that can hardly be classified as having the type of climate indicated by the name of the community. However, we use these names a broad categories to identify the communities.

In order to quantitatively explore what determines that any two countries belong to the same community, we run a Logit regression to examine the probability as a function of a set of covariates aiming to capture country-pair similarity along geographical, technological, and economic dimensions.

We estimate the following model:

$$\text{Prob}\{y_{ij} = 1|\text{X}\} = \Lambda(\alpha + \beta \text{X}_{ij} + \lambda_i + \lambda_j), \tag{5}$$

where the dependent variable y_{ij} is a dummy that indicates whether a pair of countries i and j belong to the same community; α is a constant term, X is a vector of covariates $\text{X} = \{\ln \text{Dist}_{ij}; \ln(||\text{Lat}_i| - |\text{Lat}_j||); \text{Region}_{ij}; |\ln \text{GDPpc}_i - \ln \text{GDPpc}_j|; |\ln \text{TFP}_i - \ln \text{TFP}_j|\}$; where $\ln \text{Dist}_{ij}$ indicates the geographical distance between a pair of countries; $\ln(||\text{Lat}_i| - |\text{Lat}_j||)$ is the difference in countries' latitudes (in absolute value) and proxies differences in climate and agro-ecological zones; Region_{ij} is a dummy that indicates if countries belong to the same geographical region; $|\ln \text{GDPpc}_i - \ln \text{GDPpc}_j|$ indicates differences in the development levels of countries; and, similarly, $|\ln \text{TFP}_i - \ln \text{TFP}_j|$ is the difference between agricultural total factor productivity of a pair of countries, which indicates differences in inputs endowments and technology; λ_i and λ_j are country fixed effects; and, Λ is the logistic function. In Table SI.4 of the Supplementary Information, we describe these variables and their sources.

Table 7 shows the estimation results and the marginal effects of the covariates for the cross-sections 1993 and 2013. The estimated results are stable for both years. Our findings indicate that geographical distance as well as the difference in latitudes between two countries both have a negative and statistically significant impact on the probability that two countries belong to the same community. Likewise, the variable that indicates if two countries belong to the same geographical region is positive and significant and its high relevance is observed in the estimated marginal effects.

Differences in GDP per capita of countries are also negative and statistically significant, which implies that countries with similar development levels are more likely to be in the same community. Likewise, differences in agricultural total factor productivity of countries, which aims to capture differences in labour, capital, land, and technological endowments of countries, has a negative and significant effect (in 1993), which implies that the higher the difference in the agricultural productivity of two countries, the lower the probability that they will be in the same community. This variable turns out not significant in the estimations for 2013.

Overall, these results indicate that not only geographical conditions but also other political, institutional, technological, and economic factors are important determinants of the co-presence of country pairs in the same community. And, therefore, this implies that specialization patterns of countries in agricultural production are related with a set

Table 7: Determinants of community attaching. Logit estimations and marginal effects for 1993 and 2013

	1993		2013	
Variables	Logit Est.	Marginal effects	Logit Est.	Marginal effects
Distance (ln)	-0.692***	-0.093***	-0.565***	-0.073***
	(0.064)	(0.009)	(0.060)	(0.008)
Difference in latitudes (ln)	-0.692***	-0.094***	-0.687***	-0.088***
	(0.030)	(0.005)	(0.030)	(0.004)
Same region	1.690***	0.305***	1.369***	0.228***
	(0.098)	(0.0201)	(0.095)	(0.019)
Difference in GDP pc (ln)	-1.108***	-0.150***	-1.195***	-0.154***
	(0.044)	(0.006)	(0.045)	(0.005)
Difference in TFP (ln)	-0.764**	-0.103**	-0.027	-0.003
	(0.314)	(0.043)	(0.355)	(0.046)
Constant	7.770***		6.219***	
	(0.694)		(0.666)	
Country fixed effects	yes		yes	
Observations	10,269		10,551	
Pseudo R2	0.388		0.349	

Notes: The dependent variable is a dummy indicating whether two countries belong to the same detected community. Marginal effects are computed by the delta method at averages. Robust standard errors are in parentheses. Significance level: *** p<0.01, ** p<0.05, * p<0.10.

of both natural and economic features of countries.

4.3 Fitness and Complexity

Next, we apply the Fitness and Complexity (FiCO) algorithm to the bipartite matrix of world agricultural production. Figure 5 shows a plot of the bipartite matrix, as defined in Equation (2), for 2013. In this graphical representation, 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.

An interesting feature that emerges when organizing by FiCo, is the triangular form of the matrix, which indicates nestedness in agricultural production. The pattern depicted in Figure 5 is very stable over the period of analysis, i.e. we do not observe remarkable changes in the bipartite matrix between 1993 and 2013.

Interestingly, but to some degree expected, we observe that the complexity of products is not only related to the availability of technology, institutions, capital, and skills, but also to the presence of very specific natural conditions. For example, products such as camelids and quinoa are classified as highly complex, which is not surprising considering that they are produced in the "Puna", an ecosystem that is present in a few South

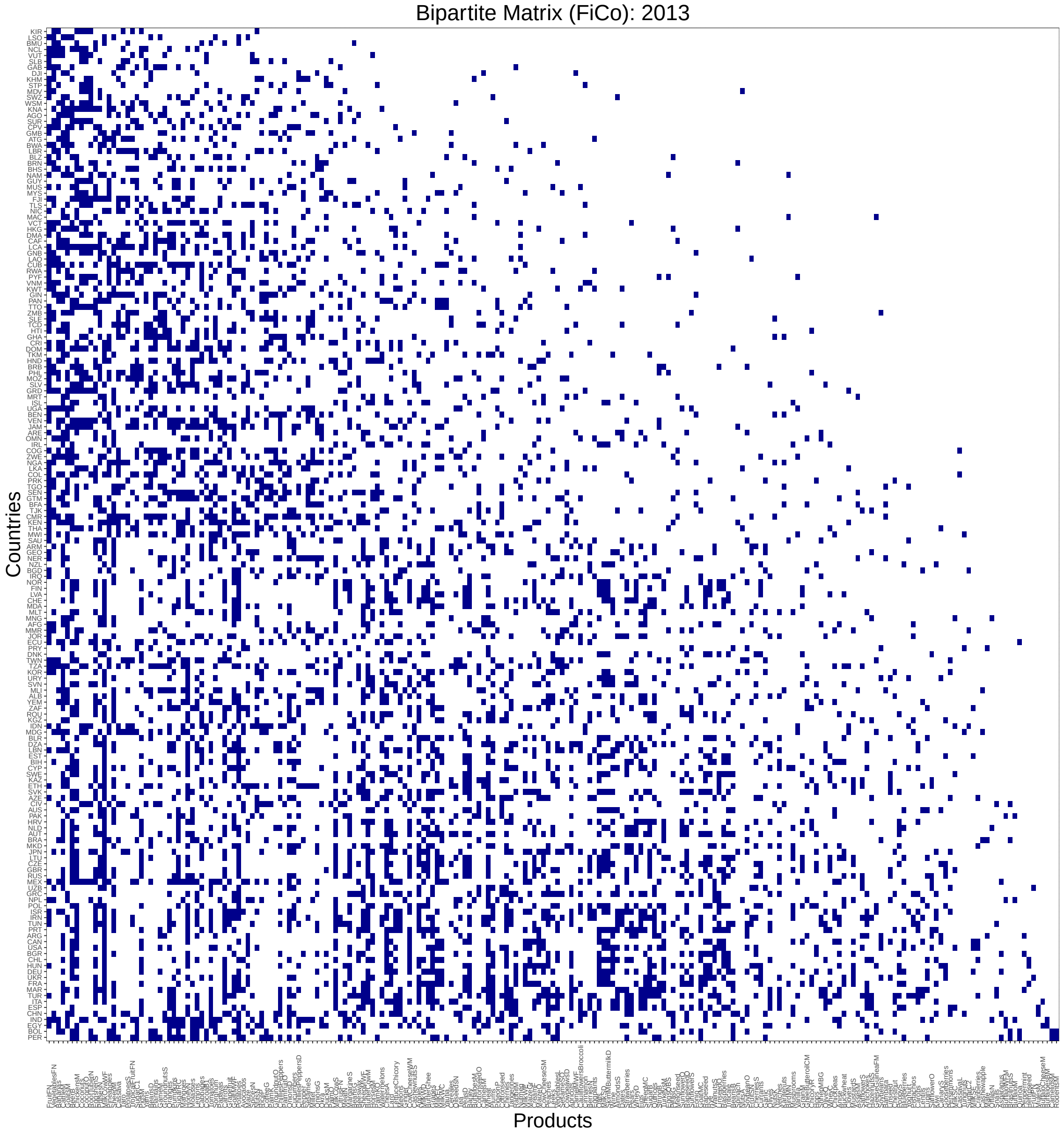

Figure 5: Country-product bipartite matrix in 2013 (y-axis countries, x-axis products). Each pixel is an $RCA \geq 1$, rows and columns are organized by FiCo.

American countries, Argentina, Bolivia, Ecuador, and Peru. Actually, camelids meat is only produced by Bolivia and Peru, and quinoa by Bolivia, Ecuador, and Peru. A similar argument applies for other products classified as complex.

This evidence highlights the relevance of considering the role of environmental conditions in addition to other type of capabilities as determinants of revealed comparative advantages in agricultural production. But also, this calls the attention on a feature of the indicator of fitness and complexity, which was pointed out by Morrison et al. (2017), who showed that this measure often highlights economies that are producing “exclusive niche products”, which are not necessarily the most complex (in terms of required capabilities). The authors showed 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 agricultural product space, we observe that some products that appear as complex and some countries that are classified as having a high fitness are not relevant in terms of global agricultural production. Thus, we re-estimated the indicators of fitness and complexity excluding the products that can be considered as "exclusive niche products" and the fitness of countries producing those products decreases, but for the remaining countries the scores and positions are similar, indicating that the measure of fitness is robust to changes in the set of products considered.[9]

We might still ask whether these cases that appear at the micro level affect the analysis at the macro level. Figure 6 shows the dispersion diagram between fitness, GDP, GPV, and food supply for 2013.

As expected, given that fitness is an indicator of competitiveness, it clearly correlates positively with the selected macro variables. The correlations are statistically significant and positive: 0.686 with GDP, 0.713 with GDP per capita, and 0.413 with food supply. In addition, the correlations are quite stable, very low variations are observed through all the cross sections (1993 to 2013). Interestingly, we observe that the countries that are classified as highly competitive because they produce what can be considered exclusive niche products, such as Peru, Bolivia, and Egypt, appear as outliers.

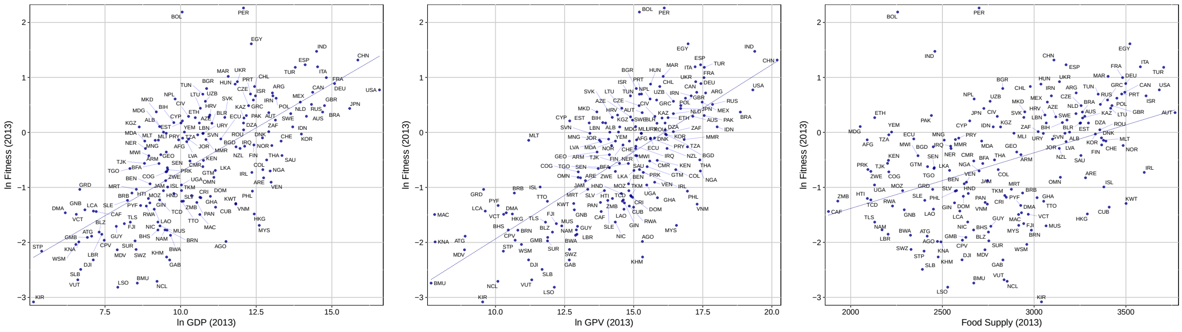

Figure 6: Countries' fitness and macro variables: GDP (left), GPV (middle), and food supply (right). 2013

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

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[9] The results are available upon request.

4.4 Specialization patterns and food supply

In order to quantitatively explore how different features of agricultural production affect food supply, we use network statistics derived from our previous analysis and we perform an econometric analysis.

We estimate the following simple model, using ordinary least squares (OLS) method and pooled data for the years between 1993 and 2013:

$$y_{it} = \beta_0 + \beta_1 X_{it} + \tau_t + \mu_{it}, \tag{6}$$

where y is food supply per capita per day, in either kilocalories, grams of proteins, or grams of fats, in a given year, X are different independent variables (that we define bellow): two alternative indexes of concentration of agricultural production, the Herfindal-Hirschman index ($HHIndex$) and the entropy index (*Entropy*), an indicator of coherence of the agricultural production basket (*Coherence*) and the weighted version of this indicator ($WCoherence$), and the indicator of countries' capabilities or competitiveness (*Fitness*), τ are time dummies, and μ are the residuals.

For a country i with a production basket of agricultural goods Ω_i in a given time t, the Herfindal-Hirschman index is defined as $HH_{it} = \sum_{k\in\Omega_{it}} s_{ikt}^2$, and entropy is defined as $S_{it} = -\sum_{k\in\Omega_{it}} s_{ikt} \ln s_{ikt}$, where s_{ikt} is the share of the k variety in the production basket.

We define the coherence of the production basket of a country as the average of the node strength of its products in the agricultural product space, which is

$$Coherence_{it} = \frac{1}{N_{it}} \sum_{k\in\Omega_{it}} NS_{kt} = \frac{1}{N_{it}} \sum_{k\in\Omega_{it}} \sum_{k'\in\Omega_{it}} P_{kk't}, \tag{7}$$

where N_{it} is the number of products produced by country i in time t. The weighted version is defined as

$$WCoherence_{it} = \frac{1}{(\sum_{k\in\Omega_{it}} Q_{ikt})^2} \sum_{k\in\Omega_{it}} \sum_{k'\in\Omega_{it}} Q_{ikt} Q_{ik't} P_{kk't}. \tag{8}$$

Notice that in the lower bound this measure converges to the $HHIndex$, since $P_{kk't} = 1$. Also, a country producing a single product would be perfectly coherent.

With the indicators of coherence, we address whether countries diversify their production baskets in products that are close to their set of capabilities (measured by the degree of similarity of products) or if, conversely, they diversify in products that are far from their capabilities.

In principle, the model could be improved by including fixed effects to control for unobserved heterogeneity and omitted variables bias. However, the dependent variable –per capita food supply– is relatively invariant over all the years considered and has a relatively low variation between countries. Thus, including countries' fixed effects does not allow us to observe the effect of the variables of interest, because fixed effects can explain by themselves most of the relatively small variations in food supply.

Table 8 shows the results of the econometric estimations using per capita food supply in calories as the dependent variable.[10]

Table 8: The effect of concentration, specialization, and capabilities on per capita food supply (in calories). 1993 to 2013

Model	(1)	(2)	(3)	(4)	(5)	(6)	(7)
HH Index	-0.570***						
	(0.061)						
Entropy		0.187***					
		(0.014)					
Coherence			0.088***			0.071***	
			(0.005)			(0.004)	
Weighted coherence				2.542***			2.233***
				(0.115)			(0.106)
Fitness (ln)					0.173***	0.157***	0.159***
					(0.006)	(0.006)	(0.006)
Constant	2.679***	2.122***	0.460***	2.071***	2.686***	0.978***	2.241***
	(0.038)	(0.049)	(0.117)	(0.041)	(0.033)	(0.109)	(0.038)
Time dummies	yes	yes	yes	yes	yes	yes	yes
Observations	3,528	3,528	3,528	3,528	3,528	3,528	3,528
R-squared	0.056	0.079	0.121	0.151	0.206	0.262	0.295

Notes: The dependent variable is food supply in calories per capita per day (average for each year). Robust standard errors are in parentheses. Significance level: *** p<0.01, ** p<0.05, * p<0.10.

We estimate that increasing concentration in agricultural production decreases daily per capita food supply, which is observed with both measures of concentration: the Herfindal-Hirschman index and the entropy index (models 1 and 2). Instead, a coherent diversification of the product baskets increases per capita food supply (models 3 and 4). This implies that diversifying in products that need capabilities that are close to those that countries have increases food supply. The indicator of competitiveness of countries that indirectly reflects their capabilities for agricultural production also increases food supply (model 5). Finally, in models (6) and (7), we combine the indicators of fitness and coherence of the diversification patterns and we find that both a higher fitness and a coherent diversification pattern increase food supply.

5 Concluding remarks

We analyze countries' specialization patterns in agricultural production, their global competitiveness, and the coherence of their production baskets, using methodologies from

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[10] The estimations using food supply measured in proteins and fats are presented in Tables SI.5 and SI.6 of the Supplementary Information.

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 is very dense and that product relatedness depends on products' similar needs of natural conditions and other set of capabilities. Despite the high density of the network, we are able to detect that these products cluster in communities of very similar products.

Similarly, the network of countries is very dense but characterized by a small number of communities, which means that given the agricultural capabilities of countries, it is possible to consistently classify them by their specialization patterns. We find that the probability that two countries belong to the same community depends not only on geographical conditions but also on other political, institutional, technological, and economic factors.

Despite the global food system has been notably changing over the years in terms of demand and dietary quality, we observe that the agricultural product space and the network of agricultural countries are very stable over the period of twenty one years.

Using the detected network statistics, we study how the patterns of product specialization affect per capita food supply. We find a positive relation between fitness and food supply, which means that most competitive countries also a better food supply. In addition, a coherent diversification pattern of production baskets also increases food supply, which implies that diversifying in products close to the current capabilities of countries helps increasing food supply. Conversely, concentrating production decreases food supply. Overall, the evidence indicates that promoting the diversification of agricultural products in a coherent way, rather than specialization, increases available food supply and contributes positively to minimize the risk of facing a food deficit.

Our analysis evidence that how and what countries produce in agriculture affect their available food supply. Thus, this 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.

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Supplementary Information

Table SI.1: List of countries and ISO codes

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

Fiji	FJI	New Zealand	NZL	Zambia	ZMB
Finland	FIN	Nicaragua	NIC	Zimbabwe	ZWE
France	FRA	Niger	NER		
French Polynesia	PYF	Nigeria	NGA		

Table SI.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

Table SI.3: List of products in the different communities of the full network of products

Vegetables and fruits (1993-2013)
Almonds, with shell; Anise, badian, fennel, coriander; Apricots; Artichokes; Broad beans, horse beans, dry; Butter and ghee, sheep milk; Carobs; Cauliflowers and broccoli; Cheese of goat milk; Cheese, buffalo milk; Cheese, sheep milk; Chestnut; Chillies and peppers, green; Cucumbers and gherkins; Dates; Eggplants (aubergines); Figs; Fruit, stone nes; Garlic; Grapes; Hazelnuts, with shell; Kiwi fruit; Lettuce and chicory; Meat, bird nes; Meat, camel; Meat, mule; Meat, sheep; Melons, other (inc.cantaloupes); Milk, whole fresh camel; Milk, whole fresh sheep; Oil, olive, virgin; Olives; Onions, dry; Onions, shallots, green; Peaches and nectarines; Pears; Peppermint; Persimmons; Pistachios; Pumpkins, squash and gourds; Quinces; Snails, not sea; Spinach; String beans; Tangerines, mandarins, clementines, satsumas; Tomatoes; Vegetables, leguminous nes; Vetches; Watermelons
Tropical fruits and crops (1993-2013)
Areca nuts; Avocados; Bambara beans; Bananas; Beans, dry; Beeswax; Cashew nuts, with shell; Cashewapple; Cassava; Cassava leaves; Chillies and peppers, dry; Cinnamon (canella); Cloves; Cocoa, beans; Coconuts; Coffee, green; Cottonseed; Cottonseed; Cow peas, dry; Eggs, other bird, in shell; Fonio; Fruit, citrus nes; Fruit, fresh nes; Fruit, tropical fresh nes; Ghee, butteroil of cow milk; Ghee, of buffalo milk; Ginger; Grapefruit (inc. pomelos); Groundnuts, with shell; Karite nuts (sheanuts); Kola nuts; Maize; Maize, green; Mangoes, mangosteens, guavas; Meat, ass; Meat, buffalo; Meat, duck; Meat, game; Meat, goat; Meat, nes; Melonseed; Milk, whole fresh buffalo; Millet; Molasses; Nutmeg, mace and cardamoms; Nuts, nes; Oil palm fruit; Oil, coconut (copra); Oil, cottonseed; Oil, groundnut; Oil, palm; Oil, palm; Oil, palm kernel; Okra; Oranges; Palm kernels; Palm kernels; Papayas; Pepper (piper spp.); Pigeon peas; Pineapples; Plantains and others; Pulses, nes; Rice, paddy; Roots and tubers, nes; Sesame seed; Sorghum; Spices, nes; Sugar cane; Sugar crops, nes; Sweet potatoes; Taro (cocoyam); Tea; Tung nuts; Vanilla; Vegetables, fresh nes; Yams; Yautia (cocoyam)
Crops and livestock (1993-2013)
Barley; Beer of barley; Berries nes; Blueberries; Buckwheat; Butter and Ghee; Butter, cow milk; Canary seed; Carrots and turnips; Cheese (All Kinds); Cheese, skimmed cow milk; Cheese, whole cow milk; Cherries, sour; Chicory roots; Cream fresh; Currants; Eggs, hen, in shell; Evaporat & Condensed Milk; Gooseberries; Grain, mixed; Hops; Lard; Linseed; Margarine, short; Meat, cattle; Meat, horse; Meat, pig; Meat, turkey; Milk, skimmed condensed; Milk, skimmed cow; Milk, skimmed dried; Milk, skimmed evaporated; Milk, whole condensed; Milk, whole dried; Milk, whole evaporated; Milk, whole fresh cow; Mushrooms and truffles; Mustard seed; Oats; Oil, linseed; Oil, rapeseed; Oil, sunflower; Peas, dry; Poppy seed; Potatoes; Rapeseed; Raspberries; Rye; Skim Milk & Buttermilk, Dry; Strawberries; Sugar beet; Sunflower seed; Triticale; Wheat; Whey, condensed; Whey, dry
Periphery
Asparagus; Brazil nuts, with shell; Mate; Meat, other camelids; Meat, other rodents; Oil, safflower; Oil, soybean; Quinoa; Safflower seed; Soybeans
Products that appear in different communities between 1993 and 2013
Apples; Asparagus; Beans, green; Brazil nuts, with shell; Butter, buffalo milk; Cabbages and other brassicas; Cereals, nes; Cherries; Chick peas; Cranberries; Fruit, pome nes; Hempseed; Honey, natural; Leeks, other alliaceous vegetables; Lemons and limes; Lentils; Lupins; Mate; Meat, chicken; Meat, goose and guinea fowl; Meat, other camelids; Meat, other rodents; Meat, rabbit; Milk, whole fresh goat; Offals, nes; Oil, maize; Oil, safflower; Oil, sesame; Oil, soybean; Oilseeds nes; Peas, green; Plums and sloes; Quinoa; Safflower seed; Soybeans; Sugar Raw Centrifugal; Walnuts, with shell; Wine; Yoghurt

Notes: The products listed in the communities “Vegetables and fruits”, “Tropical fruits and crops”, and “Crops and livestock” are those that are present during the complete period of time 1993-2013 in each community. The “Periphery” community is never composed in the same way, although a group of products appear regularly. Products that appear in different communities list all products that change community at least once during the time period considered.

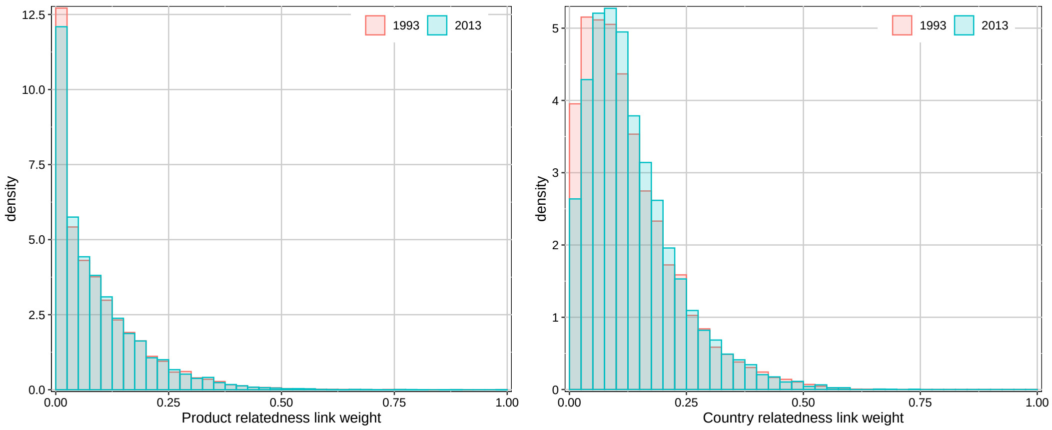

Figure SI.1: Products (left) and countries (right) link weight distribution. 1993 and 2013

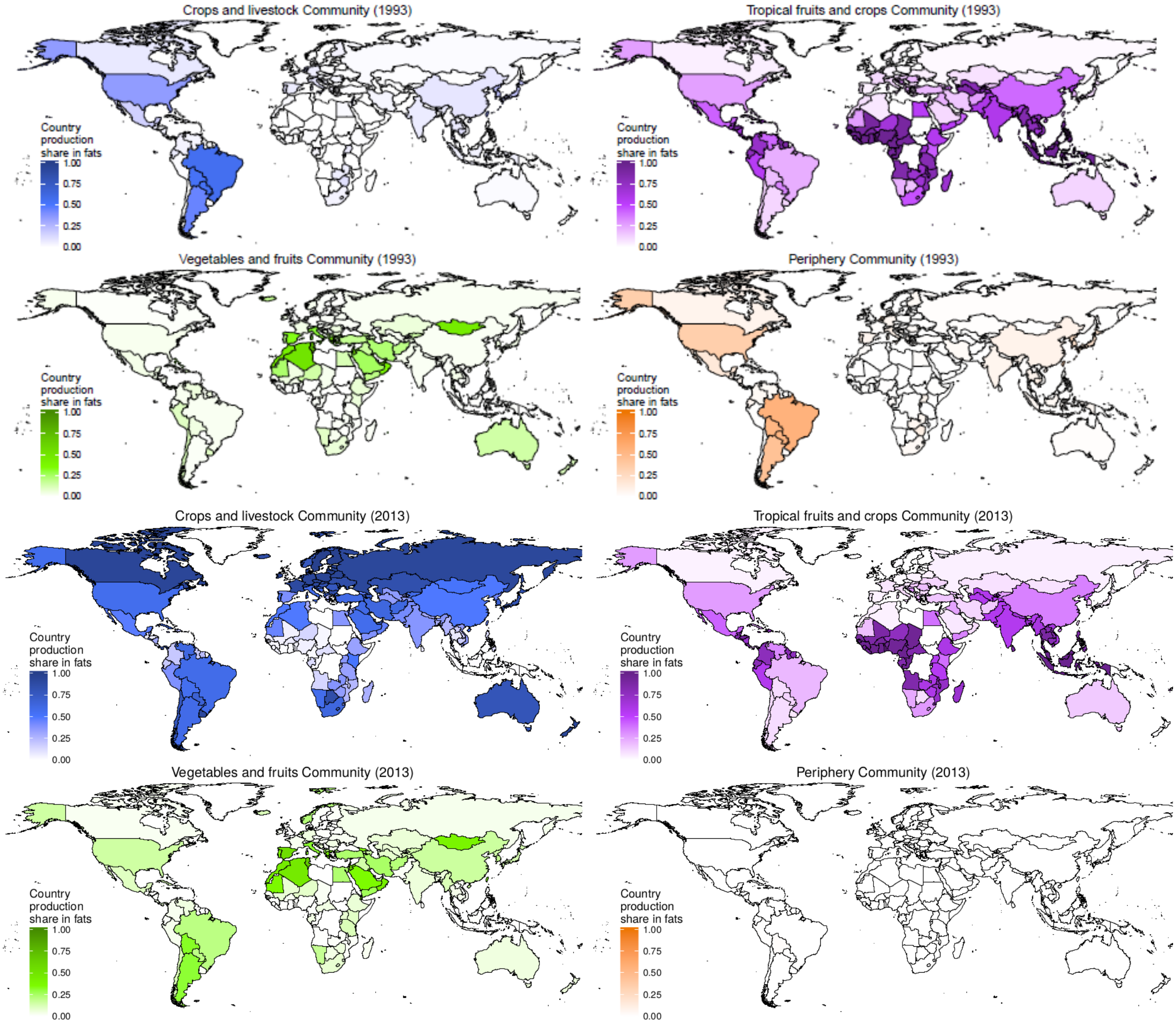

Figure SI.2: Production shares of countries in proteins in each community. 1993 and 2013. Colors represent communities as in the networks of Figure 1. Color intensity represents the share of a country's total production in the production of the community.

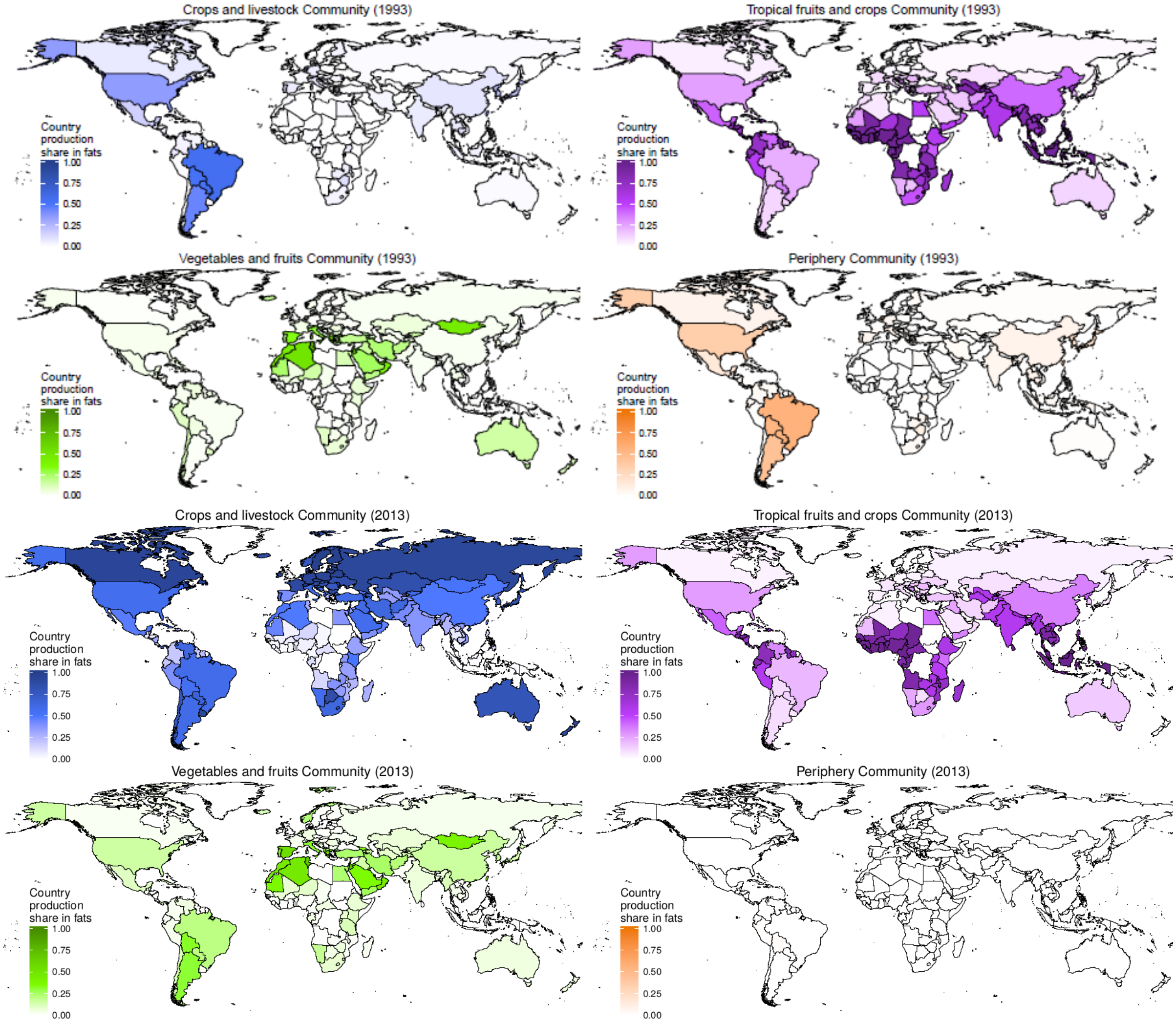

Figure SI.3: Production shares of countries in fats in each community. 1993 and 2013. Colors represent communities as in the networks of Figure 1. Color intensity represents the share of a country's total production in the production of the community.

Table SI.4: Variables used in the Logit estimations and sources

Name	Description	Source
Geographical distance	Geographical distance in km. between two countries	BACI-CEPII*
Difference in latitudes	Distance differences in countries' latitudes in absolute value. It proxies differences in climate and agro-ecological zones	BACI-CEPII*
Region	Dummy that indicates if countries belong to the same geographical region: East Asia & Pacific, Europe & Central Asia, Latin America & Caribbean, Middle East & North Africa, North America, South Asia, and Sub-Saharan Africa	WDI**
GDP per capita	Difference between the GDP per capita of a pair of countries in absolute value	Penn World Tables***
Agricultural total factor productivity	Differences between the agricultural total factor productivity index (base year 2005=100) of a pair of countries	ERS-USDA****

Notes: *`http://www.cepii.fr/CEPII/en/bdd_modele/presentation.asp?id=1`, **`https://databank.worldbank.org/source/world-development-indicators`, ***`https://www.rug.nl/ggdc/productivity/pwt/pwt-releases/pwt9.0`, ****`www.ers.usda.gov/data-products/international-agricultural-productivity`

Table SI.5: The effect of concentration, specialization, and capabilities on per capita food supply (in proteins). 1993 to 2013

Model	(1)	(2)	(3)	(4)	(5)	(6)	(7)
HH Index	-0.229***						
	(0.029)						
Entropy		0.046***					
		(0.007)					
Coherence			0.054***			0.048***	
			(0.002)			(0.002)	
Weighted coherence				1.541***			1.425***
				(0.040)			(0.037)
Fitness (ln)					0.069***	0.059***	0.058***
					(0.003)	(0.003)	(0.002)
Constant	0.757***	0.604***	-0.581***	0.463***	0.761***	-0.387***	0.522***
	(0.017)	(0.023)	(0.049)	(0.015)	(0.015)	(0.046)	(0.014)
Time dummies							
Observations	3,528	3,528	3,528	3,528	3,528	3,528	3,528
R-squared	0.039	0.033	0.199	0.310	0.170	0.305	0.413

Notes: The dependent variable is food supply in hundreds of grams of proteins per capita per day (average for each year). Robust standard errors are in parentheses. Significance level: *** p<0.01, ** p<0.05, * p<0.10.

Table SI.6: The effect of concentration, specialization, and capabilities on per capita food supply (in fats). 1993 to 2013

Model	(1)	(2)	(3)	(4)	(5)	(6)	(7)
HH Index	0.227***						
	(0.044)						
Entropy		-0.036***					
		(0.010)					
Coherence			0.070***			0.062***	
			(0.003)			(0.003)	
Weighted coherence				1.952***			1.737***
				(0.099)			(0.096)
Fitness (ln)					0.089***	0.075***	0.077***
					(0.005)	(0.005)	(0.005)
Constant	0.693***	0.819***	-0.948***	0.409***	0.794***	-0.700***	0.498***
	(0.027)	(0.036)	(0.085)	(0.030)	(0.025)	(0.083)	(0.029)
Time dummies							
Observations	3,528	3,528	3,528	3,528	3,528	3,528	3,528
R-squared	0.023	0.020	0.123	0.114	0.102	0.184	0.179

Notes: The dependent variable is food supply in hundreds of grams of fats per capita per day (average for each year). Robust standard errors are in parentheses. Significance level: *** p<0.01, ** p<0.05, * p<0.10.