Power law scaling and country-level centralization of global agricultural production and trade

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Abstract
Global food production and international trade are rapidly expanding and drive increasing agricultural globalization and specialization. Following production patterns, network properties and added-value chains, exportable surpluses of countries can offset food and feed deficits in other countries. However, production and trade patterns are barely addressed in the scientific literature as two interactive components of global agriculture. Integrated analysis of the temporal dynamics and distribution patterns of production and trade among countries can help addressing future food security challenges in view of ongoing trends. Here, we analyse the interdependent patterns of global agricultural production and trade from 1986 to 2016. We classify total production and trade mass into six product categories—cereals, oilcrops, meat, fruits and vegetables, coffee and cocoa. We estimate reexports in global trade by assessing mass balances of production, imports and exports per country. We show that global trade and reexports increase exponentially faster than production and that production and trade are highly centralized among a small number of countries. For most agricultural categories, the centralization of flows has increased in time for production and net exports, and has decreased for net imports and reexports. Accordingly, a growing number of deficient countries are sustained by a decreasing number of top-producing countries. In parallel, reexport routes are increasingly dominated by long-industrialized countries besides the increase in time in the number of reexporting countries. We discuss the interdependencies between global agricultural production and trade patterns. We highlight the drivers and implications of the observed trends for food security challenges.

1. Introduction
Global food production and international trade are key components of food security (Pinstrup-Andersen 2009) and are expanding rapidly. On global average, food production per unit land has increased threefold since 1961 (FAOSTAT) and, today, one fourth of global calories are subject to international trade (D’Odorico et al 2014). The share of traded agricultural production has increased in time from 9% in 1986 to 14% in 2018 (FAOSTAT), and trade is largely concentrated on 15 products that contribute 80% of all traded food calories (D’Odorico et al 2014).

From a production perspective, the share of global cultivated land corresponding to international exports of countries currently exceeds 20% (Qiang et al 2020) and the contribution of the livestock sector is substantial. More than 50% of all produced crop proteins are used for feed (Cassidy et al 2013), and about one forth of this feed is traded among countries (Billen et al 2014) with impacts on livestock distribution patterns, global nutrients cycling and sustainability (Naylor et al 2005). Oilcrops and cereals are by far the most traded crops with a nearly tenfold increase since the mid-20th century (Lassaletta et al 2014). Meat is also increasingly traded internationally, with a fourfold increase from 12 to 48 million tonnes between 1986 and 2013 (7% and 14% of meat production respectively (FAOSTAT)). In the coming decades, global food production and trade,
including feed, are expected to further increase under growing global population, persisting gaps between regional agricultural production and demand, economies of scale, and increasing affluence worldwide (OECD/FAO 2020).

Although increases in global agricultural production and trade have driven substantial improvements in food security over the last decades, a large share of the global population still has inadequate access to food (WHO 2019). The patterns of trade and food security are analysed in the scientific literature on the basis of net food import and export balances of countries (Porkka et al 2013, Pradhan et al 2014) and through network analysis (Puma et al 2015, Carr et al 2016). Network analysis has often built on the virtual resource flow equivalent of physical trade (Carr et al 2013, D’Odorico et al 2014) in an effort to connect domestic food production and consumption to international resource use. Growing interest is being given in addressing the topology of the international network (Konar et al 2011) as well as key network properties and dynamics such as node centrality, trade paths (Carr et al 2013) and invariance of underlying network structures (Dupas et al 2019). For instance, global food trade is reported to exhibit increasing connectivity and scaling properties (Dalin et al 2012, Konar et al 2018, Dupas et al 2019), high probability of community structures and regional clustering (Konar et al 2011, Torreggiani et al 2018), as well as a general structure that is dominated by a small number of countries (Ercey-Ravasz et al 2012, Dupas et al 2019).

However, when analysing trade patterns, the network literature implicitly considers that production is external to the network, and typically leaves it out. Symmetrically, trade is typically left-out from analysis on agricultural production patterns, which put emphasis on productivity factors and production means (Harchaoui and Chatzimpiros 2019) regardless of potential interdependencies between specialization and trade (Godfray et al 2010, Neumann et al 2010, Tilman et al 2011). An integrated analysis of production and trade both in terms of temporal dynamics and distribution among countries lacks in the scientific literature. Such analysis can help understanding the general structure and evolution of the global food system from a physical perspective, and help linking past trends to future food security challenges.

Here, we analyse the interdependent patterns of global agricultural production and trade over time—from 1986 to 2016—and across countries. We group total agricultural production and trade mass into six product categories—cereals, oilcrops, meat, fruits and vegetables, and, for comparison, coffee and cocoa that are comfort products. We distinguish net exports, net imports and reexports per product category as three meaningful measurements of global agricultural surpluses, deficits and added-value chains respectively. We show that net trade and reexports scale as power law functions of agricultural production, and that both production and trade are highly—and in many cases increasingly—centralized among a small number of countries. We provide a classification of top-producing and top-trading countries in terms of agricultural deficits and surpluses and overall centralization of production and trade flows. We discuss the drivers of the observed patterns and point out that the densification of agricultural trade networks is largely due to the intensification of reexports and added-value chains rather than to increased diversity of interconnections and stability.

2. Material and methods

2.1. Data

Data on production and trade mass per country are extracted from FAOSTAT—the statistical division of the Food and Agricultural Organisation of the United Nations (FAOSTAT) - over the period from 1986 to 2016 (1986-2013 for meat). We group total agricultural production and trade into six product categories: ‘Cereals’, ‘Oilcrops’, ‘Meat’, ‘Fruits & vegetables’, ‘Cocoa’ and ‘Coffee’. Production and trade mass aggregates primary and secondary products per product category. The conversion of secondary products into their primary-equivalent mass is done by multiplying the mass of secondary products by conversion factors provided by FAOSTAT (FAO 2000). The list of products per agricultural category and the conversion factors are shown in supplementary tables S1–S11 (available online at stacks.iop.org/ERL/17/034022/mmedia). For example, chocolate products (item code 666) are composed at 20% of cocoa beans and 80% of other materials. The cocoa-equivalent mass of chocolate is calculated by multiplying the chocolate mass by 20%.

Production mass per country is extracted from the ‘Production’ module of FAOSTAT. For meat, we use the ‘Indigenous meat’ series per country which includes the meat equivalent of exported live animals and excludes the meat equivalent of imported live animals. Accordingly, ‘indigenous meat’ per country accounts for animals raised in a country including those exported.

Trade mass per country is extracted from the FAOSTAT ‘Trade’ module. Trade data include primary and secondary products. As for production, secondary products are converted into their primary-equivalent mass using conversion factors (supplementary tables S1–S11). For ‘Meat’, trade includes raw meat and live animals (supplementary table S7). ‘Trade of live animals in FAOSTAT is reported in numbers of heads instead of kg. We aggregate meat and live animals into meat trade from country $i$ to $j$ by converting the number of heads to tonnes (1000 kg)
using carcass weight reported in FAOSTAT (2019) per animal category $p$, exporting country $i$ and year $k$ (section S2 in supplementary). If country-specific data are unavailable, we use global average carcass weight for the concerned animal category and year.

Total trade mass per agricultural category and country is the sum of exported and imported products. From total trade, we derive net trade as follows: $Net_{\text{trade}} = Export - Import$. A country is a net exporter for a given agricultural category if net trade is positive and a net importer if negative. Global net imports and net exports are respectively the sum of net imports and net exports of all countries.

Reexports per country and agricultural category ($Re_{\text{mass}}$) are calculated using the “perfect mixing” assumption:

$$Re_{\text{mass}} = s_{\text{out}} \times \frac{s_{\text{in}}}{s_{\text{in}} + P}$$

where $s_{\text{out}}$ is the exported mass, $s_{\text{in}}$ is the imported mass and $P$ is the production mass of the country. If a country has no production, the reexported mass equals the exported mass. Global reexported mass is the sum of reexports of countries.

2.2. Distributions and statistics
Production and trade data distributions are calculated with the power law package (Alstott et al 2014) in Python (2.7.15) for plotting and fitting the complementary cumulative density function (CCDF) called $P(X > x)$ where $x$ is the data variable, i.e. the mass produced or traded per country. The CCDF is tested with five model functions, i.e. power law, exponential, lognormal, Gamma and stretched exponential. The Kolmogorov–Smirnov (K-S) test is used to assess the quality of the fit, or distance $D_\alpha$, between the models and the data. supplementary figure S1 shows the $D_\alpha$ for the power law and stretched exponential functions, which are the two models that fit the best with the data.

The tails of distributions include outlier countries in global production, net trade (net imports and net exports) and reexports per product category. We define the tails of distributions by using a cutoff threshold at 60% of global production, trade or reexport mass. The choice of 60% allows including the majority of global production and trade mass in the tails of the distributions. Countries that make up 60% of global production, trade or reexport mass are respectively top-producers, top-traders or top-reexporters. The number of product categories for which a country is a top-producer or a top-reexporter defines the country’s production and reexport score respectively. Country scores range from 1 (a single category for which a country is a top-producer or top-reexporter) to 6 (all product categories).

3. Results

3.1. Global production and trade intensification
Figure 1 shows that global agricultural exports (figure 1(A)) and reexports (figure 1(B)) are power law functions of agricultural production (i.e. $Export = (production)^\alpha$ and $reexport = (production)^\beta$) for all product categories over the period 1986-2016. The black dashed line on figure 1 ($\alpha = 1$) corresponds to $x = y$, i.e. production equal to exports and production equal to reexports.

The exponent $\alpha$ of the power law is greater than 1 for all product categories (inset table of figure 1), meaning that the exported and reexported masses increase exponentially faster than the production mass. The exponential growth is stronger for reexports than exports for all product categories but oilcrops. The growth rate in exports is the highest for meat, and the lowest for oilcrops and fruits and vegetables. For cocoa and coffee, the global traded mass today exceeds the production mass (figure 1(A)). This implies that, on average, total production is traded more than once. Already in 1986, the exported mass of coffee was 4.2 million tons against global production of 5.2 million tons, and for cocoa 2.4 million tons against 2 million tons respectively. The exported mass is still lower than production for all other agricultural categories.

Growth in reexports is more heterogeneous among categories and is the highest for coffee, followed by meat, and the lowest for oilcrops and fruits and vegetables. Reexports are increasing faster than exports but are all still lower than production in all cases. Nonetheless, in 2016, the reexported mass for cocoa approaches total production (diagonal line for $\alpha = 1$), meaning that all cocoa production is on average exported (through reexports) almost twice.

3.2. Heterogeneous distribution of agricultural production and trade
Production and trade are unevenly distributed among countries and display distinct trends over time. However, they both fit with a stretched exponential distribution of type $P(X > x) = \exp(-(\lambda x)^\beta)$ for all product categories (figure 2), where $\lambda$ is the decay rate of the function derived from the statistical data (figure S3). The stretched exponential fit is validated by the K-S test for production (supplementary figure S1) and trade (supplementary figure S2). The $\beta$ value of the stretched exponential distribution is shown for production and trade in the inset figure 2. The standard deviation of the $\beta$ values is given in supplementary tables S14 and S15.

The $\beta$ value is characteristic of the distribution and, in particular, of its tail. The tails of distributions in figure 2 contain top-trading and top-producing
countries. The lower the $\beta$ value, the more the distribution is stretched and the tail is fat, meaning that the distribution approaches a scale-free function i.e. a power law as opposed to an exponential distribution where $\beta$ equals 1. The lower the $\beta$ values in stretched exponential distributions the higher the heterogeneity in production and trade among countries. The vertical lines in figure 2 designates the threshold of 60% in total production (in blue) and trade mass (in black).

Cereals, meat and fruits and vegetables display the highest $\beta$ values, implying that the production and trade of these products are more homogeneous among countries compared to cocoa, oilcrops and coffee (lowest $\beta$ values). These three latter categories display similar probability distributions between production and trade. In contrast, for cereals, meat and fruits and vegetables high production masses are an order of magnitude above high trade masses, meaning that top-producers are significantly bigger than top-traders. Constant $\beta$ values imply no major distribution change in time. No distribution change is observed for production of meat, oilcrops and fruits and vegetables and for trade of oilcrops and coffee. For these three latter categories, production in top-producing countries is almost exclusively destined to trade and is extremely centralized, with only between 2 and 7 countries accounting for 60% of global production and net exports over the study period. Simultaneously, an increasing—though limited—number of countries is involved in reexport routes (figure 3(D)). Increase in reexport routes drives part of the increase in the number of top net-importing countries (figure 3(C)).
Figure 2. Worldwide distribution of food production (in blue) and trade (in black) per agricultural product category from 1986 to 2016 (1986-2013 for meat) using a 5-year time-step (time in colour grid). All distributions fit with a stretched exponential function (heavy-tailed distribution) of type $P(X > x) = \exp\left((-\lambda x)^\beta\right)$. The change in time of the $\beta$ parameter is shown in the inset figures. The tails of distributions are distinguished by a cut-off threshold set at 60% of mass. This cut-off threshold is indicated by the vertical lines (blue for production and black for trade) following the same colour grid as the distributions.

3.3. Ranking of countries in global agricultural production and trade

Countries that centralize 60% of global production and trade in 2014/2016 (2011/2013 for meat production) are identified and ranked in decreasing order in figure 4. The grey zone indicates the threshold of 60% in production mass. Depending on the product, top-producing and top-trading countries rank differently. Net importing countries largely rely on trade for internal consumption and are indicated in red. Net exporting countries have a net contribution in global food availability and are indicated in green. The size of the dot indicates the share of net imports and net exports in total trade of countries. Countries with a net trade ratio close to 1 have high food surpluses when green and high food deficits when red. Countries with high food surpluses have high contribution in global food availability and high economic dependency on trade partners. Inversely, countries with a net trade ratio close to 0 have little net contribution.
in global food availability when green and little net dependence when red. High trade-ranking countries with low share of net imports or high share of net exports are commercial hubs.

For cereals and oilcrops, most top-trading countries are also top-producers with large surpluses (upper-right corner of the panels), whereas for fruits and vegetables, meat, cocoa and coffee, many top-trading countries have little or zero production. For the two former categories, global trade is largely dominated by top-producers, whereas for the four latter categories, global trade is largely dominated by reexporting countries involved in added-value chains. Oilcrops is the only product category for which the same five countries are both top-producers and top-traders. For cocoa, the activity of deficient top-trading countries clearly builds on reexports with the exception of the USA where trade is mainly driven by domestic demand. For coffee, half of the countries that are top-trading and net importing are top-reexporters (Germany, Italy and Belgium) and the other half are top net importers (USA, Japan, Pakistan and France). For meat and fruits and vegetables, top-producing and top-trading countries are little correlated with net imports and net exports. For instance, despite being among top-producers, India and the USA are deficient in fruits and vegetables, and Russia and Mexico in meat. This contrasts with the case of the other four product categories where top-producers are generally net exporters and small producers are net importers. China, due to its huge domestic food and feed requirements is an exception, and is deficient even for meat, cereals and oilcrops despite ranking first, second and fourth in global production respectively.

Figure 5 shows the production and reexport scores of countries in 1992/94 and 2014/16. The country score is defined as the number of product categories for which a country is a top-producer or a top-reexporter i.e. contributes in 60% of global production and reexports respectively. The production and reexport scores are indicators of the accumulation of global agricultural flows within single countries. Over the period, the number of top-producing countries has decreased from 22 to 13 and the number of top-reexporting countries has increased from 9 to 15. The production score has increased for 11 countries (United States, France, Canada, Malaysia, Poland, Italy, Brazil, China, Mexico, Denmark and Romania) and has decreased for two countries (United Kingdom and Singapore). Germany is the only country to centralize reexports for

![Figure 3](chart.png)
Figure 4. Country ranking in global production and trade (sum of exports and imports per country) per agricultural category in 2016 (2013 for meat). The ranked countries centralize 60% of global production and trade for each agricultural category. Countries are ranked in a decreasing order of production and trade mass. The grey zone indicates the threshold of 60% of global production per agricultural category. “Other ranking” indicates minor production and trade mass. Countries in red are net importers and countries in green are net exporters. The size of the dot is proportional to the ratio of net trade (net imports or net exports) to total trade per country ($\propto \frac{\text{NetImport}}{\text{Export}}$ or $\propto \frac{\text{NetExport}}{\text{Import}}$).

all six product categories in both dates, joined by the Netherlands in 2014/16. Brazil, is the only country with a production score of five in both dates followed by the USA with a production score of four and China with a production score of three today.

The number of countries that are both top-producers and top-reexporters for a given product
category is very low but the number of products in common has increased in time. In 1992/94, only three countries display this characteristic, i.e. France for meat and cereals, the USA for cereals and fruits & vegetables, and Germany for meat. In 2014/16, the USA is a top-producer and top-reexporter for four product categories (cereals, meat, oilcrops, and fruits and vegetables), France for meat and cereals, Germany for meat and Brazil for cereals. The countries that are both top-producers and top-reexporters accumulate geopolitical power in global food supply.

4. Discussion and conclusion

We show that trade and reexports of all product categories are power law functions of production with an exponent higher than 1, and that all production and trade distributions throughout the study period fit with stretched exponential functions. This type of functions indicates large discrepancies in the production and trade strengths of countries, and are common features in specialized markets (Brakman and Van Marrewijk 2009, Emran and Shilpi 2012). For global agriculture, centralization in production is generally milder that centralization in trade, with the exception of coffee and cocoa for which the geography of production is largely restrained within specific climates.

Compared to other industrial sectors for which specialization is merely driven by economic and transportation factors (Bills et al 2015), specialization in agricultural production is also largely framed by biogeophysical constraints (Van Velthuizen 2007, Licker et al 2010). Following comparative advantages in production, countries specialize within continents, and regions within countries (Bowler 1986, Carter and Lohmar 2002, Qin and Zhang 2016, Gingrich et al 2018), leading to a nested disconnection of production from local demand and, thereby, to maximization of exports (Bowles et al 2005, Koh et al 2013, Le Noë et al 2017). Trade can thus allow reducing production costs through economies of scale and increased land productivity, and also lead to resource savings, as this has been reported for global freshwater besides the uncertainty in the estimated saved volume (Chapagain et al 2006, Fader et al 2011, Liu et al 2019). However, from a point of view of local resources and global nutrient cycling, specialization and trade are also reported to have adverse impacts. For instance in China, massive soybean imports from abroad have indirectly entailed internal water and fertilizers use intensification following domestic cropland reallocation patterns (Sun et al 2018, Ren et al 2021). At the global scale, massive, reliable and cheap trade of cash crops in particular for feed have resulted in wasteful nutrients management, inducing massive environmental spillover and degradation (Carter and Lohmar 2002, Wilcox 2004, Naylor et al 2005, Song et al 2009, Billen et al 2014, Le Noë et al 2016).
Countries that are top-producers in many agricultural categories at a time are rare. In contrast, through trade, countries can score high in exports even for products they do not produce. Indeed, the probability for a country to centralize agricultural flows is higher when the flow is imported than when it is produced within the country. A reason for this is that, once the trade infrastructures are in place, they can enable countries to capture flows of different goods, make profits out of reexports and gain geopolitical power. Over the last decades, trade has entailed the decrease in the number of net exporting countries and the increase in the number of net importing countries, as well as it has allowed food processing stages and added-value chains to disperse across a growing number of partner countries following vertical integration as typically observed for the high-tech, textile and automobile sectors (Hummels et al 1998, Amador and Cabral 2009, Ingrstrup and Christensen 2017). Vertical integration intensifies international business cycles synchronisation among intermediate products and services (Hummels et al 2001, Arkolakis and Ramanarayanan 2009) based on reexports and can reduce food prices.

For agricultural systems, vertical integration includes transformation of raw products into final commodities within a given product category and, also, transformations across product categories. For instance, the transformation of cereals into flour, cocoa beans into chocolate, or livestock into meat occurs without change in the concerned product category. International trade associated with these transformations is captured by reexports. In particular for meat, the rapid increase in reexports highlights the business momentum in vertical integration of production stages across transnational livestock supply systems (Saunders and Barber 2008, Harchaoui and Chatzimpiros 2017). In contrast, product transformation across categories, such as feed conversion into livestock, is not captured by reexports. In particular, country-level specialization in the import of feed as a means to produce and export meat is an ongoing and dynamical process and equates to large-scale decoupling of fundamental agricultural system components that used to be tightly integrated locally (Wilcox 2004, Naylor et al 2005, Chatzimpiros and Barles 2013, Billen et al 2021). Accordingly, capturing the intricacy of agricultural flows within the global trade network goes beyond accounting for reexports, and requires integrating multiplex network analysis considering product flows across categories (Kivela et al 2014). Coupling trade analysis with intercountry input-output (ICIO) tables developed in economic literature can allow measuring the involvement and economic effects of countries and sectors in added-value chains (Jones et al 2016). So far, multi-layer network analysis has focused on identifying community structures and densely clustered trading groups (Torreggiani et al 2018). An integration in multi-layer analysis of cross-category food processing keeping track of both mass and monetary units can be insightful for assessing global value chains and complex food transformation structures.

Growth in international trade reflects the globalization of food markets and is associated with lower food prices and improved access to affordable food (Diaz-Bonilla and Ron 2010). Increased food availability at the national scale can promote food security at the scale of households and individuals depending on domestic distribution networks. However, globalization of markets may also induce systemic risks on global food price volatility with adverse impacts on food affordability in specific population groups and periods, in particular in poor countries. Accordingly, trade stability is essential to food security, and today mainly relies on rich countries. Indeed, capturing agricultural flows within a context of exponential growth in trade implies rapidly growing infrastructural requirements (Qin and Zhang 2016, Forero et al 2021) involving heavy investments that rich or rapidly developing countries can more easily afford. In general, the countries with the highest reexport scores are the longest-industrialized and these countries centralize more reexports today than in the early 90s. Developing countries are still little present in reexports and added-value chains. Only four developing countries (Malaysia, Brazil, China, Mexico) are among top-reexporters in 2014/2016, and they only centralize up to two product categories. The quantification of added-value chains is not a trivial task (Koopman et al 2014), and despite several approaches, food trade analysis has put little emphasis on the economic aspect of global production and trade systems.

Although trade helps closing gaps between food production and demand of countries and also lowers food prices, it can also raise geopolitical concerns requiring international cooperation for safeguarding food security (Margulis 2014, Sartori and Schiavo 2015). Trade agreements such as the International Grains Agreement in 1995 and the consolidation of interest groups such as the Cairns group (Winders 2016) have greatly influenced agribusiness governance and stimulated the internationalization of food flows with positive impacts on food security over the last three decades. In addition to that, international policy coordination is also crucial for harmonizing regulatory standards, both for business and environmental governance, in trade agreements (Rodrik 2018).

The analysis of production and trade patterns at the global scale allows putting in perspective trends and narratives at more local scales (DuPuis and Goodman 2005). For instance, local food movements advocating for a reduction in food miles and increased self-sufficiency locally are fast emerging in many countries (Chaifetz and Jagger 2014) but, are dwarfed by the ongoing globalization of supply chains.
that our analysis brings to light. Triggered by economic and geopolitical factors rather than by merely biophysical constraints to ‘localness’ (Kinnunen et al 2020), production and trade patterns largely exceed local decision making and reflect power transfer from local actors to global markets (De Roest et al 2018). From a network perspective, ‘localness’ versus ‘globalness’ in food supply have strong implications in food security (Dolfing et al 2019). Food security relies not only on the distribution of net exports, but also on the stability of the agricultural network. Strong interconnections and high diversity in food origins among regions and countries are reported to increase network stability and resilience (Sartori and Schneider 2015, Seekell et al 2017, Tu et al 2019). However, as we show, an increasing share in trade activity comes from reexports, meaning that network connectivity is increasingly due to added-value chains rather than to the multiplication of trade paths between food production and consumption locations. To improve resilience, connectivity must allow replacing disrupted connections by alternative paths. In the economic literature, increased connectivity in highly efficient and specialized systems is associated with low resilience to shocks (Kharrazi et al 2017). The centralization of global agricultural production and trade in a decreasing number of countries can improve food security through lower prices, but can also increase global food supply vulnerability to certain shocks such as climate change or price volatility in the key resources required to run the global food system.

Data availability statement

The data that support the findings of this study are openly available at the following URL/DOI: www.fao.org/faostat/en/#home.

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