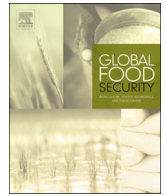


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Global Food Security

journal homepage: www.elsevier.com/locate/gfs

Global changes in crop diversity: Trade rather than production enriches supply

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ARTICLE INFO

Keywords:

Agriculture
Agrobiodiversity
Food
Homogenization
Globalization
Trade

ABSTRACT

Over the past decades, the choices of farmers and societies regarding what to grow and eat are being reshaped drastically, as suggested by the diversification of crop supply within countries and its simultaneous homogenization across them. Such a trend could be supported by parallel shifts in production (i.e. diversification within countries, homogenization across countries) or by the growing redistribution introduced by international trade which can even mask reductions in production diversity (i.e. specialization) within countries. Here we assessed the spatial and temporal trends in crop production, exports, imports, and supply diversity based on data from the Food and Agriculture Organization (FAO) for 152 countries and 49 crops from 1961 to 2013. Within countries, the diversity of crop supply increased at a faster rate than the diversity of production, which grew only slightly. Both were surpassed by the diversification of trade, which, within countries, involved a much faster diversity growth of imports compared to exports. Across countries, crop production homogenized at slower rates than crop supply, indicating that crop trade was important for explaining this decoupling. Mirroring country-based analyses, a crop-perspective indicates that crops are becoming more geographically ubiquitous for all the components of the food balance. However, this pattern had important exceptions, like oil palm which has increased its production concentrating in a few specialized countries. We evaluate our results in the context of the multiple social-ecological trade-offs related to international trade and the resilience of the global food system.

1. Introduction

Since the origin of agriculture, the choice of farmers and societies regarding what crops to grow and consume has been shaped by the complex interplay of cultural and natural factors, including traditions, technology, land access, and environmental constraints, among many others (Gepts et al., 2012; Harlan, 1992; Hunter et al., 2017; Mazoyer and Rodart, 2007). Nowadays, far from the times in which people mostly ate what they grew in their farms, the process of urbanization first, and the massive expansion of global trade, later on, have widened the gap between the composition of crops in farms and tables (Fader et al., 2013). Thus, one of the most profound changes in the global food

system has been the sustained spatial and trophic decoupling between crop production and food consumption (Fader et al., 2013). Today, more than half of the world population lives in cities and international trade conveys almost a fourth of the total global crop production to consumers that live out of the source country (D'Odorico et al., 2014). An additional process leading to farm-to-table decoupling is the growing share of grain-fed animal products in our diet (Bonhommeau et al., 2013). Today, land dedicated to sustaining livestock represents the largest global land use, explaining nearly a quarter of the terrestrial surface, while an additional 12% is explained by croplands (Foley et al., 2011). Moreover, about half of the production in croplands is currently used as feed (Herrero et al., 2015). As a result of this livestock demand,

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<https://doi.org/10.1016/j.gfs.2020.100385>

Received 4 February 2020; Received in revised form 16 May 2020; Accepted 17 May 2020

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the production of grains that rarely reach our tables directly, such as soybean and maize, has expanded. Overall, these drivers have determined important changes in the diversity of crops that humanity produces and consumes throughout the planet (Hunter et al., 2017; Zimmerer et al., 2019).

One of the most remarkable changes in the current global food system is the diversification of crop supply within countries, which has been accompanied by its global homogenization across countries (Khouri et al., 2014). These global trends in the diversity of crop supply can be the result of the combination of many diversification and/or specialization trends in crop production and trade. For example, paralleling what has been described for supply, they can be the result of the diversification of production within-countries and its homogenization across-countries or may be the result of an increase in the magnitude and diversity of trade, with production diversity remaining unchanged or even decreasing. Available studies suggest that both mechanisms coexist, indicating that supply diversification in low-income countries has been supported by a parallel diversification of domestic production it has relayed mostly on trade in high-income countries (Remans et al., 2014). Trade can not only affect the diversity of crop supply but the diversity of crop production as well, as suggested by Nelson et al. (2016), who highlighted that exporting countries tend to concentrate their production on those crops for which they are most cost-effective or efficient. None of these previous studies has simultaneously assessed the diversity of crop production, supply and trade, and the degree to which exports and imports diversification/specialization trends have led to divergent diversity changes in production versus consumption. Shedding light on these trends is important since global trade is currently in the spotlight due to its many social-ecological implications (D'Odorico et al., 2019; Meyfroidt et al., 2013; Wood et al., 2018). Hence, a comprehensive assessment of the trends in crop production, trade and supply diversity across and within countries, might contribute to obtaining a better picture of the sustainability and resilience of the global food system (Renard and Tilman, 2019; Seekell et al., 2017).

Recently, many studies have assessed the diversity of crop production at national levels, suggesting an overall increase over the past 50, yet periods and regions with increases, decreases and no-change have coexisted (Aizen et al., 2019; Martin et al., 2019; Nelson et al., 2016). Across countries production, like supply, has shown a homogenization trend (Khouri et al., 2014; Martin et al., 2019). Homogenization, one of the main consequences of globalization (Pieterse, 2015) and a key dimension of the Anthropocene (i.e. biotic homogenization, Vellend et al., 2017; Zalasiewicz et al., 2017), appears to be taking place both in tables and farms. Although Martin et al. (2019) suggest that the magnitude of homogenization for crop production is lower than for supply, their conclusions are not based on a quantitative assessment. Moreover, a comparison between trends in crop production diversity and supply diversity is complicated by the discrepancies in the diversity indicators, time periods, crop groupings, and analytical steps that are typically used.

A comprehensive assessment of the global trends in crop diversity requires exploring the temporal shifts in the geographical distribution of crops both at the production and supply ends. Concerning supply diversity, Khouri et al. (2014), suggest that several oil crops (e.g. oil palm, rape, soybean) were among those with the highest geographical spread gains (i.e. the number of countries where they are used). On the other hand, several grain staples in the Global South, such as millets and sorghum were among the major losers (Khouri et al., 2014). Surprisingly, although the changes in the area, yield, and production of many crops have been intensively described (e.g. Alston et al., 2010; Ramankutty et al. 2018), temporal changes in their geographical distribution have been scarcely explored. A similar knowledge gap exists for the role of crop trade explaining the geographical mismatches between production and supply diversity trends. Globally, the choice of which crops to grow and where to do it are increasingly affected by

trade and in turn shape some of the most important environmental footprints of humanity including those on land cover changes, water, and nutrient use and cycling, and the greenhouse gases emissions associated to production and transport (Davis et al., 2017; Jobbágy and Sala, 2014; Dalin and Rodríguez-Iturbe, 2016). Hence, a better understanding of the geographical distribution of crops, and their temporal changes, might contribute to a more efficient global allocation, particularly in the context of an increasingly vulnerable global food system (Cottrell et al., 2019).

Here, we describe the global spatial and temporal trends over the past 50 years (1961–2013) for the diversity of crop production, trade, and supply. We analyzed data from the Food and Agriculture Organization of the United Nations (FAOSTAT, 2019) for 152 countries and 49 crops. The questions that guided our analysis were: 1 - To what extent the increase in crop supply diversity within countries was supported by (i) a parallel diversification trend in production or (ii) an increasing diversification of the international exchange of crop products? 2 - How is the magnitude of crop trade affecting within-country production and supply diversity? 3 - To what extent has crop production paralleled the homogenization observed for crop supply? 4 - What are the most prominent temporal changes in the geographical distribution of crops from the perspective of their production, trade, and supply?

2. Methods

2.1. Study design and data sources

For describing the global spatial and temporal patterns and trends of the diversity of crop production, trade, and supply we used national data from FAOSTAT (FAOSTAT, 2019). We followed the same approach as in Khouri et al. (2014), considering the same countries and crop groups. We selected 152 countries, which comprise 98% of the world's population across the study period. Since some countries changed their political divisions during the study period (e.g. Russia, Ukraine, Kazakhstan), they were aggregated into their former block (e.g. USSR). Crops that were reported as different items (e.g. maize, maize for forage, sweet corn) were grouped (e.g. maize), and less important crops in terms of edible energy (e.g. strawberries, blueberries) were included in aggregate classes (e.g. other fruits). The latter grouping seeks to reduce the bias in the estimates of crop richness that results from countries reporting crop information with different quality for minor crops, particularly for fruits and vegetables. Of the 52 items included in Khouri et al. (2014), we excluded beverages (alcoholic and fermented) and animal products, limiting our analysis to 49 items which are all crops. These items represented > 96% of the total global supply of edible energy from crops in 2013.

We converted mass values to edible energy (i.e. kilocalories) using the Food Balance Sheets and the conversion rates used by Food and Agriculture Organization (2001). For supply, we included both food and feed to characterize direct crop consumption plus indirect consumption through local livestock. Crops for industrial uses were excluded. Since countries largely differ in their area and population, we estimated the proportion of each crop by normalizing the edible energy of each component of the food balance according to which of these determinants affects them to a greater extent. Thus, the edible energy of production and exports were normalized by harvested area (per area) while supply and imports were normalized by population (per capita). Also, for crop production, we assessed the changes in its diversity in terms of the amount of harvested area and production value (i.e. international constant US dollars). For this, we used other databases of FAOSTAT, namely the Crop production and the Value of Agricultural Production. Based on the normalized data on national crop production, trade, and supply we calculated different diversity indicators for describing the temporal trends of crop diversity at two levels: within-country (i.e. alpha diversity) and across-country (i.e. beta diversity,

McGill et al., 2015).

2.2. Calculation of indicators and statistical analysis

To answer our first question, we analyzed the spatial and temporal trends in crop diversity within-countries (alpha diversity as in McGill et al., 2015) and across-countries (beta diversity as in McGill et al., 2015). For assessing within-country crop diversity, and its two main components, which are richness (total number of crops) and evenness (degree of equity in the proportions of all crops), we used common diversity indices using edible energy as the currency to calculate proportions. We calculated richness (S) as the number of crops for each country and year. Crop diversity was characterized by the Shannon-Wiener index (SW) ($H' = -\sum_{i=1}^S p_i \ln(p_i)$), where p_i is the proportion of the total edible energy of a given country and year accounted by crop i of a total of S crops. In our dataset, this index ranges between 1 and 6, and higher values indicate a higher diversity, and therefore that a country has more crops and/or that their proportions are more evenly distributed. An alternative way of interpreting this index is through the effective number of crops ($e^{H'}$) that can be interpreted as the number of crops with the same proportion of edible energy that results in the observed H' (see Jost, 2006). Evenness was estimated as the Pielou index ($J = H'/\ln(S)$), which varies from 0 to 1, approaching 0 a single crop is fully dominant and the rest are present but have an insignificant share, and equaling 1 when all crops have an identical share. In addition to the previous analysis, for production, we also calculated the SW index (H') using two alternative currencies to edible energy for proportion calculations: harvested area and monetary value. Since diversity indices are unable to capture swaps in crop composition that keep proportions unchanged, we also calculated a crop composition turnover index (SI.2).

The temporal trends of within-country diversity, richness, and evenness were analyzed with generalized linear mixed-effects models (GLMM) with lme4 and MASS packages in R (Bates et al., 2014; Ripley et al., 2013). These models are extensions of linear models, commonly used when response variables do not have a normal distribution and when data is grouped, and therefore feasible of being modeled as a random effect. For the SW index, we used a Normal distribution, while for richness and evenness we used Poisson and Binomial distributions, respectively. In all cases, we used year as a fixed effect, and country as a random effect, with random slopes for year, to account for repeated measures over time. We analyzed the temporal trend in the three diversity indices for each country using Generalized Least Squares (GLS), using the same error distribution described above.

Our second question focused on how trade affects within-country crop production and supply diversity, was assessed considering traded fractions (exports/total production, imports/total supply). We analyzed the relationship of crop production diversity at the beginning (1961–2013) and end (2011–2013) of the study period with the ratio of exported to produced edible energy (0–1 range). We describe with more detail the trajectory of major food-exporting countries according to Suweis et al. (2015). Similarly, for supply diversity, we analyzed its relationship with the ratio of imported to supplied edible energy (0–1 range). In both cases, we analyzed temporal changes in the relationships with ANCOVA, with diversity (SW) being the response variable and the traded ratios and period (i.e. beginning and end) being, the continuous and categorical predictors, respectively.

The third question, regarding temporal changes across-countries and the degree of homogenization in crop production and supply, was assessed in two ways. The first was by comparing the composition of crops of production and supply of each country with the global average. By composition, we mean the identity and relative contribution of each crop. The comparison was made by calculating the Bray–Curtis distance (dissimilarity) between each country's crop production and supply composition to the global average for the beginning (1961–1963) and end (2011–2013) of the study period. As Houry et al. (2014), we

expressed the comparison in terms of similarity by subtracting dissimilarity from 1. Hence, an increase in the similarity in crop composition between a given country and the global average represents a reduction in across-country diversity, a surrogate for homogenization. The Bray–Curtis distances were calculated using the betadisper function in the R package vegan (Oksanen et al., 2010). To assess the temporal changes in the similarity of crop production and supply composition we applied ANCOVA, with similarity in supply as the response variable and production and period (i.e. beginning and end), as the continuous and categorical predictors, respectively. In the second approach, instead of comparing the composition of crops to the global average separately for production and supply, we combined them into a single analysis (see SI.3). Also, to complement these analyses, we calculated changes in the similarity of crop production and supply composition within the same country (SI.4) to assess their decoupling resulting from trade.

The fourth question, related to the geographical distribution of crop production, trade, and supply, was tackled using the same approach of within-country analyses associated with our first question. We analyzed changes in the geographical distribution of crops assessing their geographical spread (i.e. the number of countries in which it is present – equivalent to richness), geographical equity (i.e. the degree of uniformity in the proportion of all countries – equivalent to evenness and calculated in the same way), and geographical ubiquity (i.e. a measure of diversity that merges the previous two indicators using the SW index). A higher geographical ubiquity indicates that crops are produced, traded, or used in many countries and/or that their relative abundance is evenly distributed among them. To analyze the temporal change in these indicators we conducted two paired temporal comparisons using ANCOVA for each indicator. In all six analyses, the period (i.e. beginning and end) was the categorical predictor. In the first comparison, the geographical distribution (i.e. ubiquity, spread, and equity) of crop supply was the response variable, and the geographical distribution of crop production the continuous predictor. In the second, the geographical distribution (i.e. ubiquity, spread, and equity) of crop imports was the response variable and the geographical distribution of crop exports as the continuous predictor. Finally, we compared the temporal change in the geographical ubiquity of groups of crops regarding their production and supply. For this, we used linear modeling, with the SW index for each component as the response variable, and year as a continuous predictor.

3. Results

During the past 50 years, the diversity of crop production, trade, and supply within countries displayed contrasting trends. While the diversity of production remained almost unchanged, averaging an SW index of 2.5, the diversity of supply presented a slight increase, and the diversity of imports and exports displayed a very high growth (Fig. 1A). Remarkably, throughout the whole study period, the diversity of supply was always more diverse than production and trade, yet imports are close to approaching it in the present. Earlier on, in the 90s, the diversity of what countries imported approached and then exceeded the diversity of what they produced. Despite its fast growth, the diversity of what countries export was always lower than what they import, indicating that as global trade expands, sources remain more specialized than sinks, with this gap growing slightly (Fig. 1A). In the case of production, diversity was higher when it was characterized by its share of monetary value rather than by its share of or edible energy (as presented above) or by the share of harvested area. Yet, “areal diversity” is showing the greatest increases with time (Figure S11).

The changes described above were explained by raises in crop richness under relatively constant crop evenness (Fig. 1B and 1. C). Crop richness within countries averaged 23.3 and 26.4 for production at the beginning and end of the study period, respectively, whereas for exports and imports it increased from 14.3 to 27.4 and 22 to 37.5, respectively. Evenness, instead, remained stable at 0.55 and 0.5 for

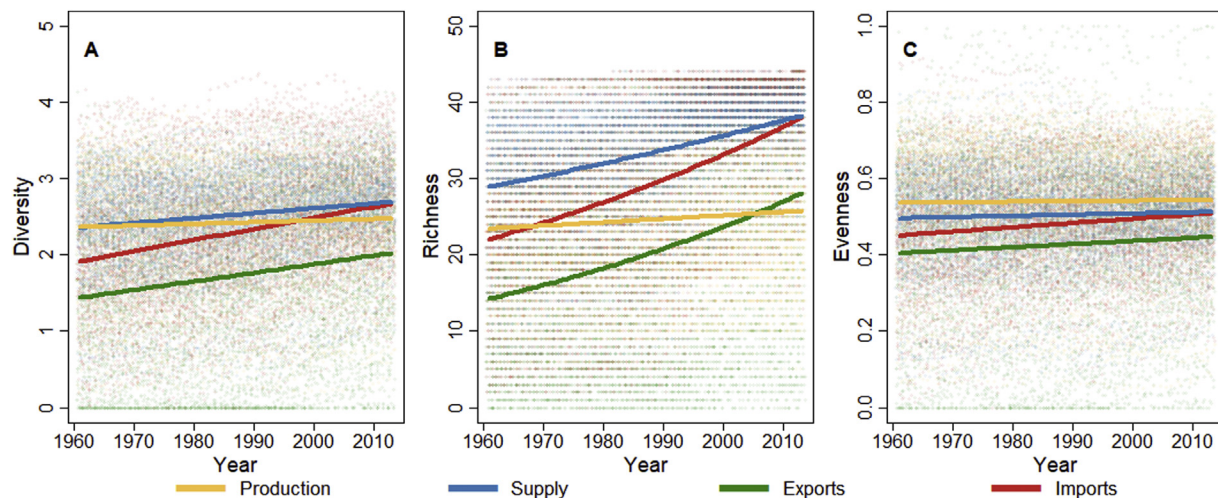


Fig. 1. Global change in within-country diversity, richness, and evenness of crops from 1961 to 2013. (A) Crop diversity measured as the Shannon-Wiener index. (B) Crop richness measured as the number of crops. (C) Crop evenness measured as the Pielou index. Points represent the data for each country and year, and lines are the globally averaged model derived from generalized linear mixed models.

production and consumption, respectively. For the components of trade, evenness grew slightly and similarly, from 0.4 to 0.42, and 0.45 to 0.5 for exports and imports, respectively (Fig. 1C).

Beyond the sustained average trends described above, important contrasts emerged between the components of the food balance, and also among countries, as revealed by the large dispersion of individual points in Fig. 1. The number of crops presented a generalized increase for all components, although these trends were counterbalanced by the mixed trends of evenness which determined resulting divergences in diversity (Fig. 2). While the diversity of supply declined only in a few countries (e.g. Brazil and the United States), the diversity of production was reduced or stable at the most in all continents, except for Africa. The diversity of crop imports also increased throughout the world, and that of exports was reduced in some countries of South America (e.g. Argentina, Brazil, Paraguay, and Uruguay) and Southeast Asia (e.g. Indonesia, Malaysia) (Fig. 2). Trade and particularly exports, had the highest composition turnover by indicating that countries changed to a greater extent the composition of crops that they traded than what they produced or consumed (SI.2).

We observed a positive relationship between the diversity of supply and the reliance if supply on imports (imports/supply ratio) (Fig. 3). The relationship was statistically significant both at the beginning (p-value = 0.048; $R^2 = 0.03$) and the end of the study period (p-value = 0.001; $R^2 = 0.12$). While the intercept of the relationship increased through time (p-value = 0.007), the slope did not change (p-value = 0.67), suggesting an overall increase in within-country crop supply diversity, but under an unchanged relationship with imports dependence. The relationship between the diversity of production and its allocation to export (export/production ratio) was negative at the beginning of the study period (p-value = 0.0002; $R^2 = 0.12$) but null at the end (p-value = 0.94; $R^2 = 0.005$). This suggests that at the beginning of the study period a larger fraction of exports were generally associated with lower diversity in crop production (i.e. specialization). Remarkably, some of the major exporting countries, reduced their production diversity (e.g. Argentina, Brazil, Malaysia, Paraguay, and United States) while others increased it (Australia and Canada) as they increased their allocation to exports, suggesting that specialization trends are far from universal (Fig. 3).

Across-countries, the overall similarity of the composition of crops between countries and the global average, is higher for supply (most countries above the 1:1 line) than for production (Fig. 4). Moreover, the significant increase in the intercept between the beginning and end of the study period (p-value = 0.0001), suggests that the homogenization

of crop composition has increased for supply but much less so for production (Fig. 4). However, the slight and marginally significant slope reduction with time (p-value = 0.08), hints an increasing homogenization of the composition of crop production as well. This simultaneous homogenization can also be observed by analyzing the temporal trajectories of the composition of crop production and supply for the 25 countries with the highest harvested area in 2013 through their generalized centripetal trajectory over the past 50 years for both production and supply (Figure SI3. A and Figure SI3. B). This trend in production has been explained by the increasing share of soybean and maize in all countries (Figure SI3. C, Table SI3.1, Table SI3.2) together with the partial replacement of some staple crops in many developing countries. For both production and supply, some Asian and African countries appear to have partially replaced their traditional staple grains such as sorghum, millet, and rice with maize and wheat (Table SI3.1 and Table SI3.2). The level of similarity of national crop production and supply composition to the global mean was more correlated at the beginning than at the end of the study period (Fig. 4, $R^2 = 0.47$ vs. 0.23). This reflects a growing decoupling in the composition of crops between domestic production and supply that is also indicated by a 15% global average reduction in the similarity (i.e. divergence) of crop production and supply composition within individual countries (Figure SI4).

Mirroring the previous country-focused analyses, the crop-focused perspective indicates that over the past 50 years, crops were more geographically ubiquitous at their supply end than at their production end (most crops located above the 1:1 line, Fig. 5A). This pattern is supported by crops being present in more countries (higher geographical spread, Figure SI.5.A) and more evenly distributed (higher geographical equity, Figure SI.5.C) for their supply than for their production. Regarding the temporal shifts (i.e. changes in intercept between 1961 and 2013), important changes were observed for the geographical ubiquity and geographical spread of crops, while their geographical equity only changed slightly (Fig. 5A, SI5A, SI5C). For both production and supply, staple crops such as maize, rice, and wheat had little changes concerning their geographical distribution. Lemons and tomatoes have grown their geographical ubiquity very rapidly both for their production and supply (Fig. 5A). Oil crops such as soybean and oil palm also had important changes in their geographical ubiquity for both production and consumption. This shift, however, was achieved in different ways. In the case of soybean, it was accompanied by a large expansion in the ubiquity of its production, whereas in the case of oil palm it resulted from a high geographical specialization of its

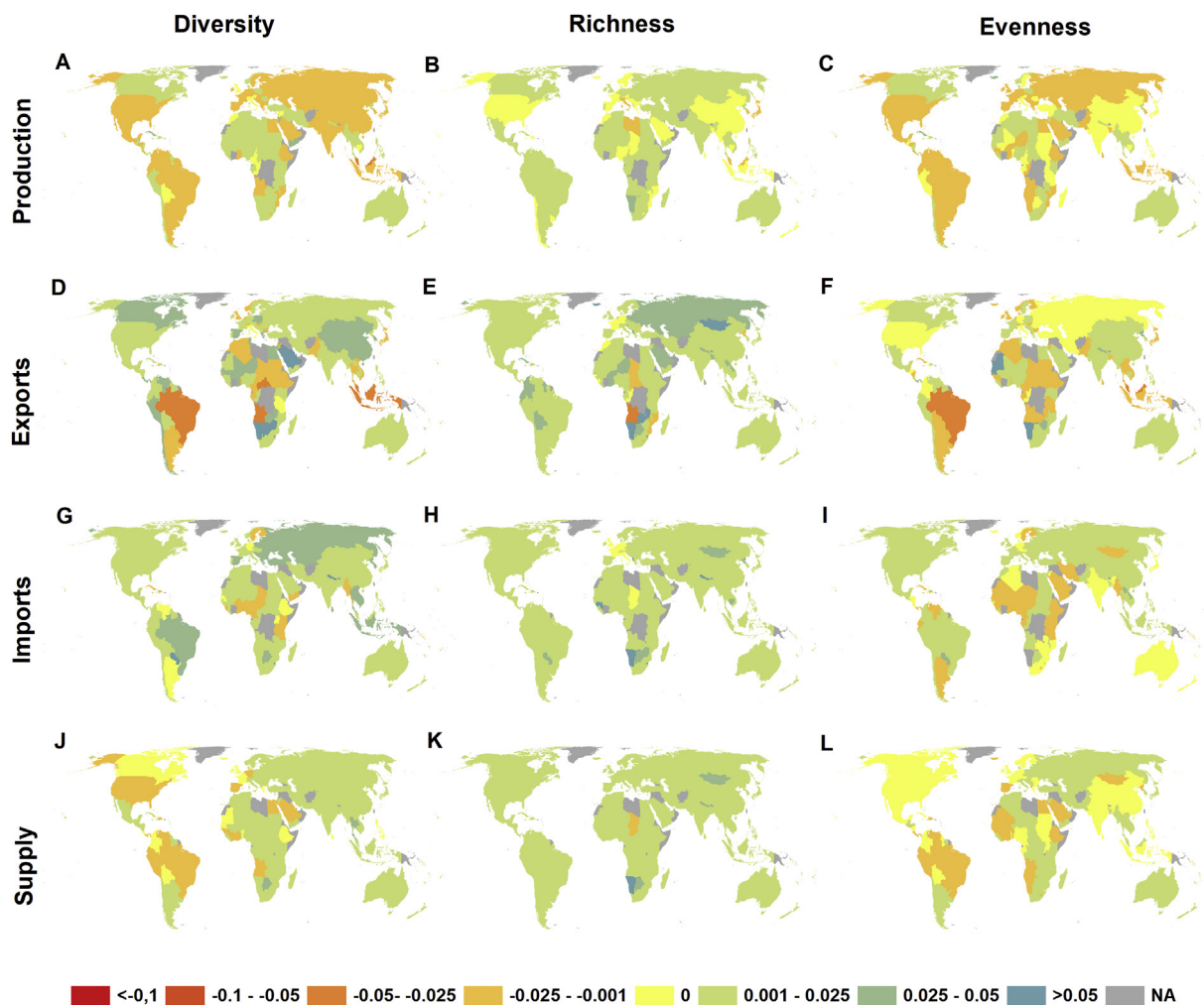


Fig. 2. Global changes in the diversity, richness, and evenness of crop production (A, B, C), export (D, E, F), import (G, H, I), and supply (J, K, L). Diversity, richness, and evenness were measured as the Shannon-Wiener index, the number of crops, and the Pielou index, respectively. The colors indicate the temporal trend derived from a generalized linear model. NA indicates not analyzed due to absent data. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

production. Millets and other secondary cereals (i.e. barley, oats, sorghum) showed reductions in their geographical distribution for both production and supply. Regarding the temporal shifts in groups of crops, while both pulses and tree nuts experienced a retraction in the geographical ubiquity of their production (specialization), the first lost ubiquity in their supply while the latter gain it (Figure SI6). In contrast, vegetables and spices, differentiate from this trend by displaying a much faster increase in the geographical ubiquity of their production

than on their supply, suggesting that domestic farming of these items might be catching up with a previous expansion of the domestic demand that was initially satisfied by imports (Figure SI6). As pointed by the country focused analyses, the perspective from crops shows a higher geographical ubiquity for imports than for exports (most crops located above the 1:1 line, Fig. 5B). This pattern is supported by crops being present in more countries (higher geographical spread, Figure SI.5.B) and being more evenly distributed across them (higher geographical

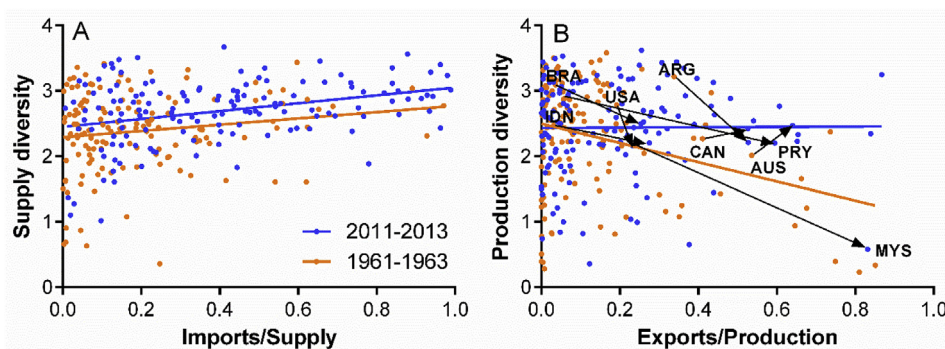


Fig. 3. Changes in crop production and supply diversity associated with the magnitude of international trade from 1961 to 2013. (A) Temporal changes in crop supply diversity and its relationship with reliance on imports (imports/supply ratio). (B) Temporal changes in crop production supply and its relationship with the allocation of production to exports (exports/production ratio). The arrows indicate temporal trajectories for major exporting countries. Except for Paraguay (PRY), the labels for the countries are placed near to their position at the beginning of the study period. Diversity was measured as the Shannon-Wiener index. Both diversity and ratios are calculated based on edible energy units (i.e. kilocalories). Arg = Argentina; AUS = Australia; BRA = Brazil; CAN = Canada; IDN = Indonesia, MYS = Malaysia, USA = United States.

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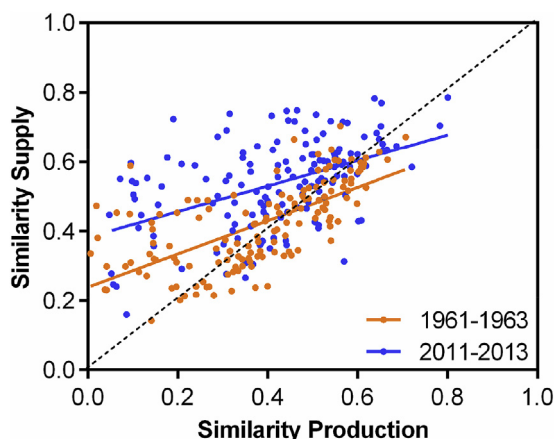


Fig. 4. The across-country similarity in the composition of crop production and supply from 1961 to 2013. Each point represents the similitude of the composition for crop production and supply composition between a given country and year and the global average. Higher values of similitude indicate a more similar composition of crops between a given country and the global average.

equity, Figure SI.5.D) for imports than for exports. Regarding the temporal shifts (i.e. changes in slopes between 1961 and 2013), important changes were observed for the geographical ubiquity and geographical equity of crop imports and exports, while their geographical spread slightly changed (Fig. 5B, SI6B, SI6D). Except for wheat, the changes in crops geographical ubiquity, and geographical spread, were much higher for imports than for exports.

4. Discussion

In this study, we simultaneously assessed the spatial and temporal trends in crop diversity for all the components of the food balance (supply, production, exports, and imports) for the past 50 years. We found that countries increased the diversity of crop supply at a faster rate than the diversity of production, thanks to the expansion and diversification of international trade. While consumption diversity increased in almost all countries, multiple trajectories were observed for the other components of the food balance. Across countries, the homogenization in crop composition was higher for supply than for production. Mirroring country-based analysis, crops have a higher geographical ubiquity for their supply than for their production. Regarding their changes between the beginning and the end of the study period, most crops increased their geographical distribution regardless of the component of the food balance. However, some singular trends emerged. For example, while soybean increased its geographical distribution for both supply and production, oil palm presented an increase in its geographical distribution for supply but a production specialization.

Over the past half-century, the increasing diversity of within-country crop supply was generally not backed up by a more diverse domestic production, but by an increase in the magnitude and diversity of crop imports. As suggested by previous studies, and reinforced by ours, the diversity of crop supply increased in almost all countries during the past 50 years (Bentham et al., 2020; Khoury et al., 2014). Conversely, production diversity had mixed trends, with increasing, decreasing, and stable trajectories (Aizen et al., 2019; Martin et al., 2019). For example, as most African countries diversified their production, several of the largest exporting countries (i.e. Argentina, Brazil, Indonesia, Malaysia, and United States, Suweis et al., 2015) have specialized their production towards a few commodity crops (soybean, oil palm, sugarcane). However, it is worth highlighting that the trends in crop production diversity are conditional to the metric used for its calculation. Our results suggest that production diversity indicators based on the harvested area (Aizen et al., 2019; Martin et al., 2019) and monetary value are higher than those based on edible energy.

Exports and imports were the components of the food balance with the highest increases in within-country crop diversity during the past 50 years. While previous studies highlighted the importance of trade as an important driver of diversifying supply (Nelson et al., 2016; Remans et al., 2014; Wood et al., 2018), their analysis did not include an explicit assessment of the change in the diversity of exported and imported crops. Our study described these components of the food balance and suggests that, although the magnitude of increase was similar for both components of trade, the globally averaged diversity of crop imports is about 26% higher than that of exports. These results have implications for the comparative advantage theory, which predicts that countries should specialize in their production and exports for those goods for which they have a comparative advantage sustaining a diversified supply through increasing imports (Krugman and Obstfeld, 2009). Our results support this prediction only partially as, exports and production lagged behind imports and supply diversity within countries but still did not show an average declining trend. Moreover, several countries have diversified their exports. Therefore, as suggested by Nelson et al. (2016), the trends in within-country crop production and trade diversity might be explained by a dual model: with some productive sectors (e.g. oil crops) or countries (e.g. large-exporters) behaving as expected from the comparative advantage theory. while others being more responsive to alternative factors, such as income restrictions, local incentives (e.g. taxes or subsidies), trade barriers, and preference for local food.

Regarding the diversity across countries, our results suggest that crop production did not homogenize as much as supply. This agrees with what Martin et al. (2019) suggested without a formal quantitative assessment. Crop production homogenized slightly at the global level, mainly as a result of changes in large-producing countries (both tropical and temperate), where there was an increase in the production and supply of maize and soybean. Also, temperate countries included, tropical and subtropical crops (e.g. millet, sorghum) and tropical and

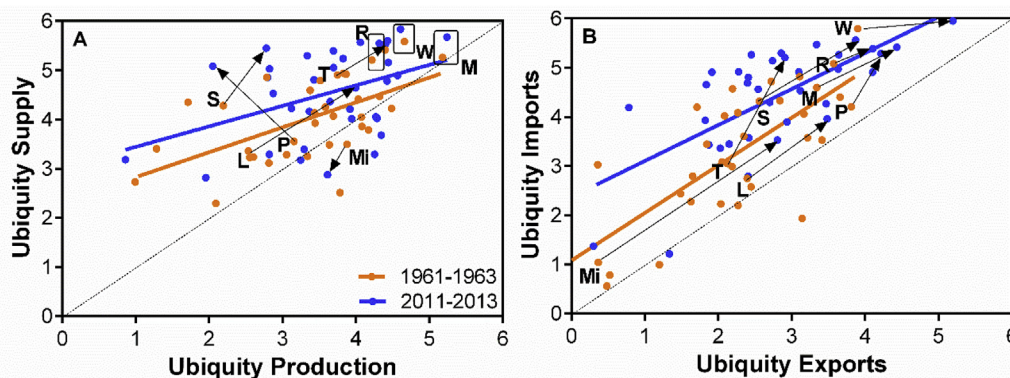


Fig. 5. Temporal changes in the geographical ubiquity of crops between 1961 and 1963 in terms of production and supply (A) and exports and imports (B). The geographical ubiquity of crops was measured as the Shannon-Wiener index. Higher values of the index indicate that a crop is present in a larger number of countries and/or more equally distributed among them. The arrows indicate the temporal trajectory for selected crops. L: Lemons, M: Maize, Mi: Millet; P: Oil Palm, R: Rice, S: Soybeans, T: Tomato and W: Wheat.

subtropical countries included temperate crops (e.g. wheat) as suggested by other studies (Pingali 2007, 2017). Hence, cultivated plants are still going through the long-dated biotic homogenizing trend of the planet (Vellend et al., 2017; Zalasiewicz et al., 2017), likely leading it as the range of a few cultivated species keeps spreading out of their domestication origin (Houry et al., 2016).

Although most crops increased their geographical distribution for all the components of the food balance, some of them presented singular trajectories. The most important staple cereals (e.g. maize, rice, wheat) slightly changed their geographical ubiquity for both production and supply, suggesting that they were among the least geographically dynamic crops. Maize was the most geographically ubiquitous crop for both production and supply, which reflects not only the wide ecological niche of this crop but also its flexible uses (direct human consumption, animal feed, biofuels, and food industry, Borrás et al., 2015). Other flexible crops, such as soybean and oil palm, were more dynamic, likely as a result of their role sustaining the global expansion of consumption of animal protein, vegetable oil, and processed food (Bonhommeau et al., 2013; Popkin et al., 2012). Yet, while soybean has simultaneously increased its geographical ubiquity for production and supply, oil palm has increased it for supply but not for production, which has concentrated in fewer and more specialized countries of Southeastern Asia. These two highly traded crops are among the main drivers of deforestation in tropical and subtropical countries where they are leaving multiple social-ecological imprints (Henders et al., 2015) and are still expanding their distribution (Furumo and Aide, 2017; Zalles et al., 2019). Accordingly, their supply chains are subject to growing scrutiny by science and policy (Gardner et al., 2019). The observed trends in crop production spread may indicate an enlargement of their ecological biotic due to breeding (see Shiferaw et al., 2011 for a review on maize), but, to our knowledge, this possibility has not been assessed in an integrative way for multiple crops so far. Thus, more research and synthesis regarding crop range shifts and their technological, environmental, and human drivers are needed, with particular focus on what traits help them get engaged in higher use and trade.

Concerning the metrics used in our analysis, it is important to highlight that within-country crop supply should be used with caution as a surrogate for crop consumption, since some crops (e.g. maize, soybean) generally reach household tables indirectly as meat that was fed on grains or as highly processed food. Hence it might be better to consider within-country crop supply as a proxy for apparent consumption. The use of this metric and its complementation with commonly used metrics of human nutrition (e.g. per capital kcal or grams of protein) could be useful for a better connection between diets and land use, particularly in a world where the consumption of processed food is increasing, and grains are intensively used as feed (Herrero et al., 2015; Popkin et al., 2012). Regarding the temporal and spatial scales of this study, it might represent a short period concerning the history of agriculture, and national trends might be backed up by heterogeneous dynamics at smaller scales (e.g. counties, farms). Concerning the latter, recent studies have described the subnational trends in crop production diversity for many countries, such as the US (Aguilar et al., 2015), Canada (Renard et al., 2016), and India (Smith et al., 2019). All these studies suggest that national-level trends are generally not explained by unique trends at the state or county level (or equivalent second or third administrative units), but instead by a mix of contrasting trends that cancel them out at a higher level. These studies suggest that a better understanding of global crop production diversity would require an updated and comprehensive global database of subnational crop data. Finally, as stated by Houry et al. (2014), the crops included in FAO-STAT (FAOSTAT, 2019) may underestimate the number of crops used in many countries, since some are only traded in local markets and/or produced for subsistence consumption in isolated areas.

Our results have implications for the structure and functioning of the global food system. Recently, the EAT-Lancet Commission on Food,

Planet, and Health called for a large transformation in the global food system and posits the need to move towards a universal sustainable diet, that is largely plant-based, and relies little on livestock products (Willet et al., 2019). This suggests that global diets should shift from their actual trend toward a common western diet (Popkin et al., 2012) to another universal diet, yet more sustainable and healthy. However, the new universal global diet has limitations regarding its adaptation to local socio-economic and cultural conditions (Tuomisto, 2019). Moreover, as suggested by our findings, the recent diversification of crop supply was heavily based on trade, and therefore increasing the diversity in crop consumption based on trade does not seem like a sustainable strategy (Tuomisto, 2019). Hence, leveraging the slight diversifying trend in within-country crop production that we find, might be a way to simultaneously increase the supply of a more diverse basket of crops and to reduce the dependence on imports, and therefore, the environmental impacts of trade as well (Dalín et al., 2012; Dalín and Rodríguez-Iturbe, 2016; Lenzen et al., 2012). Moreover, this diversification of crop production might also have positive outcomes since recent studies suggest that countries with higher crop diversity have more stable production (Renard and Tilman, 2019). Within this context, many forms of local small farming, including urban agriculture (Badami and Ramankutty, 2015; Martellozzo et al., 2014) have been suggested and evaluated as a strategy to increase the sustainability of food chains (Brunori et al., 2016). However, increasing the diversity of domestic crop production might not always be the best strategy (Edward-Jones et al., 2008; Hospido et al., 2009; Wood et al., 2018) or even feasible due to environmental limitations (D'Odorico et al., 2019; Kinnunen et al., 2020). Thus, there might not be a panacea for resolving these complex issues, and optimizing trade might be a feasible first step (Verstegen, 2020). Although more research might be needed to shed light on the local vs global food debate in the context of shifting global diets, the partial uncertainty of some issues should not be used as an argument to delay the design of a more sustainable food system.

From the perspective of individual crop species, the homogenization of crop supply is not only supported by trade but also, to a lesser extent, by an increase in the homogenization of crop production. Martin et al. (2019) suggest that the homogenization of crop production might increase the vulnerability of the global food system due to a higher susceptibility to pest outbreaks or climatic change. However, opposite effects may arise if these changes are seen as the equivalent to a spatial portfolio, where a higher geographical spread in crop distribution might be a way to increase individual crop production stability by reducing the vulnerability to local production shocks, such as droughts, floods, pest outbreaks and wars (Cotrell et al., 2019; Mehrabi and Ramankutty, 2019). Moreover, since the choice of which crops to grow, and where to do it, highly determine water and nutrients demands and productivity per unit of area or water/nutrients (Davis et al., 2017; Jobbágy and Sala, 2014), more efficient crop spatial allocation should be explored. Finally, as new crops become massively consumed by wealthy populations worldwide (Massawe et al., 2016), it is critical whether their production follows a specialized or distributed production pattern, and therefore project future crop diversity trends. Hence, future studies should combine assessments of crop diversity, with descriptions of current and future scenarios of crop allocation under a changing climate. Moreover, they should also include further analysis of the network structure of international crop trade (e.g. Marchand et al., 2016; Puma et al., 2015), since all these factors contribute to the resilience of the global food system (Nyström et al., 2019).

5. Conclusion

In this study, we simultaneously assessed the spatial and temporal trends in crop diversity for all the components of the food balance (production, exports, imports, and supply) for the past 50 years. Our results indicate that the expansion and diversification of crop trade was the main driver of the global diversification of supply since within-

country production slightly increased. The low diversification of crop production during the past 50 years results from mixed trends at the country scale, where both diversification and specialization trends co-existed and compensated each other. Most of the major exporting countries followed a specialization trend in their production. Regarding the diversity across countries, we found that the homogenization of crop supply was higher than that of production with this decoupling suggesting, again, the importance of international trade. Almost all crops have increased their geographical distribution in all the components of the food balance. Overall, our findings highlight the importance of trade for explaining one of the key aspects of the global food system, which is its diversity at the production and supply ends. These findings are critical for the design of a more resilient and sustainable global food system, particularly regarding the current debates related to local vs. global food and the definition of diets that are sustainable and resilient for both people and nature.

Declaration of competing interest

All authors declare no conflict of interest.

Acknowledgments

We are grateful to Pablo Baldassini, Ezequiel Arrieta, Pedro Laterra, Diego Ferraro, Walter Pengue, and two anonymous reviewers for thoughtful comments and suggestions. This work was carried out with the aid of grants from ANPCyT and the Inter-American Institute for Global Change Research (IAI) CRN3095 (Bridging Ecosystem Services and Territorial Planning (BEST-P)): A southern South American initiative), which is supported by the US National Science Foundation (Grant GEO- 1128040). CONICET also provided funding through a Ph.D. scholarship to S.A.

Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.gfs.2020.100385>.

References

- Aguiar, J., Gramig, G.G., Hendrickson, J.R., Archer, D.W., Forcella, F., Liebig, M.A., 2015. Crop species diversity changes in the United States: 1978–2012. *PLoS One* 10 (8), e0136580.
- Aizen, M.A., Aguiar, S., Biesmeijer, J.C., Garibaldi, L.A., Inouye, D.W., Jung, C., et al., 2019. Global agricultural productivity is threatened by increasing pollinator dependence without a parallel increase in crop diversification. *Global Change Biol.* 25 (10), 3516–3527.
- Alston, J.M., Babcock, B.A., Pardey, P.G., 2010. *The Shifting Patterns of Agricultural Production and Productivity Worldwide*. CARD Books. 2. https://lib.dr.iastate.edu/card_books/2/.
- Badami, M.G., Ramankutty, N., 2015. Urban agriculture and food security: a critique based on an assessment of urban land constraints. *Global Food Secur.* 4, 8–15.
- Bates, D., Maechler, M., Bolker, B., Walker, S., 2014. lme4: linear mixed-effects models using Eigen and S4. R Packag. Version 1 (7), 1–23.
- Bentham, J., Singh, G.M., Danaei, G., Green, R., Lin, J.K., Stevens, G.A., et al., 2020. Multidimensional characterization of global food supply from 1961 to 2013. *Nat. Food* 1 (1), 70–75.
- Bonhommeau, S., Dubroca, L., Le Pape, O., Barde, J., Kaplan, D.M., Chassot, E., Nieblas, A.E., 2013. Eating up the world's food web and the human trophic level. *Proc. Natl. Acad. Sci. Unit. States Am.* 110 (51), 20617–20620.
- Borras Jr., S.M., Franco, J.C., Isakson, S.R., Levidow, L., Vervest, P., 2015. The rise of flex crops and commodities: implications for research. *J. Peasant Stud.* 1–25.
- Brunori, G., Galli, F., Barjolle, D., Van Broekhuizen, R., Colombo, L., Giampietro, M., et al., 2016. Are local food chains more sustainable than global food chains? Considerations for assessment. *Sustainability* 8 (5), 449.
- Cottrell, R.S., Nash, K.L., Halpern, B.S., Remenyi, T.A., Corney, S.P., Fleming, A., et al., 2019. Food production shocks across land and sea. *Nat. Sustain.* 2 (2), 130.
- D'Odorico, P., Carr, J.A., Laio, F., Ridolfi, L., Vandoni, S., 2014. Feeding humanity through global food trade. *Earth's Future* 2 (9), 458–469.
- Dalin, C., Rodríguez-Iturbe, I., 2016. Environmental impacts of food trade via resource use and greenhouse gas emissions. *Environ. Res. Lett.* 11 (3), 035012.
- Dalin, C., Konar, M., Hanasaki, N., Rinaldo, A., Rodríguez-Iturbe, I., 2012. Evolution of the global virtual water trade network. *Proc. Natl. Acad. Sci. Unit. States Am.* 109 (16), 5989–5994.
- Davis, K.F., Rulli, M.C., Seveso, A., D'Odorico, P., 2017. Increased food production and reduced water use through optimized crop distribution. *Nat. Geosci.* 10 (12), 919.
- D'Odorico, P., Carr, J.A., Davis, K.F., Dell'Angelo, J., Seekell, D.A., 2019. Food inequality, injustice, and rights. *Bioscience* 69 (3), 180–190.
- Edwards-Jones, G., Canals, L.M., Hounsome, N., Truninger, M., Koerber, G., Hounsome, B., Harris, I.M., 2008. Testing the assertion that 'local food is best': the challenges of an evidence-based approach. *Trends Food Sci. Technol.* 19 (5), 265–274.
- Fader, M., Gerten, D., Krause, M., Lucht, W., Cramer, W., 2013. Spatial decoupling of agricultural production and consumption: quantifying dependences of countries on food imports due to domestic land and water constraints. *Environ. Res. Lett.* 8 (1), 014046.
- FAOSTAT, 2019. *Food and Agriculture Organization Corporate Statistical Database*. Retrieved from: <http://www.fao.org/faostat/en>.
- Foley, J.A., Ramankutty, N., Brauman, K.A., Cassidy, E.S., Gerber, J.S., Johnston, M., et al., 2011. Solutions for a cultivated planet. *Nature* 478 (7369), 337.
- Food and Agriculture Organization, 2001. *Food Balance Sheets. A Handbook*. (Rome, Italy).
- Furumo, P.R., Aide, T.M., 2017. Characterizing commercial oil palm expansion in Latin America: land use change and trade. *Environ. Res. Lett.* 12 (2), 024008.
- Gardner, T.A., Benzie, M., Börner, J., Dawkins, E., Fick, S., Garrett, R., et al., 2019. Transparency and sustainability in global commodity supply chains. *World Dev.* 121, 163–177.
- Gepts, P., Famula, T.R., Bettinger, R.L., Brush, S.B., Damania, A.B. (Eds.), 2012. *Biodiversity in Agriculture: Domestication, Evolution, and Sustainability*. Cambridge University Press.
- Harlan, J.R., 1992. *Crops and Man*. American Society of Agronomy.
- Henders, S., Persson, U.M., Kastner, T., 2015. Trading forests: land-use change and carbon emissions embodied in production and exports of forest-risk commodities. *Environ. Res. Lett.* 10 (12), 125012.
- Herrero, M., Wirsenius, S., Henderson, B., Rigolot, C., Thornton, P., Havlík, P., et al., 2015. Livestock and the environment: what have we learned in the past decade? *Annu. Rev. Environ. Resour.* 40, 177–202.
- Hospido, A., Canals, L.M., McLaren, S., Truninger, M., Edwards-Jones, G., Clift, R., 2009. The role of seasonality in lettuce consumption: a case study of environmental and social aspects. *Int. J. Life Cycle Assess.* 14 (5), 381–391.
- Hunter, D., Guarino, L., Spillane, C., McKeown, P.C., 2017. *Routledge Handbook of Agricultural Biodiversity*. Taylor & Francis, New York.
- Jobbágy, E.G., Sala, O.E., 2014. The imprint of crop choice on global nutrient needs. *Environ. Res. Lett.* 9 (8), 084014.
- Jost, L., 2006. Entropy and diversity. *Oikos* 113 (2), 363–375.
- Khoury, C.K., Bjorkman, A.D., Dempewolf, H., Ramirez-Villegas, J., Guarino, L., Jarvis, A., et al., 2014. Increasing homogeneity in global food supplies and the implications for food security. *Proc. Natl. Acad. Sci. Unit. States Am.* 111 (11), 4001–4006.
- Khoury, C.K., Achicanoy, H.A., Bjorkman, A.D., Navarro-Racines, C., Guarino, L., Flores-Palacios, X., et al., 2016. Origins of food crops connect countries worldwide. *Proc. R. Soc. B* 283 (1832), 20160792.
- Kinnunen, P., Guillaume, J.H., Taka, M., D'Odorico, P., Siebert, S., Puma, M.J., et al., 2020. Local food crop production can fulfil demand for less than one-third of the population. *Nat. Food* 1 (4), 229–237.
- Krugman, P.R., Obstfeld, M., 2009. *International Economics: Policy and Theory*. Pearson.
- Lenzen, M., Moran, D., Kanemoto, K., Foran, B., Lobefaro, L., Geschke, A., 2012. International trade drives biodiversity threats in developing nations. *Nature* 486 (7401), 109.
- Marchand, P., Carr, J.A., Dell'Angelo, J., Fader, M., Gephart, J.A., Kumm, M., et al., 2016. Reserves and trade jointly determine exposure to food supply shocks. *Environ. Res. Lett.* 11 (9), 095009.
- Martellozzo, F., Landry, J.S., Plouffe, D., Seufert, V., Rowhani, P., Ramankutty, N., 2014. Urban agriculture: a global analysis of the space constraint to meet urban vegetable demand. *Environ. Res. Lett.* 9 (6), 064025.
- Martin, A.R., Cadotte, M.W., Isaac, M.E., Milla, R., Vile, D., Violle, C., 2019. Regional and global shifts in crop diversity through the Anthropocene. *PLoS One* 14 (2), e0209788.
- Massawe, F., Mayes, S., Cheng, A., 2016. Crop diversity: an unexploited treasure trove for food security. *Trends Plant Sci.* 21 (5), 365–368.
- Mazoyer, M., Roudart, L., 2007. *A History of World Agriculture: from the Neolithic Age to the Current Crisis*. Routledge.
- McGill, B.J., Dornelas, M., Gotelli, N.J., Magurran, A.E., 2015. Fifteen forms of biodiversity trend in the Anthropocene. *Trends Ecol. Evol.* 30 (2), 104–113.
- Mehrabi, Z., Ramankutty, N., 2019. Synchronized failure of global crop production. *Nat. Ecol. Evol.* 3 (5), 780.
- Meyfroidt, P., Lambin, E.F., Erb, K.H., Hertel, T.W., 2013. Globalization of land use: distant drivers of land change and geographic displacement of land use. *Curr. Opin. Environ. Sustain.* 5 (5), 438–444.
- Nelson, E.J., Helmus, M.R., Cavender-Bares, J., Polasky, S., Lasky, J.R., Zanne, A.E., et al., 2016. Commercial plant production and consumption still follow the latitudinal gradient in species diversity despite economic globalization. *PLoS One* 11 (10), e0163002.
- Nyström, M., Joffray, J.B., Norström, A.V., Crona, B., Jørgensen, P.S., Carpenter, S.R., et al., 2019. Anatomy and resilience of the global production ecosystem. *Nature* 575 (7781), 98–108.
- Oksanen, J., Blanchet, F.G., Kindt, R., Legendre, P., O'hara, R.B., Simpson, G.L., et al., 2010. *Vegan: Community Ecology Package*. R Package Version 1.17-2. R Development Core Team. R: A Language and Environment for Statistical Computing. R Foundation for Statistical Computing, Vienna.
- Pieterse, J.N., 2015. *Globalization and Culture: Global Mélange*. Rowman & Littlefield.
- Pingali, P., 2007. Westernization of Asian diets and the transformation of food systems:

- implications for research and policy. *Food Pol.* 32 (3), 281–298.
- Pingali, P., 2017. The green revolution and crop diversity (chapter 12). In: Hunter, D., Guarino, L., Spillane, C., McKeown, P. (Eds.), *Handbook of Agricultural Biodiversity*. Routledge, New York.
- Popkin, B.M., Adair, L.S., Ng, S.W., 2012. Global nutrition transition and the pandemic of obesity in developing countries. *Nutr. Rev.* 70 (1), 3–21.
- Puma, M.J., Bose, S., Chon, S.Y., Cook, B.I., 2015. Assessing the evolving fragility of the global food system. *Environ. Res. Lett.* 10 (2), 024007.
- Ramankutty, Navin, Mehrabi, Z., Waha, K., Jarvis, L., Kremen, C., Herrero, M., Rieseberg, L., 2018. Trends in global agricultural land use: implications for environmental health and food security. *Annual review of plant biology* 69, 789–815. <https://doi.org/10.1146/annurev-arplant-042817-040256>.
- Remans, R., Wood, S.A., Saha, N., Anderman, T.L., DeFries, R.S., 2014. Measuring nutritional diversity of national food supplies. *Global Food Secur.* 3 (3–4), 174–182.
- Renard, D., Tilman, D., 2019. National food production stabilized by crop diversity. *Nature* 571 (7764), 257–260.
- Renard, D., Bennett, E.M., Rhemtulla, J.M., 2016. Agro-biodiversity has increased over a 95 year period at sub-regional and regional scales in southern Quebec, Canada. *Environ. Res. Lett.* 11 (12), 124024.
- Ripley, B., Venables, B., Bates, D.M., Hornik, K., Gebhardt, A., Firth, D., Ripley, M.B., 2013. Package ‘mass’. CRAN R.
- Seekell, D., Carr, J., Dell’Angelo, J., D’Odorico, P., Fader, M., Gephart, J., et al., 2017. Resilience in the global food system. *Environ. Res. Lett.* 12 (2), 025010.
- Shiferaw, B., Prasanna, B.M., Hellin, J., Bänziger, M., 2011. Crops that feed the world 6. Past successes and future challenges to the role played by maize in global food security. *Food Secur.* 3 (3), 307.
- Smith, J., Ghosh, A., Hijmans, R., 2019. Agricultural intensification is associated with crop diversification in India. *PLoS One* 14(12). <https://doi.org/10.1371/journal.pone.0225555>.
- Suweis, S., Carr, J.A., Maritan, A., Rinaldo, A., D’Odorico, P., 2015. Resilience and reactivity of global food security. *Proc. Natl. Acad. Sci. Unit. States Am.* 112 (22), 6902–6907.
- Tuomisto, H.L., 2019. The complexity of sustainable diets. *Nat. Ecol. Evol.* 3 (5), 720–721.
- Vellend, M., Baeten, L., Becker-Scarpitta, A., Boucher-Lalonde, V., McCune, J.L., Messier, J., et al., 2017. Plant biodiversity change across scales during the Anthropocene. *Annu. Rev. Plant Biol.* 68.
- Verstegen, J.A., 2020. The local versus global food debate. *Nat. Food* 1 (4), 198–199.
- Willett, W., Rockström, J., Loken, B., Springmann, M., Lang, T., Vermeulen, S., et al., 2019. Food in the Anthropocene: the EAT–Lancet Commission on healthy diets from sustainable food systems. *Lancet* 393 (10170), 447–492.
- Wood, S.A., Smith, M.R., Fanzo, J., Remans, R., DeFries, R.S., 2018. Trade and the equitability of global food nutrient distribution. *Nat. Sustain.* 1 (1), 34.
- Zalasiewicz, J., Waters, C.N., Summerhayes, C.P., Wolfe, A.P., Barnosky, A.D., Cearreta, A., et al., 2017. The working group on the anthropocene: summary of evidence and interim recommendations. *Anthropocene* 19, 55–60.
- Zalles, V., Hansen, M.C., Potapov, P.V., Stehman, S.V., Tyukavina, A., Pickens, A., et al., 2019. Near doubling of Brazil’s intensive row crop area since 2000. *Proc. Natl. Acad. Sci. Unit. States Am.* 116 (2), 428–435.
- Zimmerer, K.S., de Haan, S., Jones, A.D., Creed-Kanashiro, H., Tello, M., Carrasco, M., et al., 2019. The biodiversity of food and agriculture (Agrobiodiversity) in the anthropocene: research advances and conceptual framework. *Anthropocene* 25, 100192.