Global Food Security 28 (2021) 100490

Contents lists available at ScienceDirect

Global Food Security

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

Does global food trade close the dietary nutrient gap for the world's poorest nations?

Ozge Geyik [a,*], Michalis Hadjikakou [a], Baris Karapinar [b], Brett A. Bryan [a]

[a] Centre for Integrative Ecology, Deakin University, Burwood, Victoria, 3125, Australia
[b] Center for Economics and Econometrics, Bogazici University, Istanbul, 34470, Turkey

ARTICLE INFO

Keywords:
Nutrition sensitive food systems
Nutrient adequacy
Food trade networks
Dietary nutrient gap

ABSTRACT

Global food trade enables the flow of dietary nutrients between countries. However, little is known about whether trade improves nutrient supply of countries most in need. Using detailed production and bilateral trade data, we found that despite strongly connected global nutrient networks, trade did not substantively improve the nutrient adequacy of most low/lower-middle income countries (~40% of the global population), with particular concerns around vitamin A and B12. Mean imports by low/lower-middle income countries, in adequacy terms, were on average 70% lower than those of upper-middle/high income countries. Many countries with low nutrient adequacy relied upon a few major trade partners with imports dominated by cereals rather than micronutrient-rich food products. Nutrition-sensitive production and trade policies are needed to enhance global nutrition security.

1. Introduction

Adequate nutrition is fundamental for physical and cognitive development in addition to a well-functioning immune system. There is a growing body of research exploring aspects of nutrition-sensitive food systems through which not only caloric (i.e., hunger) but also micronutrient inadequacy (i.e., hidden hunger) is targeted (Gillespie and van den Bold, 2017; Popkin, 2004; Willett et al., 2019). Production-related challenges can occur at the national, regional or global scale and international trade can help ease the burden of national and regional shortages (Egbendewe et al., 2017; Janssens et al., 2020; Kinnunen et al., 2020). Although more than 80% of global food consumption is still supplied by domestic production, the share of food commodities traded internationally has increased from 10% to 14% between 1995 and 2017 (FAOSTAT, 2017). This trend is expected to continue, with a three- to four-fold expansion in developing countries' imports of major commodities forecast for 2050 (FAO, 2018). International trade, therefore, has the potential to enable a nutrition-sensitive global food system that would supply dietary nutrients to where they are needed for adequate nutrition (D'Odorico et al., 2019).

The role of global trade in dietary nutrient supply and nutrient adequacy is complex and the effects on the world's poor are not well understood. Studies assessing the relationship between international food trade and nutrition have reached widely varying conclusions depending on their scope, method, and disciplinary approach. Public health nutritionists propose that trade liberalization leads to increased rates of overweight/obese people and those with related non-communicable diseases such as type-2 diabetes in developing countries (Baker et al., 2014; Thow, 2009). Yet, recent studies have concluded that it is the social aspect of globalisation (e.g., international communication and information flows) that correlate more strongly with diet-related non-communicable disease prevalence rather than economic globalization through trade (Oberlander et al., 2017). Econometric studies have illustrated favourable consequences of trade liberalization for different dimensions of global food security such as availability (D'Odorico et al., 2019, 2014; Dithmer and Abdulai, 2017), diversity (Aguiar et al., 2020) and access (Rafeek and Samaratunga, 2011; Rutten et al., 2013). Similarly, Wood et al. (2018) have found that trade improved nutrient availability, particularly for low income countries. A recent prospective study suggests trade as a climate change adaptation mechanism against hunger in several low income countries (Janssens et al., 2020). Other studies contrast these findings by reporting on the adverse impacts of trade on local production (Panda and Ganesh-Kumar, 2009) and rural livelihoods (Ford et al., 2014), income inequality (Mary, 2019), and availability (Bezuneh and Yiheyis, 2014). These effects are particularly prevalent in countries with a comparative disadvantage in food

* Corresponding author.
E-mail address: ogeyik@deakin.edu.au (O. Geyik).

https://doi.org/10.1016/j.gfs.2021.100490
Received 4 September 2020; Received in revised form 27 December 2020; Accepted 2 January 2021
Available online 21 January 2021

production and high import dependency (e.g., net food importers of Asia and Africa) (Rutten et al., 2013). Distributional effects of trade liberalization also affect consumers and producers differently which implies non-uniform nutritional implications within countries (Panda and Ganesh-Kumar, 2009; Rafeek and Samaratunga, 2011). Recent reviews confirm these mixed results and reveal the complexity of interpretation and context-dependency of food trade assessment (Cuevas García-Dorado et al., 2019).

The complexity of global food trade and nutrition highlights the need for an in-depth understanding of the international food trade networks (Fair et al., 2017; Puma et al., 2015; Sartori and Schiavo, 2015). International food trade forms complex networks of interdependent countries (nodes) that are linked through food imports/exports (Cepeda-López et al., 2019; De Benedictis et al., 2014; Hu et al., 2020; Qi et al., 2014) via which dietary nutrients are distributed. Topological features of the whole network and individual characteristics of the nodes reveal information about network connectivity and relations. High market concentration, manifested as a disproportionate reliance on just a few trade partners, poses a risk to food security in the case of trade restrictions imposed by those partners (Puma et al., 2015). Increased nutrient availability through trade is particularly important in many low and lower-income countries where domestic production is inadequate (Geyik et al., 2020). Yet, growing connectivity in trade networks may not translate into improved availability for all nutrients.

Using highly disaggregated data quantifying the trade in 264 food commodities (Data S1) between 128 countries from 2013 to 2015, we explored the effect of international food trade on *nutrient adequacy*, defined as the potential ability of a country to meet the dietary nutrient requirements of its population through food availability. Nutrient adequacy compares nutrient availability, which we calculate using high-resolution data, at the country level to population-level requirements estimated on the basis of Recommended Nutrient Intake (RNI) (Geyik et al., 2020). The difference between what is needed and what is available, at the national-level, amounts to the *nutrient gap* which is often used to describe deficiency in the diets (Bose et al., 2019). We use network analysis to describe the global structure of dietary nutrient trade networks and patterns differentiated by income levels for energy and six essential nutrients (protein, iron, zinc, vitamin A, vitamin B12 and folate). We quantify the heterogeneity in trade links and volumes, and the trade connectivity of countries. We identify major trade partners and food sources of nutrient flows with a special focus on low and lower-middle income countries. We discuss our findings in the context of global nutrition security and identify potential avenues through which a nutrition-sensitive food systems approach could be embedded in production and trade policies.

2. Methods

2.1. Data sources, harmonization and analysis

We obtained bilateral trade data for 156 crop and 40 livestock commodities from the Food and Agriculture Organization of the United Nations (FAO) (FAOSTAT, 2019a) for the period from 2013 to 2015 (Data S1). We used the UN COMTRADE database (UN, 2020) to capture trade for 68 seafood commodities because FAO does not provide bilateral trade data for this category. For a pair of partner countries, we included commodities that appeared both in import and export matrices to minimise bias.

Import data did not always mirror export data for several reasons including a time lag in reporting, re-exports being treated differently, and data confidentiality (FAOSTAT, 2019a). We used reporter country data in our calculations following other recent studies (Kinnunen et al., 2020), thereby including only those countries with consistent trade records both as a reporter and a partner country in two different databases. Consequently, we covered 128 countries that together account for 89% of the global population for the period 2013–15. Income groupings (Table 1) are based on World Bank classifications (The World Bank, 2020) (for full list of countries see Table S1).

Table 1
World Bank income groups, corresponding income ranges, number of countries and populations for each group **(GNI = Gross National Income)** (The World Bank, 2020).

Income group	GNI per capita in 2018 ($ dollars)	Number of countries	Total Population
Low	≤1025	16	354,814
Lower-middle	1026–3995	31	2,618,361
Upper-middle	3996–12,375	36	2,279,866
High	≥12,376	45	1,218,579

To calculate energy and nutrient (hereafter simply *nutrient*) content of traded food commodities, we used the US Department of Agriculture (USDA) Food Composition Database (USDA, 2011). After matching commodities in trade databases with those in the USDA food composition database (Data S1) we subtracted the refuse ratio (e.g., shell, seed, and skin) to derive human edible nutrient content. To avoid double-counting, as more than a third of cereal supply is fed to livestock, we subtracted the amount used as animal feed from our calculations by using feed-to-supply ratios (FAOSTAT, 2017). We used median values for commodities with different varieties. For population-level nutrient requirements, we used the dataset provided by Geyik et al. (2020) which combines age- and sex-specific population data with the RNI values for energy, protein, iron, zinc, vitamin A, vitamin B12 and folate. RNI is frequently used in global assessments (Wood et al., 2018) and gives the estimated daily nutrient intake needed to meet the requirements of 97.5% of healthy individuals in a population group. We assumed median bioavailability for iron and zinc, and moderate activity level for energy requirements (see (Geyik et al., 2020) for detailed methodology). The ratio of nutrient availability, either based on domestic production or supply (i.e., production + imports – exports), to nutrient requirements gives the adequacy value for the seven nutrients of interest. Values below 1 indicate inadequate nutrient availability. We differentiated between those with low (between 0.85 and 1) and very low (<0.85) nutrient adequacy, based on an established self-sufficiency ratio referring to the ratio of domestic production to domestic supply by quantity or calories (Kinnunen et al., 2020). We use the term *inadequate* to refer to nutrient adequacy <1.0.

The term *nutrient adequacy of production* is used when referring to domestic food production. *Nutrient adequacy of supply* refers to the calculations that incorporate net trade, e.g., supply = production + imports - exports. *Nutrient gap* gives the difference between adequate and inadequate production/supply. Finally, we compared nutrient adequacy of production with nutrient adequacy of supply to assess the role of trade in distributing nutrients and provided a more comprehensive assessment for the low and lower-middle income groups.

2.2. Trade network analysis

We examined the structural features of dietary nutrient flows facilitated by international food trade. Network analysis provides insights into relationships among different actors of interest (Jackson, 2019). A growing body of literature quantifies network structure and evolution to analyse varying aspects of international trade in total merchandise (Cepeda-López et al., 2019; De Benedictis et al., 2014), energy (Geng et al., 2014), mining (Hu et al., 2020) and agricultural sector (Ercsey-Ravasz et al., 2012; Konar et al., 2011; Puma et al., 2015; Sartori and Schiavo, 2015; Torreggiani et al., 2018). Previous work on the network structure of food trade often used a simplified form by either covering only the backbone (i.e., 80%) of global trade flows (Ercsey-Ravasz et al., 2012), or focussing only on a single commodity (Konar et al., 2011; Puma et al., 2015). The backbone of the food trade may provide sufficient insights in terms of global network metrics, but ignores most low and lower-middle income countries where nutrient adequacy is of most concern.

In our analysis of nutrient trade networks, trading countries form *nodes* and nutrient trade between any two countries represent *flows* (*edges* in network terminology). Direction of the flows represents the direction of the trade, e.g., *outflows* from country i to j, or *inflows* to country i from country j. Flow weights represent total import/export volume for each nutrient when we aggregate all commodities contributing to a given nutrient. However, when we analyse commodity-level networks, flow weights represent commodity-specific nutrient information. Incorporating flow weights provides a weighted network while an unweighted version is obtained by ignoring the flow weights and simply representing the presence/absence of trade partnerships. Treating the network as undirected and unweighted shows trade partnerships between two nodes regardless of its direction and volume. Conversely, directed networks present the direction of flows (e.g., export from node i to j), and weighted networks provide information regarding the extent of such flows. We used the igraph package (version 1.2.5) in R (version February 1, 5033) for network analysis (Csardi and Nepusz, 2006).

Topological properties of networks differ as represented by a range of complimentary local and global metrics (De Benedictis et al., 2014). While local metrics are concerned with characteristics of individual nodes (i.e., countries), global metrics describe the overall network structure. We used a selection of both global and local network metrics (Table 2) to understand the structure of global nutrient trade networks and the network characteristics of individual countries. Key indicators of interest are network density and three assortativity metrics at the global level which provide insights into the connectedness and heterogeneity of connection among trading countries.

To describe local network characteristics, we chose two centrality metrics which quantify the position of a given country within the network: degree and strength. We compared local metrics per income group to examine specific network features. Finally, we explored major food sources of nutrient imports/exports by using commodity-level (e.g., carrot-based vitamin A trade) networks.

Table 2
Description of the global and local network metrics used in our analysis. Mathematical formulas apply for $i = 1, \ldots, N$ for $\forall\, i \neq j$.

Description		Direction and weight	Mathematical formula
Global metrics			
Density	Ratio of actualized trade partnerships (e.g., trade flows) over their potential number. Density ranges between 0 and 1, with 1 meaning a densely connected network.	Directed, unweighted	$D = \frac{M}{N(N-1)}$ M: number of flows N: total number of nodes
Degree assortativity	Assortativity, in broad terms, is a correlation coefficient comparing the node attributes among nodes that are linked to each other. In network analysis, the most-commonly used indicator is degree assortativity (Konar et al., 2011; Sartori and Schiavo, 2015) with which the tendency of nodes with high/low node degree (i.e., number of incoming/outgoing edges) to connect to those with high/low node degree is assessed. We used directed degree assortativity to assess the similarity of the outdegree of exporting countries and indegree of corresponding importing countries. Being a correlation coefficient, it ranges between −1 and 1, with 1 suggesting that countries with high (low) number of export partners tend to partner with countries with high (low) import partners. In contrast −1 suggests an inverse relationship (disassortative) while 0 shows lack of correlation (unassortative).	Directed, unweighted	$r = \frac{1}{\sigma_o \sigma_i} \sum_{jk} jk\left(e_{jk} - q_j^o q_k^i\right)$ e_{jk}: fraction of all edges connecting node of indegree/instrength j to one with outdegree/outstrength k $q_i^o = \sum_j e_{ij}$ and $q_i^i = \sum_j e_{ji}$, σ_o: standard deviation of q^o σ_i: standard deviation of q_i (Newman, 2003)
Degree assortativity$_{\text{weighted}}$	Assortativity can be un-/directed and un-/weighted. We used directed strength assortativity (out-in) to investigate how similar outstrength of exporting countries and instrength of corresponding importing countries are. We compared the similarity of the outstrength of exporting countries with instrength of partnering countries. It ranges between −1 and 1, and the former (latter) indicates trade partnership between nodes of similar (opposite) degrees. The range and interpretation of weighted degree assortativity is the same as its unweighted counterpart, with trade volume (e.g., strength) replacing number of trade partners in similarity.	Directed, weighted	Same as above except that e_{jk} refers to the fraction of edges that connect a node of nutrient adequacy of production j to one with nutrient adequacy of production k
Nutrient adequacy assortativity	As an indicator of homophily among node attributes, assortativity can be used with different features of interest other than degree. Given our interest in nutrient adequacy, we used this metric to explore how similar nutrient adequacy is among trading partners. We compared nutrient adequacy of production values between exporting and importing countries by adopting directed assortativity. The range and interpretation of nutrient adequacy assortativity is the same as other assortativity metrics, but similarity is assessed based on countries' nutrient adequacy of production.	Directed, unweighted	$r = \frac{\sum_i e_{ii} - \sum_i a_i b_i}{1 - \sum_i a_i b_i}$ e_{ij}: fraction of edges connecting vertices type i and j, $a_i = \sum_j e_{ij}$ and $b_j = \sum_i e_{ij}$ (Newman, 2002)
Local metrics			
Node degree	Node degree refers to the number of other nodes a given node i is connected to (e.g., indegree for import partners and outdegree for export partners) regardless of trade volume. Node degree can be between zero (no import/export partner) and one less the total number of all countries.	Directed, unweighted	$\mathbf{k}^{\mathbf{in}} = \sum^{j} a_{ji}$ $\mathbf{k}^{\mathbf{out}} = \sum^{j} a_{ij}$ a: binary adjacency matrix element (Sartori and Schiavo, 2015)
Node strength	The weighted counterpart of node degree is node strength (e.g., instrength, outstrength) which is the total import/export quantity for a given country. It ranges between zero and the maximum import/export volume among all countries.	Directed, weighted	$\mathbf{s}^{\mathbf{in}} = \sum^{j} w_{ji}$ $\mathbf{s}^{\mathbf{out}} = \sum^{j} w_{ij}$ w: sum of trade volume (Sartori and Schiavo, 2015)

3. Results

3.1. Nutrient adequacy effect of food trade

International food trade distributed dietary nutrients through imports and exports, altering the nutrient availability of countries. Trade-affected nutrient adequacy of supply varied across income groups (Fig. 2). In the high-income group, mean adequacy of supply for protein, iron, zinc, vitamin A, and B12 was lower than that of production because most countries in this group are net exporters of these nutrients. Nevertheless, mean adequacy of supply remained well above 1. Similarly, in the upper-middle income group, mean nutrient adequacy of supply for energy and folate was slightly lower than that of production but still remained adequate. At the country-level, however, high and upper-middle income countries with inadequate production, such as Singapore, Kuwait and Malta, observed the largest trade-induced

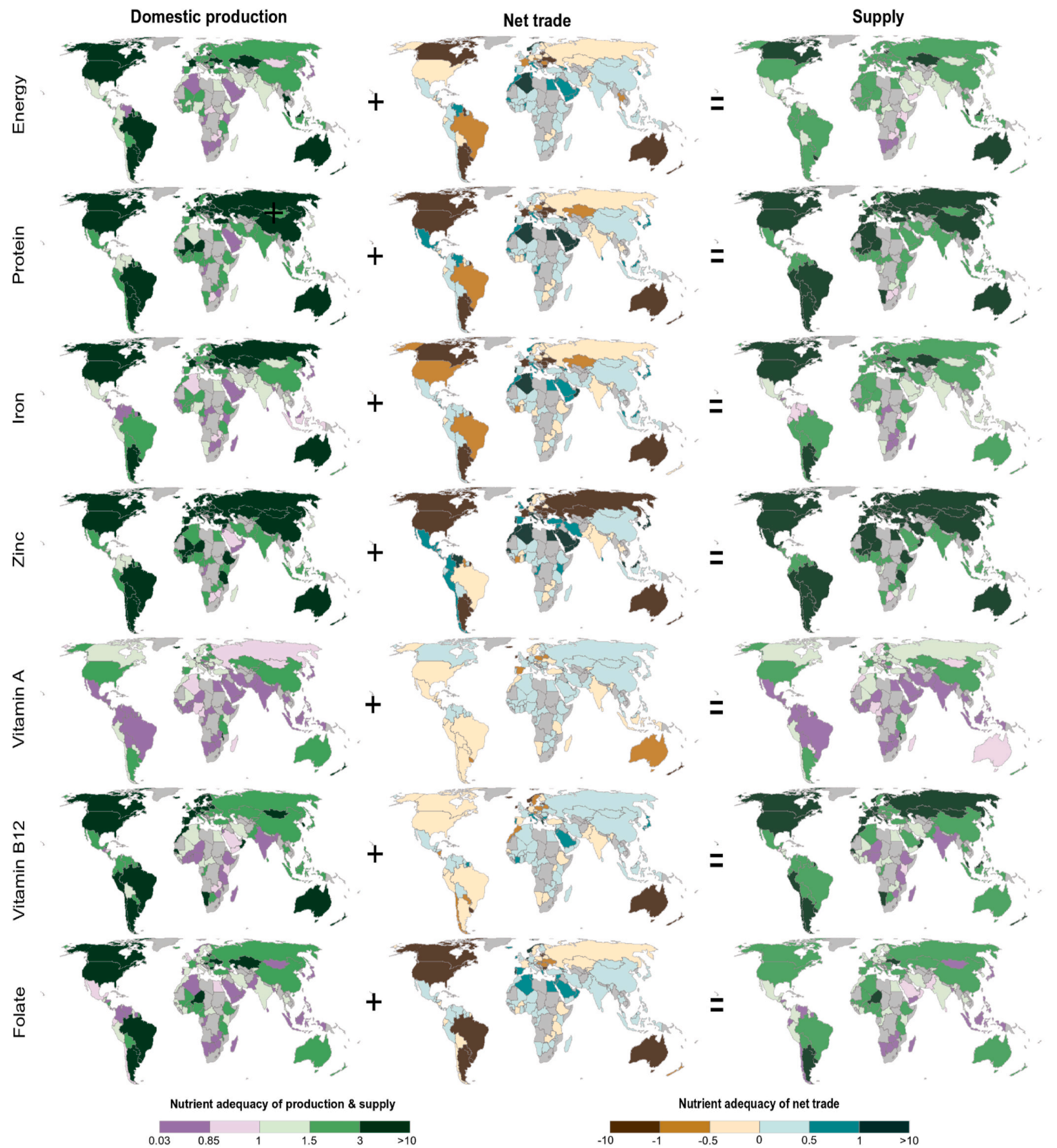

Fig. 1. Country-level nutrient adequacy based on domestic production, net trade (imports – exports) and supply (domestic production + net trade) for the period 2013–15. It highlights inadequate micronutrient availability such as in vitamin A and B12 in Sub-Saharan Africa and Southern Asia even after trade. Grey indicates missing data.

increases for all nutrients (Data S4). In the low and lower-middle (low/lower-middle hereafter) income groups, mean nutrient adequacy of supply was slightly higher than the adequacy of production across all nutrients.

In the high income group, most countries with inadequate production managed to have adequate nutrient supplies after trade for all nutrients. Most upper-middle income countries managed to reach adequate levels of supply for energy, protein, iron, zinc, and folate even when their nutrient adequacy of production was very low (<0.85). However, nearly half of those with low vitamin A and B12 adequacy of production still has inadequate supply even after trade.

Among 47 low/lower-middle income countries, one had inadequate zinc, four had inadequate protein, 11 had inadequate iron and folate, 13 had inadequate vitamin B12, 15 had inadequate energy, and 35 had inadequate vitamin A production. The gap in nutrient adequacy of production varied greatly among countries in the low/lower-middle income groups. Almost all of these countries increased their nutrient adequacy via imports. Southern and South-Eastern Asia showed somewhat smaller gains from trade compared to other lower-middle income countries of Africa. Nevertheless, those with low nutrient adequacy of production managed to reach nutrient adequacy after trade while those with very low adequacy, including highly populated countries such as India, Bangladesh, and Indonesia, did not. In South and Central America (except El Salvador), the Caribbean, and Eastern Europe, all lower-middle income countries with low iron, folate, vitamin A and B12 adequacy of production remained low in supply even after trade.

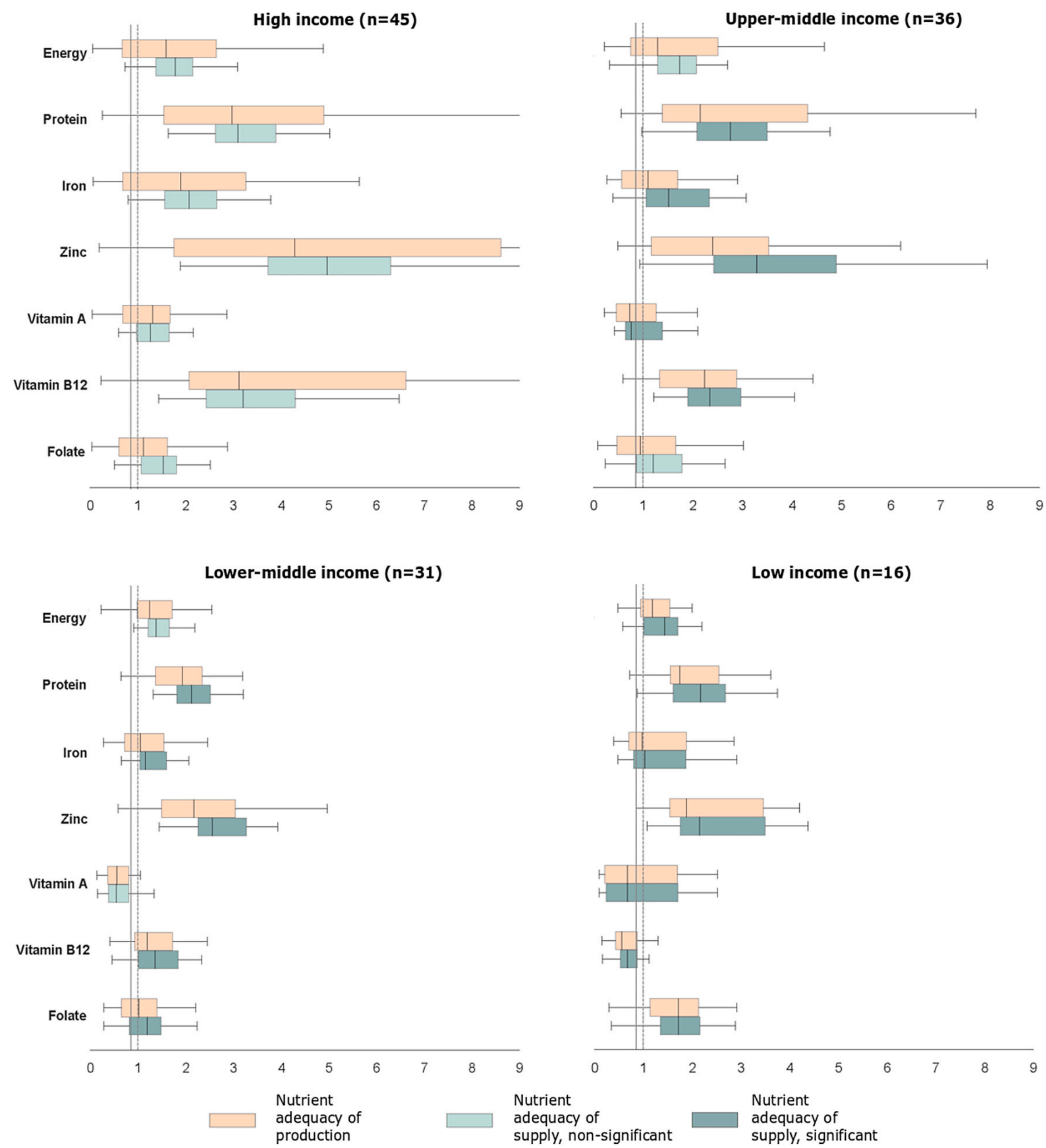

Fig. 2. Spread of nutrient adequacy with and without trade across income levels. Darker green highlights statistically significant ($\alpha = 0.05$) results at the income level according to two-tailed Wilcoxon Signed-Rank test (see Table S2 for test results). The figure highlights the limited change after trade in low and lower-middle income countries. Whiskers of the boxplots extend to $\pm$ 1.25 interquartile range while the inner line shows the median. We restricted x-axis values for visibility purposes (see Data S4 for country-specific results). Solid lines indicate very low adequacy (<0.85) and dashed line borders show low adequacy ([0.85,1)). Number of countries (n) per income group is given in parentheses. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Low income countries of Sub-Saharan Africa observed only a slight increase in their nutrient adequacy with trade, particularly for the most limited nutrients like vitamin A and B12. The observation on limited change with trade was similar within this subset of countries with a few exceptions. Since the nutrient adequacy of production is often well below 1 for these countries, the subtle contribution of trade was not sufficient to provide them with adequate supply of iron, folate, vitamin A and B12. Several Sub-Saharan African countries in the lower-middle income group experienced greater increases compared to those with low income. Yet, most of those with very low nutrient adequacy of production still remained inadequate with trade except for a few countries such as Eswatini and Zambia (Fig. 1).

3.2. Global nutrient trade networks

The unweighted topological network metrics indicated a high network density (Table 3) reflecting the large amount of realized trade links relative to the total number of potential trade connections. Since all food commodities embody calories but may lack certain nutrients like vitamins and minerals, energy showed the largest number of links and the highest network density. In contrast, since vitamin B12 is largely limited to animal-based food sources, it displayed the smallest number of links and lowest network density. The nutrient networks were also strongly connected such that every country had direct or circuitous ties with the others revealing the complexity of the global food trade.

We found weak negative degree assortativity across all nutrients (Table 3). This shows that there is some tendency for countries with many export partners to form partnerships with those having few import partners. Such structure is defined as *hub-and-spoke* structure in network terminology (Sartori and Schiavo, 2015). On the other hand, weighted degree assortativity, having incorporated the volume of the global food trade networks, was near zero. This contrast suggests that flows from the countries with many export partners to those with few import partners typically involve low volumes (Barrat et al., 2004). In addition to degree assortativity, we quantified nutrient adequacy assortativity to assess similarity in nutrient adequacy of production between trading partners. Unassortative patterns were observed for all nutrients indicating no preferential attachment between partners in terms of production-based nutrient adequacy. In other words, nutrient exports do not necessarily move from adequate to inadequate countries.

The backbone of the global nutrient networks, representing ≥80% of the global bilateral trade volume, consisted of less than one-third of all countries that are typically high or upper-middle income (Fig. 3). Most of the importers already had adequate production in the backbone of global energy, protein, iron, zinc and vitamin B12 trade networks. This observation is consistent with unassortative nutrient adequacy patterns as both suggest no preferential trade flows from adequate to inadequate countries. Similarly, the export market concentration ratio, defined as the total market share of the top four exporters, was around 30% for vitamin B12, 32% for vitamin A, 40% for energy, around 45% for protein, iron and zinc, and 56% for folate (Data S3). Consequently, nutrient exports showed high concentration that is typical for trade in major agricultural commodities (FAO, 2018).

Regarding key trade actors, China was by far the largest net nutrient importer as it accounted for ≥20% of net energy, protein, iron, zinc, and vitamin B12, in addition to >40% of net folate imports. Japan (11%) and Russia (10%) were the largest net vitamin A importers. On the exporter side, the USA was the largest net exporter of protein, iron, zinc and folate despite being a large importer of these nutrients itself. Brazil, the USA, Canada and Argentina accounted for more than 50% of energy, protein, iron and folate net exports. Canada was in the second place after the USA for net zinc exports. The Netherlands and New Zealand each represented 13% of net vitamin A exports. Lastly, Australia (14%) and New Zealand (10%) accounted for a quarter of net vitamin B12 exports.

Commodity-level networks showed that more than half of the global energy trade volume was attributed to wheat products (e.g., wheat, wheat flour and bread), sugar products (e.g., cane/beet raw sugar and refined sugar), rice and soybeans. Global iron and zinc trade were largely (>70%) attributed to wheat products and maize products (e.g., maize and maize flour), barley products (e.g., barley and pearled barley), rice and soybeans. Similarly, wheat products, soybeans, pulses and beans accounted for 80% of folate trade. Vegetables, particularly carrots and tomato products (e.g., tomato and tomato juice/paste, etc.), dairy products (e.g., milk, dried milk, butter etc.) and fruits accounted for more than 70% of vitamin A trade while seafood, dairy products and ruminant products (e.g., meat and offals) covered more than 70% of vitamin B12 trade.

3.3. Nutrient trade networks by income level

Bilateral flows (Data S2) of most low/lower-middle income countries were largely missing from the backbone of the global nutrient trade except for a handful of countries such as Bangladesh, the Philippines, and Yemen. We analysed the local network metrics by income group and illustrated the trade network of low/lower-middle income countries to reveal distinctive trade patterns. On average, we found smaller node degrees particularly for low income countries (Fig. 5). Node strength was also much lower for the low/lower-middle income groups. Difference across income levels was much more pronounced for vitamin A and B12. Smaller shares by the low/lower-middle income groups were even more striking (Fig. 4) as these countries represent more than 40% of total population while accounting for less than 15% of total node strength for all nutrients. The largest share of total trade occurred within the high income group and it was closely followed by exports from the high income to upper-middle income group for all nutrients (Fig. 4). Intra-class trade among the high-income group was highest for vitamin A and B12. Nutrient imports from the high-income group to the low and lower-middle groups represented less than 15% and 1%, respectively.

Nutrient imports were highly concentrated in the trade networks of low/lower-middle income countries (Fig. 6). On average, ten countries accounted for around 80% of total imports for all nutrients while their average number of import partners was at least six times as large. Market concentration of the major import partners was slightly higher for vitamin A and B12 for which the largest two partners already accounted for half of total imports in several countries of the low income group (Data S2). For the low income group, countries of which are entirely located in Sub-Saharan Africa, several countries from high (France, Russia, and the USA), lower-middle (India and Pakistan), and upper-middle (Argentina, China and Thailand) income groups emerged as the key partners with the highest frequency for energy, protein, iron,

Table 3
Network topology metrics for the global food trade network.

Nutrient	Density	Degree assortativity	Degree assortativity$_{weighted}$	Nutrient adequacy assortativity	Number of trade links
Energy (10^{12} kcal)	0.61	−0.23	−0.06	−0.01	9864
Protein (10^{12} g)	0.59	−0.24	−0.04	−0.01	9675
Iron (10^{9} mg)	0.61	−0.23	−0.04	−0.01	9849
Zinc (10^{9} mg)	0.60	−0.23	−0.04	−0.01	9831
Vitamin A (10^{9} μg)	0.55	−0.24	−0.09	−0.02	8917
Vitamin B12 (10^{9} μg)	0.42	−0.25	−0.10	−0.01	6847
Folate (10^{12} μg)	0.59	−0.24	−0.03	−0.01	9643

Fig. 3. The backbone of global food trade (representing ≥ 80% of total volume) for all nutrients in 2013–15. Node colours represent nutrient adequacy of production such that purple shades represent inadequate while green shades suggest adequate production. Node sizes represent income levels based on World Bank grouping that are defined by using Gross National Income per capita (Table 1) so that the largest-sized nodes belong to the high income group while the smallest-sized nodes belong to the low income group. Since the flow directions represent net trade between any pair of trade partners nodes with a larger number of inflows of higher volume than outflows tend to be net importers, e.g., New Zealand in vitamin A network; or, vice versa, e.g., China in vitamin B12 network. We used Cytoscape (Shannon et al., 2003) to draw the networks. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

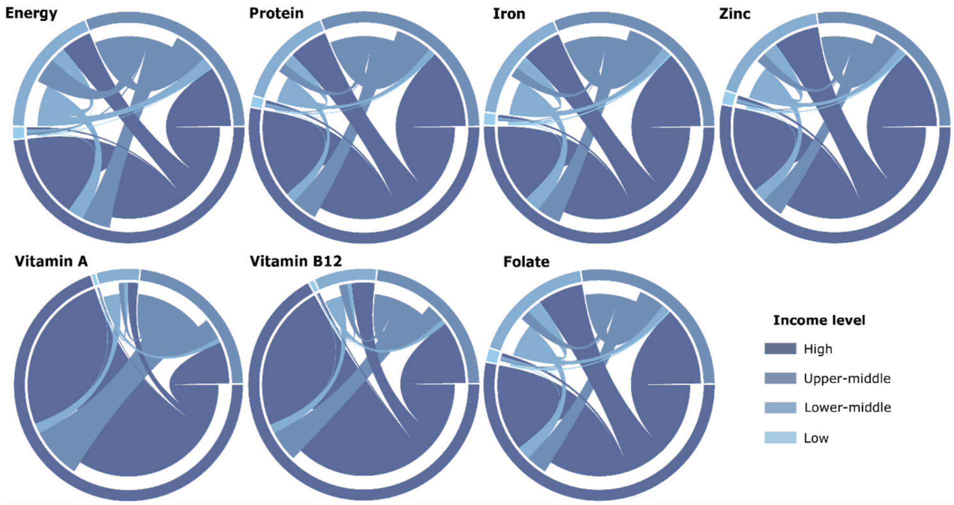

Fig. 4. Nutrient trade flows among income groups. Nutrients are distributed from where the flow is further away from the outer rim towards where it is closer to the outer rim. For example, a larger portion of nutrients moves within the high-income group. It also shows the low trade volume observed by the low and lower-middle income groups. Trade volumes are given for each country in Data S3.

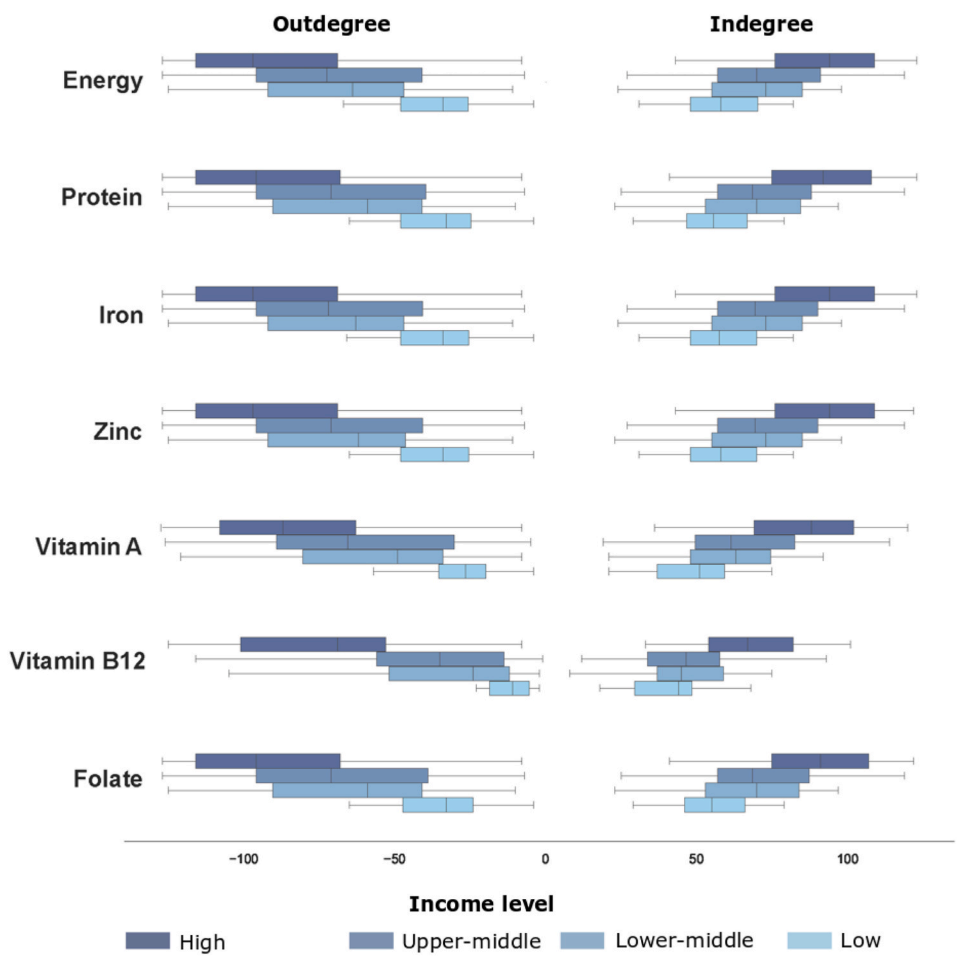

Fig. 5. Distribution of node in-/out-degrees across income groups and nutrients. Box plots show minimum, maximum and median values per income group (see Data S5 for country-specific node in-/outdegrees). The figure suggests that most low income countries have the smallest number of trade partners. Outdegree values are plotted against indegree values as the former represent the number of export partners hence the negative coordinates.

zinc, and folate imports. Looking at the commodity-level nutrient trade networks, wheat was the primary imported source of energy, protein, iron, zinc and folate while rice dominated imports of those nutrients from India, Pakistan and Thailand. Protein, iron, zinc and folate imports from Argentina was dominated by wheat while the bulk of its energy exports was based on soybean oil. In contrast, all nutrient imports from China were largely based on vegetables, particularly carrots and tomato products.

Fig. 6. Backbone of the nutrient trade network of the low and lower-middle income countries. Node colours represent nutrient adequacy of domestic production. Purple shades show nutrient adequacy below 1 and green shades show those of above 1. Node sizes represent World Bank income groups. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

The USA was by far the one with a much bigger number of links as an energy, iron, zinc and folate exporter to the lower-middle income group. Its exports were dominated by wheat. Additionally, other countries from high income (Canada, France and Russia), upper-middle income (Argentina, Brazil, Kazakhstan and Thailand), and other lower-middle income (India and Ukraine) countries were the most-frequent trade partners exporting to the lower-middle income group. Sources of nutrients were similar to those of the low income group such that wheat was the primary commodity for energy, protein, iron, zinc, and folate imports from Canada, France, Russia, Ukraine and Kazakhstan. Argentina and Brazil's energy exports to lower-middle income countries, however, were dominated by soybean oil and sugar, respectively. Imports from Thailand were mostly based on rice across all nutrients while those from India were largely based on wheat for all but energy. In contrast to other nutrients, rice represented the most of India's energy exports to lower-middle income countries.

For vitamin A, high income countries (Italy and the Netherlands) and upper-middle income countries (China and Malaysia) were the key trade partners exporting to low income countries. While imports from the Netherlands were mostly animal products such as offals, dairy products, and poultry, Italy's major exports were dominantly tomato products and other vegetables (e.g., carrots) too. Vegetables constituted most vitamin A imports from China and Malaysia's vitamin A exports were dominated by dairy and eggs. On the other hand, New Zealand and the USA were by far the most common trade partners exporting to lower-middle income countries, followed by other high income countries like Australia, France, Ireland and the Netherlands in addition to upper-middle income China and Brazil. Dairy products provided the most of vitamin A imports from New Zealand and the USA in addition to offals and pelagic fishes (e.g., tuna and sardines) in the former and poultry and soybean oil in the latter. China's exports, on the other hand, were dominated by tomato products, carrots, oranges, apples and molluscs.

High (France and the Netherlands), upper-middle (China) and lower-middle (Morocco) income countries acted as the most frequent vitamin B12 partners exporting to low income countries. Imports from France and the Netherlands were mostly based on poultry, dairy and pelagic fishes while China and Morocco exported their vitamin B12 predominantly through pelagic fishes and other marine and freshwater fishes. In contrast, lower-middle income countries partnered mostly with high income countries (the Netherlands, New Zealand, and the USA) for their vitamin B12 imports. Offals, dairy and pelagic fishes dominated these nutrient flows. Brazil's exports of offals, bovine meat and poultry and China's seafood exports were also common vitamin B12 sources from the upper-middle to the lower-middle income group.

4. Discussion

4.1. Key findings

We have quantified the impact of international food trade on nutrient adequacy of national food supplies (e.g., domestic production + net trade) with a focus on low and lower-middle income countries. International food trade distributes substantial volumes of dietary nutrients and its impact on nutrient availability differs between countries. In low/lower-middle income countries, the role of trade in bridging the nutrient adequacy gap was only marginal. While international trade closed the nutrient gap in most high and upper-middle income countries even where domestic production was of very low adequacy, low/lower-middle income countries did not gain enough from trade in this sense.

Despite the common perception that trade bridges surplus and deficit regions (Janssens et al., 2020), nutrients did not necessarily move from countries with adequate nutrient production to those with inadequate production. Nutrient exports showed high (between 36% and 60%) market concentration and the backbone (80%) of the global trade consisted typically of upper-middle and high income countries. Several high and upper-middle income countries such as the USA, France, Russia, Argentina, and Thailand were key suppliers of energy, protein, iron, zinc and folate through cereals. Yet, most low/lower-middle income countries had a peripheral role in global nutrient networks despite the need for imports to close their nutrient adequacy gaps.

For vitamin A and B12, both of which are essential micro-nutrients, the bulk of the global trade occurred within the high income group. New Zealand, the Netherlands, the USA and China were other major suppliers of these nutrients. The smallest import/export volume was observed in the low income group, where these nutrients are most in need.

4.2. Significance and innovation

Our findings based on a network analysis of the global nutrient trade, which we reconstructed by using detailed commodity trade data, provide a differentiated approach to the debate on international food trade and nutrition. Complementary to the current literature relating trade liberalization with increased calorie availability (D'Odorico et al., 2019), improved access to food (Minot and Goletti, 2000; Rafeek and Samaratunga, 2011; Rutten et al., 2013) and higher supply diversity (Aguiar et al., 2020); or, increased number of overweight/obese people and related NCDs (Baker et al., 2014; Clark et al., 2012; Thow, 2009), impoverished livelihoods (Ford et al., 2014) and reduced nutrient intake by the poorest (Panda and Ganesh-Kumar, 2009), we provided insights as to how international trade redistributes dietary nutrients. Based on our high-resolution analysis complemented by network metrics, nutrient flows do not necessarily move from adequate to inadequate countries. Although our findings agree that food trade often improves nutrient adequacy of supply for low/lower-middle income countries (D'Odorico et al., 2014; Dithmer and Abdulai, 2017), we found the extent of this positive impact to be limited where nutrient adequacy of production is very low and the need for these essential nutrients are highest. Recent findings based on aggregate (e.g., FBS) agricultural data that support the view that food trade reduces nutritional inequality (D'Odorico et al., 2019; Wood et al., 2018) may therefore need to be revisited.

Our methodology is also innovative. Most of the current nutrient supply estimates (Beal et al., 2017; Bezuneh and Yiheyis, 2014; Kumssa et al., 2015; Wessells et al., 2012) used broad food groups (e.g., Food Balance Sheets of the FAO) blurring the specific food-nutrition linkages. For example, seafood, which is a crucial part of dietary nutrients in the global south (Belton and Thilsted, 2014), is a particularly broad category in the FBS. This poses the risk of aggregation errors that can lead to significant over-/under-estimations (Geyik et al., 2020). Moreover, network analysis has often been used to assess the vulnerability of global food systems but studies have focused on aggregate food trade (Sartori and Schiavo, 2015) or on single commodities (Fair et al., 2017; Puma et al., 2015), without consideration to specific nutrient flows. Conventional approaches to network analysis in food trade also often bundle all countries, in contrast to our method, into one global network, which may mask country-specific circumstances particularly for low income countries of which trade network metrics vary greatly. Our disaggregated approach - differentiating among World Bank income groups - revealed a smaller number of trade partners and higher market concentration, especially for the most-commonly inadequate nutrients like vitamin A and B12. In terms of global network metrics, we found the global food trade to be of higher density. This indicates higher connectivity among the studied countries compared to the values found in the relevant literature (Dupas et al., 2019; Sartori and Schiavo, 2015) which we attribute to the difference in the number and composition of countries and commodities.

4.3. Policy implications

Most countries supply the bulk of their nutrients through domestic production while international food trade complements and buffers local food production shortfalls in several countries (Friel et al., 2020; Kinnunen et al., 2020; Porkka et al., 2017). Comparative and competitive advantage, income, geographical location and trade and other economic policies jointly determine trade structure and food basket composition (Jambor and Babu, 2016). Hence, production and trade profiles, and nutrient gaps, varied substantially across countries. Policymakers could prioritize domestic production of certain nutrients that their populations lack and have the resources to produce while selectively benefiting from international trade for others.

The right to food requires countries to enable suitable conditions for food security (D'Odorico et al., 2019). The financial resources that poor countries could allocate to food production are already limited. Resource poor economies often face multiple development challenges and competing objectives in relation to food policies. However, broader macroeconomic policies need to account for micro-level nutritional impacts (Babu et al., 2017a). Achieving adequate supplies at the population-level do not necessarily equate to enhanced nutritional status at the individual-level due to access- and utilization-related determinants. Factors that have been increasingly more important are food entitlements, nutritional capabilities and the relationship between food intake and nutrition. The latter requires a range of complementary policies that aim to improve education, health care, sanitation, and clean drinking water services, in addition to macro-economic policies to reduce the wealth gap and to enhance the livelihoods of the poor (Babu et al., 2017b; Dreze and Sen, 1989; Gillespie and van den Bold, 2017; Panda and Ganesh-Kumar, 2009). It is also important to understand consumer behaviour at different income quantiles (Babu et al., 2017b).

Government support policies could be adjusted to improve nutrient supplies through different pathways. For instance, local production of vitamin A is not adequate in most low/lower-middle income countries, yet it is not necessarily produced abundantly in upper-middle and high income countries either. Hence, the former which exhibit low vitamin A adequacy of supply – such as Ethiopia, Guatemala, Mongolia and Egypt – could invest in domestic production of vitamin A-rich crops including cabbages, carrots, pumpkins, squash and sweet potatoes which are already produced across these countries, albeit at low yields (FAOSTAT, 2019b). Efforts to reduce pre- and post-harvest losses could be enhanced towards these commodities, given that vegetables and fruits are easily perishable, with particularly high losses being observed during processing (up to 25%) and distribution (up to 17%) in low income countries (FAOSTAT, 2017). Domestic support measures could be directed to target improved supplies of these micronutrient-rich commodities. Adverse nutritional outcomes are observed when the food self-security goals are approached from a staples-dominated perspective and, hence, there is little incentive for farm diversification and extension investments (Babu et al., 2017a).

Low/lower-middle income countries could benefit more from international trade for the supplies of vitamin B12 because production is abundant in the upper-middle and high income countries. In the bottom ten countries with the lowest levels of vitamin B12 adequacy, home to ~1.9 billion people, trade contributes to only a small (5.8%) increase in overall supplies. Currently, these countries apply tariffs that are much higher on vitamin B12-rich products – such as dairy, fish and meat – than those applied on food products in general. Based on the World Trade Organization's tariff profiles data, in the bottom ten countries excluding India the average of applied tariffs on animal, dairy and fish products are 30% higher than the simple average most-favoured-nation (referring to non-discriminatory tariff) rates applied on other agricultural products (World Trade Organization, 2019). The average tariff difference is as high as 60% for Uganda, Burundi and Tanzania. These tariffs could selectively be lowered on vitamin B12-rich products to gradually increase the contribution of trade to B12 adequacy. Countries such as Burundi and Uganda which exhibit inadequate iron supplies could also lower their trade barriers for products such as pulses and beans, in addition to seafood and meat, to increase iron adequacy of supply. While this policy would lead to wider implications in relation to domestic production, tariff revenues and the balance of payment, it would increase domestic consumption as lowering tariffs would reduce the domestic price of these commodities.

Net-exporting low/lower-middle income countries with inadequate nutrient production may prefer to avoid exporting commodities that are rich in these nutrients. For example, despite having inadequate production, Cabo Verde and Guatemala were net vitamin A exporters to high and upper-middle and high and lower-middle income countries, respectively. Dairy products dominated exports to most countries while vegetables also played a significant role in exports to high income countries most of which already producing adequate vitamin A. Selective export restrictions could be imposed on vitamin A-intensive commodities. Taxes that could be imposed on exports to high/upper-middle income countries, while avoiding prohibitive taxes to low/lower-middle income countries, would increase domestic availability of supplies without inflicting damage on the latter group. Export restrictions that serve the objective of preventing domestic food shortages are lawful under international trade law (Karapinar, 2012).

In order for low/lower-middle income countries to improve their nutrient adequacy through trade, high and upper-middle income countries should ensure their export supplies are reliable and predictable. Our network analysis shows that the bulk of trade is among the high and upper-middle income groups. While low income countries have limited prominence in international trade networks, they are disproportionately affected by price hikes and volatility in global markets as experienced during the food crisis of 2007–8. Export restrictions created shortages and consequent anxiety on the global market, sparking a spiral of disruptive measures. The resulting price hikes and volatility are particularly damaging for low/lower-middle income countries. Hence, high and upper-middle income countries with large domestic production volumes should avoid restricting their food exports (Janssens et al., 2020).

As experienced during the COVID-19 pandemic, as well as in the past, several key export partners of low/lower-middle income countries, such as Russia, Kazakhstan, Ukraine and Viet Nam, have imposed export restrictions in times of crisis (Beckman et al., 2019). Russia, the world's largest exporter of wheat, imposed an export quota on grains for April–June 2020 amid the COVID-19 pandemic and drought conditions in its wheat producing regions (Russian Prime Minister, 2020). Ukraine and Romania followed with their own restrictions. Viet Nam and Myanmar restricted their rice exports, Thailand banned exports of eggs (FAO, 2020). A stricter regulation of this area of international trade policy, which is largely unregulated by international trade law, is needed. Numerous reform proposals have been placed on the agenda of the World Trade Organization since the food crisis of 2007–8. A future trading system where importing countries' obligations to reduce import barriers are balanced with major exporting countries' obligations to provide reliable supplies is essential for global nutrition security (Tanaka and Karapinar, 2019).

Regional integration of trade is also critical to improve nutrition security at the regional level and to reduce risks in relation to international markets. Our network analysis reveals that most low income countries of Sub-Saharan Africa import at least a third of their vitamin A and B12 from within the region, Morocco being a large livestock exporter, highlighting the importance of intra-regional trade. Efforts to deepen regional integration through bilateral and regional trade agreements, and through investments in regional connectivity, would enhance nutrient adequacy at the regional level. It is important to note that a higher regional integration in food trade requires increased production and yields in Sub-Saharan Africa because current production patterns fail to mee nutritional requirement at the regional level (Geyik et al., 2020).

Finally, global nutrient supplies have been and are likely to be exposed to the increasing risks of weather-induced productivity shocks due to climate change. Major cereal yields could decline, weather-induced yield volatility increases, and the centers of production move to geographies that are more vulnerable to the impacts of climate change (IPCC, 2014). Increased reliance on imports is a risk factor for food systems resilience (Suweis et al., 2015) and can have a cascade effect through teleconnected climatic and political risks (Bren D'Amour et al., 2016), while the exposure of domestic production to climate change carries its own risks (Janssens et al., 2020). Hence, for low/lower-middle income countries which already experience inadequate nutrient supplies, achieving nutrient adequacy will be more challenging than ever. Nutrition-sensitive climate risk assessment, adaptation and mitigation policies are needed to address these challenges.

4.4. Major assumptions and limitations

Production and trade data present inherent quality limitations which may lead to under-/overestimations in adequacy quantification and the role of trade. For example, a number of lower income countries have a higher percentage of missing data or data reported as *not elsewhere stated (nes)* which aggregate different commodities into a single category such as *Vegetables, fresh nes.* However, FAO databases remain as the primary reference for national agricultural statistics of global coverage (D'Odorico et al., 2019; Wood et al., 2018). Because we do not have re-export/import information, we cannot draw conclusions on potential interdependencies among countries through third-party nodes serving as indirect linkages. However, our focus on primary (e.g., wheat) and primary processed products (e.g., wheat flour) rather than ultra-processed commodities (e.g., biscuits) is likely to involve limited re-exports/re-imports. Similarly, trade data may include food aid for some countries (FAOSTAT, 2019a), for instance Yemen, leading to overestimations in the role of trade while also highlighting the need for nutrition-sensitive food aid. Nevertheless, country-specific import shares are less than 2% for those countries.

Our assumption of moderate bioavailability may under-/overestimate the role of trade because combination of nutrients and antinutrients (e.g., phytate, calcium oxalate and tannins) in diets, in addition to underlying health conditions of the individuals, has a strong influence on the absorption of iron and zinc. For instance, an abundance of phytate-rich cereals in contrast to limited amount of absorption-enhancing animal food sources may reduce bioavailability (Beal et al., 2017; Geyik et al., 2020; Wood et al., 2018). Furthermore, our estimates likely overestimate what is actually available for consumption due to not controlling for food losses which can be significant for perishable commodities such as vegetables and fruits (FAOSTAT, 2017).

Feeding grain to livestock converts vitamin A and B12-poor crops into vitamin A and B12-rich animal products while reducing the availability of several other nutrients. Therefore, subtraction of the feed use may omit the indirect role of trade but provides a more realistic assessment of what is available for direct consumption as opposed to not accounting for feed grain use as done in the literature (Wood et al., 2018). However, this is more likely so for high and upper-middle income countries because cereals are mainly used for human consumption in the least developed countries (FAOSTAT, 2017). Therefore, indirect contribution of trade, as animal feed, to vitamin A and B12 adequacy is also limited in those countries.

5. Conclusion

We showed that more than 40% of the global population, mostly from low/lower-middle income countries, remain at the periphery of the global food trade networks and continue to experience inadequate nutrient supply even with trade. Current food trade flows, the majority of which occur between high and upper-middle income countries, do not favour reorientation of nutrients from nutrient-abundant to inadequate regions. For low/lower-middle income countries, typically low trade volumes, coupled with predominance of lower-cost commodities like cereals, result in limited improvement in adequacy of particularly vitamin A and B12. Low/lower-middle income countries need a diverse portfolio of nutrition-sensitive food policies that would complement broader macroeconomic policies. These include production- and trade-related measures that target nutrients in need. Domestic support measures could prioritize enhancing production of and infrastructure for commodities high in the most limited nutrients such as vitamin A and B12. Tariff rates could be selectively lowered on commodities providing the nutrients most needed in low/lower-middle income countries where tariffs are often quite high. While low/lower-middle income countries with inadequate nutrient supply may increase their domestic availability by reducing exports of such commodities to high/upper-middle income countries, a similar approach by higher income countries would disproportionally impact low/lower-middle income countries. International trade laws and regulations also need to be reformed for trade to play a more conducive and reliable role in enhancing global nutrition security. Increased domestic production, selectively reduced import barriers, reliable export supplies and regional integration, together with policies to reduce inequality and enhance food entitlements, are essential for global nutrition security.

Data availability

All input data are publicly available through online sources given in the references. Results are provided online through Mendeley Data.

Declaration of competing interest

We wish to confirm that there are no known conflicts of interest associated with this publication and there has been no significant financial support for this work that could have influenced its outcome.

Acknowledgements

The authors acknowledge the financial support for research and publication of this paper: Deakin University, Australia (DUPR-STRATEGIC – 0000018831).

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.gfs.2021.100490.

References

Aguiar, S., Texeira, M., Garibaldi, L.A., Jobbágy, E.G., 2020. Global changes in crop diversity: trade rather than production enriches supply. Glob. Food Sec. 26, 100385 https://doi.org/10.1016/j.gfs.2020.100385.

Babu, S.C., Gajanan, S.N., Hallam, J.A., 2017a. Macroeconomic aspects of nutrition policy. Nutr. Econ 63–77. https://doi.org/10.1016/b978-0-12-800878-2.00005-0.

Babu, S.C., Gajanan, S.N., Hallam, J.A., 2017b. Microeconomic nutrition policy. Nutr. Econ. 43–62. https://doi.org/10.1016/b978-0-12-800878-2.00004-9.

Baker, P., Kay, A., Walls, H., 2014. Trade and investment liberalization and Asia's noncommunicable disease epidemic: a synthesis of data and existing literature. Glob. Health 10. https://doi.org/10.1186/s12992-014-0066-8.

Barrat, A., Barthélemy, M., Pastor-Satorras, R., Vespignani, A., 2004. The architecture of complex weighted networks. Proc. Natl. Acad. Sci. U. S. A 101, 3747–3752. https://doi.org/10.1073/pnas.0400087101.

Beal, T., Massiot, E., Arsenault, J.E., Smith, M.R., Hijmans, R.J., 2017. Global trends in dietary micronutrient supplies and estimated prevalence of inadequate intakes. PloS One 12, e0175554. https://doi.org/10.1371/journal.pone.0175554.

Beckman, J., Estrades, C., Aguiar, A., 2019. Export taxes, food prices and poverty: a global CGE evaluation. Food Secur 11, 233–247. https://doi.org/10.1007/s12571-018-0876-2.

Belton, B., Thilsted, S.H., 2014. Fisheries in transition: food and nutrition security implications for the global South. Glob. Food Sec. 3, 59–66. https://doi.org/10.1016/j.gfs.2013.10.001.

Bezuneh, M., Yiheyis, Z., 2014. Has trade liberalization improved food availability in developing countries? An empirical analysis. J. Econ. Dev. 39, 63–78.

Bose, I., Baldi, G., Kiess, L., de Pee, S., 2019. The "Fill the Nutrient Gap" analysis: an approach to strengthen nutrition situation analysis and decision making towards multisectoral policies and systems change. Matern. Child Nutr. 15, 1–11. https://doi.org/10.1111/mcn.12793.

Bren D'Amour, C., Wenz, L., Kalkuhl, M., Christoph Steckel, J., Creutzig, F., 2016. Teleconnected food supply shocks. Environ. Res. Lett. 11 https://doi.org/10.1088/1748-9326/11/3/035007.

Cepeda-López, F., Gamboa-Estrada, F., León, C., Rincón-Castro, H., 2019. The evolution of world trade from 1995 to 2014: a network approach. J. Int. Trade Econ. Dev. 28, 452–485. https://doi.org/10.1080/09638199.2018.1549588.
Clark, S.E., Hawkes, C., Murphy, S.M.E., Hansen-Kuhn, K.A., Wallinga, D., 2012. Exporting obesity: US farm and trade policy and the transformation of the Mexican consumer food environment. Int. J. Occup. Environ. Health 18, 53–65. https://doi.org/10.1179/1077352512Z.0000000007.
Csardi, G., Nepusz, T., 2006. The igraph software package for complex network research. Int. J. Complex Syst.
Cuevas García-Dorado, S., Cornselsen, L., Smith, R., Walls, H., 2019. Economic globalization, nutrition and health: a review of quantitative evidence. Glob. Health 15, 15. https://doi.org/10.1186/s12992-019-0456-z.
De Benedictis, L., Nenci, S., Santoni, G., Tajoli, L., Vicarelli, C., 2014. Network analysis of World Trade using the BACI-CEPII dataset. Global Econ. J. 14, 287–343. https://doi.org/10.1515/gej-2014-0032.
Dithmer, J., Abdulai, A., 2017. Does trade openness contribute to food security? A dynamic panel analysis. Food Pol. 69, 218–230. https://doi.org/10.1016/j.foodpol.2017.04.008.
Dreze, J., Sen, A., 1989. Production, entitlements and nutrition. In: Hunger and Public Action. Oxford University Press, New York, pp. 165–177.
Dupas, M.C., Halloy, J., Chatzimpiros, P., 2019. Time dynamics and invariant subnetwork structures in the world cereals trade network. PloS One 14, 1–21. https://doi.org/10.1371/journal.pone.0216318.
D'Odorico, P., Carr, J.A., Laio, F., Ridolfi, L., Vandoni, S., 2014. Feeding humanity through global food trade. Earth's Futur 2, 458–469. https://doi.org/10.1002/2014EF000250.
D'Odorico, P., Carr, J.A., Davis, K.F., Dell'Angelo, J., Seekell, D.A., 2019. Food inequality, injustice, and rights. Bioscience 69, 180–190. https://doi.org/10.1093/biosci/biz002.
Egbendewe, A.Y.G., Lokonon, B.O.K., Atewemba, C., Coulibaly, N., 2017. Can intra-regional food trade increase food availability in the context of global climatic change in West Africa? Clim. Change 145, 101–116. https://doi.org/10.1007/s10584-017-2083-0.
Ercsey-Ravasz, M., Toroczkai, Z., Lakner, Z., Baranyi, J., 2012. Complexity of the international agro-food trade network and its impact on food safety. PloS One 7, 1–7. https://doi.org/10.1371/journal.pone.0037810.
Fair, K.R., Bauch, C.T., Anand, M., 2017. Dynamics of the global wheat trade network and resilience to shocks. Sci. Rep. 7, 7177. https://doi.org/10.1038/s41598-017-07202-y.
FAO, 2018. The Future of Food and Agriculture – Alternative Pathways to 2050. Rome.
FAO, 2020. Why Export Restrictions Should Not Be a Response to COVID-19: Learning Lessons from Experience with Rice in Asia and the Pacific.
FAOSTAT, 2017. Food balance Sheets [WWW Document]. URL. http://www.fao.org/faostat/en/#data/FBS. accessed 8.3.19.
FAOSTAT, 2019a. Detailed trade matrix [WWW Document]. URL. http://www.fao.org/faostat/en/#data/TM. accessed 1.30.20.
FAOSTAT, 2019b. Production [WWW Document]. URL. http://www.fao.org/faostat/en/#data. accessed 10.20.19.
Ford, J.R.D., Dell'Aquila, C., Conforti, P., 2014. Agricultural Trade Policy and Food Security in the Caribbean, Agricultural Trade Policy and Food Security in the Caribbean. FOOD AND AGRICULTURE ORGANIZATION OF THE UNITED NATIONS, Rome.
Friel, S., Schram, A., Townsend, B., 2020. The nexus between international trade, food systems, malnutrition and climate change. Nat. Food 1. https://doi.org/10.1038/s43016-019-0014-0.
Geng, J.B., Ji, Q., Fan, Y., 2014. A dynamic analysis on global natural gas trade network. Appl. Energy 132, 23–33. https://doi.org/10.1016/j.apenergy.2014.06.064.
Geyik, O., Hadjikakou, M., Bryan, B.A., 2020. Spatiotemporal trends in adequacy of dietary nutrient production and food sources. Glob. Food Sec. 24, 100355. https://doi.org/10.1016/j.gfs.2020.100355.
Gillespie, S., van den Bold, M., 2017. Agriculture, food systems, and nutrition: meeting the challenge. Glob. Challenges 1, 1600002. https://doi.org/10.1002/gch2.201600002.
Hu, X., Wang, C., Lim, M.K., Koh, S.C.L., 2020. Characteristics and community evolution patterns of the international scrap metal trade. J. Clean. Prod. 243, 118576. https://doi.org/10.1016/j.jclepro.2019.118576.
IPCC, 2014. Summary for policymakers. In: Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change.
Jackson, M.O., 2019. Representing and measuring networks. In: Social and Economic Networks. Princeton University Press, pp. 20–53. https://doi.org/10.2307/j.ctvcm4gh1.5.
Jambor, A., Babu, S., 2016. In: Jambor, A., Babu, S. (Eds.), Food Security and Global Agri-Food Trade BT - Competitiveness of Global Agriculture: Policy Lessons for Food Security. Springer International Publishing, Cham, pp. 7–24. https://doi.org/10.1007/978-3-319-44876-3_2.
Janssens, C., Havlík, P., Krisztin, T., Baker, J., Frank, S., Hasegawa, T., Leclère, D., Ohrel, S., Ragnauth, S., Schmid, E., Valin, H., Van Lipzig, N., Maertens, M., 2020. Global hunger and climate change adaptation through international trade. Nat. Clim. Change. https://doi.org/10.1038/s41558-020-0847-4.
Karapinar, B., 2012. Defining the legal boundaries of export restrictions: a case law analysis. J. Int. Econ. Law 15, 443–479. https://doi.org/10.1093/jiel/jgs021.
Kinnunen, P., Guillaume, J.H.A., Taka, M., D'Odorico, P., Siebert, S., Puma, M.J., Jalava, M., Kummu, M., 2020. Local food crop production can fulfil demand for less than one-third of the population. Nat. Food 1, 229–237. https://doi.org/10.1038/s43016-020-0060-7.
Konar, M., Dalin, C., Suweis, S., Hanasaki, N., Rinaldo, A., Rodriguez-Iturbe, I., 2011. Water for food: the global virtual water trade network. Water Resour. Res. 47, 1–17. https://doi.org/10.1029/2010WR010307.
Kumssa, D.B., Joy, E.J.M., Ander, E.L., Watts, M.J., Young, S.D., Walker, S., Broadley, M.R., 2015. Dietary calcium and zinc deficiency risks are decreasing but remain prevalent. Sci. Rep. 5, 1–11. https://doi.org/10.1038/srep10974.
Mary, S., 2019. Hungry for free trade? Food trade and extreme hunger in developing countries. Food Secur 11, 461–477. https://doi.org/10.1007/s12571-019-00908-z.
Minister, Russian Prime, 2020. Order of the Government of the Russian Federation of March 31, 2020 No. 385. Russian Federation.
Minot, N., Goletti, F., 2000. Rice Market Liberalization and Poverty in Viet Nam: International Food Policy Research Institute; Research Report; 114, Research R. International Food Policy Research Institute.
Newman, M.E.J., 2002. Assortative mixing in networks. Phys. Rev. Lett. 89, 1–5. https://doi.org/10.1103/PhysRevLett.89.208701.
Newman, M.E.J., 2003. Mixing patterns in networks. Phys. Rev. E 67, 13. https://doi.org/10.1103/PhysRevE.67.026126.
Oberlander, L., Disdier, A.-C., Etilé, F., 2017. Globalisation and national trends in nutrition and health: a grouped fixed-effects approach to intercountry heterogeneity. Health Econ. 26, 1146–1161. https://doi.org/10.1002/hec.3521.
Panda, M., Ganesh-Kumar, A., 2009. Trade Liberalization, Poverty, and Food Security in India IFPRI Disc.
Popkin, B.M., 2004. The Burden of Disease from Undernutrition and Overnutrition in Countries Undergoing Rapid Nutrition Transition : A View from Brazil Diabetes Prevalence Among Puerto Rican Adults in New York City , NY, vol. 94, pp. 433–434, 2000.
Porkka, M., Guillaume, J.H.A., Siebert, S., Schaphoff, S., Kummu, M., 2017. The use of food imports to overcome local limits to growth. Earth's Futur 5, 393–407. https://doi.org/10.1002/2016EF000477.
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 https://doi.org/10.1088/1748-9326/10/2/024007.
Qi, H., An, H., Hao, X., Zhong, W., Zhang, Y., 2014. Analyzing the international exergy flow network of ferrous metal ores. PloS One 9. https://doi.org/10.1371/journal.pone.0106617.
Rafeek, M., Samaratunga, P., 2011. Trade liberalisation and its impact on the rice sector of Sri Lanka. Sri Lankan J. Agric. Econ. 3, 143. https://doi.org/10.4038/sjae.v3i0.3494.
Rutten, M., Shutes, L., Meijerink, G., 2013. Sit down at the ball game: how trade barriers make the world less food secure. Food Pol. 38, 1–10. https://doi.org/10.1016/j.foodpol.2012.09.002.
Sartori, M., Schiavo, S., 2015. Connected we stand: a network perspective on trade and global food security. Food Pol. 57, 114–127. https://doi.org/10.1016/j.foodpol.2015.10.004.
Shannon, P., Markiel, A., Ozier, O., Baliga, N.S., Wang, J.T., Ramage, D., Amin, N., Schwikowski, B., Ideker, T., 2003. Cytoscape: a software environment for integrated models of biomolecular interaction networks. Genome Res. 13, 2498–2504. https://doi.org/10.1101/gr.1239303.
Suweis, S., Carr, J.A., Maritana, A., Rinaldo, A., D'Odorico, P., 2015. Resilience and reactivity of global food security. Proc. Natl. Acad. Sci. U. S. A 112, 6902–6907. https://doi.org/10.1073/pnas.1507366112.
Tanaka, T., Karapinar, B., 2019. How to improve world food supply stability under future uncertainty: potential role of WTO regulation on export restrictions in rice. J. Food Secur. 7, 129–150. https://doi.org/10.12691/jfs-7-4-5.
The World Bank, 2020. Data: World Bank Country and Lending Groups. World Bank Ctry. Lend. Groups [WWW Document]. https://datahelpdesk.worldbank.org/knowledgebase/articles/906519-world-bank-country-and-lending-groups. accessed 2.2.20.
Thow, A.M., 2009. Trade liberalisation and the nutrition transition: mapping the pathways for public health nutritionists. Publ. Health Nutr. 12, 2150–2158. https://doi.org/10.1017/S1368980009005680.
Torreggiani, S., Mangioni, G., Puma, M.J., Fagiolo, G., 2018. Identifying the community structure of the food-trade international multi-network. Environ. Res. Lett. 13 https://doi.org/10.1088/1748-9326/aabf23.
UN, 2020. UN Comtrade Statistics. United Nations Stat. Off [WWW Document]. http://comtrade.un.org/. accessed 3.6.19.
USDA, 2011. USDA national nutrient database for standard reference [electronic resource] [WWW Document]. http://www.ars.usda.gov/ba/bhnrc/ndl. accessed 12.15.17.
Wessells, K.R., Singh, G.M., Brown, K.H., 2012. Estimating the global prevalence of inadequate zinc intake from national food balance Sheets: effects of methodological assumptions. PloS One 7, e50565. https://doi.org/10.1371/journal.pone.0050565.
Willett, W., Rockström, J., Loken, B., Springmann, M., Lang, T., Vermeulen, S., Garnett, T., Tilman, D., DeClerck, F., Wood, A., Jonell, M., Clark, M., Gordon, L.J., Fanzo, J., Hawkes, C., Zurayk, R., Rivera, J.A., De Vries, W., Majele Sibanda, L., Afshin, A., Chaudhary, A., Herrero, M., Agustina, R., Branca, F., Lartey, A., Fan, S., Crona, B., Fox, E., Bignet, V., Troell, M., Lindahl, T., Singh, S., Cornell, S.E., Srinath Reddy, K., Narain, S., Nishtar, S., Murray, C.J.L., 2019. Food in the Anthropocene: the EAT–Lancet Commission on healthy diets from sustainable food systems. Lancet 393, 447–492. https://doi.org/10.1016/S0140-6736(18)31788-4.
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, 34–37. https://doi.org/10.1038/s41893-017-0008-6.
World Trade Organization, 2019. Tariff profiles [WWW Document]. https://www.wto.org/english/res_e/statis_e/tariff_profiles_list_e.htm. accessed 6.22.20.