Current Research in Food Science 6 (2023) 100517

Contents lists available at ScienceDirect

Current Research in Food Science

journal homepage: www.sciencedirect.com/journal/current-research-in-food-science

Evolution of global food trade network and its effects on population nutritional status

Murilo Mazzotti Silvestrini [a], Nick W. Smith [b], Flavia Mori Sarti [a,*]

[a] School of Arts, Sciences and Humanities, University of Sao Paulo, Sao Paulo, 03828-000, Brazil
[b] Riddet Institute, Massey University, Manawatu-Wanganui, 4442, New Zealand

ARTICLE INFO

Handling Editor: Professor A.G. Marangoni

Keywords:
Food systems
Global trade
Complex networks
Globalization
Nutritional status

ABSTRACT

Changes in food systems during the last decades fostered the establishment of global food networks based on exchanges between countries with different income levels. Recent studies explored configuration and factors associated with trade networks of specific food items during limited periods; however, there is lack of evidence on evolution of trade networks of foods for human consumption and its potential effects on population nutritional status. We present the evolution of the global trade network of foods for human consumption from 1986 to 2020, according to country income level, and we explore potential effects of country network centrality and globalization processes on the prevalence of overweight and obesity. Results show intensification of international food trade and globalization processes in the period of analysis with implications for population nutritional status worldwide.

1. Introduction

Recent transformations in food systems at local and global levels have resulted in modifications of supply and demand conditions of international food trade. Changes in structures of production and patterns of food consumption throughout the last decades are linked to economic, social, and political globalization processes, potentially leading to homogenization of diets worldwide (Hawkes, 2006; Goryakin et al., 2015; Fox et al., 2019). In addition, fluctuations in income level have been influencing global food trade between countries (Serrano and Pinilla, 2010), creating uncertainties in relation to food security of populations in the long run.

Studies on international food trade have usually focused on concerns related to macroeconomic effects arising from disruptions in world food supply, especially regarding food security at a population level in specific periods (Gephart and Pace, 2015; Puma et al., 2015; Suweis et al., 2015; De Winne and Peersman, 2016; Marchand et al., 2016; Fair et al., 2017; Geyik et al., 2021). Other studies debated issues referring to relationships between developed and developing countries in international trade (Falconí et al., 2017), and problems related to food scarcity in low-income countries (Beal et al., 2017).

Current developments in the investigation of food systems worldwide include the use of complex networks analysis to explore patterns of trade, identifying network structures (Shutters and Muneepeerakul, 2012), analyzing prices of food *commodities* (Lagi et al., 2012), measuring global nutrient gaps (Geyik et al., 2021), and evaluating interdependence between countries in relation to natural resources required for food production (Khoury et al., 2015).

However, major part of studies using complex networks approaches for analysis of international food trade present substantial limitations in data analysis, particularly in relation to its connections with globalization processes and their implications on the triple burden of malnutrition (i.e., coexistence of underweight, overweight and obesity, and micronutrient deficiency in certain populations) within countries (Ercsey-Ravasz et al., 2012; UNICEF, 2019).

Thus, the present study investigated the evolution of the global trade network of foods for human consumption from 1986 to 2020, according to country income level. In addition, we explored the effects of country participation in the food trade network and its level of globalization in economic, social, and political dimensions on short- and long-term indicators of population nutritional status.

* Corresponding author.
E-mail address: flamori@usp.br (F.M. Sarti).

https://doi.org/10.1016/j.crfs.2023.100517
Received 5 April 2023; Received in revised form 5 May 2023; Accepted 8 May 2023
Available online 30 May 2023

2. Materials and methods

2.1. Datasets

Two separate datasets were organized for the study: the first dataset included origin-destination matrices of global food trade between 1986 and 2020 to perform complex network analysis, and the second dataset comprised a panel of country-level data to implement regression analysis on the effects of country participation in food trade and its globalization level on population nutritional status (Table S1, Supplementary Materials).

The first dataset was based on the matrix of bilateral exchanges of agricultural and livestock products suitable for human consumption between countries from 1986 to 2020, latest year available of the Detailed Trade Matrix with corresponding data on population, and domestic supply-to-food ratios of the Food Balances from the Food and Agriculture Organization on May 05, 2023 (FAOSTAT, 2023). Supplementary data on bilateral trade of fisheries from the World Integrated Trade Solution (WITS) of the World Bank (World Bank, 2022) were incorporated into the dataset, following previous studies (Gephart and Pace, 2015; Geyik et al., 2021). Information on country income classification obtained from the World Bank (World Bank, 2021) was incorporated in the first dataset to allow the construction of food trade networks according to country income level.

The second dataset was assembled for investigation of potential effects of country participation in global food trade network and its globalization level on the nutritional status of the population, including:

- Country network metrics per year (output of the complex network analysis), comprising a set of metrics corresponding to country's position within global food trade network;
- Economic, social, and political dimensions *de facto* (i.e., trade, financial, and political activities, services, etc.) and *de jure* (i.e., trade, financial, infrastructure, and political regulations) of the KOF Globalisation Index (Gygli et al., 2019; KOF, 2023);
- Sociodemographic, economic, and geographic characteristics of the country available in the World Development Indicators platform (World Bank, 2021);
- Information on population and calorie supply per capita per year from Food Balance Sheets (FAOSTAT, 2023);
- Estimated energy requirements of the population (World Bank, 2021; FAO/WHO/UNU, 2001);

  •Age-standardized prevalence of overweight and obesity from the World Health Organization (WHO, 2022), representing health outcomes of the analysis.

2.2. Variables

2.2.1. Complex network analysis

The first dataset encompassed food flows between countries from 1986 until 2020, considering the availability of information on bilateral trade with corresponding data on population, domestic supply-to-food ratios, and income level. Data referring to items inappropriate for human food consumption were excluded from the dataset.

The information extracted from FAOSTAT and WITS platforms was organized in the format of origin-destination matrices of import quantity data according to year to establish the flow of food items from abroad into food supply of the country. Values of food imports were checked to ensure exclusion of re-exports and to verify the symmetry of the matrix in terms of exports.

Data on food items exchanged between countries included information registered under diverse units of measure, therefore, food trade amounts were converted into calories per capita per day within the country during the period from 1986 to 2020. Thus, exchanges of live animals or whole animals registered in units were converted to tons of food items after slaughter, using rates of live weight over dead weight, based on the literature on yield in the slaughter of animals for the production of meat (FAO, 1991; Bender, 1992; USDA-ERS, 1992; FAO, 2000; FAO, 2011; Boudt and Luu, 2018).

Domestic food availability per country per year (in tons) extracted from Food Balances was used to estimate the domestic supply-to-food ratios and estimate the fraction of food trade corresponding to food for human consumption in the corresponding year, based on FAO (2001) and GSARS (2017). Food Balances assume that the domestic supply of food products corresponds to the destinations (utilization) of the food products within the country, therefore, the proportion of food for human consumption corresponds to the fraction of food in relation to other uses of the domestic food supply (FAOSTAT, 2023).

The final amount of each food item imported for human consumption was converted into calories, applying technical conversion factors and nutritive factors available at FAO tables, considering only edible fractions (FAO, 2000, 2020). Calories of n food items exchanged between pairs of countries i and j during year t were aggregated and converted into calories per capita per day by dividing total calories by the population of the country and days of the year.

Therefore, information in the first dataset represented bilateral relationships between the country of origin j and the country of destination i in exchanges of calories, comprising adjacent matrices of international trade per year from 1986 to 2020. The adjacent matrix A_t represents bilateral trade between countries j $(1, \ldots, p)$ with countries i $(1, \ldots, p)$ of calories of x $(1, \ldots, n)$ food items during the period t with main diagonal 0 (i.e., there are no exports to or imports from the country itself), comprising directed relations between countries (Equation (1)):

$$A_t = \begin{bmatrix} 0 & \cdots & a_{x,1jt} & \cdots & a_{n,1pt} \\ \vdots & & \vdots & & \vdots \\ a_{x,i1t} & \cdots & 0 & \cdots & a_{x,ipt} \\ \vdots & & \vdots & & \vdots \\ a_{n,p1t} & \cdots & a_{x,pjt} & \cdots & 0 \end{bmatrix} \tag{1}$$

where: $a_{x,ijt}$ = calories of food item x exchanged between the country of origin j and the country of destination i in period t.

In addition, data on country income level in the year of trade was also included in the first dataset, according to four categories proposed by the World Bank: low-income, lower middle-income, upper middle-income and high-income (World Bank, 2021). Countries without income classification were coded separately (not determined, ND).

2.2.2. Regression analysis

The second dataset comprised a panel of country-level data assembled to allow the estimation of regression models for investigation of the effects of country participation in the global food trade network and its globalization level on population nutritional status.

The annual country network metrics extracted from the complex network analysis of the global food trade referred to indegree and outdegree centrality, corresponding to the directional connections of graph nodes (Sartori and Schiavo, 2015), according to Equation (2):

$$k_{it} = \sum_{j=1}^{p} a_{ijt} \tag{2}$$

where: k_{it} = degree of country i in year t; a_{ijt} = element of binary adjacency matrix A_t. considering that the food trade matrix comprises directed network, indegree represents the sum of edges directed to the reporter country i, whilst outdegree represents the sum of edges directed to partner countries of i.

The age-sex population composition of each country obtained from the World Bank (World Bank, 2021) was used to estimate energy requirements per capita per year during the period of analysis, based on human energy requirements (FAO/WHO/UNU, 2001). Other variables included in the study were incorporated in the second dataset in their original format.

2.3. Data analysis

The complex network analysis was performed through graphic representation of countries represented by nodes with connections between nodes (vertices) corresponding to the calories imported for human consumption in a certain year (w_{ijt}), using the first dataset of the study. Information on income level classification was adopted to allow visual identification of countries within directed graphs on bilateral food trade.

The attributes of nodes in the food trade network included income level (represented in different colors), and weighted indegree (representing node diameter), i.e., calories per capita per day imported by the country. The density of vertices represented the volume of calories traded between pairs of countries connected by bilateral exchange. The layout Frutcherman-Reingold (Fruchterman and Reingold, 1991) was adopted for representation of global food trade networks, based on direct force algorithm that represents nodes connected with higher intensity by closeness proximity, whilst presenting uniform distribution of network nodes that minimizes intersections between arcs.

The complex network analysis was performed using Python 3 language in Gephi 0.9.2 software. The dynamic network was based on the annual networks, adapted in film format, and including labels on nodes and marks of periods through software Adobe After Effect 2020.

Finally, regression models were estimated using the second dataset of the study to identify potential effects of changes in country participation in the international food trade network and its globalization level on the prevalence of overweight and obesity of the population, using software Stata version 17 with significance level $p < 0.05$.

Lagged variables of overweight and obesity prevalence were created considering zero, one, and three years after the measurement of the country network metrics and other country characteristics to allow capturing short- and long-term effects of the changes in country participation within the international food trade network. Considering the absence of normal distribution in prevalence of obesity, logistic regression models were estimated following the details of Equation (3):

$$L_{it+x} = \beta_0 + \beta_1.G_{it} + \beta_2.F_{it} + \beta_3.T_{it} + \beta_4.S_{it} + \beta_5.I_{it} + \beta_6.C + \varepsilon \quad (3)$$

where: L_{it+x} = log-odds of the population of country i in the lagged period $t + x$ (being $x = 0$, 1 or 3) categorized in the highest tercile of prevalence of obesity (0 = no; 1 = yes); G_{it} = matrix of globalization index in economic, social, and political dimensions/components of the country i in period t; F_{it} = matrix of characteristics of food availability in the country i in period t; T_{it} = matrix of metrics of the country i within the food trade network in period t; S_{it} = matrix of sociodemographic and economic characteristics of the population of country i during period t; I_{it} = income level of the country i during period t.; C = matrix of control variables referring to region, year, and interaction between region and year; and ε = error term.

3. Theory

The use of complex networks approach for analysis of trade relations (vertices) between countries (nodes) was initially proposed in the late 1970s (Snyder and Kick, 1979), being adopted for further investigation of economic consequences of international trade and its effects in domestic economies during the 1990s (Smith and White, 1992;Arnade, Pick and Gopinath, 1998).

During the first decades of the 21st. century, there were significant advances in the use of complex networks for analysis of international trade of goods in general, encompassing research related to economic complexity (Hidalgo and Hausmann, 2009; Liao and Vidmer, 2018); international crises (Valentinyine Endresz and Skudlny, 2016); macroeconomic volatility and economic shocks (Chakrabarti, 2018); geolocation, evolution and network simulation (Abbate et al., 2018; Ikeda and Iyetomi, 2018); energy flows and productive resources (Chen et al., 2018); and topology and metrics of complex networks (Bhattacharya et al., 2008; Fagiolo, 2010; Barigozzi et al., 2010; Peluso et al., 2016).

The majority of studies using complex networks approach to analyze the global food trade have been published in the last decade, especially focusing on identification of similarities or inequities in bilateral exchanges between countries (Haq and Meilke, 2011; Falconí et al., 2017). Other studies focused on food safety at international level, using data on monetary value of foods (Ercsey-Ravasz et al., 2012; Torreggiani et al., 2018; Bentham et al., 2020) or, alternatively, volume of trade (in tons) of certain food products (Fair et al., 2017).

In the field of food security, certain studies investigated the effects of country interactions within the global food system on social, political, economic, or environmental dimensions at national or regional levels (Ericksen, 2008; Lagi et al., 2012; Shutters and Muneepeerakul, 2012; Sartori and Schiavo, 2015; García, 2019; Geyik et al., 2023), including analysis of sustainability and interdependence of countries on natural resources for food production (D`Odorico et al., 2014; Khoury et al., 2015).

There was limited evidence on evolution and influence of global food trade on food security at global and national levels. Only two studies investigated the effects of international trade on food consumption patterns referring to calorie and nutrient availability at a national level (Falconí et al., 2017; Geyik et al., 2021), with only one study focusing exclusively foods for human consumption, based on data limited to the period between 2013 and 2015 (Geyik et al., 2021).

4. Results

The evolution of global trade of food items for human consumption included information on approximately 570 food items suitable for human consumption traded among 254 countries from 1986 to 2020, resulting in 35 complex networks representing the dynamics of bilateral exchange of calories between pairs of countries per year (Video V1, Supplementary Materials). The trade networks of calories corresponding to the years 1986, 2006 and 2020 are presented to show a static picture of the evolution of global trade from the beginning to the end of the period analyzed in the study (Fig. 1).

Supplementary video related to this article can be found at https://doi.org/10.1016/j.crfs.2023.100517.

There was increase in countries participating in the food trade networks during the period from 177 countries in 1986 to 223 countries in 2020. In terms of income level, the proportion of countries in the high- and upper middle-income groups tended to increase from the mid-2000s onwards (Table S2, Supplementary Materials).

There was intensification in the trade of calories for human consumption between countries throughout the period, indicated by the increase in number of connections (average degree) and volume of calories exchanged between countries (average weighted degree), the latter represented by the density of vertices linking nodes. In terms of network density, there were irregular fluctuations in periods of international economic crises (1990s and late 2000s), highlighting the frailty in connections between pairs of countries through food trade. Yet, average clustering indicates that countries in the network tend to establish high density neighboring (Table S3, Supplementary Materials).

The largest flows of calories occurred between pairs of high-income (H) countries, which represented approximately 25%–40% of calories traded worldwide, reaching only approximately 10%–15% of the global population from 1986 to 2020. There was an increase in the proportion of calories exported from high- (H), upper middle- (UM) and lower middle-income (LM) countries in relation to their population, whilst low-income countries (L) decreased the proportion of calories exported in relation to their population (Table 1).

Although high-income countries represented a high proportion of global trade of calories for human consumption during the period from 1986 to 2020, their participation in global food trade peaked in middle-

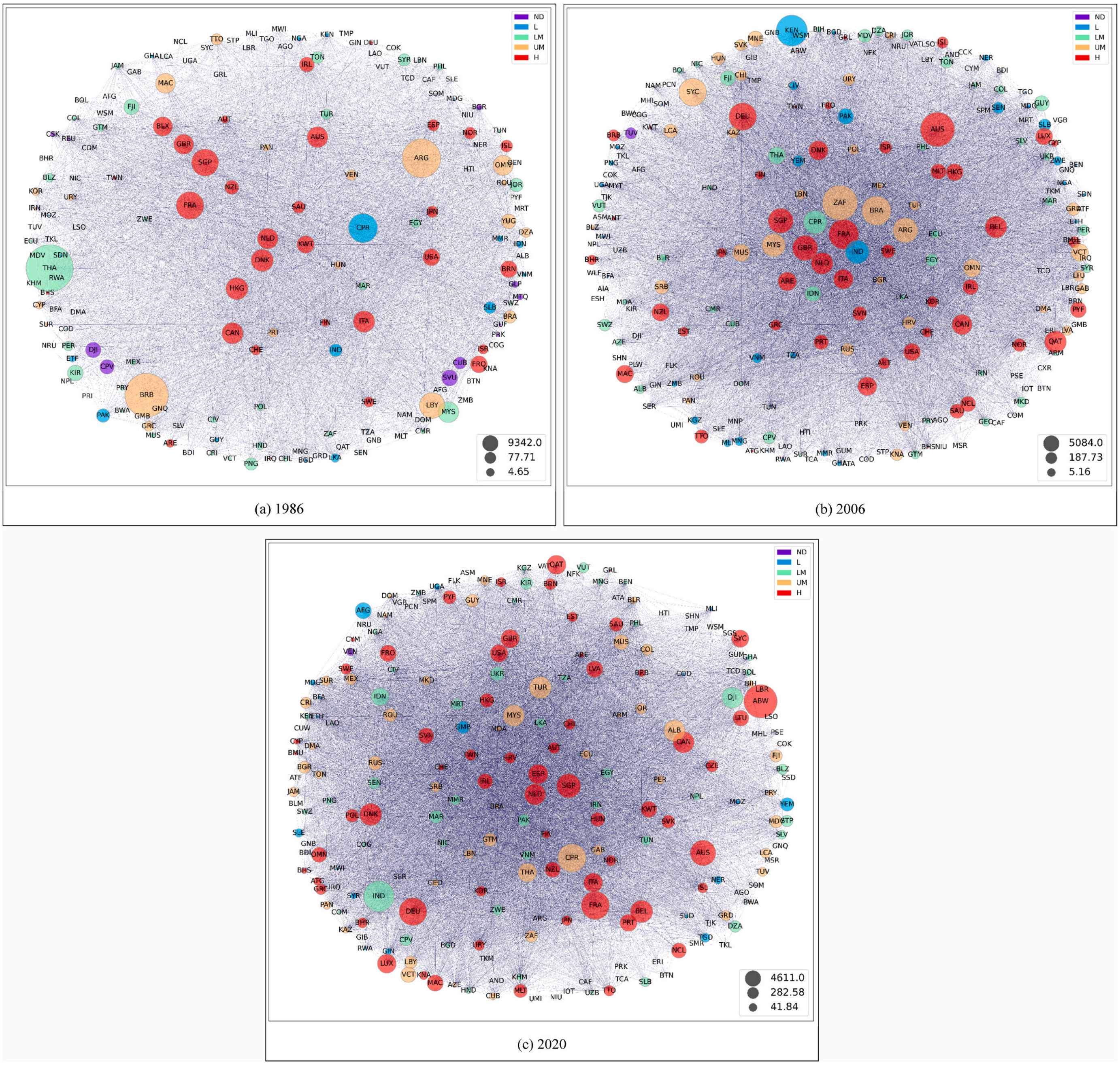

Fig. 1. Evolution of trade networks of foods for human consumption between countries (in calories per capita per day), color-coded by income level. 1986–2020. H = high-income countries; UM = upper middle-income countries; LM = lower middle-income countries; L = low-income countries; ND = countries of undetermined income level. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

1990s. The proportion of calories imported by lower middle-income countries decreased in comparison to their population during the period (Table 1).

High- and upper middle-income countries generally presented higher dependency on imports for domestic supply of calories for human consumption throughout the period of analysis. In addition, major part of high- and upper middle-income countries also showed higher availability of calorie per capita per day than the global average of calories. It was mainly lower middle- and low-income countries that had lower availability of calories per capita per day for their population than the mean global calorie supply (Table 2).

There was growing prevalence of overweight and obesity in countries participating in the global food trade network, matching the increase in calorie supply compared to estimated energy requirements of populations (Tables S4 and S5, Supplementary Materials).

The KOF Globalisation Index showed occurrence of intensification in economic, social, and political globalization, particularly from 1989 until 2006, guided by *de facto* political and economic dimensions (i.e., trade, financial, and political activities), followed by *de facto* political and economic dimensions (i.e., trade, financial, and political regulations), and social dimensions (i.e., activities, infrastructure and regulations involving interpersonal contact, travel, services, and cultural events) (Table S6, Supplementary Materials).

The results of logistic regression models showed that countries with higher indegree and outdegree centrality presented lower probability of being in the highest tercile of overweight and obesity prevalence, after controlling for characteristics of domestic calorie supply, country income level, globalization index, sociodemographic and economic

Table 1
Exchange of calories according to income level of origin and destination countries in comparison to population in destination countries.

Trade flow			1986		1996		2006		2016		2020	
O	→	D	Kcal*	Pop⁑	Kcal*	Pop⁑	Kcal*	Pop⁑	Kcal*	Pop⁑	Kcal*	Pop⁑
H	→	H	29.1	15.6	40.4	11.3	27.0	10.4	26.2	11.3	24.3	11.8
H	→	UM	8.6	2.3	3.8	2.1	5.7	3.5	16.6	11.1	14.4	10.4
H	→	LM	10.5	3.7	11.4	4.3	9.5	9.4	6.0	11.1	5.6	12.7
H	→	L	3.7	9.9	7.1	12.1	2.3	8.1	0.9	1.7	0.6	1.5
H	→	ND	12.9	1.2	0.0	0.0	0.0	0.1	0.0	0.1	0.1	0.1
UM	→	H	3.2	9.3	4.9	6.4	6.5	7.0	7.8	9.2	8.0	8.8
UM	→	UM	2.0	1.1	3.8	0.9	5.0	2.2	15.4	8.8	18.2	8.4
UM	→	LM	1.5	1.4	3.4	1.9	9.7	5.3	8.0	7.5	8.1	7.6
UM	→	L	0.7	3.7	4.2	5.5	3.4	4.8	2.5	0.9	1.7	0.7
UM	→	ND	1.9	0.6	0.0	0.0	0.0	0.0	0.0	0.0	0.3	0.1
LM	→	H	8.7	16.5	7.1	13.3	6.0	9.1	4.3	8.9	4.1	9.2
LM	→	UM	1.5	1.6	1.4	2.0	2.3	2.8	5.1	8.5	6.5	8.1
LM	→	LM	1.2	2.1	2.9	3.7	4.0	7.7	4.5	7.3	6.1	7.7
LM	→	L	1.5	4.0	1.9	8.0	2.2	4.6	1.8	0.9	1.4	0.8
LM	→	ND	1.0	1.1	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.0
L	→	H	3.4	11.3	3.5	11.6	1.8	8.7	0.1	4.1	0.1	3.9
L	→	UM	0.7	0.7	0.8	1.3	11.6	2.0	0.3	3.5	0.3	2.9
L	→	LM	0.4	1.3	2.0	2.4	1.7	7.3	0.2	3.9	0.2	3.9
L	→	L	0.6	6.5	1.3	11.7	1.4	6.2	0.2	0.4	0.0	0.2
L	→	ND	1.9	1.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
ND	→	H	0.9	2.4	0.1	1.0	0.0	0.5	0.0	0.6	0.0	0.5
ND	→	UM	0.3	0.3	0.0	0.1	0.0	0.1	0.0	0.2	0.0	0.3
ND	→	LM	0.2	0.5	0.0	0.1	0.0	0.2	0.0	0.0	0.0	0.3
ND	→	L	0.1	1.4	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.0
ND	→	ND	3.4	0.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Origin	**1986**		**1996**		**2006**		**2016**		**2020**	
	Kcal	**Pop**	**Kcal**	**Pop**	**Kcal**	**Pop**	**Kcal**	**Pop**	**Kcal**	**Pop**
High-income	64.9	32.7	62.7	29.9	44.5	31.5	49.7	35.3	44.9	36.5
Upper middle-income	9.4	16.0	16.2	14.8	24.5	19.3	33.8	26.4	36.2	25.6
Lower-middle income	13.9	25.4	13.3	27.0	14.5	24.2	15.7	25.6	18.2	25.8
Low-income	7.0	20.9	7.6	27.1	16.5	24.3	0.8	11.8	0.7	11.0
Undetermined income	4.8	4.9	0.1	1.2	0.0	0.8	0.0	0.8	0.0	1.1

Destination	**1986**		**1996**		**2006**		**2016**		**2020**	
	Kcal	**Pop**	**Kcal**	**Pop**	**Kcal**	**Pop**	**Kcal**	**Pop**	**Kcal**	**Pop**
High-income	44.4	52.7	55.8	42.6	41.3	35.2	38.4	33.5	36.5	33.6
Upper middle-income	12.8	5.8	9.8	6.3	24.6	10.4	37.3	31.9	39.5	29.8
Lower-middle income	13.7	8.4	19.7	12.5	24.9	29.7	18.8	29.7	20.0	31.9
Low-income	6.5	24.1	14.6	37.4	9.3	23.6	5.5	3.9	3.7	3.2
Undetermined income	21.2	4.4	0.0	0.0	0.0	0.2	0.0	0.1	0.3	0.3

Obs.: (*) Proportion of calories traded in the year; (⁑) Proportion of population in destination countries; H = high-income countries; UM = upper middle-income countries; LM = lower middle-income countries; L = low-income countries; ND = countries of undetermined income level.

characteristics of the population, region, year, and crossed effects of region and year (Table 3).

The results indicate that there was inverse relation between participation in global food trade in relation to prevalence of overweight and obesity. In addition, economic globalization and normative aspects of political globalization showed either negative association or lack of statistically significant association with overweight and obesity prevalence. A potential explanation on the counterintuitive results refers to the increase in competitiveness in food supply, leading to higher diversity and quality of foods available at national level.

Social globalization *de jure* and political globalization *de facto* presented positive associations with overweight and obesity prevalence in countries. In addition, upper middle- and lower middle-income countries showed higher probability of being in the highest tercile of obesity prevalence in comparison to high- and low-income countries, consistent with recent evidence on trends of nutrition transition worldwide (Hawkes, 2006).

5. Discussion

The study showed important changes in the structure of the global trade network of foods for human consumption over 35 years. Food systems worldwide became increasingly interconnected throughout time: the dynamics of international food trade documented through complex network analysis from 1986 until 2020 points to increased connectedness and, simultaneously, higher interdependence of countries in the global food trade network, confirming previous evidence (Khoury et al., 2015).

The evolution of the global food trade network showed substantial growth in its contribution to calories for human consumption within countries during the period. There were increases in the participation of countries within the network in terms of exchange of calories and diversification of trade partnerships throughout the period, except in periods of economic crises.

The degree of participation in the global food trade network showed statistically significant negative association with trends in overweight and obesity prevalence, independently of country globalization level, after controlling for characteristics of domestic calorie supply, population sociodemographic and economic characteristics, country income level, region, year, and crossed effects of region and year.

The findings are consistent with previous evidence showing that global food trade and economic globalization processes may present

Table 2
Proportion of calories from food imports (mean and standard deviation) and proportion countries with calorie supply equal or higher than global supply of calorie per capita per day, according to income level.

Year	% Calories for human consumption from food imports μ (SD)				% Countries with calorie availability equal or higher than global mean supply of calorie per capita per day			
	H	UM	LM	L	H	UM	LM	L
1986	50.7 (60.6)	51.0 (128.5)	15.4 (24.1)	2.8 (9.1)	96.4	75.0	40.5	0.0
1987	41.6 (62.3)	30.3 (40.0)	16.3 (26.6)	2.6 (8.6)	92.9	79.2	40.5	2.3
1988	40.2 (62.2)	27.0 (38.3)	17.7 (27.1)	1.7 (5.8)	96.4	82.6	33.3	0.0
1989	44.2 (57.6)	35.4 (74.6)	17.7 (28.1)	1.6 (5.2)	96.7	75.0	35.3	4.7
1990	39.7 (61.6)	34.7 (42.0)	21.2 (33.0)	2.6 (7.3)	93.1	70.8	37.0	2.2
1991	46.5 (75.1)	32.8 (40.3)	23.1 (33.7)	3.7 (9.2)	93.3	72.0	44.9	2.1
1992	49.1 (73.5)	34.0 (38.0)	11.8 (21.8)	6.1 (13.2)	90.0	69.0	44.4	2.1
1993	51.3 (69.3)	39.5 (44.0)	13.1 (22.8)	3.5 (8.2)	90.0	78.6	43.5	5.8
1994	56.7 (74.2)	36.1 (37.2)	15.9 (24.8)	4.9 (9.7)	97.0	78.3	47.5	7.0
1995	54.8 (82.1)	32.8 (37.0)	14.3 (23.0)	5.9 (12.9)	97.1	72.7	47.5	5.4
1996	54.4 (76.6)	34.0 (43.0)	15.1 (21.3)	5.3 (9.6)	97.2	82.6	47.4	3.6
1997	50.8 (75.9)	36.2 (43.4)	23.0 (30.3)	8.2 (13.8)	97.3	67.9	51.9	7.3
1998	65.7 (103.8)	42.1 (38.9)	18.7 (25.7)	9.8 (17.2)	94.6	71.4	58.0	5.3
1999	57.3 (79.4)	43.9 (39.3)	21.8 (23.1)	10.4 (16.8)	94.6	73.3	56.3	1.7
2000	62.6 (77.9)	49.7 (38.6)	26.7 (27.5)	11.5 (17.5)	94.9	73.3	55.3	1.8
2001	71.2 (79.0)	55.9 (40.9)	35.0 (32.4)	11.7 (17.0)	94.6	74.2	51.1	1.8
2002	71.6 (78.3)	54.5 (40.4)	34.3 (32.9)	17.3 (20.5)	90.2	71.4	53.1	1.8
2003	74.1 (80.0)	63.4 (44.2)	29.8 (26.9)	15.5 (21.9)	89.7	67.7	58.8	1.9
2004	67.1 (77.4)	60.5 (50.9)	33.3 (29.0)	12.4 (20.4)	92.5	69.7	51.0	3.8
2005	74.8 (81.1)	62.0 (42.3)	35.6 (31.3)	15.3 (23.6)	90.2	75.8	43.4	6.4
2006	74.6 (80.1)	67.6 (72.4)	30.6 (30.0)	12.0 (20.5)	91.1	73.5	46.9	4.3
2007	80.9 (82.1)	63.6 (75.8)	32.8 (32.3)	18.6 (27.5)	89.6	72.2	37.5	4.7
2008	74.8 (83.7)	56.9 (64.4)	29.3 (31.1)	18.3 (27.8)	87.8	65.9	31.9	2.6
2009	77.3 (80.3)	52.2 (57.3)	29.6 (33.8)	11.9 (18.8)	92.0	65.1	25.5	5.7
2010	75.4 (82.9)	56.6 (90.4)	24.7 (30.1)	13.4 (20.2)	91.7	64.7	22.4	3.1
2011	73.3 (84.5)	61.1 (115.5)	28.0 (32.0)	12.3 (19.1)	87.8	62.7	20.8	3.0
2012	76.3 (83.4)	49.4 (55.9)	31.4 (34.5)	12.5 (16.5)	87.0	54.0	22.7	3.1
2013	83.4 (83.8)	45.7 (43.0)	27.4 (33.4)	13.6 (19.2)	88.9	54.0	22.2	3.2
2014	89.7 (81.6)	58.0 (39.6)	41.4 (41.4)	21.8 (22.7)	89.3	56.3	23.4	0.0
2015	94.3 (80.1)	58.0 (41.8)	38.2 (39.3)	25.0 (24.2)	90.6	56.9	23.4	0.0
2016	97.8 (83.8)	57.3 (43.4)	44.6 (51.0)	29.4 (29.4)	90.4	58.0	20.4	3.6
2017	97.8 (88.5)	57.4 (38.5)	44.5 (43.7)	29.7 (30.5)	87.3	56.0	20.9	6.5
2018	96.8 (88.1)	55.8 (39.5)	43.0 (50.1)	25.3 (27.3)	88.9	56.6	22.7	0.0
2019	95.2 (81.4)	56.3 (39.9)	45.1 (49.0)	20.5 (23.6)	91.5	54.0	22.9	3.7
2020	91.9 (84.2)	56.3 (36.0)	45.8 (59.1)	23.7 (32.6)	91.1	53.1	30.2	4.0

Obs.: μ = mean; SD = standard deviation; H = high-income countries; UM = upper middle-income countries; LM = lower middle-income countries; L = low-income countries.

either absence of negative effects or occurrence of positive effects on population wellbeing through promotion of increased food supply in importing countries and growth in income for exporting countries (Porkka et al., 2013; Miljkovic et al., 2015; Fox et al., 2019; Mary and Stoler, 2021).

There are numerous potential explanations on the unexpected inverse associations identified between engagement in bilateral food exchanges and prevalence of overweight or obesity. First, the imports of raw and unprocessed foods may play a central role in the negative association between participation in global food trade network and prevalence of overweight and obesity (Miljkovic et al., 2015); therefore, fostering the sustainable production and consumption of unprocessed foods at national level may empower local food systems and ensure food security of the population.

Second, there is evidence that advances in global trade tend to improve domestic food availability worldwide; yet, food self-sufficiency of countries remains relatively unchanged throughout time (Porkka et al., 2013). Thus, international food trade is still crucial to enable access to wide array of essential nutrients for populations worldwide (Wood et al., 2018), and strategies to improve local food production should be guided to gradually incorporate additional food products that allow increase in self-sufficiency.

Third, food trade regulations and taxation systems may comprise important mechanisms for prevention of overweight and obesity: countries imposing higher tariffs on foods with higher energy density and lower nutritional value (sweets, sugar, fats, and oils) generally have lower overweight and obesity prevalence; whilst government subsidies to certain foods tend to increase the prevalence of overweight and obesity (Abay et al., 2020). In fact, evidence on economic incentives towards healthy food consumption indicate that public policies at national level should focus on the combination of taxation and subsidy on foods/beverages according to nutritional profile (Niebylski et al., 2015).

Fourth, a major part of the literature on the link between global food trade and obesity highlights that the economic drivers of globalization play minor roles in obesity trends in comparison to social and political drivers at domestic level (Hawkes, 2006; Costa-i-Font and Mas, 2016; Goryakin et al., 2015). Consequently, programs fostering healthy lifestyles should comprise national public health strategies addressing social and political determinants of local food environments, promotion of physical activity, and disincentives sedentarism (Melo et al., 2023).

Fifth, the results of the present study indicate that global food trade may be an economic driver for diversification of population diets at national level, potentially through increase in food supply competition, contributing for improvements in diet quality and nutrient intake (Fox et al., 2019; Miljkovic et al., 2015). Therefore, policies directed towards promotion of competitiveness in local food systems and insertion in international trade networks may generate structural conditions to stimulate economic growth at national level (Hidalgo and Hausmann, 2009), whilst favoring food security for the population.

The present study conveys valuable evidence for design and implementation of public policies towards the improvement of connections of local and global food systems, especially considering the potential role of bilateral or regional trade agreements on food availability that fulfill

Table 3
Coefficients of regression models regarding prevalence of overweight and obesity. 1986–2015.

Tercile of overweight prevalence		Lag 0		Lag 1		Lag 3	
		OR	Sig.	OR	Sig.	OR	Sig.
Indegree centrality		0.034	***	0.028	***	0.019	***
Outdegree centrality		0.158	***	0.189	***	0.296	*
Economic globalization *de facto*		0.997	ns	0.998	ns	1.000	ns
Economic globalization *de jure*		0.992	ns	0.992	ns	0.988	*
Social globalization *de facto*		1.015	ns	1.011	ns	1.002	ns
Social globalization *de jure*		1.032	***	1.034	***	1.038	***
Political globalization *de facto*		1.031	***	1.031	***	1.028	***
Political globalization *de jure*		0.968	***	0.969	***	0.974	***
Calories in comparison to EER	%	262.843	***	290.568	***	695.731	***
Caloric availability > global mean supply	(yes = 1)	1.065	ns	0.972	ns	0.715	ns
Population 0–14 years	%	0.997	ns	0.997	ns	0.983	ns
Population 15–64 years	%	0.890	***	0.885	***	0.861	***
Female population	%	0.954	ns	0.938	ns	0.902	**
Urban population	%	1.114	***	1.115	***	1.119	***
High-income country	(yes = 1)	1.716	ns	1.733	ns	1.723	ns
Upper middle-income country	(yes = 1)	8.286	***	8.330	***	9.556	***
Lower middle-income country	(yes = 1)	6.363	***	6.435	***	6.701	***
Tercile of obesity prevalence		**Lag 0**		**Lag 1**		**Lag 3**	
		OR	**Sig.**	**OR**	**Sig.**	**OR**	**Sig.**
Indegree centrality		0.273	*	0.240	*	0.225	*
Outdegree centrality		0.414	*	0.402	*	0.356	*
Economic globalization *de facto*		1.000	ns	1.000	ns	1.002	ns
Economic globalization *de jure*		0.982	***	0.983	***	0.982	***
Social globalization *de facto*		1.015	ns	1.013	ns	1.010	ns
Social globalization *de jure*		1.020	*	1.021	*	1.022	*
Political globalization *de facto*		1.029	***	1.030	***	1.032	***
Political globalization *de jure*		0.956	***	0.956	***	0.957	***
Calories in comparison to EER	%	109.324	***	145.349	***	211.146	***
Caloric availability > global mean supply	(yes = 1)	1.531	**	1.453	*	1.471	*
Population 0–14 years	%	0.961	ns	0.958	*	0.953	*
Population 15–64 years	%	0.954	ns	0.953	ns	0.944	Ns
Female population	%	1.093	**	1.089	**	1.086	*
Urban population	%	1.080	***	1.080	***	1.082	***
High-income country	(yes = 1)	0.872	ns	0.801	ns	0.725	ns
Upper middle-income country	(yes = 1)	6.981	***	6.702	***	7.210	***
Lower middle-income country	(yes = 1)	8.244	***	8.692	***	10.133	***

Obs.: ***p < 0.001; **p < 0.01; *p < 0.05; ns = not significant. EER = estimated energy requirements per capita per day. Models include control for region, year, and crossed effects for region and year.

the nutritional requirements of populations (Beal et al., 2017; Geyik et al., 2021).

The robust analysis performed on the evolution of global food trade network throughout 35 years allowed to identify potential frailties and strengths in the process of globalization of food consumption patterns (Beal et al., 2017), comprising cues with substantial policy implications in geopolitical, sociocultural, and economic dimensions of global food systems.

The density of the global food network showed fluctuations related to periods of international economic crises, particularly during the 1990s and at end of the 2000s; reinforcing the role of macroeconomic conditions on food security. In addition, the results showed that country income was associated with participation on global food trade network and occurrence of overweight and obesity. The influence of countries similarity on the establishment of bilateral exchanges, i.e., Linder effect (Haq and Meilke, 2011), indicate that the establishment of local/regional trade agreements or South-South cooperation treaties may comprise potential strategies towards increase in the centrality of developing countries within the global food trade network.

There are certain limitations of the study. Data gathered in the present study refers to information publicly available assembled by international organizations (FAO, WITS, World Bank, and World Health Organization), registered by countries' officials. Therefore, it is important to acknowledge potential issues regarding missing information (e.g., lack of identification of trading partners), and variations in trade flows informed by partner countries, which may be due to errors or confidentiality, resulting in minor asymmetry between import and export data. However, a subsample of the data was tested to verify the degree of deviations between import and export flows, showing that major part of the bilateral food exchange presents substantial symmetry.

Additionally, we adopted the assumption that domestic supply-to-food ratios estimated for food items and food groups within Food Balances correspond to the uses of foods imported through global trade; however, domestic use of imported foods may differ from destination of domestic production. Nevertheless, considering the absence of other reliable sources of information referring to the proportion of food imports dedicated to specific utilization, it is reasonable to assume certain degree of similarity between uses of foods from diverse sources within the same country in the same year.

The study limited the analysis to calorie flows; however, it is important to highlight that nutrition is a complex phenomenon broader than the analysis of calories. Future work should consider the flows of other nutrients essential in the human diet, and their importance for national nutrition security, according to the initial proposal by Geyik et al. (2021, 2023). Moreover, the path between calorie availability/-consumption and weight gain may be influenced by the source of calories, glycemic load, and genetics (Ludwig et al., 2021). In addition, the study lacks exploration of economic, cultural, and social factors involved in food choices and nutritional status at individual level, considering the adoption of country-level information. However, considering the available data at the population level, the present approach represents an important contribution to understanding the role of global food trade networks in population nutritional status.

Finally, it is important to emphasize that the information on nutritional status of the population was available for major part of the period of analysis. Therefore, the regression models with lagged variables for 0, 1 and 3 years of overweight and obesity prevalence encompassed data corresponding to periods of 30, 29, and 27 years, respectively. However, the robustness of results obtained in the regression models showed long lasting negative associations between country indegree and outdegree centrality in the food trade network (i.e., centrality in food imports and exports) and overweight or obesity prevalence.

6. Conclusion

The present study illustrates comprehensively the trajectory of the global food trade network from 1986 to 2020. The coupling of complex network analysis with logistic regression methods comprises a powerful tool to investigate the evolution of bilateral exchanges in international food commerce and its short- and long-term effects on population nutritional status, concurrently with economic, social, and political globalization processes.

The assessment of progress in exchanges of foods for human consumption throughout the last decades and their links with social, economic, and political globalization processes convey important evidence on the mechanisms underlying nutritional transitions worldwide.

The negative effects of participation on global food trade on overweight and obesity prevalence represent key evidence to support the implementation of strategies that foster participation in the global food trade network, independently of country income level, whilst adopting national regulatory environment and taxation systems designed to incentive healthy food consumption patterns and foster healthy lifestyles.

Funding sources

The study was supported by the Brazilian Ministry of Science and Technology (Conselho Nacional de Desenvolvimento Científico e Tecnológico - Brasil, CNPq) - [grant numbers 301109/2019–2 and 310368/2022–7], and partially financed by the Brazilian Ministry of Education (Coordenação de Aperfeiçoamento de Pessoal de Nível Superior - Brasil, CAPES) - [finance code 001]. Sponsors of the study had no involvement in definition of the study design; data collection, analysis and interpretation; manuscript writing; or decision to submit the article for publication.

CRediT authorship contribution statement

Murilo Mazzotti Silvestrini: Investigation, Data curation, Formal analysis, Writing – original draft, Visualization. **Nick W. Smith:** Writing – review and editing, Validation. **Flavia Mori Sarti:** Data curation, Conceptualization, Methodology, Formal analysis, Writing – original draft, Writing – review and editing, Supervision, Validation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgements

Authors would like to than the Brazilian Ministry of Science and Technology and the Brazilian Ministry of Education for financial support to conduct the research.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.crfs.2023.100517.

References

Abay, K.A., Ibrahim, H., Breisinger, C., Bayasgalanbat, N., 2020. Food Policies and Their Implications on Overweight and Obesity Trends in Selected Countries in the Near East and North Africa Region. FAO, Rome. https://doi.org/10.4060/cb2338en9/12/20.

Abbate, A., De Benedictis, L., Fagiolo, G., Tajoli, L., 2018. Distance-varying assortativity and clustering of the international trade network. Network Science 6 (4), 633. https://doi.org/10.1017/nws.2018.7.

Arnade, C., Pick, D., Gopinath, M., 1998. Testing oligopoly power in domestic and export markets. Appl. Econ. 30 (6), 753–760. https://doi.org/10.1080/000368498325453.

Barigozzi, M., Fagiolo, G., Garlaschelli, D., 2010. Multinetwork of international trade: a commodity-specific analysis. Phys. Rev. 81 (4), 046104 https://doi.org/10.1103/PhysRevE.81.046104.

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 (4), e0175554. https://doi.org/10.1371/journal.pone.0175554.

Bender, A., 1992. Meat and Meat Products in Human Nutrition in Developing Countries. FAO, Rome. Available at: http://www.fao.org/3/t0562e/t0562e00.htm. (Accessed 4 March 2019).

Bentham, J., Singh, G.M., Danaei, G., Green, R., Lin, J.K., Stevens, G.A., Ezzati, M., 2020. Multidimensional characterization of global food supply from 1961 to 2013. Nat. Food 1 (1), 70–75. https://doi.org/10.1038/s43016-019-0012-2.

Bhattacharya, K., Mukherjee, G., Saramäki, J., Kaski, K., Manna, S.S., 2008. The international trade network: weighted network analysis and modelling. J. Stat. Mech. Theor. Exp. 2008 (2), P02002 https://doi.org/10.1088/1742-5468/2008/02/P02002.

Boudt, K., Luu, H.A., 2018. Is The Technical Conversion Factor Informative about the Price Ratio of Processing Livestock? Paper prepared for the 16th. Conference of International Association of Official Statisticians (IAOS), Paris. OECD headquarters, 19-21 September. Available at: https://papers.ssrn.com/sol3/papers.cfm?abstract_id=3100894. (Accessed 4 March 2019).

Chakrabarti, A.S., 2018. Dispersion in macroeconomic volatility between the core and periphery of the international trade network. J. Econ. Dynam. Control 88, 31–50. https://doi.org/10.1016/j.jedc.2018.01.019.

Chen, B., Li, J.S., Wu, X.F., Han, M.Y., Zeng, L., Li, Z., Chen, G.Q., 2018. Global energy flows embodied in international trade: a combination of environmentally extended input-output analysis and complex network analysis. Appl. Energy 210, 98–107. https://doi.org/10.1016/j.apenergy.2017.10.113.

Costa-i-Font, J., Mas, N., 2016. 'Globesity'? The effects of globalization on obesity and caloric intake. Food Pol. 64, 121–132. https://doi.org/10.1016/j.foodpol.2016.10.001.

De Winne, J., Peersman, G., 2016. Macroeconomic Effects of Disruptions in Global Food Commodity Markets: Evidence For the United States. Brookings Papers on Economic Activity, pp. 183–263. Available at: https://www.brookings.edu/wp-content/uploads/2017/02/dewinnetextfall16bpea.pdf. (Accessed 20 April 2020).

D'Odorico, P., Carr, J.A., Laio, F., Ridolfi, L., Vandoni, S., 2014. Feeding humanity through global food trade. Earth's Future 2, 458–469. https://doi.org/10.1002/2014EF000250.

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 (5), e37810. https://doi.org/10.1371/journal.pone.0037810.

Ericksen, P.J., 2008. Conceptualizing food systems for global environmental change research. Global Environ. Change 18 (1), 234–245. https://doi.org/10.1016/j.gloenvcha.2007.09.002.

Fagiolo, G., 2010. The international-trade network: gravity equations and topological properties. J. Econ. J. Econ. 5 (1), 1–25. https://doi.org/10.1007/s11403-010-0061-y.

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.

Falconí, F., Ramos-Martin, J., Cango, P., 2017. Caloric unequal exchange in Latin America and the Caribbean. Ecol. Econ. 134, 140–149. https://doi.org/10.1016/j.ecolecon.2017.01.009.

Food and Agriculture Organization - Statistics Division (FAOSTAT), 2023. Food And Agriculture Data. FAO, Rome. Available at: http://www.fao.org/faostat/en/#home. (Accessed 5 May 2023).

Food and Agriculture Organization (FAO), 1991. *Guidelines For Slaughtering, Meat Cutting and Further Processing*. FAO Animal Production and Health Paper 91. FAO, Rome. Available at: http://www.fao.org/3/t0279e/t0279e00.htm. (Accessed 4 March 2019).

Food and Agriculture Organization (FAO), 2000. Technical Conversion Factors for Agricultural Commodities. FAO, Rome. Available at: http://www.fao.org/fileadmin/templates/ess/documents/methodology/tcf.pdf. (Accessed 4 March 2019).

Food and Agriculture Organization (FAO), 2001. Food Balance Sheets: a Handbook. FAO, Rome. Available at: http://www.fao.org/3/x9892e/x9892e00.htm. (Accessed 20 April 2020).

Food and Agriculture Organization (FAO), 2011. Livestock Statistics: Concepts, Definitions and Classifications. FAO, Rome. Available at: http://www.fao.org/3/cb2461en/cb2461en.pdf. (Accessed 4 March 2019).

Food and Agriculture Organization (FAO), 2020. Nutritive Factors. FAO, Rome. Available at: http://www.fao.org/economic/the-statistics-division-ess/publications-studies/publications/nutritive-factors/en/. (Accessed 4 March 2019).

Food and Agriculture Organization, World Health Organization, United Nations University (FAO/WHO/UNU), 2001. Human Energy Requirements. FAO, Rome. Available at: https://www.fao.org/3/y5686e/y5686e00.htm. (Accessed 27 February 2022).

Fox, A., Feng, W., Asal, V., 2019. What is driving global obesity trends? Globalization or "modernization". Glob. Health 15, 32. https://doi.org/10.1186/s12992-019-0457-y.

Fruchterman, T.M., Reingold, E.M., 1991. Graph drawing by force-directed placement. Software Pract. Ex. 21 (11), 1129–1164.

García, C.M., 2019. Association of globalization in its different dimensions with overweight and obesity: an analysis in 10 Latin American and Caribbean countries. Salud Publica Mex. 61 (2), 174–183. https://doi.org/10.21149/8886.

Gephart, J.A., Pace, M.L., 2015. Structure and evolution of the global seafood trade network. Environ. Res. Lett. 10, 125014 https://doi.org/10.1088/1748-9326/10/12/125014.

Geyik, Ö., Hadjikakou, M., Karapinar, B., Bryan, B.A., 2021. Does global food trade close the dietary nutrient gap for the world's poorest nations? Global Food Secur. 28 (2021), 100490 https://doi.org/10.1016/j.gfs.2021.100490.

Geyik, Ö., Hadjikakou, M., Bryan, B.A., 2023. Climate-friendly and nutrition-sensitive interventions can close the global dietary nutrient gap while reducing GHG emissions. Nat. Food 4, 61–73. https://doi.org/10.1038/s43016-022-00648-y.

Global Strategy to improve Agricultural and Rural Statistics (GSARS), 2017. Guidelines For the Compilation of Food Balance Sheets. Food and Agriculture Organization of the United Nations, Rome. Available at: http://www.cisstat.com/gsagr/GS-FBS-Guidelines-ENG-completo-03.pdf. (Accessed 5 September 2021).

Goryakin, Y., Lobstein, T., James, W.P.T., Suhrcke, M., 2015. The impact of economic, political and social globalization on overweight and obesity in the 56 low and middle income countries. Soc. Sci. Med. 133, 67–76. https://doi.org/10.1016/j.socscimed.2015.03.030.

Gygli, S., Haelg, F., Potrafke, N., Sturm, J.-E., 2019. The KOF globalisation index - revisited. Rev.Int. Organ. 14 (3), 543–574. https://doi.org/10.1007/s11558-019-09344-2.

Haq, Z.U., Meilke, K.D., 2011. Does the Linder effect hold for differentiated agri-food and beverage product trade? Appl. Econ. 43, 4095–4109. https://doi.org/10.1080/00036846.2010.484000.

Hawkes, C., 2006. Uneven dietary development: linking the policies and processes of globalization with the nutrition transition, obesity and diet-related chronic diseases. Glob. Health 2, 4. https://doi.org/10.1186/1744-8603-2-4.

Hidalgo, C.A., Hausmann, R., 2009. The building blocks of economic complexity. Proc. Natl. Acad. Sci. USA 106 (26), 10570–10575. https://doi.org/10.1073/pnas.0900943106.

Ikeda, Y., Iyetomi, H., 2018. Trade network reconstruction and simulation with changes in trade policy. Evol. Inst. Econ. Rev. 15 (2), 495–513. https://doi.org/10.1007/s40844-018-0110-0.

Khoury, C.K., Achicanoy, H.A., Bjorkman, A.D., Navarro Racines, C., Guarino, L., Flores Palacios, X., Castañeda-Álvarez, N.P., 2015. Estimation of Countries' Interdependence in Plant Genetic Resources Provisioning National Food Supplies and Production Systems. Research Study 8. FAO, Rome. Available at: http://www.fao.org/3/bq533e/bq533e.pdf. (Accessed 5 September 2021).

Konjunkturforschungsstelle Swiss Economic Institute (KOF), 2023. KOF Globalization Index. KOF Swiss Economic Institute, Zurich. Available at: https://kof.ethz.ch/en/forecasts-and-indicators/indicators/kof-globalisation-index.html. (Accessed 20 March 2023).

Lagi, M., Bar-Yam, Y., Bertrand, K.Z., Bar-Yam, Y., 2012. Economics of food prices and crises. Cambridge: new england complex systems institute (NECSI). Available at: https://necsi.edu/s/food_book.pdf. (Accessed 5 September 2021).

Liao, H., Vidmer, A., 2018. A comparative analysis of the predictive abilities of economic complexity metrics using international trade network. Complexity, 2825948. https://doi.org/10.1155/2018/2825948.

Ludwig, D.S., Aronne, L.J., Astrup, A., de Cabo, R., Cantley, L.C., Friedman, M.I., Heymsfield, S.B., Johnson, J.D., King, J.C., Krauss, R.M., Lieberman, D.E., Taubes, G., Volek, J.S., Westman, E.C., Willett, W.C., Yancy Jr., W.S., Ebbeling, C.B., 2021. The carbohydrate-insulin model: a physiological perspective on the obesity pandemic. Am. J. Clin. Nutr. 114 (6), 1873–1885. https://doi.org/10.1093/ajcn/nqab270.

Marchand, P., Carr, J.A., Dell'Angelo, J., Fader, M., Gephart, J.A., Kummu, M., Magliocca, N.R., Porkka, M., Puma, M.J., Ratajczak, Z., Rulli, M.C., Seekell, D.A., Suweis, S., Tavoni, A., D'Odorico, P., 2016. Reserves and trade jointly determine exposure to food supply shocks. Environ. Res. Lett. 11, 095009 https://doi.org/10.1088/1748-9326/11/9/095009.

Mary, S., Stoler, A., 2021. Does agricultural trade liberalization increase obesity in developing countries? Rev. Dev. Econ. 25 (3), 1326–1350. https://doi.org/10.1111/rode.12757.

Melo, G., Aguilar-Farias, N., López Barrera, E., Chomalí, L., Moz-Christofoletti, M.A., Salgado, J.C., Swensson, L.J., Caro, J.C., 2023. Structural responses to the obesity epidemic in Latin America: what are the next steps for food and physical activity policies? The Lancet Regional Health - Americas 21, 100486. https://doi.org/10.1016/j.lana.2023.100486.

Miljkovic, D., Shaik, S., Miranda, S., Barabanov, N., Liogier, A., 2015. Globalisation and obesity. World Econ. 38 (8), 1278–1294. https://doi.org/10.1111/twec.12260.

Niebylski, M.L., Redburn, K.A., Duhaney, T., Campbell, N.R., 2015. Healthy food subsidies and unhealthy food taxation: a systematic review of the evidence. Nutrition 31 (6), 787–795. https://doi.org/10.1016/j.nut.2014.12.010.

Peluso, S., Mira, A., Muliere, P., Lomi, A., 2016. International Trade: a Reinforced Urn Network Model. *arXiv preprint*, arXiv:1601.03067.

Porkka, M., Kummu, M., Siebert, S., Varis, O., 2013. From food insufficiency towards trade dependency: a historical analysis of global food availability. PLoS One 8 (12), e82714. https://doi.org/10.1371/journal.pone.0082714.

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, 024007 https://doi.org/10.1088/1748-9326/10/2/024007.

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.

Serrano, R., Pinilla, V., 2010. Causes of world trade growth in agricultural and food products, 1951-2000: a demand function approach. Appl. Econ. 42, 3503–3518. https://doi.org/10.1080/00036840802167368.

Shutters, S.T., Muneepeerakul, R., 2012. Agricultural trade networks and patterns of economic development. PLoS One 7 (7), e39756. https://doi.org/10.1371/journal.pone.0039756.

Smith, D.A., White, D.R., 1992. Structure and dynamics of the global economy: network analysis of international trade 1965-1980. Soc. Forces 70 (4), 857–893. https://doi.org/10.1093/sf/70.4.857.

Snyder, D., Kick, E.L., 1979. Structural position in the world system and economic growth, 1955-1970: a multiple-network analysis of transnational interactions. Am. J. Sociol. 84 (5), 1096–1126. Available at: https://www.jstor.org/stable/2778218. (Accessed 5 September 2021).

Suweis, S., Carr, J.A., Maritan, A., Rinaldo, A., D'Odorico, P., 2015. Resilience and reactivity of global food security. Proc. Natl. Acad. Sci. USA 112, 6902–6907. https://doi.org/10.1073/pnas.1507366112.

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 (5), 054026 https://doi.org/10.1088/1748-9326/aabf23.

United Nations International Children's Emergency Fund (UNICEF), 2019. The State of the World's Children 2019. Children, Food and Nutrition: Growing Well in a Changing World. UNICEF, New York. Available at: https://www.unicef.org/media/63016/file/SOWC-2019.pdf. (Accessed 5 September 2021).

United States Department of Agriculture - Economic Research Service (Usda-Ers), 1992. Weights, Measures, and Conversion Factors for Agricultural Commodities and Their Products. Agricultural Handbook No. 697. USDA, Washington DC. Available at: https://www.ers.usda.gov/webdocs/publications/41880/33132_ah697_002.pdf?v=3863.2. (Accessed 5 September 2021).

Valentinyine, E.M., Skudelny, F., 2016. Crisis Severity and the International Trade Network. Working Paper Series 1971. European Central Bank. Available at: https://op.europa.eu/en/publication-detail/-/publication/34430371-aa63-11e6-aab7-01aa75ed71a1. (Accessed 5 September 2021).

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 Bank, 2021. List of Economies According to Income Groups. World Bank, Washington, DC. Available at: https://datatopics.worldbank.org/world-development-indicators/the-world-by-income-and-region.html. (Accessed 5 September 2021).

World Bank, 2022. *World integrated trade solution (WITS) database*. Washington, DC: united nations. Available at: https://comtrade.un.org/. (Accessed 15 July 2022).

World Health Organization, 2022. The Global Health Observatory - Indicators. Available at:. WHO, Geneva https://www.who.int/data/gho/data/indicators. (Accessed 24 February 2022).