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Trends in Global Trade of Red Meats from 1986 to 2023: A Complex Network Analysis with Implications for Public Health

Amanda Dias Assoni Scartezini [1] and Flavia Mori Sarti [2,*]

[1] Fresenius Kabi, São Paulo 06460-200, Brazil
[2] School of Arts, Sciences and Humanities, University of Sao Paulo, São Paulo 03828-000, Brazil
* Correspondence: flamori@usp.br

Abstract

During the last decades, there have been increasing concerns in public health debates regarding the production and consumption of red meat, considering connections between the occurrence of nutrition transition and an increase in the prevalence of chronic non-communicable diseases. The consumption of red meat has been linked to adverse health outcomes; however, current evidence reveals controversies regarding the intake of diverse red meats. In addition, barriers to meat consumption include sanitary legislation linked to foodborne diseases connected to livestock, whilst governments of diverse countries provide incentives for its production and export worldwide. Thus, the objective of the present study was to investigate the evolution in the global trade of processed and unprocessed red meat from 1986 to 2023, using network analysis. Data on the trade of red meat between pairs of 216 countries were obtained from the Food and Agriculture Organization Database (FAOSTAT). The dataset, comprising the mean annual volume of processed and unprocessed red meat exchanged from reporting countries (origin) to partner countries (destination), was used to map global trade networks of red meats and identify global trends in red meat consumption according to country income level. The results indicate substantial intensification in the global trade of processed (0.202 in 1986 to 0.453 kg per capita in 2023) and unprocessed red meat (1.415 in 1986 to 3.315 Kg per capita in 2023). The volume of trade of unprocessed red meat remains greater than the volume processed red meat; yet, the findings indicate a threefold increase in the average weighted degree of processed red meat trade (0.002 to 0.006) from 1986 until 2023, whilst unprocessed red meat showed a twofold increase (0.009 to 0.019). The results raise public health concerns regarding the long-term consequences of consuming processed foods with high sodium and fat content. Additionally, the global trade of red meat showed fluctuations in periods of major foodborne outbreaks related to meat consumption, particularly during the 1990s. The findings of the study highlight strategies at the national level to advance food system transformations towards improvements in public health, nutrition, and sustainability.

Keywords: international trade; network analysis; meat trade; public health; nutrition

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1. Introduction

The global consumption of red meat has grown in the 21st century and includes substantial differences in red meat consumption patterns among countries [1]: whilst some countries consume a higher proportion of unprocessed red meat than processed red meat (e.g., Russia, South Africa, and China), other countries consume a higher proportion of processed red meat than unprocessed red meat (e.g., Philippines Congo, Ethiopia,

and Indonesia). Unprocessed red meat, encompassing beef and pork, represents an important source of certain nutrients in the human diet, including a high concentration of essential amino acids and fatty acids, vitamins, iron, zinc, potassium, phosphorus, and manganese [2,3]. Processed red meat comprises beef, pork, and by-products transformed through diverse processes, including salting, curing, and smoking, which reduces the content of water and increases the concentration of sodium or other substances (e.g., nitrites and polycyclic aromatic hydrocarbons), with negative consequences for human health [4].

The production and consumption of red meat involve considerable controversies in public health and other fields of knowledge, including hygiene, nutrition, and environmental sustainability [5,6]. On the one hand, the imposition of sanitary barriers to meat trade provides a justification to limit trade between countries due to political and economic interests, relying on public health concerns related to foodborne outbreaks to maintain production and exports, considering aspects related to employment, trade balance, and tax revenues, among others [7–9].

On the other hand, the connections between the occurrence of nutrition transition and an increase in prevalence of chronic noncommunicable diseases have raised concerns regarding the potential effects of processed and unprocessed red meat consumption on population wellbeing. Global food trade reinforces red meat availability to populations worldwide, supporting increased demand at escalating health costs, including a rise in the occurrence of noncommunicable diseases [10]. Current nutritional recommendations focus on the regular intake of fresh foods, with an emphasis on whole grains, fruits, vegetables, and nuts, moderate consumption of dairy, fish, poultry, and eggs, and sparing use of unsaturated oils, in addition to the limited intake of red meats, with a particular avoidance of processed meats [11,12]. The Mediterranean diet, and its adaptations to diverse cultural contexts, has been consistently associated with a lower risk of obesity and its comorbidities, including cardiometabolic diseases [13–16].

Yet, recent trends in global food consumption patterns show an increase in the consumption of processed foods, consolidating the nutrition transition toward Western diets in developed and developing countries [17]. In particular, the links between the regular consumption of processed red meats and adverse health outcomes have been highlighted in numerous studies [18,19], whilst other findings highlight the absence of robust evidence to support allegations of health risks attributable to the moderate consumption of unprocessed red meats [19–28]. In addition, evidence from dose-response studies referring to protein consumption from vegetal or animal source foods also indicates a lower mortality risk due to cardiovascular diseases, cancer, and other chronic non-communicable diseases [29–31]. Additional evidence regarding mounting protein requirements for the growing global population, increase in red meat demand due to the rise in income, and environmental impacts attributable to meat production emphasize the substantial challenges involved in the analysis of the global meat trade [32,33].

Current advances in food science have been contributing to global market trends that address health, nutritional, and/or environmental concerns from consumers through plant-based or lab-grown meat alternatives, including processed plant-based products, insect protein-based meat, and restructured, cultured, or hybrid cultured meat [34,35]. However, consumers' acceptance of plant-based meat analogues is usually lower than meat due to their sensorial properties, texture, and nutritional contents [36], limiting the scope of alternative proteins to a minor proportion of the global protein consumption [34,37]. Furthermore, food safety hazards still pose challenges to the adoption of plant-based products, and lab-grown meat alternatives deal with challenges in production scalability [38,39], directing consumers to substitute red meats (e.g., beef) with other alternative animal-source foods [40].

The complex dynamics of elements within food systems require the adoption of a systems approach for the investigation of the global impacts of food production and consumption [41,42], encompassing multiple dimensions related to social, environmental, health, and economic dimensions that link consumer preferences, employment, income, trade, and prices [43,44]. Nonetheless, many studies on the issue neglect to incorporate elements of the systems approach [42]. A single study highlighted the potential links between the global red meat trade and diet-related non-communicable diseases between 1993 and 2018, although lacking further exploration of complex networks [10]. Thus, considering the lack of evidence regarding the evolution of the bilateral commerce of red meat at the international level through net-work analysis [10], the objective of the present study was to investigate the evolution in the global trade of red meat from 1986 to 2023 using network analysis of trade flows between countries.

2. Materials and Methods

2.1. Data Extraction

Publicly available data on exports of unprocessed and processed red meat (tons) and live animals for meat production (heads) were extracted from the Detailed Trade Matrix of the Food and Agriculture Organization Database (https://www.fao.org/faostat/en/#data/TM [Accessed: 31 July 2025]) (FAOSTAT) for the period from 1986 to 2023 [45]. Datasets available from FAOSTAT comprise data "*collected, processed and disseminated by FAO according to the standard International Merchandise Trade Statistics (IMTS) Methodology, (. . .) provided by UNSD, Eurostat, and other national authorities (. . .) The trade database includes all food and agricultural products imported/exported annually by all the countries in the world*" (https://bulks-faostat.fao.org/production/datasets_E.xml [Accessed: 31 July 2025]). Data on trade provided to the FAO are checked for outliers, and food aid is incorporated by the FAO into the dataset to account for global trade exchanges (https://www.fao.org/faostat/en/#data/TM/metadata [Accessed: 31 July 2025]). Thus, red meat trade data obtained from the FAOSTAT website were re-checked solely to verify any potential remaining errors and ensure consistency. Further data cleaning or imputation was unnecessary, considering the absence of missing data or outliers during verification.

The following data were selected from FAOSTAT, comprising only food items corresponding to red meats according to the definitions proposed by O'Connor et al. [46]. The ontology of red meat and poultry food group methods used in nutrition research was synthesized by the authors, based on the concepts extracted from the Food Patterns Equivalents Database [47] in combination with a systematic review of meat terminology. Thus, the following disaggregated variables identified within the ontology [46] and respective FAOSTAT items were adopted in the present study:

- Processed red meats, corresponding to "*frankfurters, sausages, corned beef, cured ham and luncheon meat that are made from beef, pork*" according to the NCI Processed Meat Categories SAS program [48]: (a) bovine meat that is salted, dried, or smoked; sausages and similar products of such meat; offal or blood of beef and veal; beef and veal preparations; homogenized meat preparations; (b) pig meat and cuts that are salted, dried, or smoked (bacon and ham); sausages and similar products of such meat; offal or blood of pig; pig meat preparations; (c) other meat and edible meat offal, salted, in brine, dried, or smoked; (d) edible flours and meals of meat or meat offal; and (e) meat prepared n.e.c.
- Unprocessed red meats, including live animals, corresponding to "*beef, veal, pork, lamb, and game meat; excludes organ meat and cured meat*" [46]: (a) Cattle: meat of cattle with the bone, fresh or chilled; meat of cattle, boneless, fresh or chilled; (b) Buffalo: meat of buffalo, fresh or chilled; (c) Sheep: meat of sheep, fresh or chilled; (d) Goat: meat of

goat, fresh or chilled; (e) Swine/pig: meat of pig with the bone, fresh or chilled; meat of pig, boneless, fresh or chilled; (f) Horses: horse meat, fresh or chilled; (g) Asses: meat of asses, fresh or chilled; (h) Mules and hinnies; (i) Camels: meat of camels, fresh or chilled; other camelids; and (j) Game meat, fresh, chilled, or frozen.

Further details on FAOSTAT codes, descriptions, and definitions of the food items comprising the red meat categories investigated in the present study are included in the Supplementary Materials (Table S1), including the technical specifications of products.

The information on exports was organized into a dataset comprising the amount exported from reporting countries (origin) to partner countries (destination). Exports of live animals were converted into weight (kilograms) of red meat ready for consumption through the application of live-into-dressed weight conversion rates [49], and aggregated-into-unprocessed red meat exports, according to methods described in previous studies [50–52].

Data on country population according to year, obtained from the publicly available dataset on World Development Indicators of the World Bank (https://databank.worldbank.org/source/world-development-indicators [Accessed: 31 July 2025]) [53], were incorporated into the database to allow the estimation of red meat per capita per year imported from origin countries to destination countries. Additional information on the income level of countries according to year, based on World Bank classification (https://blogs.worldbank.org/opendata/new-world-bank-group-country-classifications-income-level-fy24 [Accessed: 1 March 2025]) [54], allowed analysis of red meat trade according to country income level (Supplementary Materials, Tables S2 and S3).

Thus, the dataset comprised data in the format of adjacent matrix R_t, with directed connections representing the global red meat trade per year between each country of origin (exporter) and each country of destination (importer) from 1986 to 2020. The values of the main diagonal of the trade matrix are 0, considering the absence of imports and exports from and to the country itself (Equation (1)).

$$R_t = \begin{bmatrix} 0 & \cdots & r_{1pt} \\ \vdots & \ddots & \vdots \\ r_{p1t} & \cdots & 0 \end{bmatrix} \quad (1)$$

where r_{ijt} is the aggregated flow of processed or unprocessed red meats exchanged between country i and country j in the year t, based on original data for food items from FAOSTAT.

2.2. Network Analysis

Information on processed and unprocessed red meat (in kilograms per capita per year) was organized into a single dataset representing a directional matrix of exports from the origin country to the destination country, including weight and year during the period of analysis (1986 to 2023), allowing the identification of patterns in international trade networks. The network analysis was based on directional graphs representing connections of red meat trade (edges) between countries (nodes) within the global trade network. Thus, the outputs of the analysis represent encompass graphs of the processed and unprocessed meat trade between pairs of countries, using annual data, on Gephi 0.10.1 in the Noverlap layout to allow identification of the countries involved in the global red meat trade. Graphs show countries' codes according to official codes of the Detailed Trade Matrix from the Food and Agriculture Organization [45].

Network properties synthesizing characteristics of the graphs of processed and unprocessed red meat exchanges for each year within the period of analysis (1986–2023) were compared to identify trends in the evolution of the global trade of red meat. The network properties analyzed in the study included average degree, average weighted

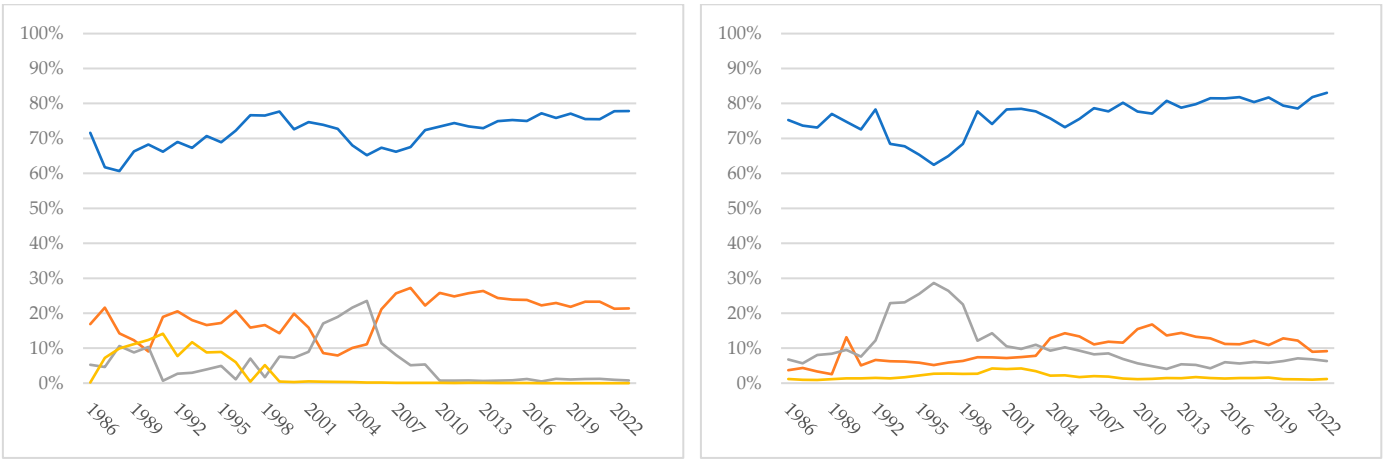
degree, network density, modularity, and average clustering coefficient [55]. The average degree corresponds to the occurrence of transactions of red meat between pairs of countries in the period, i.e., connections (edges) between nodes (countries), whilst the average weighted degree represents the connection weighted by the amount of red meat traded between countries (kilograms per capita per period). The network density corresponds to the proportion of connections established in the network in relation to the total potential connections between nodes, i.e., a higher network density denotes the involvement of a higher number of countries in the global trade of red meat. The modularity represents the existence of a high density of connections within subgroups of nodes in relation to sparse connections among subgroups. Finally, the average clustering coefficient identifies the density of connections within the network in comparison to random networks.

2.3. Statistical Analysis

Data on the network metrics of countries were obtained through network analysis using Gephi 0.10.1 to allow testing for differences according to periods. Descriptive analysis of the trade volume of red meat according to country income level considered World Bank income classification. Due to the absence of normal distribution in network metrics, the Kruskal–Wallis test was conducted to verify changes in red meat trade according to years, and the Friedman test was performed to identify differences in countries' network properties among years, using Stata software version 17, with significance at $p < 0.05$.

3. Results

The global trade of processed and unprocessed red meat presented a substantial increase from 1986 to 2023, growing from 0.202 and 1.415 kg per capita in 1986 to 0.453 and 3.315 kg per capita in 2023, respectively (Table 1). High-income countries represent a major part of the trade (65% to 86%) throughout the period (Table 1), though upper-middle-income countries showed increasing participation in trade from the mid-2000s onwards (Figure 1). There were significant changes only in the volume of red meat imports across years. In addition, the countries involved in the processed red meat trade increased, whereas participation in the unprocessed red meat trade showed stable trends (Table 1).



(**a**) (**b**)

Figure 1. *Cont.*

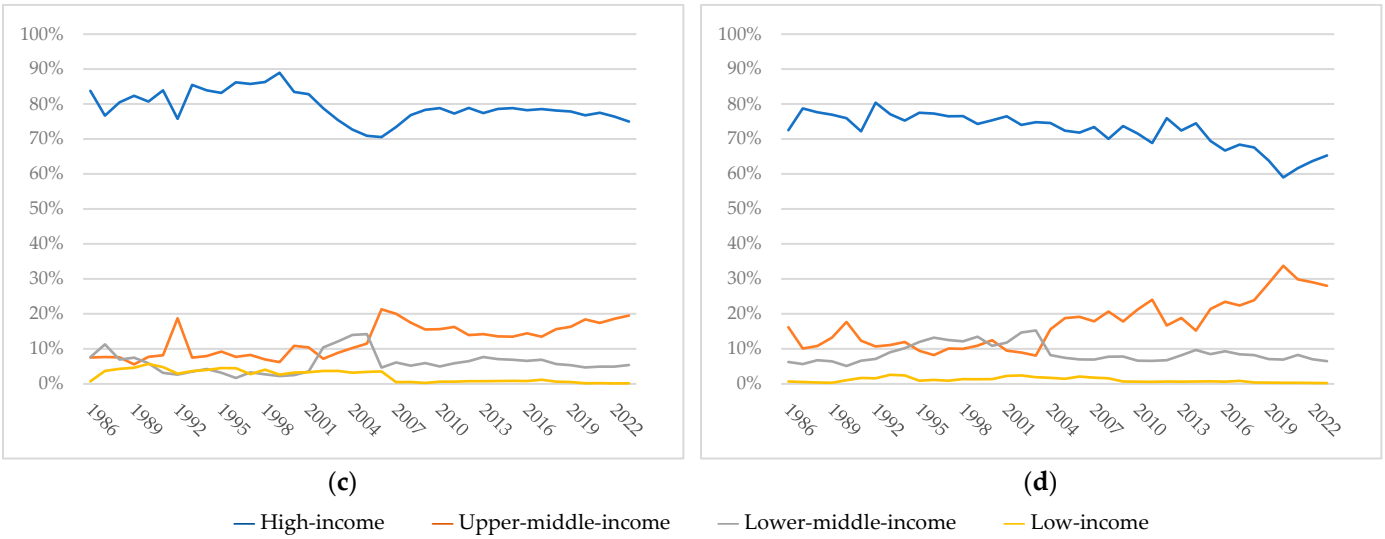


Figure 1. Proportion of processed and unprocessed red meat trade according to country income level, 1986–2023. (**a**) Processed red meat exports. (**b**) Processed red meat imports. (**c**) Unprocessed red meat exports. (**d**) Unprocessed red meat imports.

Table 1. Proportion of annual global trade volume of processed and unprocessed red meat according to country income level, 1986–2023.

Income Level	Processed Red Meat Trade				
	1986	**1998**	**2010**	**2023**	**Total**
Volume per capita (kg)	0.202	0.298	0.438	0.453	
Exports					
High-income country	71.58%	76.55%	73.36%	77.84%	72.84%
Upper-middle-income country	16.87%	16.60%	25.81%	21.39%	20.68%
Lower-middle-income country	5.24%	1.68%	0.73%	0.77%	4.60%
Low-income country	0.18%	5.17%	0.11%	0.00%	1.67%
Undefined income level	6.13%	0.00%	0.00%	0.00%	0.21%
N	65	82	112	113	
Ranksum	118,461.5	162,746.0	220,735.0	229,467.0	
p	0.9660				
Imports					
High-income country	75.26%	68.41%	77.69%	83.05%	77.41%
Upper-middle-income country	3.70%	6.34%	15.45%	9.16%	10.57%
Lower-middle-income country	6.78%	22.54%	5.69%	6.32%	9.15%
Low-income country	1.20%	2.67%	1.16%	1.18%	1.75%
Undefined income level	13.05%	0.04%	0.01%	0.29%	1.13%
N	164	192	192	198	
Ranksum	424,545.5	612,637.5	76,4226.0	840,040.5	
p	0.0001				

Table 1. *Cont.*

Income Level	Unprocessed Red Meat Trade				
	1986	**1998**	**2010**	**2023**	**Total**
Volume per capita (kg)	1.415	1.951	2.948	3.315	
Exports					
High-income country	83.80%	86.31%	78.81%	74.98%	78.48%
Upper-middle-income country	7.50%	6.96%	15.63%	19.52%	13.80%
Lower-middle-income country	7.58%	2.72%	4.97%	5.35%	6.02%
Low-income country	0.68%	4.01%	0.59%	0.16%	1.68%
Undefined income level	0.44%	0.00%	0.00%	0.00%	0.02%
N	73	98	111	114	
Ranksum	145,918.5	195,541.5	237,090.5	254,568.5	
p	0.7424				
Income Level	**Unprocessed Red Meat Trade**				
	1986	**1998**	**2010**	**2023**	**Total**
Imports					
High-income country	72.51%	76.53%	71.55%	65.28%	70.83%
Upper-middle-income country	16.14%	9.97%	21.26%	28.03%	19.37%
Lower-middle-income country	6.22%	12.12%	6.58%	6.46%	8.53%
Low-income country	0.64%	1.35%	0.60%	0.22%	0.94%
Undefined income level	4.49%	0.03%	0.00%	0.01%	0.33%
N	164	193	194	198	
Ranksum	466,131.0	619,260.0	774,069.5	802,852.5	
p	0.0001				

Note: N = number of countries.

Countries initially presented connections with an average degree of 4.421 and 5.643 for processed and unprocessed red meat in 1986, respectively, reaching 11.515 and 13.098 in 2023. Although the unprocessed red meat trade presented a higher average weighted degree throughout the period of analysis, there was a threefold increase in the average weighted degree of the processed red meat trade from 1986 to 2023, whilst unprocessed red meat showed a twofold increase (Table 2). The Friedman test was conducted on the network properties of countries involved in the global trade of red meat to identify differences according to periods, indicating significant differences in node metrics for the processed and unprocessed red meat trade across years ($p = 0.000$) (Table 2).

Table 2. Network properties of global trade of processed and unprocessed red meats according to period, 1986–2023.

	Processed Red Meat					
Network Metrics	**1986**	**1998**	**2010**	**2023**	**Q(37)**	***p***
Average degree	4.421	6.992	8.947	11.515	3400.000	0.000
Average weighted degree	0.002	0.003	0.005	0.006	2100.000	0.000
Growth		50%	150%	200%	211.789	0.000
Graph density	0.017	0.026	0.034	0.043	2100.000	0.000
Modularity	0.611	0.553	0.616	0.600	1700.000	0.000
Average clustering coefficient	0.312	0.368	0.357	0.398	153.887	0.000

Table 2. *Cont.*

Unprocessed Red Meat						
Network Metrics	**1986**	**1998**	**2010**	**2023**	**Q(37)**	***p***
Average degree	5.643	8.568	11.162	13.098	3200.000	0.000
Average weighted degree	0.009	0.010	0.016	0.019	1500.000	0.000
Growth		11%	78%	111%	255.995	0.000
Graph density	0.021	0.032	0.042	0.049	1500.000	0.000
Modularity	0.495	0.557	0.541	0.546	1500.000	0.000
Average clustering coefficient	0.311	0.382	0.367	0.401	166.556	0.000

The growth in bilateral trade connections represented by increases in average degree and network density indicates an increase in the involvement of countries in the global trade of processed and unprocessed red meat throughout the period of analysis. The growth in the average weighted degree of processed red meat trade (+200%) was higher than the rise in unprocessed red meat trade (+111%) from 1986 until 2023. Furthermore, the gradual incorporation of additional countries into global exchanges of processed red meats was also superior in comparison to unprocessed red meat, and the strength of connections between countries within subgroups of the global trade network of processed red meat was higher than connections observed between countries exchanging unprocessed red meat, according to indicators of network modularity (Table 2).

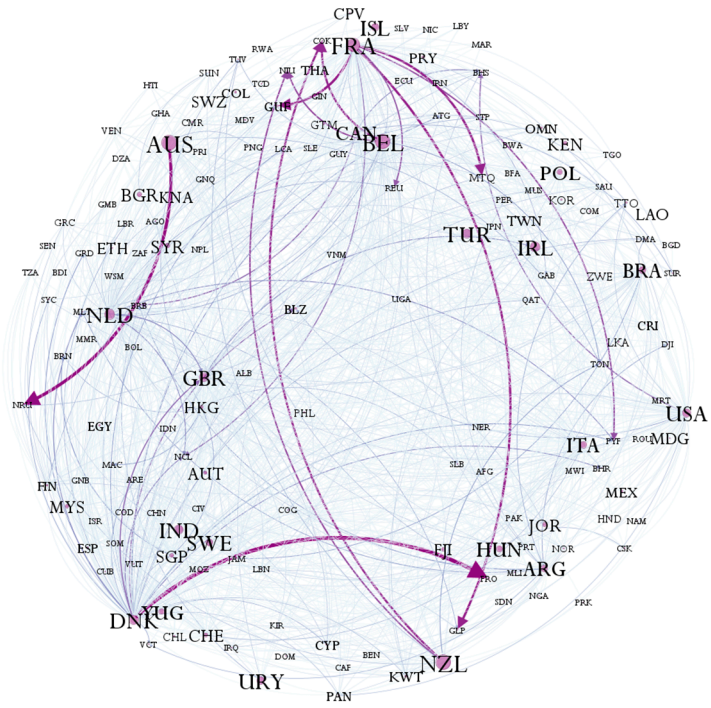
Graphs showing the beginning, intermediary points, and final year of network analyses (1986, 1998, 2010, and 2023) are included, with details on the proportion of the global red meat trade represented by the ten major exporters and importers (Figures 2 and 3).

Minor changes occurred in the average clustering coefficient of the global red meat trade networks, showing that the density of connections between nodes within the international trade of processed (between 0.312 and 0.398) and unprocessed red meat (between 0.311 and 0.401) was relatively stable throughout the period of analysis. Graphs show the dominance of few countries in the international trade of red meat throughout the period of analysis, particularly indicating minor changes in the leadership in red meat exports.

Countries (nodes) located in the center of the graphs present higher centrality within the red meat trade network. Node sizes and colors, in addition to the font size of countries' names, were represented proportionally to the volume of exports (weighted outdegree), whilst the thickness of directed edges represents the volume of trade connections (weight in kilograms per capita per day). The main exporters and importers of processed and unprocessed red meat and their respective participation in global red meat trade flows are presented according to year (Figures 2 and 3).

The major exporters of processed red meat throughout the period of analysis were Denmark (DNK), the Netherlands (NLD), China (CHN), Brazil (BRA), and the United States (USA), whilst the main exporters of unprocessed red meat were Australia (AUS), the Netherlands, Denmark, France (FRA), Belgium (BEL), the United States, Canada (CAN), and Germany (DEU).

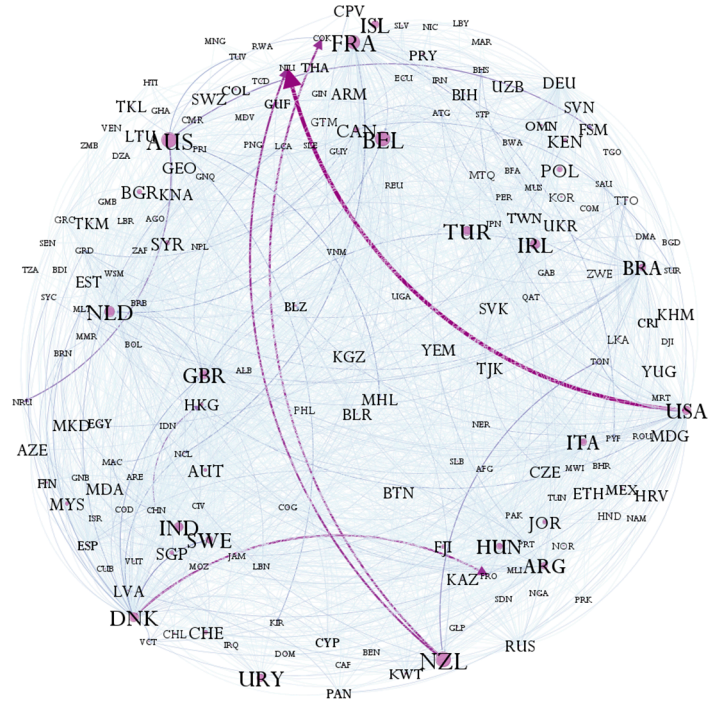
The increase in connections between countries within red meat trade networks and the significance of changes in imports throughout the period point to a substantial growth in imports, potentially linked to rise in income of certain countries, resulting in higher demand for red meat. Yet, countries like the United Kingdom (GBR), the United States, France, Hong Kong (HKG), the Netherlands, Japan (JPN), Germany (DEU), Italy (ITA), and Russia (RUS) represented major importers of processed and unprocessed red meat in the global trade network throughout the period from 1986 to 2023.



(**A**) 1986

Exports	Imports
DNK	GBR
31.59%	37.83%
NLD	USA
16.23%	20.40%
BEL	SUN
7.74%	10.01%
ARG	FRA
6.17%	5.24%
BGR	NLD
6.13%	2.62%
HUN	ITA
5.13%	2.55%
POL	JPN
4.18%	1.73%
FRA	EGY
3.08%	1.70%
BRA	BEL
2.57%	1.61%
ITA	AGO
2.40%	1.20%

0.000 0.143

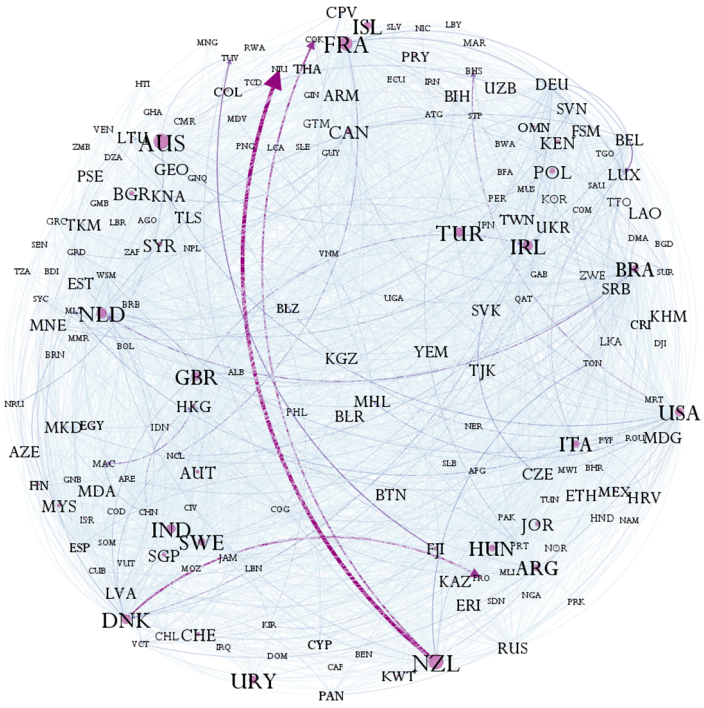


(**B**) 1998

Exports	Imports
DNK	GBR
17.40%	22.06%
BEL	RUS
10.52%	14.09%
USA	USA
10.00%	8.50%
NLD	DEU
7.90%	7.18%
FRA	FRA
6.93%	4.71%
BRA	HKG
6.43%	4.68%
CHN	JPN
4.93%	4.36%
ITA	NLD
4.22%	4.35%
ARG	SWE
4.19%	2.68%
DEU	BEL
4.17%	2.53%

0.000 0.159

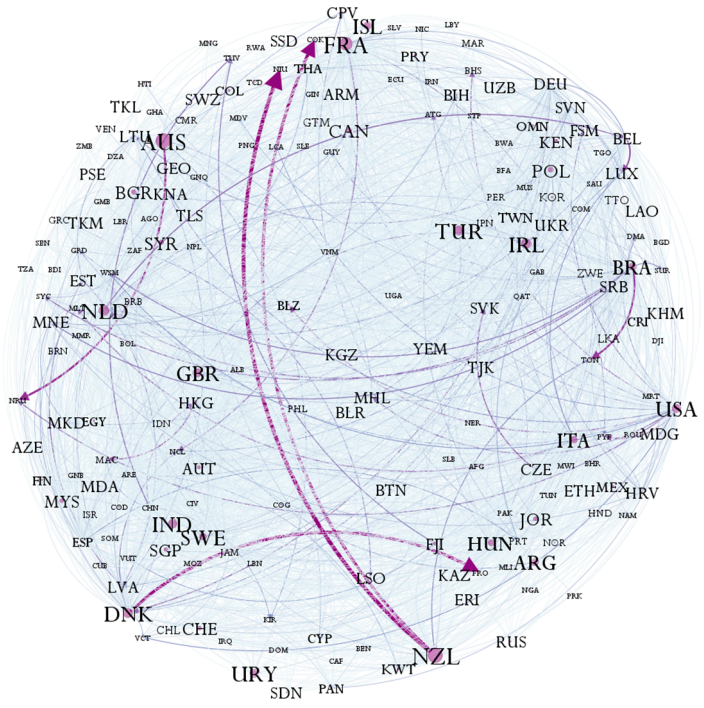
Figure 2. *Cont.*



(**C**) 2010

Exports	Imports
BRA	GBR
13.30%	19.72%
USA	NLD
11.65%	8.15%
DEU	DEU
10.13%	7.73%
NLD	FRA
8.47%	5.96%
DNK	JPN
6.30%	5.44%
CHN	MEX
4.89%	4.53%
ITA	CAN
4.51%	3.64%
POL	USA
4.28%	3.53%
ESP	HKG
3.83%	3.19%
BEL	BEL
3.77%	2.95%

0.000 — 0.193

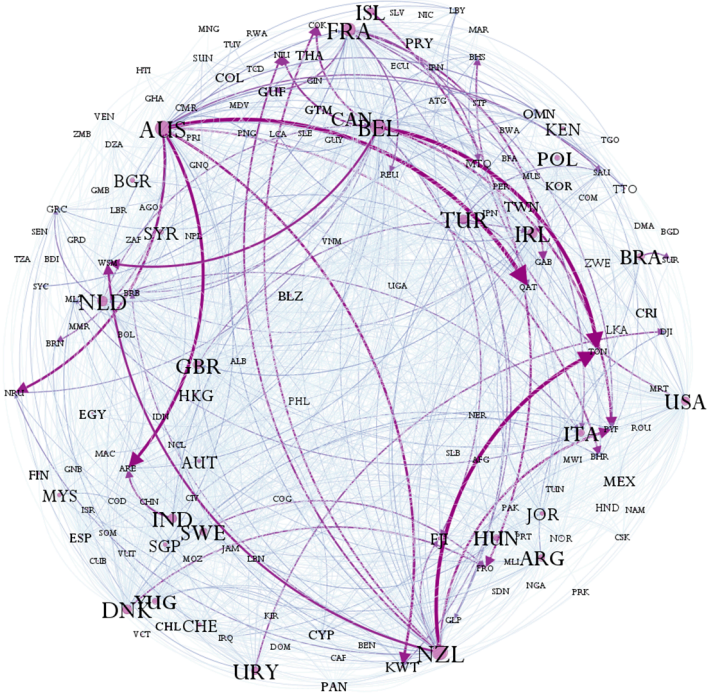


(**D**) 2023

Exports	Imports
BRA	GBR
10.54%	15.45%
NLD	DEU
9.73%	9.02%
USA	NLD
9.71%	7.83%
DEU	FRA
8.77%	7.08%
POL	USA
7.43%	5.04%
ITA	BEL
6.03%	4.58%
ESP	CAN
5.83%	4.41%
DNK	JPN
4.16%	3.42%
BEL	DNK
3.54%	2.63%
IRL	MEX
3.16%	2.35%

0.000 — 0.208

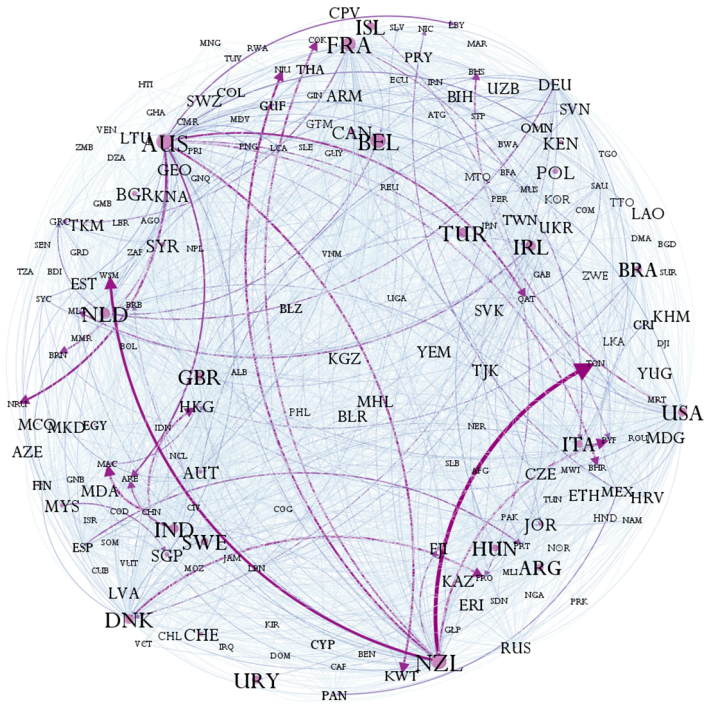
Figure 2. Global trade network of processed red meat and countries with major contribution to processed meat exchanges, according to period, 1986–2023. AGO = Angola; ARG = Argentina; BEL = Belgium; BGR = Bulgaria; BRA = Brazil; CAN = Canada; CHN = China; DEU = Germany; DNK = Denmark; EGY = Egypt; ESP = Spain; FRA = France; GBR = United Kingdom; HKG = Hong Kong; HUN = Hungary; IRL = Ireland; ITA = Italy; JPN = Japan; MEX = Mexico; NLD = Netherlands; POL = Poland; RUS = Russian Federation; SUN = Soviet Union; SWE = Sweden; USA = United States.



Exports	Imports
12.51%	USA
AUS	17.96%
11.69%	ITA
NLD	17.00%
11.22%	FRA
FRA	9.37%
11.11%	JPN
NZL	8.31%
9.56%	BRA
IRL	5.38%
5.93%	GBR
DNK	5.04%
5.81%	IRN
CAN	4.07%
4.99%	SUN
USA	3.89%
3.38%	SAU
HUN	2.70%
2.83%	GRC
12.51%	2.19%

(**A**) 1986

0.000 — 0.488

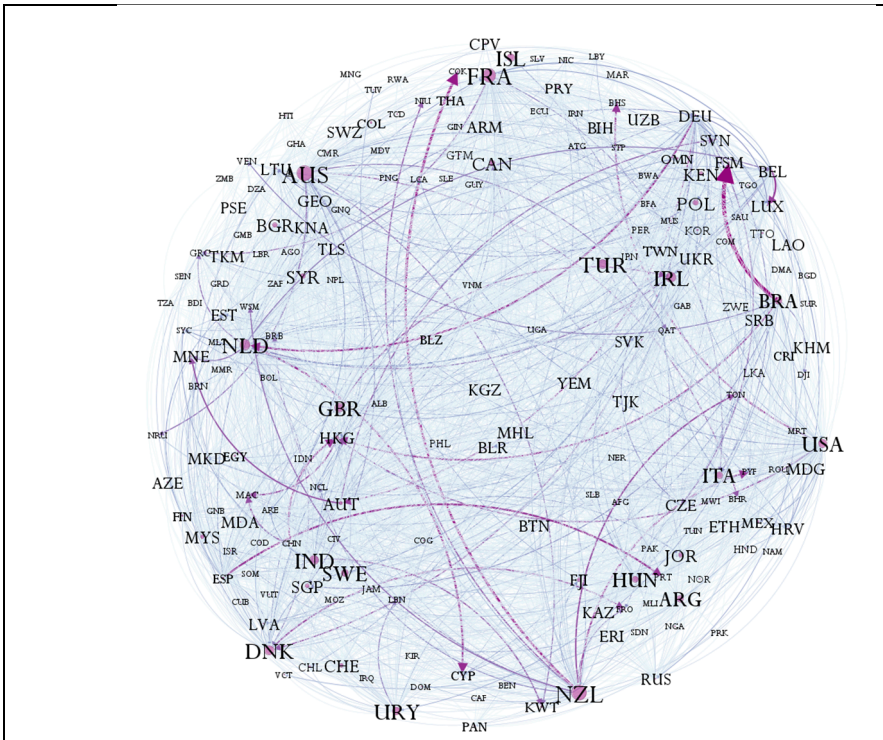


Exports	Imports
AUS	USA
12.16%	12.78%
USA	ITA
9.51%	11.80%
FRA	JPN
8.54%	10.46%
CAN	DEU
8.31%	10.16%
DNK	FRA
8.25%	6.37%
NLD	RUS
8.05%	4.83%
BEL	NLD
6.17%	3.78%
DEU	GBR
6.16%	3.30%
NZL	ESP
5.68%	2.45%
IRL	MEX
4.32%	2.30%

(**B**) 1998

0.000 — 0.534

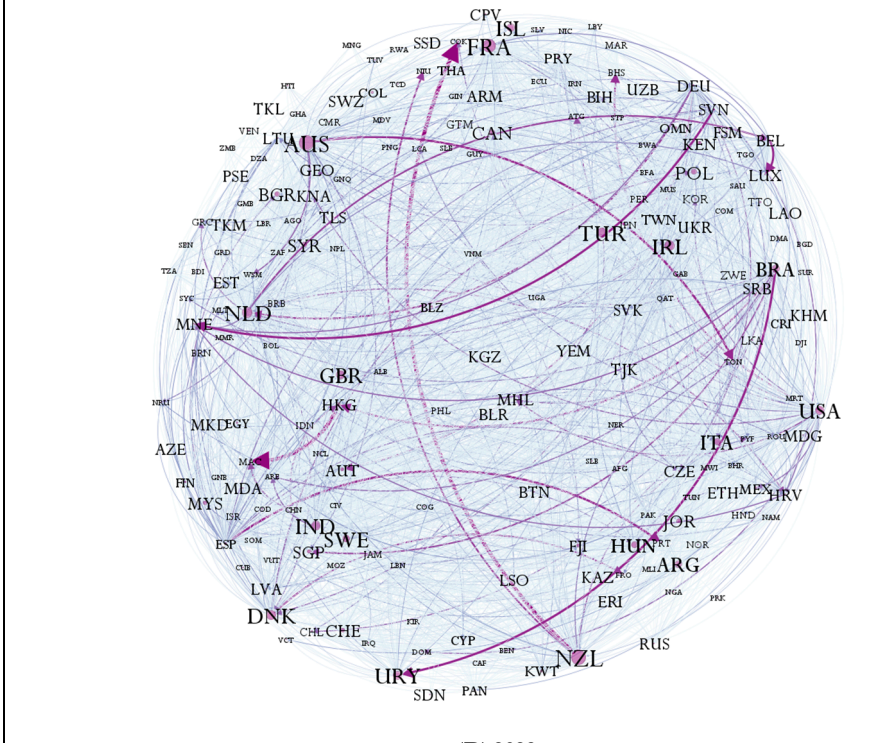
Figure 3. *Cont.*



Exports	Imports
DEU	ITA
10.02%	8.53%
USA	USA
9.37%	8.26%
CAN	DEU
7.53%	8.12%
NLD	RUS
7.40%	7.15%
BRA	JPN
7.40%	6.72%
AUS	FRA
7.08%	4.29%
DNK	NLD
6.66%	4.21%
ESP	GBR
5.26%	3.81%
FRA	HKG
5.02%	2.70%
BEL	POL
4.22%	2.66%

0.000 — 0.491

(**C**) 2010



Exports	Imports
BRA	CHN
11.56%	15.64%
USA	USA
11.52%	8.30%
ESP	ITA
8.45%	6.37%
AUS	DEU
7.01%	5.42%
NLD	JPN
6.71%	5.12%
CAN	MEX
6.39%	4.59%
DEU	POL
6.04%	3.57%
DNK	KOR
5.16%	3.42%
IND	NLD
4.11%	3.16%
FRA	FRA
3.84%	2.50%

0.000 — 0.486

(**D**) 2023

Figure 3. Global trade network of unprocessed red meat and countries with major contribution to unprocessed meat exchanges according to period, 1986–2023. AUS = Australia; BEL = Belgium; BRA = Brazil; CAN = Canada; CHN = China; DEU = Germany; DNK = Denmark; ESP = Spain; FRA = France; GBR = United Kingdom; GRC = Greece; HKG = Hong Kong; HUN = Hungary; IND = India; IRL = Ireland; IRN = Iran; ITA = Italy; JPN = Japan; KOR = South Korea; MEX = Mexico; NLD = Netherlands; NZL = New Zealand; POL = Poland; RUS = Russia; SAU = Saudi Arabia; SUN = Soviet Union; USA = United States.

4. Discussion

The study investigated the evolution of trade networks of processed and unprocessed red meat between 1986 and 2023. The results showed an increase in exports and im-ports of red meat among high-income countries. There was a rise in the international commerce of red meat between countries through the gradual incorporation of additional countries into the global trade network from 1986 to 2023, considering the increase in network degree.

In addition, network analysis showed growth in trading partnerships between countries (average degree) and an increase in the trade of calories (average weighted degree) throughout the period of analysis, pointing to an intensification in the global trade of processed and unprocessed red meat. The rise in average weighted degree pointed to growth in the volume of exchanges of red meat (kilograms per capita per period), consistent with trends in nutrition transition occurring during the last decades [17].

The global increase in red meat demand has been particularly linked to changes in income level, advances in technology and logistics, changes in the geopolitical landscape, a decrease in the relative prices of commodities, and growth in population, which lead to growth in the food supply worldwide [56]. Considering the potential for tax revenues, employment, and other economic benefits linked to meat production chains, governments of diverse countries have incentives for meat production and exports.

Negative fluctuations identified in the global trade of red meat in certain periods may be connected to financial crises that generated global instability, influencing exports worldwide, and foodborne outbreaks [57–62]. Other studies highlighted changes in the global trade of red meat during the middle-1990s and 2000s linked to zoonosis outbreaks in Europe, the United States, and other regions, like foot-and-mouth disease, swine fever, avian flu and, specifically in the beef chain, bovine spongiform encephalopathy [57–60].

Foodborne outbreaks generate waves of intensification of sanitary barriers within production chains worldwide, increasing production costs and reducing meat production and trade [59,60]. In addition, zoonosis outbreaks may also provide justification to limit food imports in certain countries due to political and economic interests at the local level, reducing competition and increasing food prices for the population.

Network metrics referring to modularity showed the dominance of high- and upper-middle-income countries in the international trade of processed and unprocessed red meat throughout the period. Graph analysis reinforced that leadership in the global exports of red meat was concentrated among a few countries from 1986 until 2023, especially high-income countries, similarly to findings on the global trade networks referring to calories, nutrients, and carbon and water footprints [50–52].

Yet, there were major changes in exports leadership throughout the period: the United States, Brazil, and Germany presented a substantial increase in processed and unprocessed red meat exports throughout the period, surpassing Denmark, the Netherlands, and China in processed red meat exports, and Australia, Netherlands, New Zealand, and Denmark in unprocessed red meat exports. Government incentives and private investments were key elements in leveraging modifications in the global scenario of red meat production and exports throughout the period between 1986 and 2023 [8,9].

In addition, the increase in global income level exerted substantial influence in changes identified on the demand side of global markets for red meat. The leadership in processed red meat imports presented minor changes, being dominated by Great Britain, followed by the United States, Russia, France, Germany, and the Netherlands, whilst unprocessed red meats showed major changes throughout the period, being generally dominated by the United States, Japan, and European countries. Low-income countries remained in the networks' periphery, particularly due to a lack of resources for production and trade as well as inequalities in income distribution among individuals in their populations [63].

Considering that trade matrix datasets from FAO also encompass food donations between countries, part of the exchanges identified for low-income countries probably referred to connections established to provide humanitarian aid.

The results of the present study showed acceleration in the bilateral commerce of processed red meat compared to unprocessed red meat, raising public health concerns regarding the long-term consequences of consuming processed foods with high sodium and fat content [2–4]. The finding confirms trends identified in studies investigating the global nutrition transition during the last decades [17,64], indicating a gradual convergence toward Western dietary patterns with ahigh consumption of processed foods, including processed red meat. The robust evidence on connections between Western diets and non-communicable diseases emphasizes the need for implementation of public policies directed to food system transformation, encompassing the integration of nutrition and climate actions. Reinforcing healthy food consumption patterns like the Mediterranean diet at the population level support improvements in nutritional and health outcomes, in addition to a reduction in the environmental impacts of food production and consumption [65].

Yet, connectivity and volume of commerce between countries within trade networks of unprocessed red meat remained higher in comparison to processed red meat networks, indicating a higher pervasiveness of unprocessed red meat demand at the international level. Nevertheless, it is important to consider that certain countries may import unprocessed red meat for further processing at the national level [66]. Therefore, the policy actions of national governments should focus on the fulfillment of the nutritional requirements of their populations within strategies for health promotion [41], targeting the satisfaction of food demand through high-quality nutrient-dense fresh foods, including regular access to sources of protein in low-income settings instead of processed foods, especially in view of the conflicting evidence on the suggested low levels of unprocessed red meat consumption within healthy dietary patterns [26–28,66].

Although there is still a high prevalence of inadequate protein intake among individuals worldwide [63], the debate on recommendations to limit or promote red meat intake has been marked by intense controversy [20–25,29–31,67–71]. The promotion of healthy dietary patterns within sustainable food systems requires limited intake of unprocessed red meats and minimal consumption of processed foods, including processed red meats [13–16]. Therefore, findings from the present study reinforce the need for evidence-based strategies for health promotion in public policies at the national level, including nutrition education tools like nutritional guidelines and graphic models validated in the local context, for dissemination of knowledge on diet–health–environment connections [72–74]. Thus, considering current nutritional recommendations [11,12], the escalation in bilateral commerce in the processed red meat trade worldwide may represent a worrying trend in the context of the global syndemics of obesity, undernutrition, and climate change [75].

Finally, it is important to emphasize that previous evidence based on bilateral trade information was based on datasets limited to subsets of countries or shorter timespans [10,76–81]. The present study conveys valuable evidence for the design and implementation of public policies toward the improvement of global food systems, especially considering the role of bilateral or regional trade agreements on food availability that fulfill the nutritional requirements of populations [63]. Potential strategies at the national level to achieve an adequate protein supply at a national level should target bilateral trade agreements or multilateral agreements through benefits represented by the formation of regional blocs, based on alignment of trade policy and public interest goals [65], in addition to investments in research and development on alternative protein sources [35,36,41]. Initiatives in nutrition education, investments in cleaner production, and the adoption of evidence-informed strategies in trade policies at the national level may contribute to ad-

dress complex issues involved in red meat production, consumption, and trade to support food system transformation towards sustainability [41].

5. Conclusions

The study presented the evolution of global trade networks of processed and unprocessed red meat from 1986 to 2023, showing the growth of bilateral exchanges between countries over 38 years. Long-term trends identified in the study indicate a concentration of red meat production, exports, and imports among a minority of high- and upper-middle-income countries throughout the period of analysis. The acceleration in the processed red meat trade compared to the unprocessed red meat trade was consistent with results of previous studies showing the progression of nutrition transition processes registered in diverse countries worldwide, raising public health and environmental concerns on the global syndemics. The present study presents original contributions to the literature through insights on long-term relations among countries participating in the red meat trade, especially focusing economic and health repercussions arising from trends in processed red meat production, trade, and consumption. Yet, the literature on food system dynamics still lacks further long-term evidence on the complexity permeating meat trade networks at the global level; therefore, future studies should address additional attributes and implications in the global food trade in terms of social, economic, political, health, and environmental dimensions, particularly integrating multiple layers into complex networks.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/j8030035/s1, Table S1: Food items according to category of red meat and respective definitions in the FAOSTAT dataset. Table S2: Countries included in the study. Table S3. Countries included in the study and their respective income levels, according to year. 1986–2023.

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Conflicts of Interest: Author Amanda Dias Assoni Scartezini is employed by the company Fresenius Kabi. The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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