

Complex network analysis and health implications of nutrient trade

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ABSTRACT

Food trade plays a key role in global nutrition, but the essential nutrients within this trade are understudied. We investigated the global nutrient trade network from 1986 to 2020, examining the relationship with income level and health outcomes. Bilateral nutrient trade data for 48 nutrients and 254 countries/economies was produced, made accessible through an interactive online application. Nutrients of interest in the context of food security and health (protein, calcium, iron, and vitamins A and B12) were examined using network analysis, animated graphs, and logistic regression to demonstrate the inequitable nature of nutrient trade, but its positive role in current nutrition-related disease. Food trade policy should be set with micronutrient content and deficiency in mind to address food security, nutrition, and health.

1. Introduction

Food security and nutrition are key components of the definitions of both sustainable food systems and sustainable healthy diets (FAO, 2018; FAO/WHO, 2019). Progress towards achieving food and nutrition security is currently going backwards, with the population undernourished rising by nearly 200 million since 2015 and increases in severe food insecurity observed in all global regions (FAO, 2022a).

Food trade plays a central role in determining food security. In general, increases in global food trade and trade connectivity since the mid-20th century have increased the diversity of food supply at national levels, and have done so to a greater extent than has the increased diversity of production (Aguilar et al., 2020). This increased diversity of food offering generally comes at the cost of increased dependence on imports for food security, which is not problematic when sufficient connectivity and redundancy exists in the system (Kummu et al., 2020). These dynamics are coupled with frequent national or regional specialization in production and export of foods for which a comparative advantage exists.

The 2021 UN Food Systems Summit emphasized the contribution of trade to driving diversity of diets, but also its role in environmental degradation (Hendriks et al., 2021; Hertel et al., 2021). Papers from the Summit's Scientific Group called for policy discussion that bridges the

concepts of nutritious food with those of agriculture, trade, and environmental sustainability.

There is clear justification for the study of food trade to gain a better understanding of how it can best aid the achievement of food and nutrition security. Many such studies exist, predominantly using network modelling and analysis, with the strongest focus to date being on trade in cereals (particularly wheat), due to their high contribution to global diets (Wang et al., 2021; Dupas et al., 2019; Raj et al., 2022), and on either food mass or caloric content (Grassia et al., 2022; Silvestrini et al., 2023; Janssens et al., 2020).

Recently, several studies have taken the further step to considering trade in the many nutrients within food, which provides a greater degree of insight into how food trade aids populations to meet their nutritional requirements (Wood et al., 2018; Hoffmann et al., 2021; Nash et al., 2022; Ge et al., 2021; Geyik et al., 2021). This approach is strongly justified, given that both global and national gaps exist between nutrient supply and population requirement for specific micronutrients (Wood et al., 2018; Smith, 2021; Geyik et al., 2020; Chen et al., 2021). These studies emphasize that it is generally not dietary energy or protein that is in short supply at a national level, but rather key vitamins and minerals, including calcium, vitamin A and vitamin E. As such, there is a need to move beyond the study of trade in cereals, food mass, or calories, and understand micronutrient trade.

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Geyik et al. previously investigated trade in seven essential nutrients from food from 2013 to 2015 and ascertained how trade contributes to nutrient adequacy in the world's countries (Geyik et al., 2021). This work was highly valuable in demonstrating the role of specific trade flows in achieving food and nutrition security and identified the inequitable role of trade between high-income countries (HIC) and low-income countries (LIC). Here, we extend this approach with the inclusion of 48 nutrients over 35 years of trade data, to examine the evolution of nutrient trade networks and their relationships with population health status. We also present the integration of this data into an accessible online tool, allowing nutrient trade dynamics at a national level to be investigated by interested stakeholders. Finally, we identify the links between nutrient trade and human health outcomes: anemia, infant mortality rate, probability of dying among children, and life expectancy.

2. Materials and methods

2.1. Datasets

Country-level bilateral trade data from 1986 to 2020 for food items appropriate for human consumption was obtained from the FAOSTAT Detailed Trade Matrix (FAOSTAT, 2021) and the United Nations Database on International Trade Statistics (United Nations, 2023). Additional details on data processing have been recently published elsewhere (Silvestrini et al., 2023). Income classification of countries over the same period was obtained from the World Bank (World Bank, 2019). Data on annual population and domestic supply-to-food ratios was obtained for each food item and country from the Food Balance Sheets in FAOSTAT (FAOSTAT, 2021).

Two strategies were used for the data analysis: (1) complex network analysis, based on construction of single-year country-level trade networks, and (2) regression analysis, based on extraction of network metrics to compose a second dataset with socioeconomic and

demographic characteristics and health outcomes potentially associated with food consumption patterns. Fig. 1 provides a conceptual overview of the inputs and outputs of the analysis in this paper.

Health outcome data including infant mortality rates, probability of death among children from 5 to 14 years old, prevalence of anemia among women of reproductive age, and life expectancy were sourced from the World Health Organization (WHO. The Global Health Observatory, 2023), based on evidence in the literature linking the consumption of nutrients in the diet with short-, and long-term effects on population health. In addition, considering potential confounding factors linked to economic, social, and political aspects of the globalization process occurring worldwide during the period, we included indicators of the KOF Globalization Index connected to dimensions of de facto (activities) and de jure (regulations) globalization (Gygli et al., 2019; Konjunkturforschungsstelle Swiss Economic Institute (KOF), 2023). The synthesis of variables in the datasets of the study are presented in the Supplementary Materials (Table S1).

2.2. Variables

Food import data from FAOSTAT was combined with fisheries import data from COMTRADE into a single dataset. Domestic supply-to-food ratios for each food item in each importing country were applied to items traded to ascertain the portion consumed as food, based on the share of each item within the domestic supply declared as food for human consumption in the Food Balance Sheets (see Supplementary Material). Values were further converted into tonnes of each food item for consumption using appropriate conversion factors to exclude inedible parts (e.g., animal bones, vegetable peel, etc.).

2.3. Nutritional composition

The conversion of food trade data to nutrient trade data was performed using the framework of the DELTA Model® (Smith, 2021). Food

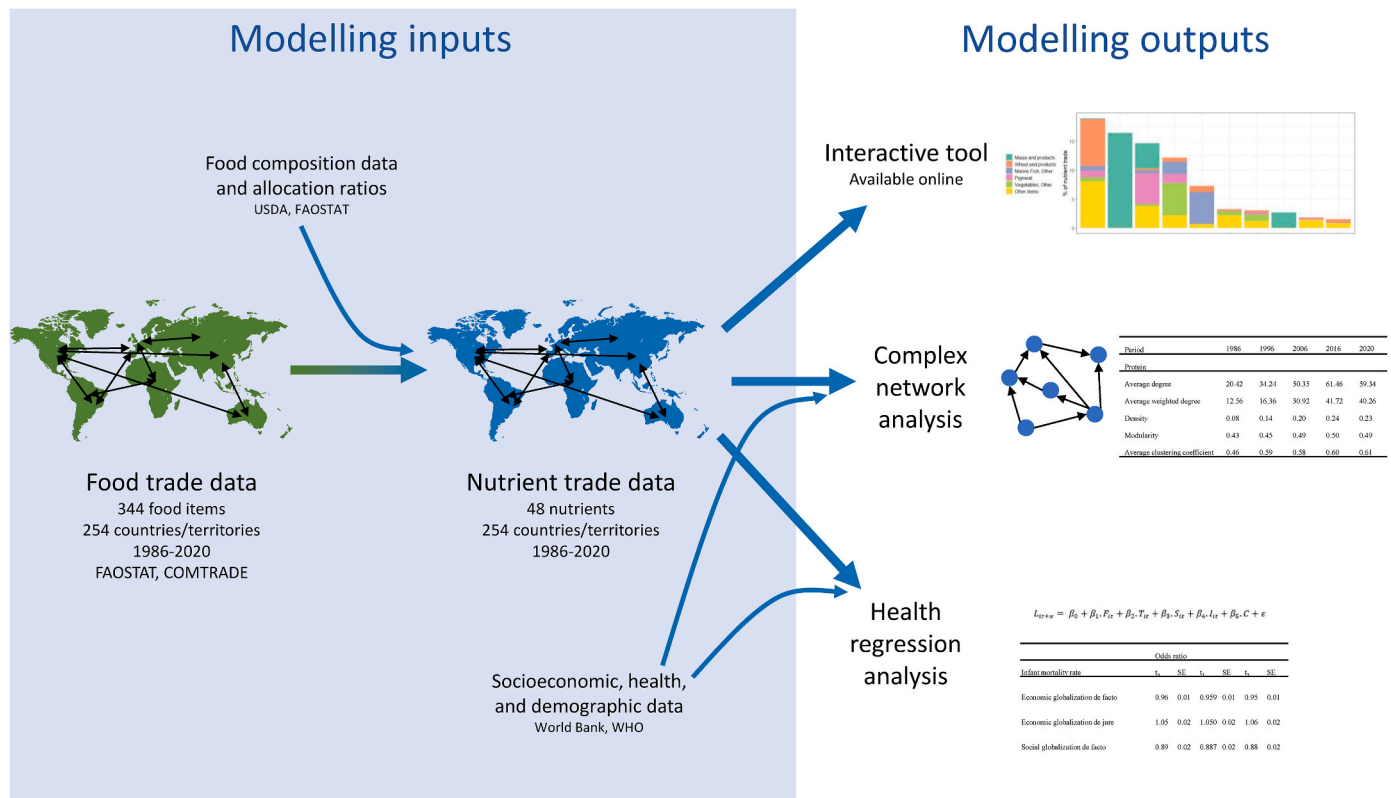


Fig. 1. Conceptual diagram showing the data sources used and methodological process followed in this study.

items were matched to food composition data from the United States Department of Agriculture Food Composition Tables (USDA, 2020), and the quantities of 48 nutritional components (hereafter referred to as nutrients) were calculated, including energy, fiber, sugars, cholesterol, carbohydrate, protein, and lipid, 11 trace elements (calcium, copper, iron, magnesium, manganese, folate, phosphorus, potassium, selenium, sodium, and zinc), 12 vitamins (vitamins A in retinol activity equivalents, B1/thiamin, B2/riboflavin, B3/niacin, B5/pantothenic acid, B6/pyridoxine, B8/choline, B12/cobalamin, C, D, E, and K), and 18 amino acids (alanine, arginine, aspartic acid, cystine, glutamic acid, glycine, histidine, isoleucine, leucine, lysine, methionine, phenylalanine, proline, serine, threonine, tryptophan, tyrosine, and valine). In this paper, we present analysis on key nutrients associated with food security: protein, calcium, iron, vitamin A, and vitamin B12. The full dataset can be found at 10.17632/dmm4gnx5w7.1.

2.4. Data analysis

The nutrients included in n food items exchanged between pairs of countries i and j during the t years of analysis were aggregated into bilateral nutrient trade flows, following previously proposed methods (see Supplementary Material) (Silvestrini et al., 2023). This data was used to construct graphs of nutrient trade between countries and converted into animation videos on the network evolution over time for each nutrient. Countries were represented by nodes with color according to weighted outdegree of nutrient trade, size according to weighted degree of nutrient trade, and connections established through nutrient trade represented by edges with thickness according to mass of nutrient trade.

Data organization, processing, analysis, and network modelling were conducted using R and Python 3 language in Gephi 0.9.2 software, using the Noverlap and the Fruchterman-Reingold layout to represent networks in figures and video, respectively. The Noverlap layout prevents node overlaps in addition to maintaining the graph shape; whilst the Fruchterman-Reingold layout is based on direct force algorithm (Fruchterman et al., 1991). The nutrient trade tool was constructed using this same data and built in R using the Shiny package (Chang W et al., 2023).

For the second dataset of the study, nutrient network metrics (degree centrality, indegree centrality, and outdegree centrality) were compiled. Socioeconomic and demographic characteristics of countries and health outcomes associated with food consumption, especially nutrient intake, were incorporated into the dataset to allow the analysis of potential effects of global nutrient trade on population food security and health.

Health outcome variables were tested for normality using scaled normal density plot (Supplementary Fig. 1). Due to the absence of normal distribution, logistic regression models were used to investigate the effects of food trade networks on population health status (Equation (1)).

$$L_{it+x} = \beta_0 + \beta_1.F_{it} + \beta_2.T_{it} + \beta_3.S_{it} + \beta_4.I_{it} + \beta_5.C + \varepsilon \quad (1)$$

Where: L_{it+x} = log-odds of the health outcome of interest (infant mortality rate, probability of dying among children from 5 to 14 years old, prevalence of anemia among women of reproductive age, and life expectancy) of the population of country i in lagged period $t+x$ ($x = 0, 1, \text{ or } 3$); F_{it} = characteristics associated with nutrient availability in country i in period t ; T_{it} = network metrics of the country i in period t ; S_{it} = sociodemographic characteristics of country i population during period t ; I_{it} = income level of country i during period t ; C = control variables referring to region and year; and ε = error term.

Log likelihood and Wald chi-square statistics were used to establish the quality of fit of the logistic regression models. The regression analyses were performed using Stata version 17 with significance level $p < 0.05$.

3. Results

3.1. Nutrient trade dynamics by income level

Considering the volume of information in the analysis, we focus here on five nutrients (protein, calcium, iron, vitamin A, and vitamin B12) determined by previous research to be of interest in the context of global food and nutrition security (Smith, 2021; Beal et al., 2017; Passarelli et al., 2022; Lividini et al., 2022), over the period of analysis (1986–2020). Energy was omitted from the analysis due to recent presentation of this data elsewhere (Silvestrini et al., 2023). The full results for 48 nutrients, and sociodemographic, health, and food commerce characteristics of countries involved in the food trade networks are available in the Supplementary Materials (Tables S1 to S4, and 10.17632/dmm4gnx5w7.1) and the interactive application (described in the following section).

344 food items suitable for human consumption were included in the analysis, traded among 254 countries/economies. Country income level was used to aggregate the data for visual presentation (Fig. 2).

For each nutrient, an increasing trajectory was observed over the analyzed period, of an order comparable to that of total food mass trade. Protein, calcium, iron, and vitamin A all displayed relatively minor growth between 1986 and ~1997, before accelerating in subsequent years. Contrastingly, the rate of increase for vitamin B12 trade was greatest over this early period. This can be attributed to the dynamics for milk and marine fish products trade over this period, which were also the two greatest contributors to animal-sourced (and thus vitamin B12-containing) food trade throughout the studied period.

A discontinuity can be observed in the protein, calcium, and iron dynamics in Fig. 2 in 2010, with an abrupt shift in dominance of imports by lower-middle income countries (LMIC) to upper-middle income countries (UMIC). This is largely the result of the change in income classification for China, the imports of which accounted for 10–22% of total food mass imports between 2008 and 2020. These imports were dominated by soy, which has high protein, calcium, and iron content, but relatively low vitamin A and B12 content, compared to other food items in the dataset.

Exchanges between HIC and UMIC dominated trade of all five focus nutrients from 2010 onwards. However, the distribution of trade between these two groups differed markedly between nutrients. For protein, calcium, and iron, it was the UMIC that accounted for the majority of imports, whereas for vitamins A and B12, HIC dominated. This is partly the result of the soy dynamics described above, but also a result of the high concentration of animal-sourced food imports into high-income countries.

Between 1986 and 1990, a notable proportion of global nutrient trade (up to 43% for vitamin A in 1989) did not have either the exporter or importer country recorded. However, this issue was mostly resolved in all data past 1991, and represented <2% of total trade of each nutrient in each year thereafter.

3.2. Nutrient trade tool

To facilitate easy use and dissemination of the nutrient trade data produced here, an online, accessible application was developed. This tool allows users to view the import or export dynamics for any nutrient and country combination in the dataset, including both the trade partners and the traded food items contributing to nutrient exchange. The data shown is averaged over the most recent five years in the dataset, to be as representative as possible of current dynamics. Fig. 3 shows an example output of the tool for New Zealand vitamin A imports. The tool can be accessed at www.sustainablenutritioninitiative.com.

3.3. Network analysis

Global nutrient trade showed centrality of HIC in the network,

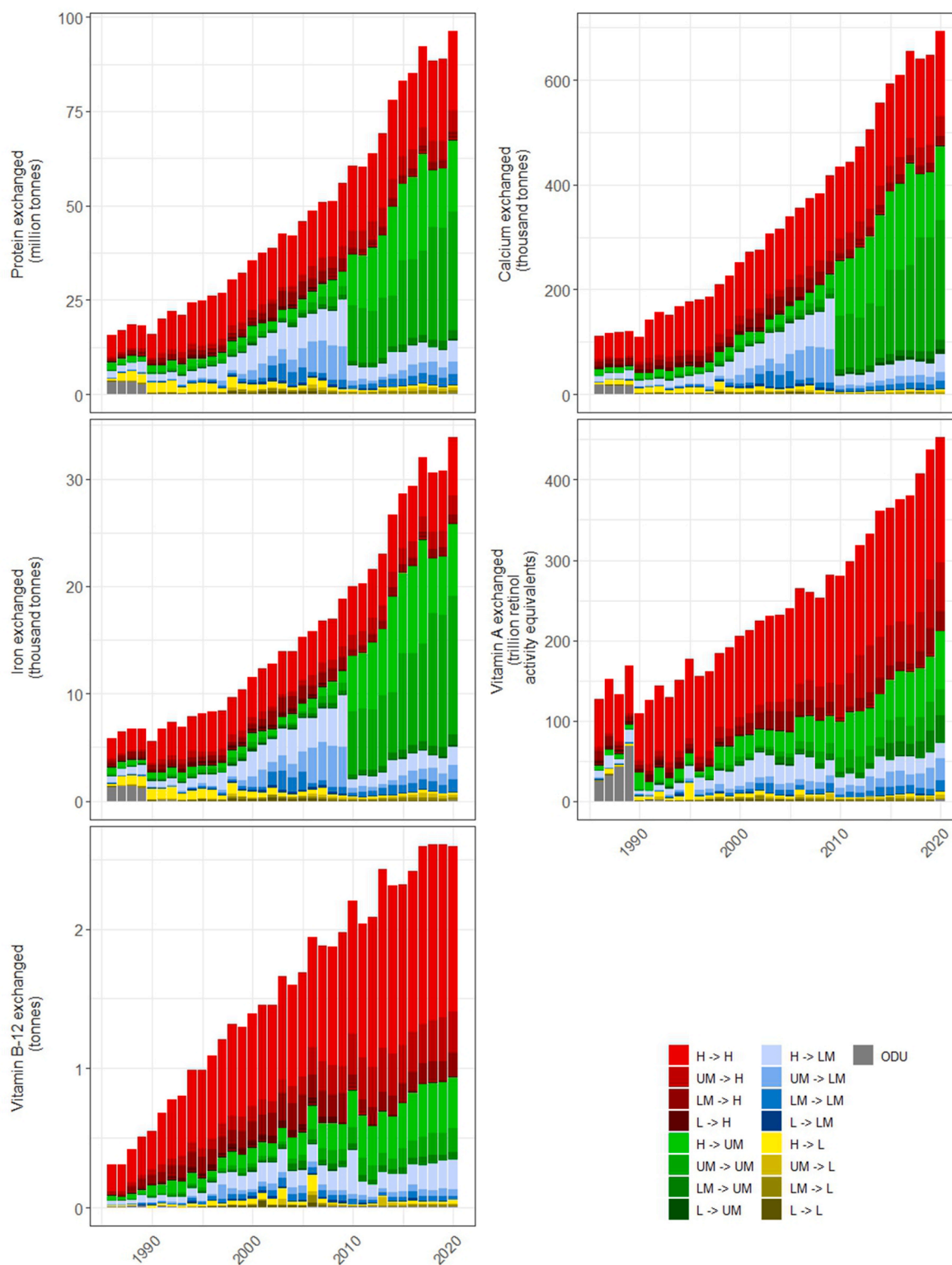


Fig. 2. Distribution of bilateral trade of selected nutrients between countries according to income level. H = high-income countries; UM = upper middle-income countries; LM = lower middle-income countries; L = low-income countries; ODU = origin or destination not recorded.

alongside a few UMIC and LMIC with significant participation in exchange of foods for human consumption, including Brazil, South Africa, and China (Fig. 4 and supplementary animations at 10.17632/dmm4gnx5w7.1).

The networks metrics indicated a continuous increase in average clustering coefficient in trade of most nutrients throughout the period of analysis, pointing to growth in probability of connections between

neighboring countries. There was intensification in average degree, average weighted degree, modularity, and density of nutrient trade from 1986 until mid-2010s, followed by a slight decrease in 2020. The changes in average degree and average weighted degree show modifications in number of connections and volume of nutrient traded between countries, respectively, whilst modifications in modularity point to establishment of highly connected subgroups of countries. Network



Fig. 3. New Zealand vitamin A imports, as displayed by the developed nutrient trade tool. Bars show percentage of total vitamin A imports sourced from New Zealand's top ten vitamin A-supplying trading partners. Color coding shows the five most important food items for vitamin A imports to New Zealand, with all other items aggregated into the "Other items" category. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

density identifies the connectedness of the graph (i.e., prevalence of connections between pairs of countries; Table 1).

3.4. Nutrient trade and health

Health outcomes related to food consumption patterns, particularly associated with intake of nutrients of interest in the study, showed different trajectories in the period. Infant mortality rates and probability of dying between 5 and 14 years old declined substantially, whilst anemia among women of reproductive age showed only minor changes. Life expectancy increased from 1986 to 2019, followed by a decline in 2020, likely due to the COVID-19 pandemic (Supplementary Materials, Table S3).

The odds ratios obtained in the logistic regression models showed statistically significant effects of country position within the nutrient trade networks on health outcomes throughout the period of analysis. Indicators of higher country involvement in nutrient trade networks were significantly associated with improvements in health outcomes during infancy and adulthood, independently of country socioeconomic, demographic and health characteristics, globalization levels, food trade dependency, and geographical region (Table 2).

Closeness centrality and harmonic closeness centrality in the protein trade network showed negative effects on infant mortality rates and probability of death among children 5–14 years old, respectively. These indicators capture the efficiency of network nodes (countries) in transmitting signals (food trade) through the graph. That is, countries with shortest distances in relation to other countries in the global trade network tended to benefit from lower infant mortality rates and deaths among children in the period of analysis, indicating potential effects of protein trade in reducing negative outcomes during childhood.

For adults, prevalence of anemia among women of reproductive age was negatively associated with closeness centrality in the iron trade network, whilst betweenness centrality in the protein trade network presented positive effects on life expectancy, being related to the influence of nodes on the flow of signals (food trade) in the graph (shortest path). In sum, countries that act as intermediate pathways for distribution of nutrients in the global food trade network (betweenness) presented higher life expectancy, whilst countries closely connected to other countries (closeness) showed lower prevalence of anemia among adult women.

Considering the role of dietary protein during childhood, the results

point to the importance of countries in participating of the global food trade to ensure proper nutrition for their population. Trends in health outcomes during infancy (mortality and probability of death) and adulthood (life expectancy) were associated with positioning of countries within the global nutrient trade network. In addition, the country connections within the trade network were also linked to health outcomes among adult women (prevalence of anemia).

4. Discussion

4.1. Key findings and originality

Adequate nutrition for all is a key feature of a sustainable food system (FAO, 2018; FAO/WHO, 2019). It is not sufficient, when assessing sustainability, to restrict the view of nutrition to solely calories and/or protein; as holistic an approach as feasible should be taken. Here, we have examined global food trade from a human nutrition and health perspective, mapping the international flows of 48 nutrients over a 35-year period, and connecting this data to health outcomes. It has been demonstrated that diversification of food imports has a greater role in diversified national supply than diversification of production (Aguilar et al., 2020; Kummur et al., 2020). Further, diversity of production in many regions has decreased, due to specialization, resulting in increased reliance on imports for a diverse food supply. These facts justify the focus here on international nutrient flows for dietary health.

4.1.1. The role of economics in nutrient trade over time

The dominance of HIC and UMIC in nutrient trade reinforces findings elsewhere for food mass and for selected nutrients (Wang et al., 2021; Geyik et al., 2021). We extended this work by the inclusion of a greater number of nutrients, and an extended time period. Global trade in all nutrients has increased rapidly since 1986, but this increase has been largely confined to HIC and UMIC. No clear trend was observable for low-income countries, and only small positive trends existed in LMIC for specific nutrients, despite their increasing population (both in absolute terms and as a proportion of the global population). It has been demonstrated that this has resulted in a minimal impact of food trade on nutrient adequacy in LMIC and LIC, where malnutrition is most prevalent (Geyik et al., 2021). Current trade dynamics have little positive influence on nutrient deficiency rates in poorer populations, and this does not appear likely to change in the short term based on trends up to

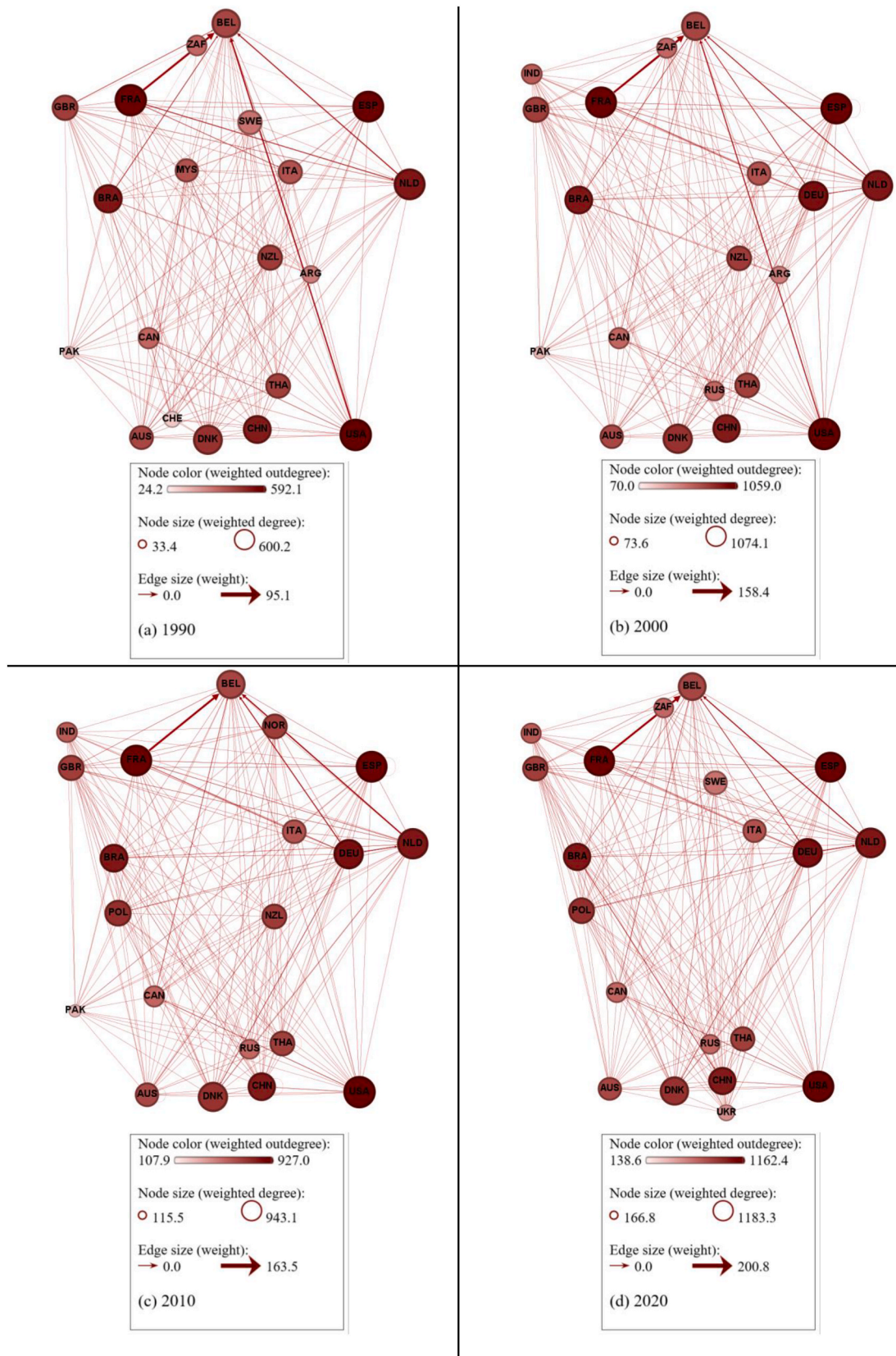


Fig. 4. Main exporters within the global protein trade network, according to weighted outdegree, 1986–2020. Obs.: ARG = Argentina; AUS = Australia; BEL = Belgium; BRA = Brazil; CAN = Canada; CHE = Switzerland; CHN = China; DEU = Germany; DNK = Denmark; ESP = Spain; FRA = France; GBR = Great Britain; IND = India; ITA = Italy; MYS = Malaysia; NLD = Netherlands; NOR = Norway; NZL = New Zealand; PAK = Pakistan; POL = Poland; RUS = Russian Federation; SWE = Sweden; THA = Thailand; UKR = Ukraine; USA = United States; ZAF = South Africa.

Table 1
Network properties of global trade of selected nutrients, 1986–2020.

Period	1986	1996	2006	2016	2020
Protein					
Average degree	20.42	34.24	50.35	61.46	59.34
Average weighted degree	12.56	16.36	30.92	41.72	40.26
Density	0.08	0.14	0.20	0.24	0.23
Modularity	0.43	0.45	0.49	0.50	0.49
Average clustering coefficient	0.46	0.59	0.58	0.60	0.61
Calcium					
Average degree	20.81	34.75	51.20	62.51	60.28
Average weighted degree	89.53	109.90	206.84	263.79	258.90
Density	0.08	0.14	0.20	0.25	0.24
Modularity	0.38	0.39	0.47	0.47	0.45
Average clustering coefficient	0.47	0.59	0.59	0.60	0.62
Iron					
Average degree	21.36	35.41	52.15	63.74	61.41
Average weighted degree	4.51	4.47	7.72	10.76	10.62
Density	0.08	0.14	0.21	0.25	0.24
Modularity	0.46	0.43	0.52	0.52	0.52
Average clustering coefficient	0.47	0.59	0.59	0.61	0.62
Vitamin A					
Average degree	16.33	30.35	45.30	55.31	53.48
Average weighted degree	80.70	107.63	219.79	353.50	317.78
Density	0.06	0.12	0.18	0.22	0.21
Modularity	0.44	0.48	0.51	0.57	0.55
Average clustering coefficient	0.43	0.57	0.57	0.57	0.60
Vitamin B12					
Average degree	10.76	26.27	39.76	49.20	47.27
Average weighted degree	0.28	1.08	2.17	2.63	2.35
Density	0.04	0.10	0.16	0.19	0.19
Modularity	0.45	0.50	0.52	0.49	0.47
Average clustering coefficient	0.35	0.56	0.55	0.55	0.58

2020 shown here.

Regarding specific nutrients, previous modelling has identified vitamins A and B12 to be problematic, both in terms of total global supply, and the way they are traded compared to need. Geyik et al. found that, in countries of upper-middle income and below, insufficient domestic production of these nutrients was not resolved by trade (Geyik et al., 2021). This is highly relevant, as the impact of vitamin A and B12 deficiency on human health is widespread, profound, and felt most acutely in low-income populations, and among children and women of reproductive age (Beal et al., 2017; Passarelli et al., 2022; Stevens et al., 2022). Our results show no clear progress in increasing the availability of these nutrients in LIC and LMIC through international trade.

Calcium has been omitted from similar previous studies but was included here following previous work indicating a global nutrient gap between availability and requirement for this nutrient (Smith, 2021). Trade dynamics for calcium were comparable to those of protein and iron. This is interesting, as calcium trade is concentrated in fewer food items compared to protein and iron trade: soy accounted for 12–44% of calcium trade over the time period with an upwards trend, while dairy contributed a further 20–31% (traded quantity increasing, but more slowly than soy). This information should be viewed alongside the fact that dairy is responsible for approximately half of global food calcium consumption (Smith et al., 2022). These results together indicate that dairy calcium supply is predominantly domestically sourced, whereas soy calcium, while more heavily traded, is a smaller part of global calcium consumption.

Several acute shocks to the global food system have occurred over the analyzed period, such as the global financial crisis (GFC) of 2007/8. While total traded food mass fell by around 3% in 2008 compared to 2007, it had regained its former trajectory by 2009. This was accompanied by minor decreases in trade in some nutrients (vitamin A and B12), but not all. The GFC had notable impacts on food prices, with knock-on consequences for dietary quality, of greatest consequence in developing regions (Brinkman et al., 2009). Correspondingly, food trade with LIC declined sharply from 2006 to 2010 onwards (on both a total and per capita basis) and has not increased notably since. It should be

noted that this period also saw the reclassification of a large proportion of the low-income population as lower-middle income, but per capita trends show that the remaining countries have had disproportionately low involvement in international food trade compared to population size, likely weakening food and nutrition security.

4.1.2. Positive links between nutrient trade and health

This study identified robust associations between indicators of higher participation in nutrient trade networks with favorable population health outcomes during childhood and adulthood in the short and long term, matching previous results focused on the effects of involvement in global food trade networks on population nutritional status (Silvestrini et al., 2023). The evolution of global trade networks showed low but increasing participation of UMIC and LMIC in bilateral food and nutrient exchange, fostering improvements in health conditions of populations worldwide. However, there are still substantial inequities among countries and income levels. Furthermore, the adoption of health indicators sensitive to the consumption of specific nutrients (e.g., prevalence of anemia in relation to iron, and infant mortality rates in relation to protein) allowed for identification of the potential effects of connections within nutrient trade networks, which should be applied in the prevention and mitigation of diet-related health conditions.

4.2. Policy implications

By making this data accessible in an interactive format, it is hoped that the nutrient trade tool will result in wider dissemination and understanding of this data than would otherwise be possible. This is particularly relevant for national-level policy makers, who will be concerned with their own country's trade, or that of trading blocs. The national-level view for every country possible with the interactive tool developed here, which is beyond the scope of an academic paper, gives a depth of insight not possible to fully capture here. For example, Fig. 3 indicates that New Zealand has diverse trade partners and commodities contributing to its vitamin A imports, thus would be resilient to shocks impacting a small number of trade partners or commodities. In contrast, New Zealand imports of many other nutrients are dominated by Australian wheat, indicating a need for other sources if this supply were disrupted. Moving to a broader scope, the Asia-Pacific Economic Cooperation (APEC) Food Security Roadmap Towards 2030 committed member economies to the achievement of regional food security (Asia-Pacific Economic Cooperation, 2021). Research and tools such as that presented here can (and have, in the case of New Zealand's role in APEC) aid in understanding vulnerabilities and opportunities for the achievement of national and regional nutrient security.

High dependence on trade for nutrient security leads to vulnerability to shocks. Previous work has investigated the nutritional vulnerability of individual countries to shocks in international food trade (Grassia et al., 2022; Tanaka et al., 2021). Grassia et al. identified that shocks to food production in any one country propagate through the global food system, and showed that it was LIC in Africa, the Middle East, East Asia, Latin America, and the Caribbean that were most exposed to reductions in calorie supply, even when the production shock occurred elsewhere (Grassia et al., 2022). Specifically for shocks to wheat trade, Tanaka et al. made the timely contribution of identifying the countries and nutrients at greatest risk of shortfalls if Russian and Ukrainian wheat supply were disrupted (Tanaka et al., 2021). They found that high nutritional dependence on imported wheat could lead to substantial reductions in availability of some nutrients (particularly minerals), especially in North African and Middle Eastern countries. The identified vulnerabilities have recently been validated using observed data, although only to the extent of energy supply (Bertassello et al., 2023). When the shock came, it was indeed a food security crisis, causing a spike in the FAO Food Price Index and prompting widespread aid action to these heavily affected regions (FAO, 2023; IMF, 2023). This work demonstrates the value of investigating future shock scenarios from a

Table 2

Coefficients of regression model on factors associated with child mortality, infant mortality rate, anemia among women, and life expectancy according to lag periods (0, 1 and 3 years).

Infant mortality rate	Odds ratio								
	t ₀		SE	t ₁		SE	t ₃	SE	
Economic globalization de facto	0.96	*	0.01	0.959	*	0.01	0.95	* 0.01	
Economic globalization de jure	1.05	*	0.02	1.050	*	0.02	1.06	* 0.02	
Social globalization de facto	0.89	*	0.02	0.887	*	0.02	0.88	* 0.02	
Social globalization de jure	0.97	ns	0.02	0.986	ns	0.02	1.01	ns 0.02	
Political globalization de facto	1.02	ns	0.01	1.019	ns	0.01	1.03	* 0.01	
Political globalization de jure	0.99	ns	0.02	0.994	ns	0.02	1.00	ns 0.02	
Closeness centrality (protein)	0.00	*	0.00	0.000	*	0.00	0.00	* 0.00	
Food dependency ratio	1.00	ns	0.00	1.000	ns	0.00	1.00	ns 0.00	
DPT vaccine coverage <24 months	0.87	*	0.01	0.862	*	0.01	0.85	* 0.01	
Population ≤14 years old	2.76	*	0.36	3.032	*	0.43	3.23	* 0.51	
Population 15–64 years old	3.19	*	0.50	3.581	*	0.59	3.79	* 0.69	
Proportion of female population	2.29	*	0.27	2.392	*	0.29	2.34	* 0.30	
Urban population	0.97	*	0.01	0.970	*	0.01	0.96	* 0.01	
High income country	–	ns	–	–	ns	–	–	ns –	
Upper-middle income country	0.67	ns	0.36	0.654	ns	0.38	1.32	ns 0.83	
Lower-middle income country	0.41	*	0.15	0.453	*	0.17	0.72	ns 0.28	
Wald χ^2 (df)	382.91 (192)	*		361.32 (185)	*		306.36 (169)	*	
Log likelihood	–355.43			–334.62			–298.98		
Probability of dying per 1000 children aged 5–14 years									
	t ₀		SE	t ₁		SE	t ₃	SE	
Economic globalization de facto	0.97	*	0.01	0.97	*	0.01	0.97	* 0.01	
Economic globalization de jure	1.05	*	0.02	1.05	*	0.02	1.03	ns 0.02	
Social globalization de facto	0.94	*	0.02	0.93	*	0.02	0.92	* 0.02	
Social globalization de jure	0.93	*	0.02	0.95	*	0.02	0.97	ns 0.02	
Political globalization de facto	1.06	*	0.01	1.06	*	0.01	1.05	* 0.01	
Political globalization de jure	0.96	*	0.02	0.97	*	0.02	0.97	ns 0.02	
Harmonic closeness centrality (protein)	0.00	*	0.01	0.00	*	0.01	0.01	* 0.03	
Food dependency ratio	1.00	*	0.00	1.00	*	0.00	1.00	* 0.00	
DPT vaccine coverage <24 months	0.91	*	0.01	0.91	*	0.01	0.89	* 0.01	
Population ≤14 years old	2.87	*	0.44	3.05	*	0.49	4.02	* 0.74	
Population 15–64 years old	3.26	*	0.58	3.50	*	0.66	4.76	* 1.01	
Proportion of female population	1.60	*	0.20	1.64	*	0.21	1.84	* 0.27	
Urban population	0.99	ns	0.01	0.98	ns	0.01	0.98	ns 0.01	
High income country	0.02	*	0.03	0.05	*	0.06	0.13	ns 0.16	
Upper-middle income country	0.37	ns	0.22	0.70	ns	0.42	0.97	ns 0.60	
Lower-middle income country	0.44	*	0.18	0.68	ns	0.27	0.80	ns 0.32	
Wald χ^2 (df)	324.35 (142)	*		320.05 (139)	*		292.54 (134)	*	
Log likelihood	–294.31			–289.10			–263.28		
Anemia among women									
	t ₀		SE	t ₁		SE	t ₃	SE	
Economic globalization de facto	1.02	*	0.01	1.02	*	0.01	1.02	* 0.01	
Economic globalization de jure	1.00	ns	0.01	1.00	ns	0.01	0.99	ns 0.01	
Social globalization de facto	0.93	*	0.01	0.92	*	0.01	0.93	* 0.01	
Social globalization de jure	0.98	ns	0.01	0.98	ns	0.01	0.98	* 0.01	
Political globalization de facto	0.96	*	0.01	0.96	*	0.01	0.96	* 0.01	
Political globalization de jure	1.05	*	0.01	1.06	*	0.01	1.06	* 0.01	
Closeness centrality (iron)	0.01	*	0.02	0.01	*	0.01	0.00	* 0.00	
Proportion of imported calories	1.89	*	0.33	1.97	*	0.35	1.84	* 0.34	
Population ≤14 years old	1.58	*	0.12	1.60	*	0.12	1.58	* 0.12	
Population 15–64 years old	1.45	*	0.13	1.47	*	0.13	1.44	* 0.13	
Proportion of female population	0.59	*	0.05	0.58	*	0.05	0.64	* 0.05	
Urban population	1.03	*	0.01	1.03	*	0.01	1.02	* 0.01	
High income country	0.00	*	0.00	–	ns	–	–	ns –	
Upper-middle income country	0.49	*	0.17	0.56	ns	0.19	0.73	ns 0.25	
Lower-middle income country	0.33	*	0.07	0.33	*	0.07	0.36	* 0.08	
Wald χ^2 (df)	604.40 (117)	*		594.38 (116)	*		604.85 (116)	*	
Log likelihood	–665.09			–659.03			–672.42		
Life expectancy									
	t ₀		SE	t ₁		SE	t ₃	SE	
Economic globalization de facto	1.00	ns	0.01	1.00	ns	0.01	0.99	ns 0.01	
Economic globalization de jure	1.00	ns	0.01	1.00	ns	0.01	1.00	ns 0.01	
Social globalization de facto	1.09	*	0.02	1.09	*	0.02	1.09	* 0.02	
Social globalization de jure	1.08	*	0.02	1.07	*	0.02	1.07	* 0.02	
Political globalization de facto	0.96	*	0.01	0.96	*	0.01	0.96	* 0.01	
Political globalization de jure	1.11	*	0.01	1.10	*	0.01	1.09	* 0.01	
Betweenness centrality (protein)	1.01	*	0.00	1.01	*	0.00	1.01	* 0.00	
Food imports	1.10	*	0.02	1.08	*	0.02	1.06	* 0.02	
Food exports	1.01	*	0.01	1.01	*	0.01	1.02	* 0.01	
Obesity prevalence	0.75	*	0.03	0.74	*	0.03	0.72	* 0.03	
Underweight prevalence	0.56	*	0.04	0.54	*	0.04	0.51	* 0.04	

(continued on next page)

Table 2 (continued)

Infant mortality rate	Odds ratio								
	t ₀		SE	t ₁		SE	t ₃	SE	
Age dependency ratio (children)	0.92	*	0.01	0.92	*	0.01	0.92	*	0.01
Age dependency ratio (elderly)	1.10	*	0.03	1.09	*	0.03	1.09	*	0.03
Proportion of female population	0.53	*	0.03	0.53	*	0.03	0.53	*	0.04
Urban population	1.03	*	0.01	1.03	*	0.01	1.03	*	0.01
High income country	7.50	ns	8.49	8.52	ns	9.55	14.33	*	16.25
Upper-middle income country	3.96	ns	4.41	4.15	ns	4.59	5.61	ns	6.25
Lower-middle income country	3.75	ns	4.11	3.73	ns	4.05	4.36	ns	4.76
Wald χ^2 (df)	511.27 (161)	*		510.95 (162)	*		498.22 (164)	*	
Log likelihood	-665.73			-666.33			-649.32		

Obs.: t₀ = lag period 0; t₁ = lag period 1 year; t₃ = lag period 3 years; SE = standard error. Models include control for year and region. * indicates statistical significance ($p < 0.05$).

nutrient perspective when setting trade policy that aims to minimize future vulnerability via the correct balance of diverse import sources, consumed commodities, and domestic production.

Climate change presents a further threat to food security via many mechanisms, and food trade will have a role to play in either mitigating or exacerbating the impact, depending on the direction taken. Janssens et al. explored how adequate caloric supply can best be delivered under a range of climate futures (Janssens et al., 2020). Negative changes to trade dynamics were shown to inflate the global undernourished population by 33–47% in the most extreme scenario, and by as much as 181% in South Asia. Contrastingly, directed changes and infrastructure investments could contribute to significantly mitigating this increase. There is, therefore, a responsibility on policy makers to integrate climate adaptation for nutrition into their food trade decisions.

As well as assessing future resilience, nutrient trade dynamics should be used to understand to what extent current food trade meets national and international goals. This need not be restricted to individual countries. For example, it has been demonstrated that the European Union is a net importer of iron and zinc, largely in animal feed material, the majority of which comes from areas facing malnutrition (Hoffmann et al., 2021). In contrast, it is a net vitamin A exporter, largely to areas with population-level deficiency. As the data produced here includes food aid, it can be used to ascertain whether this aid addresses the full scope of nutritional need in the destination country, perhaps informing shifts to target food commodities and destinations. It should also be compared to national and international commitments, such as to the achievement of the Sustainable Development Goals, and whether current trade policy aids or hinders progress towards these.

The political aspects of current food trade policy and activity have been under recent scrutiny. The FAO has expressed concern around a greater observed regionalization of trade, rather than globalization, with the potential to lead to fragmentation of global trade into semi-closed, competing regions (FAO, 2022b). This trend particularly impacts LIC with limited negotiation capacity, which may therefore be unable to join trading blocs, potentially worsening the nutrient trade dynamics shown here. Both regionalized and globalized trade have advantages, and trade agreements can be set at each level to address specific challenges (for example, agreements to address food and nutrition security in regions at risk, and global agreements to address climate issues).

The role of tariffs in these dynamics is not straightforward. Removal of tariffs encourages international trade, but complete removal of tariffs on food trade would have mixed results for nutrition, increasing food availability in some regions, while decreasing it elsewhere (due to increased exports (Janssens et al., 2020)). Tariffs and regulation also have an environmental role to play: the comparative environmental advantage that one country may have in the production of a food commodity can be realized as a global gain when trade is more open, increasing global food diversity and food security (FAO, 2022b). On the other hand, high demand for a food commodity can result in unsustainable production to maximize profit. In these instances, trade

regulation can play a role in reducing the environmental impacts of production by incentivizing sustainable practices.

The move to analysis of nutrient trade emerging in the scientific literature in recent years facilitates consideration of these dynamics in the setting of trade policy. While policies based on the exchange of individual nutrients may be impractical, policies attached to foods rich in one or more key nutrients of national shortfall are achievable and have the potential to achieve beneficial results.

4.3. Assumptions and limitations

The data presented here was synthesized from publicly available, open access sources maintained by multilateral organizations. Such data has limitations, such as some missing information for trading partners, and low specificity of food item names in some cases. The former limitation was partially addressed by verifying symmetry of food trade when comparing import records with export records. The latter limitation was addressed by averaging the nutritional composition of several possible food items when the commodity name was vague.

We assumed that domestic supply-to-food ratios drawn from Food Balance Sheets were representative of the use of traded food items. However, imported foods may be utilized differently to their domestically produced counterparts, which would result in inaccurate allocation. In the absence of specific estimates for food use of imported items, our assumption appears the best available.

It should be noted that this analysis refers solely to nutrient flow between countries, and does not capture distribution within countries, which is clearly inequitable. Populations at greatest risk of nutrient deficiency, as discussed above, will not necessarily be those that receive the greatest benefit from nutrient imports. However, ensuring that every individual in a country is well nourished is impossible without ensuring that the country as a whole has enough, therefore the national level approach is useful.

Our data is also limited to supply, and therefore does not necessarily reflect consumption of traded nutrients. It has been shown that supply side estimates of food consumption can differ widely from dietary survey data (as much as 10-fold for some food groups, usually in lower-income settings), even in highly reputable and widely used sources (Beal et al., 2021). As such, our results must be seen as relating to food supply, and not necessarily to consumption.

We have examined food trade dynamics and their implications for nutrition and health, without examining the causes of these dynamics. The low involvement of LIC in international food trade is the result of complex economic and socio-political drivers, which are beyond the scope of our analysis. Food trade should always be viewed against the broader background of the global food and economic systems within which it operates. Adding nutrient-level trade data to this broader picture should allow research unifying nutrition with economic analyses for future simulations.

Finally, it is important to highlight that the estimation of regression models matching nutrient trade data to population health outcomes

comprises ecological analysis, i.e., the results should be interpreted with caution, considering the existence of confounding effects. We made efforts to include major factors influencing health outcomes investigated in the study, according to data availability from reputable organizations reporting national-level information. However, the analysis lacks certain potential confounding factors due to either unavailability or limitations in datasets identified during the investigation, e.g., educational attainment, and water, sanitation, and health infrastructure. There is substantial evidence on the role of education and infrastructure in reducing the occurrence of diseases through prevention; yet, the absence of comprehensive time series data on these variables prevents additional exploration of their influence in the context of globalization processes throughout the period of analysis.

However, the study relies on robust statistical analysis through control of other potential confounders (e.g., sociodemographic, economic, and health characteristics of the population, geographical region, and year) to minimize effects of unobservable variables. Thus, considering the close relationship of these values with confounders missing in international databases, e.g., economic characteristics in relation to infrastructure and education, lends credence to the validity and reliability of our results. In addition, we investigated potential short- and long-term effects of country insertion in nutrient trade networks on health outcomes that are recognized for their sensitivity to contextual conditions (anemia, child mortality, and life expectancy), thus providing opportunity to further explore country globalization levels occurring simultaneously to participation in international trade.

5. Conclusion

Our results emphasize the inequitable nature of global nutrient trade based on country income level, demonstrate its positive role in population health, and have made nutrient trade data more accessible to stakeholders and decision makers through an interactive tool.

Lower income populations are not represented in nutrient trade proportionally to their size, food insecurity, and malnutrition rates, and this study has shown that this situation has worsened over the last 35 years. Increasing involvement in food trade was linked here to beneficial outcomes for multiple nutrition-related disease rates.

Considering the role of nutrition and health in supporting human capital formation, efforts towards the promotion of trade in nutrient-dense foods to increase access for at-risk populations should be prioritized through public policies focusing on population wellbeing.

In more recent years than studied here, food insecurity and malnutrition has continued to rise at an alarming and unabated rate, driven by global conflict, weather events, and inflation, prompting strong and diverse action from multi-national organizations (World Bank, 2023). Food trade has a decisive role to play in this, which can be facilitated by the targeted removal of disincentivizing tariffs and barriers coupled with positive actions, both of which should be informed by an understanding of the nutritional role and potential of food trade.

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CRedit authorship contribution statement

Murilo Mazzotti Silvestrini: Conceptualization, Data curation, Formal analysis, Methodology, Visualization, Writing – review & editing. **Nick W. Smith:** Conceptualization, Data curation, Formal analysis, Methodology, Visualization, Writing – original draft, Writing – review & editing. **Andrew J. Fletcher:** Conceptualization, Methodology, Supervision, Writing – review & editing. **Warren C. McNabb:** Methodology, Supervision, Writing – review & editing. **Flavia Mori Sarti:** Conceptualization, Data curation, Formal analysis, Methodology, Supervision, Visualization, Writing – original draft, Writing – review & editing.

Declaration of competing interest

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Nick W. Smith reports financial support was provided by New Zealand Ministry for Primary Industries. Flavia Mori Sarti reports financial support was provided by National Council for Scientific and Technological Development. Flavia Mori Sarti reports financial support was provided by Coordination of Higher Education Personnel Improvement. Andrew J Fletcher reports a relationship with Fonterra Co-operative Group Limited that includes: employment.

Data availability

Data is in a Mendeley repository, with doi included in the manuscript

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Appendix A. Supplementary data

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