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Elevated diversity of the supply chain boosts global food system resilience

Junwen Jia[1,2,3], **Weiqiang Yang**[1,3], **Fang Wu**[1] **and Xuefeng Cui**[1,*]

[1] School of Systems Science, Beijing Normal University, Beijing 100875, People's Republic of China
[2] School of Earth and Environmental Sciences, Cardiff University, Cardiff CF10 3AT, United Kingdom
[3] These authors contributed equally to this work and should be considered as co-first author.
[*] Author to whom any correspondence should be addressed.

E-mail: xuefeng.cui@bnu.edu.cn

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Abstract

Food supply shock is defined as a drastic shortage in food supply, which would likely threaten the achievement of Sustainable Development Goals 2: zero hunger. Traditionally, highly-connected global food supply system was deemed to help overcome shortages easily in response to food supply shock. However, recent studies suggested that overconnected trade networks potentially increase exposure to external shocks and amplify shocks. Here, we develop an empirical–statistical method to quantitatively and meticulously measure the diversity of international food supply chain. Our results show that boosting a country's food supply chain diversity will increase the resistance of the country to food shocks. The global diversity of food supply chain increased gradually during 1986–2021; correspondingly, the intensity of food shocks decreased, the recovery speed after a shock increased. The food supply chain diversity in high-income countries is significantly higher than that in other countries, although it has improved greatly in the least developed regions, like Africa and Middle East. International emergencies and geopolitical events like the Russia–Ukraine conflict could potentially threaten global food security and impact low-income countries the most. Our study provides a reference for measuring resilience of national food system, thus helping managers or policymakers mitigate the risk of food supply shocks.

1. Introduction

In November 2022, setting against a difficult geopolitical backdrop, the United Nations Climate Change Conference COP27 delivered decisions for moving forward on the Global goal on adaptation and sustainability (COP27 2022), because, gradually, serious loss and damage to food production may be caused by climate change, extreme weather events and geopolitical conflict (Diffenbaugh *et al* 2015, Naumann *et al* 2018, Jia *et al* 2023). For example, more than 820 million people had insufficient food supply, and many more consumed low-quality diets (Willett *et al* 2019). In 2021, 29% of the global population suffered from moderate-to-severe food insecurity, especially in the Global South (FAO, IFAD, UNICEF, WFP & WHO 2021). Even when food supply shortages are temporary, periods where essential nutrients are lacking can adversely impact the health of vulnerable populations (Gephart *et al* 2017), such as low-income populations, pregnant women, children, and the ills (Block *et al* 2004). Against this background, global food supply security is essential to achieve Sustainable Development Goals (SDG) 2: zero hunger (CBD Core Team 2022) and deserves more attentions (Gomez *et al* 2021).

Food supply shock (known as food shock) is a key threat to food security and is defined as a drastic shortage in food supply, which increases the probability of simultaneous global food security failure (Gaupp *et al* 2020). Extreme events that may be exacerbated by climate change (Lesk *et al* 2016), geopolitical crises or policy changes (Cottrell *et al* 2019) are the main causes of food shocks in global food systems (Gomez *et al* 2021). Traditionally, the international food trade has been reported to be an effective way to tackle food shocks by filling shortages (Grêt-Regamey *et al* 2019). However, recent studies reported that excessive food suppliers may have a dual effect on a country's food security (Suweis *et al* 2015). A country with a highly-connected global food supply system could obtain food inflows more easily through international trade during food shock periods, thus enhancing food system resilience (Grêt-Regamey *et al* 2019). However, overconnected food supply systems would likely increase exposure to global food shocks (Tu *et al* 2019) and may amplify shocks compared with local self-sufficiency patterns (Nyström *et al* 2019). Therefore, it is essential to meticulously and quantitatively monitor the reliability and stability of the national food supply system and thus guiding national food policy for suitable connectivity to maintain the stability of food supply chains (Kummu *et al* 2020).

To measure food system reliability and stability, food system resilience is an essential concept with multiple debatable meanings; this can have consequences for evaluating, understanding, and managing systems, depending on which definition is used (Nyström *et al* 2019). Generally, there are 'three R's' of food system resilience: robustness, recovery and reorientation (Zurek *et al* 2022). Although, there are some debates regarding the definition and explanation of resilience (Helfgott 2018, Zurek *et al* 2018, Allen *et al* 2019, Parker *et al* 2019, Puma 2019, Savary *et al* 2020, Jia and Cui 2022), the diversity of the food supply chain (DFSC) still is a core of resilience theory (Wood *et al* 2023). According to resilience theory, diversity is closely related to robustness and recovery (Gao *et al* 2016, Lucini *et al* 2020, Zurek *et al* 2022). In addition, empirically, a higher DFSC usually indicates a weaker impact of food shock (Gomez *et al* 2021). Therefore, the DFSC is a potential way to reflect national food system resilience, thus further measuring the stability of the national food supply system to help manage connectivity.

In another hand, integrated management, policymaking and scientific research are the 'keystone actors' for steering the global food supply system toward a sustainable trajectory (Nyström *et al* 2019). Especially, considering that the fast-changing world with international emergencies and geopolitical events like the Russia–Ukraine conflict will be serious challenges to food security and achievement of SDGs (Diffenbaugh *et al* 2015, Naumann *et al* 2018). Therefore, an empirical–statistical method that can meticulously quantify the stability of global and national food supply systems is necessary for food system management, policymaking, further research and multinational cooperation, thus promoting sustainable development and achieving the SDGs (Gomez *et al* 2021, Mirón *et al* 2023). Therefore, in this study, we had the following aims: (a) to develop an integrated approach for measuring the global food supply system through DFSC; (b) to analyze global and national food supply system conditions on this basis; and (c) to address the impact on the world or nations when unexpected emergence occurs using the Russia–Ukraine conflict as a case study.

The remainder of the paper is organized as follows. Section 2 introduces the data and method. Then, section 3 will first present the results of the DFSC calculation of global food supply system, and then present the potential impacts led by Russia–Ukraine conflict. Finally, brief discussions and conclusions will be provided in section 4.

2. Data and methods

2.1. Dataset of food flow networks

Annual food flow networks for approximately 173 countries were obtained from the FAOSTAT database (FAOSTAT 2023), which includes 11 food groups (cereals, fruits and vegetables, roots, sugar, oil, oilseeds, meat, milk, eggs, beverages, other; including 83 food items with details listed in supplementary table 1). Food quantity units (tons) were converted into calories (kcal) for consistency (FAO 2001, Marchand *et al* 2016).

2.2. DFSC index

Referring to the calculation methods provided by previous study (Gomez *et al* 2021), DFSC index was established to measure the annual supply chain diversity. In this section, we made a brief description, please see Gomez *et al* (2021) for more details. The functional distance d between country i and any of its trading partners j was calculated by combining five different indicators (r). These five indicators represented five different characteristics of a country and were further described in 2.3 of the Methods. The functional distance d_{ij}^r for an indicator r between any pair of connected nodes (i,j) was calculated as:

$$d_{ij}^r = N^{-1}\left|r_i - r_j\right|$$

where the normalization constant N is determined as the maximum value of $|r_i - r_j|$ between any node i in the network and j. In this equation, $d_{ij}^r = 0$ for functionally similar nodes and $d_{ij}^r = 1$ for dissimilar nodes.

To combine five distance indicators into a single measure, the average functional distance indicator $\langle d_{ij}^r \rangle$ was calculated as the arithmetic mean of the five functional distance indicators for any connected nodes (i,j). Then, by utilizing the Shannon entropy (Shannon 1948) and the discrete probability distribution of national food inflows binned by $\langle d_{ij}^r \rangle$ categories, the supply chain diversity $D_{i,c}^t$ of node i and food item c was obtained for the given year t as:

$$D_{i,c}^t = \frac{-\sum_{k=1}^{K} Y_{i,c}^t(k)\, lnY_{i,c}^t(k)}{logK}$$

where $Y^t_{i,c}(k)$ is the proportion of food inflows to node i within bin k in year t for food item c. The k bin is calculated by binning all the $\langle d^r_{ij} \rangle$ values for node i into a total number of K bins.

2.3. Functional distance indicators

To evaluate the difference between a country and its trading partners, thus making trading partner classification bins. Five functional distance indicators were calculated as:

(1) Physical distance indicator (PDI). The PDI was used to measure the physical distance between two countries. The distances were calculated, following the method provided by Centre détudes Prospectives et d'Informations Internationals (CEPII; Mayer and Zignago 2011), by computing the Euclidean distance of the centroid of the geographic distribution of the population within two countries.
(2) Climate correlation indicator (CCI). This indicator was used to measure the differences on climate types in different countries. The average correlation of national monthly mean temperature and precipitation was calculated to represent the CCI between a country and trading partners. Data was obtained from The World Bank, climate change knowledge portal for development practitioners and policy-makers (https://climateknowledgeportal.worldbank.org/download-data).
(3) Economic indicator (EI). The EI represented the differences in economic development between a country and trading partners. The difference in gross domestic product adjusted by purchasing power was calculated to indicate the EI. Data was provided by World Bank Open Data (https://data.worldbank.org/).
(4) Network modularity indicator (NMI). NMI was used to identify the countries that belonged to the same trade community. The communities were identified by maximizing the modularity measure of Newman (Girvan and Newman 2002, Newman 2006) using the greedy optimization algorithm (Blondel *et al* 2008, Garcia and Mejia 2019) with aggregating the flows from the 11 food groups (cereals, fruits and vegetables, roots, sugar, oil, oilseeds, meat, milk, eggs, beverages, other) into a single-layer network. Please see Gomez *et al* (2021) for more details about establishment of this indicator.
(5) Production ability indicator (PAI). The PAI represented differences in food production capacity between countries. The PAI was calculated by the average of difference of per-capita production of each food item between two countries. Per-capita production data was obtained from FAOSTAT (2023).

2.4. Probabilities of food shock

Referring to Gomez *et al* (2021) and Renard and Tilman (2019), we quantified the probability of food shock. This probability was calculated by categorizing all nodes into 17 classification bins (please see supplementary figure 1 for details) that were arranged from least to most functional diversity D. For each country i and food item c, we calculated the food shock $S^t_{i,c}$ as:

$$S^t_{i,c} = \left(1 - \frac{I^t_{i,c}}{\langle I^t_{i,c} \rangle}\right) \times 100\%$$

where $I^t_{i,c}$ is the total food inflows to node i for food item c in year t, and $\langle I^t_i \rangle$ is the average of food inflows to node i for item c during year $t-1$, $t-2$ and $t-3$ (please see supplementary figure 4 for details).

For each diversity bin b, the number of observations n_b (of N_b, the total number of observations in bin b) that meet the criteria $S^t_{i,c} > s$ for $s \in \{5, 10, 15, \ldots, 70\}$ is calculated, with s being a threshold of intensity of food shock. The probability of a food shock S being greater than s in bin b is calculated as:

$$P_b(S > s) = \frac{n_b}{N_b}.$$

2.5. Recovery speed

We calculated the ratio of the total food inflows change in the year after food shock to the food shock $S^t_{i,c}$. For each country i and food item c, the recovery speed was determined as:

$$RS^t_{i,c} = \frac{I^t_{i,c} - I^{t-1}_{i,c}}{\langle I^{t-1}_{i,c} \rangle - I^{t-1}_{i,c}}$$

where $I^t_{i,c}$ is the total food inflows to node i for item c in year t (the year when the country begins to recover), and $I^{t-1}_{i,c}$ is total food inflows to node i for item c in year $t-1$ (the year when the food shock occurred). $\langle I^{t-1}_{i,c} \rangle$ has the same definition as that in Probabilities of food shock. The recovery speed could be a negative value meaning that total food inflows of a country continue to decrease after a food shock happened.

2.6. Intensity of global food shock

To measure the food shock intensity at the global scale, we used the sum of the global food shock S, adjusted by population weight. We calculated the intensity of global food shock intensity^t as:

$$\text{intensity}^t = \sum_i \text{POP}^t_i \times S^t_i$$

where POP^t_i is the proportion of the population of country i in the world population in year t. S^t_i is the food shock in country i in year t. It was calculated in terms of energy (kcal). The energy was calculated by summing each food item converting food quantity into calories. A larger value means a more unstable food supply system.

2.7. Diversity of the global food supply chain

To measure the diversity of the world food supply system, we calculated the diversity of global supply chain D^t as:

$$D^t = \sum_i \mathrm{POP}_i^t \times D_i^t$$

where POP_i^t is the proportion of the population of country i in the world population in year t. D_i^t is the DFSC in country i in year t calculated in terms of calories.

2.8. Global mean recovery speed

To measure the food shock intensity at the global scale, we calculated the global mean recovery speed intensity^t as:

$$\mathrm{GMRS}^t = \frac{1}{I} \sum_i RS_i^t$$

where I is the total number of countries that recover in year t. RS_i^t is the recovery speed in country i in year t calculated in terms of calories.

2.9. Calculation of DFSC changes from the Russia–Ukraine conflict

The average change of DFSC during the period from 2017 to 2021 is calculated to reflect the potential negative impact of the Russia–Ukraine conflict on each country. The trading volumes between Ukraine and trading partners is cut to zero and the trading volumes between Russia and countries in the Unfriendly Countries List is reduced to zero. Besides, to evaluate the worst possible effects of the Russian–Ukrainian conflict on the food supply chain, it is assumed that trading partners do not compensate this reduced inflow from Russia or Ukraine using other trading partners. The Unfriendly Countries List is as follows: Australia, Albania, Andorra, United Kingdom (including Jersey, Anguilla, British Virgin Islands, Gibraltar), Member States of the European Union, Iceland, Canada, Liechtenstein, Federated States of Micronesia, Monaco, New Zealand, Norway, Republic of Korea, San Marino, North Macedonia, Singapore, United States of America, Taiwan (Region of China), Ukraine, Montenegro, Switzerland, Japan.

3. Results

3.1. Overconnected food supply systems do have duality

Functional distance classification (Walker *et al* 1999, Gomez *et al* 2021) was used to measure supply chain diversity and compared with supplier numbers in the absence of functional distance classification (figure 1, supplementary figures 6 and 7). Our results showed that global food supply connectivity did have duality when only considering the number of food suppliers because there was a U-shaped relation between supplier number and the probability of food shocks (figure 1(a)). This means that when the number of food suppliers surpassed a threshold (for instance, the possibility of the occurrence of a 70% level shock increased when the number of suppliers was over 31), an overconnected food supply chain amplified the possibility that a country will be impacted by a food shock. The intensity of food shocks declined monotonically in response to increasing supply chain diversity (figure 1(b)). This indicates that countries with higher values of DFSC were more likely to avoid or resist food shocks. For example, at the 5% shock intensity level, the occurrence of food shocks in countries with diversity values less than 0.1 was nearly three times greater than that in countries with diversity values higher than 0.8. Although there was a downtrend in the possibility that a higher intensity level shock occurs in countries with the same DFSC value, increasing supply chain diversity could significantly avoid the occurrence of the same intensity level shock. Therefore, this DFSC index model may provide a reference to manage the connectivity of a country in the international food trade system, which is an essential issue for policymaking (Kummu *et al* 2020).

3.2. Global food supply system becoming more stable during 1986–2021

The diversity of the global food supply chain, intensity of global food shocks and global mean recovery speed were calculated to measure changes in the global food system from 1986 to 2021 (see Methods). The correlations between the diversity of the global food supply chain, the intensity of global food shocks and the global mean recovery speed were all significant (at the 0.01 level, supplementary table 2). Generally, the diversity of the global food supply chain increased from 0.43 to 0.58 from 1986 to 2021 (figure 2(a)). The developing global transportation system and international specialization could contribute to this increasing DFSC (supplementary figure 5, supplementary table 4). Based on ecological and resilience theory, an increasing DFSC usually corresponded to decreasing intensity of food shock and increasing recovery speed (Zurek *et al* 2022; figure 1 and supplementary figure 2). According to our results, the intensity of global food shock decreased from approximately 0.25–0.03 (figure 2(b)). This means that the influence of food shocks on the global population weakened from 1986 to 2021, which may indicate that the global food supply system was becoming more stable and reasonable during this period. Regarding recovery, the global mean recovery

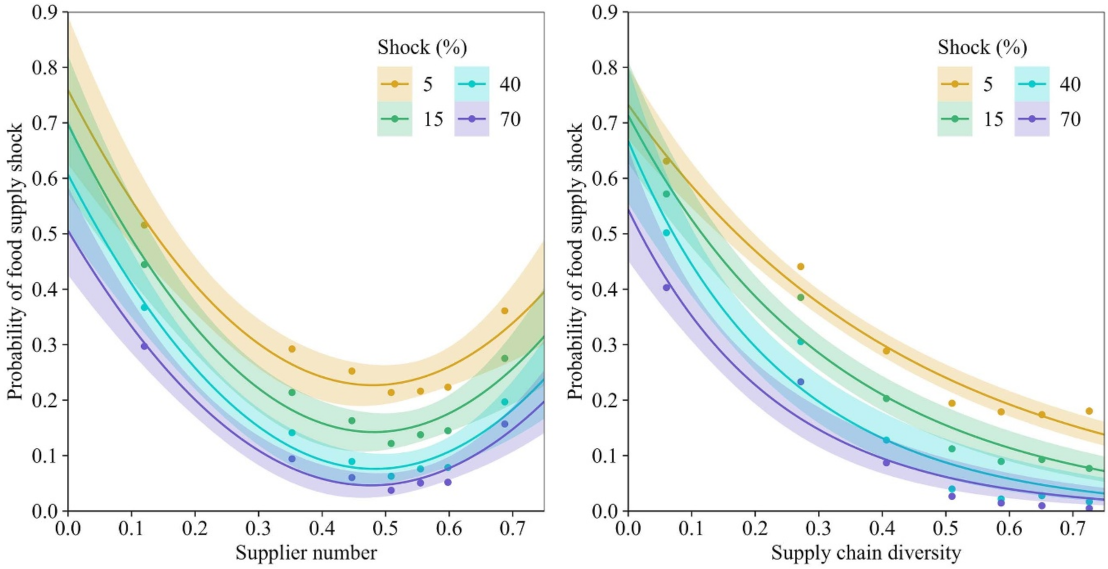

Figure 1. Empirical relationship between the probability of food shocks and supplier number and supply chain diversity. (a), supplier number. (b), supply chain diversity. Supplier number (a) was calculated using the equation in 2.2, but only considering the number of suppliers without classification combining five functional distance indicators. Supply chain diversity (b) was calculated through the DFSC equation (2.2) with functional distance classification (2.3). The confidence bounds represent ±1 standard deviation of the fitted curves. To comprehensively reflect the relationship between diversity and food shock, the inflow-outflow quantity of each food sector (tons) was translated to integrated calories (kcal). The shock intensity was quantified by the country that experiences a food supply loss greater than specified percentage thresholds (5%, 15%, 40% and 70%). The probability of food shocks was defined as the proportion of countries in the world that experience specified shock intensity (please see probabilities of food shock in Methods for details).

speed increased in the same period, increasing from approximately 0.3–0.8 (figure 2(c)). All three indicators suggested that the global food supply was moving toward a better condition with a higher stability level and faster recovery speed. On the other hand, the DFSC correlated significantly with the intensity of food shock and recovery speed. Therefore, the DFSC could be a useful tool for determining the condition of food shock intensity and recovery speed.

3.3. Distributions of food supply system indicators

There were step-wise distributions of three food supply resilience indicators (DFSC, food shock intensity and recovery speed) along the national income groups (according to World Bank classification in 2022) during the period from 1986 to 2021. Generally, high-income countries have the highest values for DFSC and recovery speed and the lowest values for food shock intensity (figure 3; the 95% confidence interval error bar chart was provided at supplementary figure 3), meaning that high-income countries have more stable food supply systems than countries belonging to other income groups. In addition, the intensity of food shocks in high-income countries was much weaker than that in low-income countries (figure 3(b)), and the recovery speed was the fastest once food shocks occurred (figure 3(c)). Regarding middle- and low-income countries, although the overall trends in these three indicators improved, there were still fluctuations in some countries, such as Egypt, Kenya, Burkina Faso, and Guinea. (figure 3). However, the condition of the food supply system became worse (decreasing DFSC and increasing intensity of food shock) during the period from 1986 to 2021 in some countries mainly belonging to the upper-middle-income group (such as Argentina and Thailand). This may be the reason for the comparatively lower mean value of recovery speed in the upper-middle-income group (figure 3(c)). Overall, the national food supply system indicators remained unevenly distributed, which may indicate unbalanced development of the global food supply system.

At the global spatial scale, the overall global DFSC improved during the period from 1986 to 2021. We extracted the two timescales, 1986–1990 (figure 3(d)) and 2017–2021 (figure 3(e)), to make comparisons to see the change in national DFSC during 1986–2021. The most obvious improvement was observed in sub-Saharan Africa and the Middle East where have the greatest number of the least developed countries. The regional mean value of the DFSC index rose from approximately 0.2 to approximately 0.4. The increasing number of trading partners and increasing trading volume were the reasons for the improvement in DFSCs in these two regions. It is worth noting that the value of supply chain diversity was reduced in countries such as Kazakhstan, Ukraine, Belarus, Lithuania, Estonia, Serbia, and Croatia. The disintegration of the former USSR, former Yugoslavia and geopolitical events could be the reasons for the change.

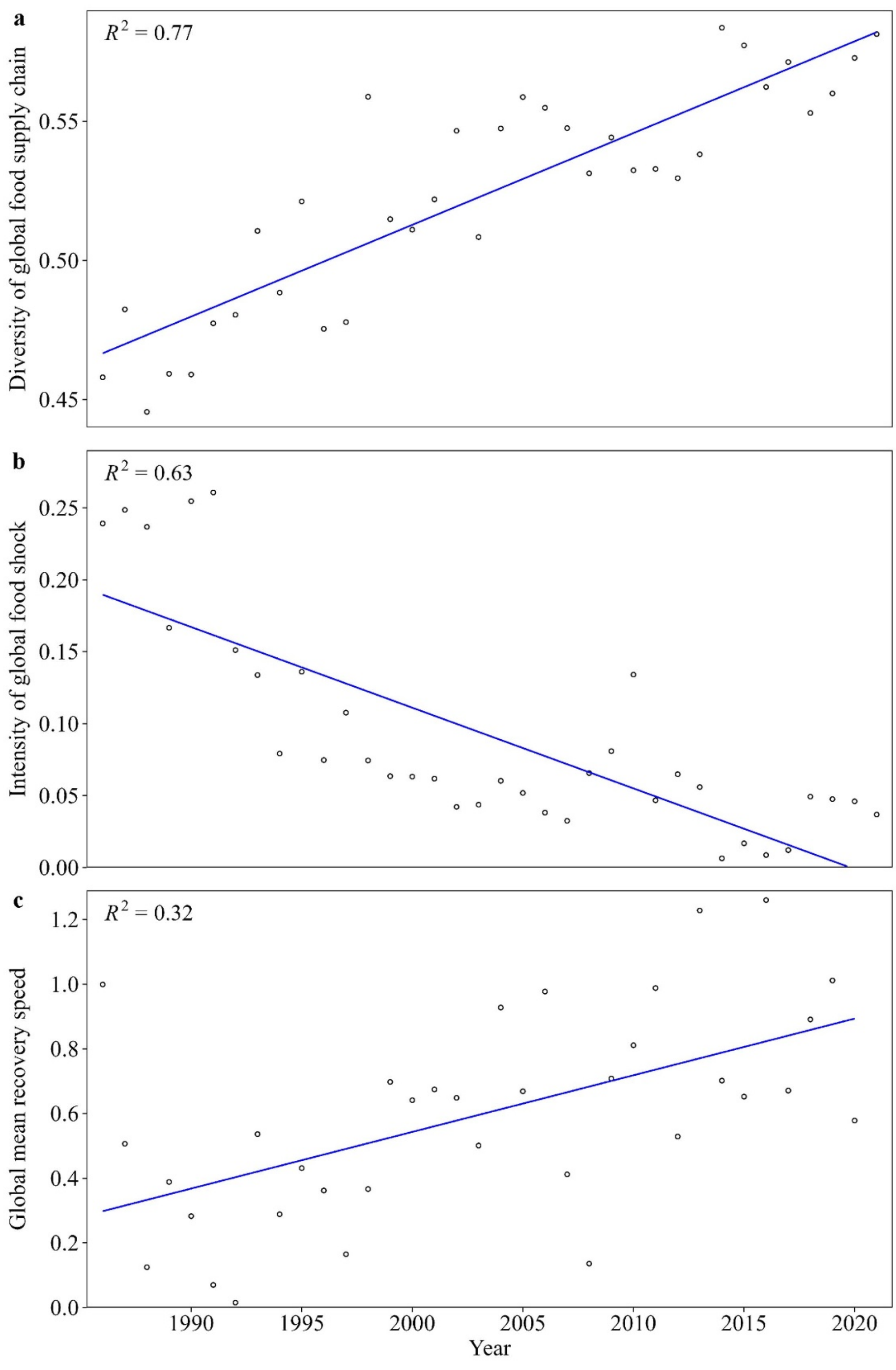

Figure 2. Changing on global food supply chain diversity, global food shock intensity and relationship between recovery and diversity. (a), Diversity of global food supply chain. (b), intensity of global food shock. (c), Global mean recovery speed. The diversity of the global food supply chain and the intensity of global food shocks were calculated as global annual population-adjusted values, and the global mean recovery was calculated as the mean value of recovery speed for countries in recovery (see Methods for calculation details).

3.4. The potential impacts of the Russia–Ukraine conflict

The global wheat supply was seriously impacted because of the Russia–Ukraine conflict. In addition to Russia, the diversity of the wheat supply chain for many countries in Africa (such as Ethiopia, Madagascar and Morocco), the Middle East (such as Iran and Syria), and Southeast Asia (such as Thailand and Vietnam) would likely decrease significantly (figure 4(a)). Considering the diversity-recovery relationship and development level of the region, more time may be needed for countries in the region to recover from the food shock than other regions. Several countries in Europe (such as German, Italy, Sweden, Spain, and Turkey), as well as China, may be seriously impacted by maize supply shocks (figure 4(b)). Because Ukraine and Russia are the main origins of global sunflower oil, the Russia–Ukraine conflict may influence the sunflower oil supply. According to our estimation, the shock on

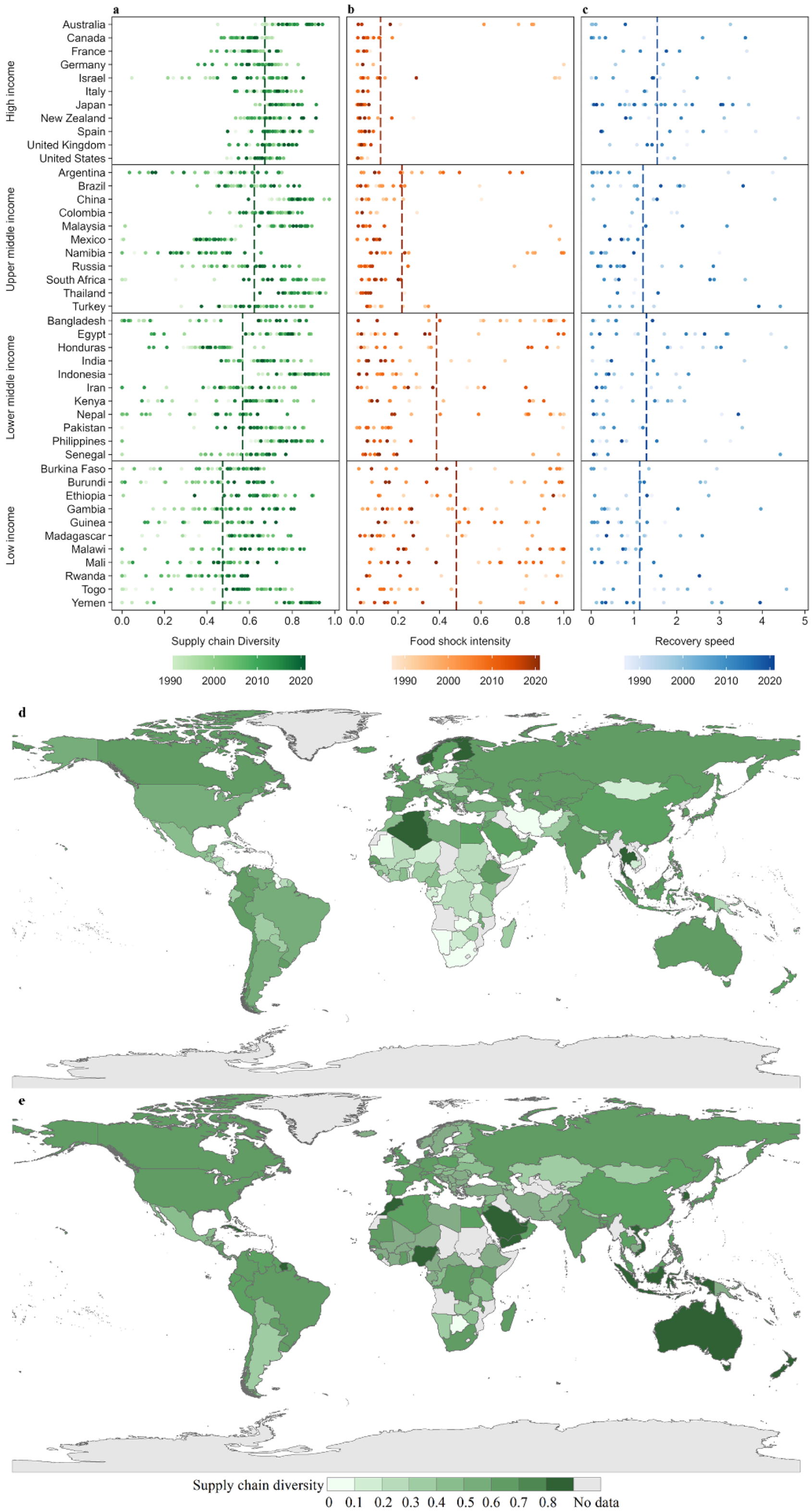

Figure 3. Distributions of food supply chain diversity, food shock intensity and recovery speed. Diversity of food supply chain (a), intensity of food shock (b) and recovery speed (c) distribution along national income group. The spatial distribution of the DFSC average during the period from 1986 to 1990 (d) and during the period from 2017 to 2021 (e). The reference line for each indicator for each income group in (a)–(c) is the average for all countries in the income group (see Methods for calculation details).

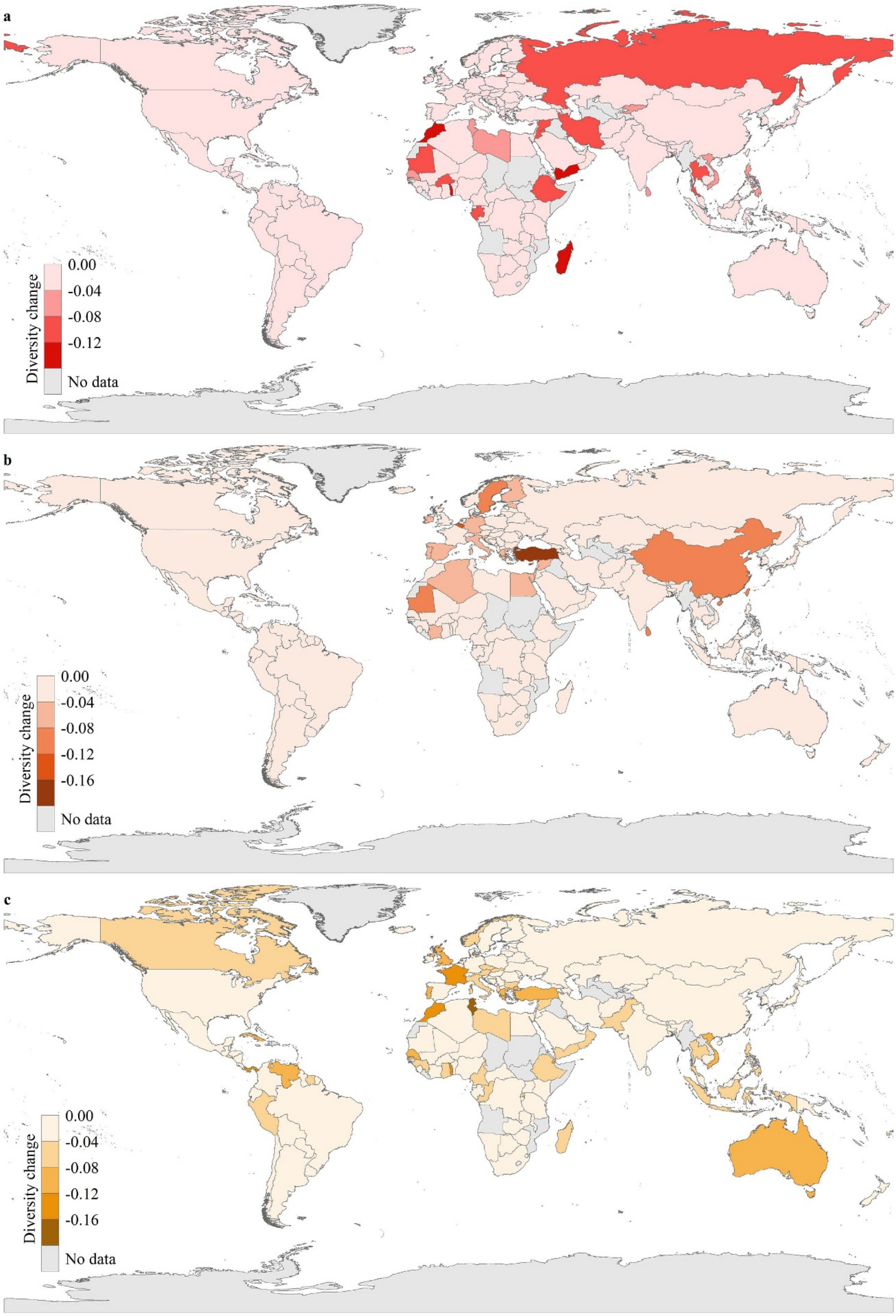

Figure 4. Potential negative changes in supply chain diversity for wheat, maize and sunflower oil led by the Russia–Ukraine conflict. (a), wheat. (b), maize. (c), sunflower oil.

sunflower oil supply may influence many countries, such as Canada, France, Australia, Vietnam, and Tunisia, significantly (figure 4(c)). However, the impact of shock on sunflower oil supply may not be as serious as the shock on wheat and maize supply. Because the global total trading volume of sunflower oil was only approximately 0.7% that of wheat and maize (FAOSTAT 2023), empirically, many other oil products could be alternatives to sunflower oil.

4. Discussion and conclusions

We developed a national empirical–statistical method following Gomez *et al* (2021), with theory that analogous to biodiversity buffering ecosystems against external shocks (Bennett *et al* 2020, Isbell *et al* 2015). Our study indicated that countries or regions owning a greater DFSC value had a lower probability of suffering a food shock, lower intensity of impact when a food shock occurred and faster recovery speed after a food shock happened. Many previous studies asserted that overconnected food supply systems may have a dual effect, increasing exposure to shocks (Tu *et al* 2019) and amplifying shocks (Nyström *et al* 2019). Our results could support this viewpoint, overconnected supply chains do increase the probability of food shocks because of excessive suppliers (figure 1(a)). The supply chain diversity could actually affect the probability of food shocks (figure 1(b)) thus effect of overconnection could also be mitigated by contributing to supply chain diversity. This study will contribute to quantify the stability of food supply systems meticulously by DFSC index. Therefore, our study can provide a strong tool for building food system resilience by managing connectivity in the face of the fast-changing world.

Although the global food supply system improved overall during the period from 1986 to 2021 (figure 2), unbalanced national developments in the food supply system were still observed (figure 3). On the global scale, the intensity of food shock is decreasing, and the recovery speed after food shock is increasing, corresponding to the growing DFSC index. On the spatial distribution scale, generally, high-income countries had comparatively higher DFSC values than countries in the rest of world, indicating better robustness and recovery to food shocks. The DFSCs in sub-Saharan Africa and the Middle East have increased obviously (figure 3). It is a positive sign that the food supply system is becoming better in the least developed region in the world. However, there are still potential risks to food security in Africa and the Middle East. For example, a recent study reported that more than 820 million people had an insufficient food supply, and many more consumed low-quality diets (Willett *et al* 2019). In addition, in 2021, 29% of the global population suffered from moderate-to-severe food insecurity, and unfortunately, most of the reported population was distributed in Africa, the Middle East and South Asia (FAO, IFAD, UNICEF, WFP & WHO 2021). Especially, considering the conspicuous population growth rate worldwide (FAOSTAT 2023), maintaining the stability of the food supply in these regions will still be a challenge.

International emergencies and geopolitical events such as the Russia–Ukraine conflict could potentially threaten the global food supply system and impact low-income countries the most. The Russia–Ukraine conflict has the greatest potential impact on the global supply chain of wheat, maize and sunflower oil (figure 4). Because Russia and Ukraine are the main suppliers of wheat to many countries in Africa and the Middle East, a significant reduction in the diversity of the wheat supply chain would likely be observed in these two regions (figure 4(a)). This could seriously threaten the food security of these countries, resulting in the occurrence of more intense and frequent wheat supply shocks and comparatively more times needed for recovery. Finding substitute trading partners and relieving geopolitical tensions may help these countries maintain the stability of their food supply. The maize supply shock led by the Russia–Ukraine conflict would theoretically have the greatest impact on many countries in Europe and China. However, these countries may replenish their maize supply more easily by importing from other suppliers because of their advantages on international trade and economic development. Therefore, the risk of supply shortages for maize may ultimately be borne by low-income or the least developed countries. Sunflower oil supply shocks may impact Canada, France, Australia, and others. The effect of sunflower oil supply shortages may be limited because the global total trading volume of sunflower oil is comparatively low (FAOSTAT 2023). Our empirical–statistical method of the food supply system and the results generated by it could provide a reference for quantifying the stability of the national food supply system, thus helping insurers, engineers, emergency managers and policymakers mitigate the risk of food shocks.

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

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Author contributions

Junwen Jia: Conceptualization, Writing—original draft, Methodology, Writing—review & editing.

Weiqiang Yang: Conceptualization, Methodology, Software. Fang Wu: Visualization, Software. Xuefeng Cui: Funding acquisition, Conceptualization, Validation, Investigation, Writing—review & editing, Supervision.

Conflict of interest

The authors declare no competing interests.

ORCID iDs

Junwen Jia https://orcid.org/0000-0001-6334-1150
Xuefeng Cui https://orcid.org/0000-0002-9617-072X

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