Environmental Science and Pollution Research (2023) 30:2315–2328
https://doi.org/10.1007/s11356-022-22337-w

RESEARCH ARTICLE

# Spatial correlation network characteristics of embodied carbon transfer in global agricultural trade

Guofeng Wang[1] · Qinyang Guo[1] · Xinsheng Zhou[1] · Fan Zhang[2]

Received: 15 April 2022 / Accepted: 28 July 2022 / Published online: 5 August 2022


## Abstract
Agricultural carbon emission is an important cause of climate change, and the carbon transfer caused by agricultural trade is a key area related to carbon emissions of all countries. Based on the Eora database, this paper aims to constructs a multi-region input–output database of 185 countries or regions, analyzes a spatial correlation network of embodied net carbon transfer in global agricultural trade by using UCINET, selects multi-dimensional network measurement indicators, and comprehensively studies the global evolution characteristics and functional features of network plate role of embodied carbon transfer in the global agricultural trade. The result shows that the embodied net carbon transfer network of global agricultural trade is densely connected, the spatial correlation spillover effect is significant, and the edge of the network core structure is clear. On the one hand, the top four countries or regions in terms of embodied carbon outflow in agricultural trade are the USA, Australia, Vietnam, and China. On the other hand, the top four countries or regions of embodied carbon inflow are Malaysia, Central Africa, Singapore, and Serbia. From the perspective of outdegree, indegree, proximity centrality, and intermediary centrality, Cambodia, the Netherlands, Vietnam, Ghana, and South Africa, with the high frequency of the shortest path of the globally embodied net carbon transfer network, have a strong influence and linking facility in spatial correlation and have a strong control ability to the spatial correlation of other countries or regions. The embodied carbon emission network of global agricultural trade can be divided into four sectors: main spillover, two-way spillover, broker, and main benefit. The main spillover segment, constituted by the USA, India, Germany, and China, has significant embodied carbon spillover effects on the internal segment and other segments. It is the main embodied carbon spillover sector of embodied net carbon transfer of global agricultural trade. Countries should reasonably allocate the responsibility of carbon reduction according to the trading embodied carbon transfer and made efforts to optimize the export structure of agricultural products.

**Keywords** Agricultural trade · Input–output model · Social network analysis · Block model · Climate adaptation

## Introduction

There is a strong correlation between climate change and $CO_2$ emissions. The United Nations Intergovernmental Panel on Climate Change (IPCC 2021) released *Climate Change 2021: The Physical Science Basis* (Irfan et al. 2021a), which reveals the relationship between climate change and human activities (Lynn and Peeva 2021). After the industrial revolution, carbon emissions surged and the global temperature also rose (Wang et al. 2019). From 1850 to 2019, the change of global temperature is directly proportional to the cumulative carbon emission (Deng et al. 2017). The correlation between global temperature change and carbon emission can be seen in the fact that global temperatures are likely to rise by 1.5–2.5° in 2050. Climate change is closely related to human activities, especially carbon emissions (Wang et al. 2020). In November 2021, the 26th conference of the parties to *the United Nations Framework Convention on Climate Change* (UNFCCC) pointed out that emissions should be reduced by 50% by 2050 in order to ensure the 1.5 °C target. The global temperature has risen by 1.1 °C compared to the pre-industrial period, and the

Responsible Editor: Arshian Sharif

✉ Fan Zhang
zhangf.ccap@igsnrr.ac.cn

[1] Faculty of International Trade, Shanxi University of Finance and Economics, Taiyuan 030006, China

[2] Key Laboratory of Land Surface Pattern and Simulation, Institute of Geographical Sciences and Natural Resources Research, Chinese Academy of Sciences, Beijing 100101, China

average mole fraction of global carbon dioxide has exceeded 410 ppm. The climate critical point is approaching rapidly. Once exceeded, it will cause great disasters to human beings (Zhang et al. 2021a, b). To this end, countries around the world have actively responded. By the end of 2021, 136 countries or regions have proposed the development goal of carbon neutrality (Zhao et al. 2022). Coping with climate change has become an urgent and huge threat to mankind, and adapting to and mitigating climate change has become the voice of all mankind (De La Peña et al. 2022; Irfan et al. 2020).

The issue of embodied carbon in trade has become a controversial point of global carbon emission reduction (Xu et al. 2020). With the acceleration of economic globalization, especially the differences in the order of the value chain of products in the global division of labor and cooperation, has led to the separation of carbon emissions from production and consumption in time and space (Zhang et al. 2021a, b). Developed countries have high value-added products such as high-end technology, while developing countries have become the production places of high energy consumption, high emission, and low value-added products, which has led to global developing countries becoming pollution havens (Zheng and Shi 2017), while developed countries enjoy the resulting high consumption levels. In this regard, the issue of carbon emissions caused by trade is gaining attention (Wang and Han 2021). Agricultural trade, as an important part of a trade, has become increasingly prominent. Especially after the outbreak of COVID-19, agricultural products have become the best "good medicine" to fight against the epidemic. According to the report on *the State of Agricultural Commodity Markets in 2020* released by the FAO, the global agricultural and food trade has more than doubled since 1995, and the trade volume reached US $1.5 trillion in 2018 (FAO 2020). Among them, the exports of emerging markets and developing countries have continued to grow, accounting for more than one-third of the global total. The participation of countries in global agricultural trade depends on a number of factors, including countries' comparative advantage in production and consumer preferences (Cao et al. 2021), but at the same time, the embodied carbon flow generated by agricultural trade also separates production from consumption (Beghin and Schweizer 2021). The analysis of the embodied carbon network flow of global agricultural trade can help countries grasp the characteristics of the global agricultural network of the embodied carbon of agricultural products (Lun et al. 2021).

## Literature review

In addition to adaptation, what we can do is to prevent further climate deterioration, that is, to low-carbon transformation and zero-carbon development (Hao et al. 2021; Deng et al. 2016; Yang et al. 2021). The research on embodied carbon transfer of agricultural products has become a hot spot of academic research at home and abroad (Balogh and Jámbor 2017), with most studies focusing on the embodied carbon flow of bilateral and single country import and export of agricultural products (Jiang et al. 2020). Scholars investigated the embodied carbon emissions in Korean trade by using multi-regional input–output analysis (Cui et al. 2019). Also, systematically studies examined the embodied net carbon emissions of trade between the largest net exporter of developing countries (China) and the largest net exporter of developed countries (Germany) (Abbasi et al. 2022; Balogh 2020). Quasi-input–output analysis method was used to analyze specific land use and greenhouse gas emissions in global agricultural trade, to track the flow of agricultural land and greenhouse gas emissions among 151 countries or regions worldwide, and discussed the interdependence between land and emissions in different economic systems (Wood et al. 2020). In summary, the research on the global virtual carbon transfer network of agricultural products needs to be further deepened (Zhou et al. 2021), the coverage needs to be more comprehensive at the national or regional level, and the cross-global agricultural trade network needs to be established (Müller-Casseres et al. 2021).

This paper makes some innovations on the basis of predecessors and adopts a global input–output table to observe the different segments and clarify their roles in the embodied carbon transfer in global agricultural trade, and explore the link between different segments. This paper constructs the input–output data table of agricultural trade in 185 countries or regions in the world in 2016, and uses the multi-regional input–output model and social network analysis method to calculate the embodied carbon flow data of agricultural trade in various countries. It analyzes the major agricultural trade countries and identifies various characteristic indicators of the network, including individual characteristics, overall characteristics, and sub-segment characteristics of the network. Compared with other studies, this paper adopts the latest data and covers more comprehensive countries and regions. The analysis of the measured embodied carbon in global agricultural trade and the spatial correlation network of embodied carbon in global agricultural trade has important reference significance for policymakers of various countries. This paper focuses on the spatial correlation network characteristics of carbon implicit transfer in global agricultural trade and provides a new global perspective for understanding the net carbon implicit transfer of agricultural trade by constructing a spatial correlation network. In short, we have a comprehensive understanding of the overall network of embodied net carbon transfer in global agricultural trade.

## Methodology and data

### Methodology

This paper uses the multi-regional input–output analysis method, which was first proposed by Leontief, and it was Leontief who used this method to discover the Leontief paradox (Muradov 2021). In the middle of the last century, it was more widely used by economists among multiple countries, resulting in the MRIO model, which can easily and accurately calculate the embodied carbon flows of agricultural products by using multi-regional input–output model (Cabernard and Pfister 2021).

#### Global MRIO table construction

Assuming a total of $R$ countries or regions in the world, the agricultural sector of each country or region is reflected in the input–output table, which is the world input–output table of the agricultural sector. $Z^{EF}$ is the intermediate input matrix of the agricultural sector of country $E$ to the agricultural sector of country $F$ ($E$, $F=1, 2,\ldots.., R$), where the matrix element $z^{EF}$ is the amount of intermediate inputs from the agricultural sector of country $E$ to the agricultural sector of country $F$. $Y^{EF}$ is the 1*6-dimensional final demand matrix of the agricultural sector of country $E$ for country $F$, where the matrix element $y_i^{EF}$ ($i=1, 2\ldots, 6$) is the final use of the agricultural sector of country $E$ for the final demand 6 departments of country $F$.

$X^E$ represents the total output of country $E$, where the matrix element $x_i^E$ ($i=1, 2,\ldots, R$) is the $R$*1-dimensional output vector. According to the environmental satellite account of the Eora database, the emission matrix of $CO_2$ emissions $L^E$ from the agricultural sector of each country is obtained, where the matrix element $l^E$ ($E=1, 2,\ldots, R$) represents the $CO_2$ emissions from the agricultural sector of country $E$. Based on $CO_2$ emissions $L^E$ and total output, the coefficient matrix of direct carbon consumption coefficient $G$ (direct emissions of $CO_2$ per unit of output). $G$ is the total output of direct emissions of $CO_2$, that is, $G=\left[g^A g^B \ldots.. g^R\right]$, is calculated, where the matrix element $g^E$(E=1,2…R) is the direct carbon emission coefficient of the agricultural sector of each country with 1*$R$-dimensional matrix.

$$Z^{EF}=\begin{bmatrix} Z^{AA}\ldots Z^{AR} \\ \ldots\ldots\ldots\ldots\ldots \\ Z^{RA}\ldots Z^{RR}\end{bmatrix}, Y^{CD}=\left[y_1^{CD} y_2^{CD}\ldots y_6^{CD}\right], X^E=\begin{bmatrix} x^A \\ \ldots \\ x^R\end{bmatrix} \tag{1}$$

Thus, the horizofntal balance of input–output models of agricultural products around the world is as follows:

$$\begin{cases} Z^{AA}+Z^{AB}+\ldots.+Z^{AR}+Y^{AA}+\ldots+Y^{AR}=X^A \\ Z^{BA}+Z^{BB}+\ldots.+Z^{BR}+Y^{BA}+\ldots+Y^{BR}=X^B \\ \\ Z^{RA}+Z^{RB}+\ldots.+Z^{RR}+Y^{RA}+\ldots+Y^{RR}=X^R \end{cases} \tag{2}$$

The direct consumption coefficient matrix $A$ is calculated as the total input or output of the agricultural sector. The Leontief inverse matrix $(I-A)^{-1}$ is calculated by using the software MATLAB R2014b, and $I$ is the unit matrix with diagonal 1.

Calculate the total export value of intermediate input and final demand from the agricultural sector of country $E$ ($E=1, 2,\ldots., R$) to 26 sectors of country $F$ ($F=1, 2,\ldots, R$).

$$EX=\left[EX^A EX^B\ldots..EX^R\right]$$

$$EX^A=\left[ex_B^A ex_C^A\ldots..ex_R^A\right] \tag{3}$$

The intermediate input and final demand of the agricultural sector of country $E$ to the 26 sectors of each country are added by country to obtain a $EX^{EF}$ export matrix of the agricultural sector of country $E$ to each country. The matrix dimension is 185*185, where the matrix element $ex^{EF}$ ($E\backslash F=1, 2,\ldots, R$) represents the export value of the agricultural sector of country $E$ to 184 countries (excluding the home country). Based on the calculation of global 185 countries or regions' trade embodied carbon exports $C^{EF}$, we can get the export matrix with the 185*185-dimensional matrix and diagonal 0, where the matrix element $C^{EF}$ represents the embodied carbon outflows of the agricultural sector of country $E$ to different countries. The calculation formula is:

$$C^{EF}=G(I-A)^{-1}EX^{EF} \tag{4}$$

Based on the calculated export value, we can get the embodied carbon emission value of country $E$ to country $F$ and the value of country $F$ to country $E$. From this, the embodied net carbon emission value of country $E$ to country $F$ can be obtained:

$$\Delta C^{EF}=C^{EF}-C^{FE} \tag{5}$$

According to the above formula, if the result is greater than 0, it is the net outflow of country $E$ to country $F$. And if it is less than 0, it is the net outflow of country $F$ to country $E$.

#### Construction of network main indicators

Taking countries or regions as nodes and the embodied net carbon transfer relationship between countries or regions as edges, the embodied net carbon transfer relationship network of 185 countries or regions around the world $J=(M, V, W)$ is constructed, where $M$ represents the vertex set of the network, $V$ is the edge set, and $W$ is the weight set. The adjacency matrix $Z=(z_{EF})$ of the network is defined to represent the embodied net carbon transfer relationship between each country or region in the network. When the embodied net carbon transfer of country $E$ to country $F$ is strictly greater than 0, there exists an edge $v_{EF}$ pointing from node $E$ to node $F$. At this time, $z_{EF}$ is equal to 1; otherwise, $z_{EF}$ is equal to 0 ($E$, $F=1, 2,\ldots, 185$). The weight $z_{EF}$ of the edge is $w_{EF}$ taken as the embodied net carbon transfer from country $E$ to country $F$. The overall characteristics of the network are characterized by four indicators: network density, network relevance, average clustering coefficient, and average path length. Network density is the ratio of the actual number of edges in the network to the most likely number of edges in theory, and it is an important index to reflect the closeness of the network association. If the global embodied net carbon transfer network density is higher, the trade embodied carbon transfer links of various countries or regions are more frequent. $|V|$ represents the number of edges and $n$ is the number of nodes in the network, and then the network density $U$ is calculated as follows:

$$U = \frac{|V|}{n(n-1)} \tag{6}$$

Network relevance is a measure of the degree of network relevance through accessibility, and it is the primary index to describe the robustness and vulnerability of the network.

The higher the relevance of the embodied net carbon transfer network of global trade, the better the relevance of the network and the more robust the network is. $M_1$ is used to represent the number of unreachable point pairs in the network, and the calculation formula of correlation degree $Z$ is:

$$Z = 1 - \frac{2M_1}{n(n-1)} \tag{7}$$

The clustering coefficient, the measurement of the probability of connection between the adjacent nodes of nodes, is used to measure the degree of clustering of nodes in the global trade embodied net carbon transfer network. The clustering coefficient $GC$ of the whole network is the average value of the clustering coefficients of all nodes in the network. Assuming that the node $m_E$ has $k_E$ adjacent nodes and the number of edges between these adjacent nodes is $V_E$, and the clustering coefficient $GC_{EF}$ of the node $m_E$ is:

$$GC_E = \frac{V_E}{k_E(k_E-1)} \tag{8}$$

The average path length is the average value of the shortest path between all node pairs in the network. A smaller average path length means that nodes in the network can be connected with other nodes through shorter paths. This index is mainly used to measure the embodied carbon transfer efficiency of the global trade embodied net carbon transfer network. Using $d\,(m_E, m_F)$ to represent the shortest path length between node $m_E$ and node $m_F$, then the average path length $GL$ is calculated as follows:

$$GL = \frac{\sum_{E,F} d\,(m_E, m_F)}{n(n-1)} \tag{9}$$

The network individual characteristics mainly select three core metrics to reflect the network topology: degree centrality, intermediary centrality, and proximity centrality. In directed networks, the degree centrality of nodes is divided into outdegree centrality and indegree centrality. In the global trade embodied net carbon transfer network, the outdegree centrality $d_E^{out}$ and indegree centrality $d_E^{in}$ of node $m_E$ reflect the number of embodied net carbon outflow and net inflow relationships from country $E$ to other countries, respectively. Considering the influence of weight, the weighted outdegree $W_E^{out}$ and weighted indegree $W_E^{in}$ of node $m_E$ can be defined as the embodied net carbon outflow and net inflow from country $E$ to other countries, respectively:

$$d_E^{out} = \sum\nolimits_{v_{EF}\in P} z_{EF}, d_E^{in} = \sum\nolimits_{v_{EF}\in P} z_{FE}$$

$$w_E^{out} = \sum\nolimits_{v_{EF\in}V} w_{EF}, w_E^{in} = \sum\nolimits_{v_{EF}\in V} w_{FE} \tag{10}$$

The intermediate centrality refers to the frequency of nodes appearing on the shortest path of the network. If a node is on the shortest path of many other point pairs, the intermediary centrality of the node is higher, and the country or region corresponding to the node plays a greater role as a communication bridge in the global trade embodied net carbon transfer network. Assuming that the number of shortest paths existing between node $m_D$ and node $m_F$ is $j_{DF}$, the number of shortest paths passing through node $m_E$ between node $m_D$ and node $m_F$ is $j_{DF}(E)$, where $D \neq E \neq F$, then the intermediary centrality $BC_E$ of nodes $m_E$ is calculated as:

$$BC_E = \frac{2\sum\limits_{D}\sum\limits_{F} g_{DF}(E) / g_{DF}}{n^2 - 3n + 2} \tag{11}$$

The proximity centrality is a measure that nodes are not restricted by other nodes. In the network of embodied carbon transfer in global trade, if a country or region has a short distance from other nodes in the network, it has a high proximity centrality. Such a country or region is close to many other nodes and is less controlled by other countries (regions). The calculation formula of the proximity centrality $CC_E$ of the node $m_E$ is:

$$CC_E = \frac{n-1}{\sum d_E^{short}} \tag{12}$$

where $d_E^{short}$ can represent the shortest path length from node $m_E$ to other points or other points to node $m_E$, and then calculate the out-proximity centrality and in-proximity centrality, respectively.

### Block model analysis

Block model analysis is an important method to block the network location based on the network structure information, and study the network location and role. According to the block model theory, this paper firstly uses Convergent Correlations (CONCOR) to block the whole network based on the structural similarity of embodied net carbon transfer in each country or region, and then analyzes the status and role of each country or region in the network of embodied carbon transfer in global agricultural trade based on the embodied net carbon transfer relationship between the interior and exterior of each block.

Assuming that the number of countries or regions contained in plate $q$ is $R_q$, the total number of possible relationships within plate $q$ is $R_q(R_q-1)$. In the network of embodied carbon transfer in global trade, there are $R$ countries or regions in total, and the number of all possible relationships of each member of plate $q$ is $R_q(R-1)$. Thus, the expected value of the overall proportion of carbon transfer relationships within plate $q$ is calculated as $R_q(R_q-1)/R_q(R-1)=(R_q-1)/(R-1)$. Further combining the proportion of internal and external relations of the plate, the network of embodied carbon transfer in global trade can be divided into the following four types of position relations (Table1).

## Data

The input–output databases commonly used by scholars are WIOD, Eora, GTAP, AIIOT, and EXIOBAS. For example, WIOD mainly includes 40 countries, including EU countries and 15 developed and developing countries. The Eora database contains 189 countries or regions. Only Eora meets the global requirements of our paper.

The 2016 world input–output table (Dummy Mrio) in Eora database covers the trade data of goods and services between the 26 industrial sectors in 189 countries or regions including intermediate inputs, final demand, and environmental satellite account (mainly using $CO_2$ emission data). The dimension of trade data matrix reaches 5106*5106, which fully reflects the input–output relationship between intermediate input, added value, total input and intermediate, final use and total output within and among different regions of agricultural products trade. The latest data of Eora database is 2016, and the data content includes global input–output table and environmental account. Therefore, this paper selects Eora database.

According to the data provided by Eora database, Dummy Mrio multi-regional input–output data table is formed. This paper covers 185 countries or regions (China consists of mainland China, Hong Kong, Taiwan, and Macau, excluding data from the former Soviet Union), including 26 departments, and obtaining the input–output data of agricultural sectors in 185 countries.

**Table 1** Classification method of position relation plate in net transfer network

| Relationship proportion within position | Relationship proportion received by position | |
|---|---|---|
| | ≈0 | >0 |
| $\geq (R_q-1)/(R-1)$ | Two-way spillover plate | Main beneficiary plate |
| $\leq (R_q-1)/(R-1)$ | Main overflow plate | Broker plate |

## Results

### Carbon transfer network in global agricultural trade

This paper draws the embodied carbon export, import, and net transfer network of global agricultural products on the basis of the embodied carbon transfer matrix of agricultural products in 185 countries or regions around the world. The embodied net carbon transfer network of global agricultural products is densely connected, and the number of network relationships reaches 17,700. The embodied carbon transfer in global agricultural trade has obvious spatial correlation characteristics. The relevance degree of the embodied carbon network of global agricultural trade is 1, which shows that the global agricultural trade transfer network has good accessibility and obvious spatial spillover effect. The network density is 0.496, and the links between nodes are close, indicating that with the economic development, the links between various countries or regions gradually tend to be close, resulting in more frequent transfer of carbon emissions from agricultural products.

From the perspective of the global embodied net carbon transfer network of agricultural products, the degree of most nodes in the network is very small, and the relationship with other nodes is small. Most countries are at the edge of the network and are at the edge in the global agricultural trade. They do not play a prominent role in the net carbon transfer of global agricultural trade. A few nodes

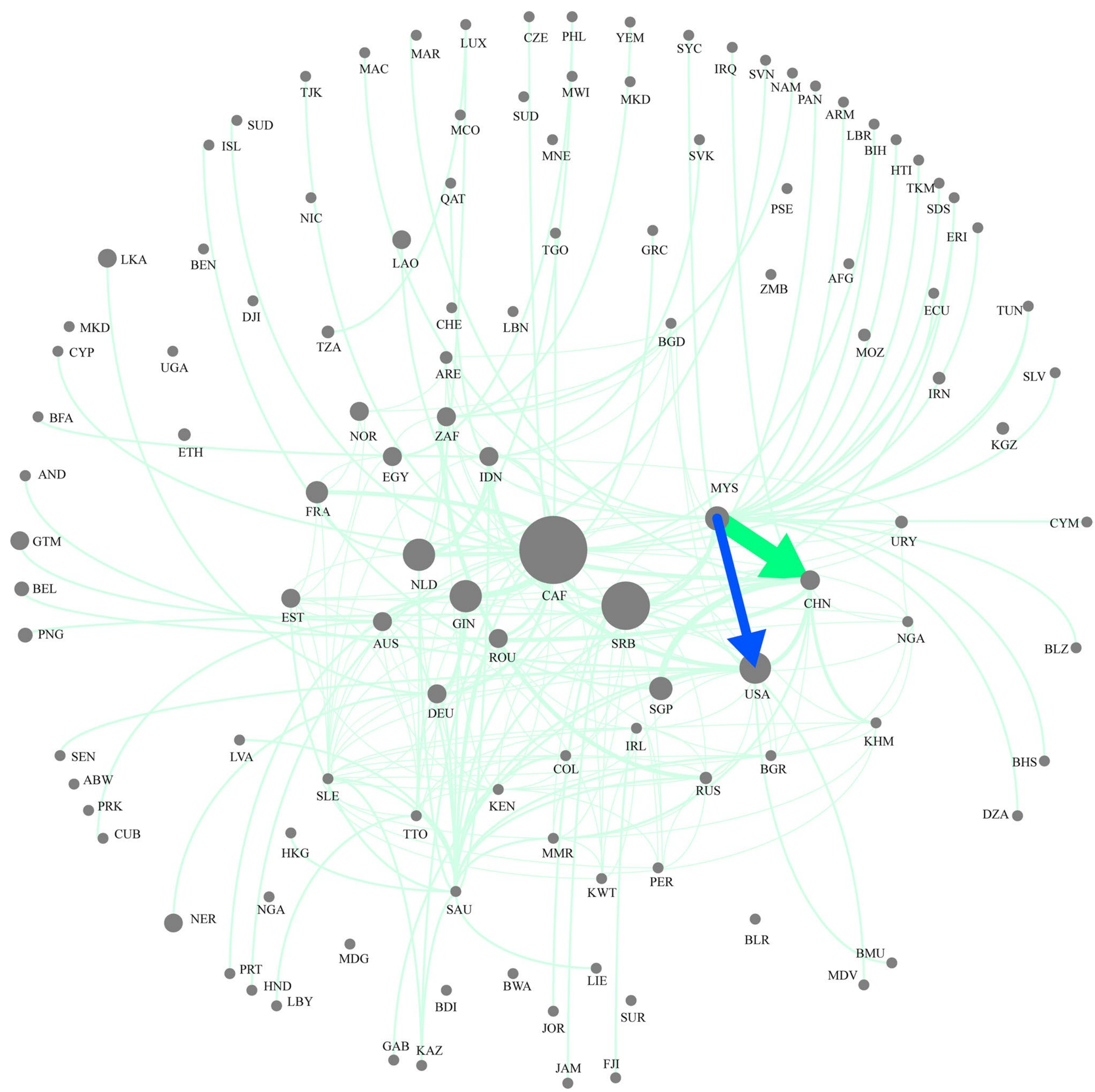


**Fig. 1** Global agricultural trade embodied net carbon transfer network in 2016

in the network are at the center. The core nodes in the network are mainly concentrated in Central Africa (Fig. 1), Serbia, the Netherlands, Singapore, Malaysia, the USA, China, India, Romania, Estonia, Brazil, and other countries. These countries, as the core of agricultural trade, have spatial heterogeneity in the relationship between net carbon transfer and its inflow and outflow. From the overall characteristics of the network, the network density is 0.026, the average network degree is 5.032, the average network clustering coefficient is 0.325, the agglomeration effect is obvious, and the average path length of the network is 3.219, indicating that although most areas in the network are not directly connected, they can be reached through a few steps. The embodied net carbon transfer network of global agricultural trade has large average clustering coefficient and short average path length, indicating that the global agricultural trade has typical small world characteristics. In this network, the possibility of establishing links between any node is large. Changing the embodied carbon transfer amount or transfer relationship of agricultural products in some core countries or regions will have a great impact on the characteristics of the whole network.

## Carbon transfer inflow and outflow network

From the perspective of the embodied carbon transfer outflow end of global agricultural products, the top four countries with the largest embodied carbon transfer outflow of agricultural products in 2016 were the USA, Australia, Vietnam, and China. As the world's largest exporter of agricultural products, the outdegree centrality of the USA is 46,932.289. The top five trading partner countries of the USA with embodied carbon transfer outflow are Malaysia (8.07 Mt), Singapore (7.09 Mt), Mexico (3.30 Mt), the Netherlands (2.36 Mt), and Guinea (2.11 Mt). Australia is the second largest country of embodied carbon transfer outflow. Australian top five countries with trading embodied carbon transfer outflow are Malaysia (15.93 Mt), Singapore (10.99 Mt), Central Africa (3.58 Mt), Serbia (2.15 Mt), and Indonesia (1.69 Mt). Vietnam is the third country with embodied carbon transfer outflow. Vietnamese top five countries with trading embodied carbon transfer outflow are Malaysia (8.35 Mt), Singapore (6.87 Mt), Central Africa (5.49 Mt), Serbia (2.10 Mt), and Australia (1.54 Mt). China is the fourth country with embodied carbon transfer outflow. Chinese top five countries with trading embodied carbon transfer outflow are Malaysia (17.07 Mt), Singapore (8.10 Mt), Central Africa (3.26 Mt), Thailand (2.10 Mt), and Serbia (1.52 Mt) (Fig. 2).

From the perspective of the embodied carbon transfer inflow end of global agricultural trade, the top four countries with the largest embodied carbon transfer inflow of agricultural products in 2016 were Malaysia, Central Africa, Singapore, and Serbia. Malaysia is the world's largest country with embodied carbon transfer inflow in agricultural trade. Malaysian top five countries with embodied carbon transfer inflow are China (17.07 Mt), Australia (15.93 Mt), Cambodia (13.24 Mt), Indonesia (9.32 Mt), and Vietnam (8.35 Mt). Central African is the second largest country of embodied carbon inflow in global agricultural trade. The Central African top five major countries with embodied carbon transfer inflow are Vietnam (5.79 Mt), Australia (3.58 Mt), China (3.26 Mt), India (2.95 Mt), and Sudan (2.75 Mt). Singapore is the third country with embodied carbon transfer inflow. Singaporean top five countries with embodied carbon transfer inflow are Indonesia (12.59 Mt), Australia (10.99 Mt), Malaysia (8.52 Mt), China (8.10 Mt), and the USA (7.08 Mt). Serbia is the fourth country in terms of embodied carbon transfer inflow. Serbian top five countries with embodied carbon transfer inflow are Australia (2.14 Mt), Vietnam (2.10 Mt), China (1.52 Mt), India (1.50 Mt), and the UK (1.48 Mt) (Fig. 3).

## Individual characteristics of carbon transfer network

By calculating the degree centrality, proximity centrality, and intermediary centrality of each node in the embodied net carbon transfer network of agricultural trade in the top 15 countries or regions, it is concluded that the USA, China, Australia, Vietnam, and Indonesia occupy the top five in terms of outdegree centrality. These countries are also the central nodes of global agricultural trade and are in the active position in the embodied net carbon transfer of agricultural trade, which has the main influence on other countries. The average outdegree centrality is 3943.160, and there are 48 countries or regions higher than the average, indicating that there are more nonlinear spatial correlations between these countries and other countries. Besides, Malaysia, Central Africa, Singapore, Serbia, and the Netherlands occupy the top five in terms of indegree centrality. These countries are more influenced by other countries in the process of embodied carbon transfer in agricultural trade. In addition, the top five countries in terms of proximity centrality are Nigeria, Niger, UAE, Argentina, and Guatemala, indicating that the average embodied net carbon transfer path from other countries or regions to them are longer. In particular, the top five countries with out-proximity centrality are Central Africa, Serbia, Guinea, Romania, and Portugal, which are far away from the center, have low independence in receiving embodied net carbon inflow, enhanced restrictions by other countries or regions, and have weak influence. What is more, the top five countries are Cambodia, the Netherlands, Vietnam, Ghana, and South Africa in terms of intermediary centrality. These countries appear on the shortest path of the global embodied net carbon transfer network with high frequency and have a strong influence and bridge role in spatial correlation. These countries are in the central of the global correlation network of embodied net carbon transfer in global agricultural trade, and have strong control over the spatial correlation of other countries or regions (Table 2).

## Block model result analysis

Based on the block model approach, the 2016 global embodied net carbon transfer network of agricultural products is identified by using the CONCOR module in UCINET for plate identification. The position roles of each plate are positioned according to the ratio of actual and expected internal relationships within the plate and the number of internal and external relationships of the plate. Finally, the countries or regions in the global embodied net carbon transfer network are divided into four plates. On the whole, the global embodied net carbon transfer network of agricultural trade in 2016 contains 1742 spatial correlations, including 161

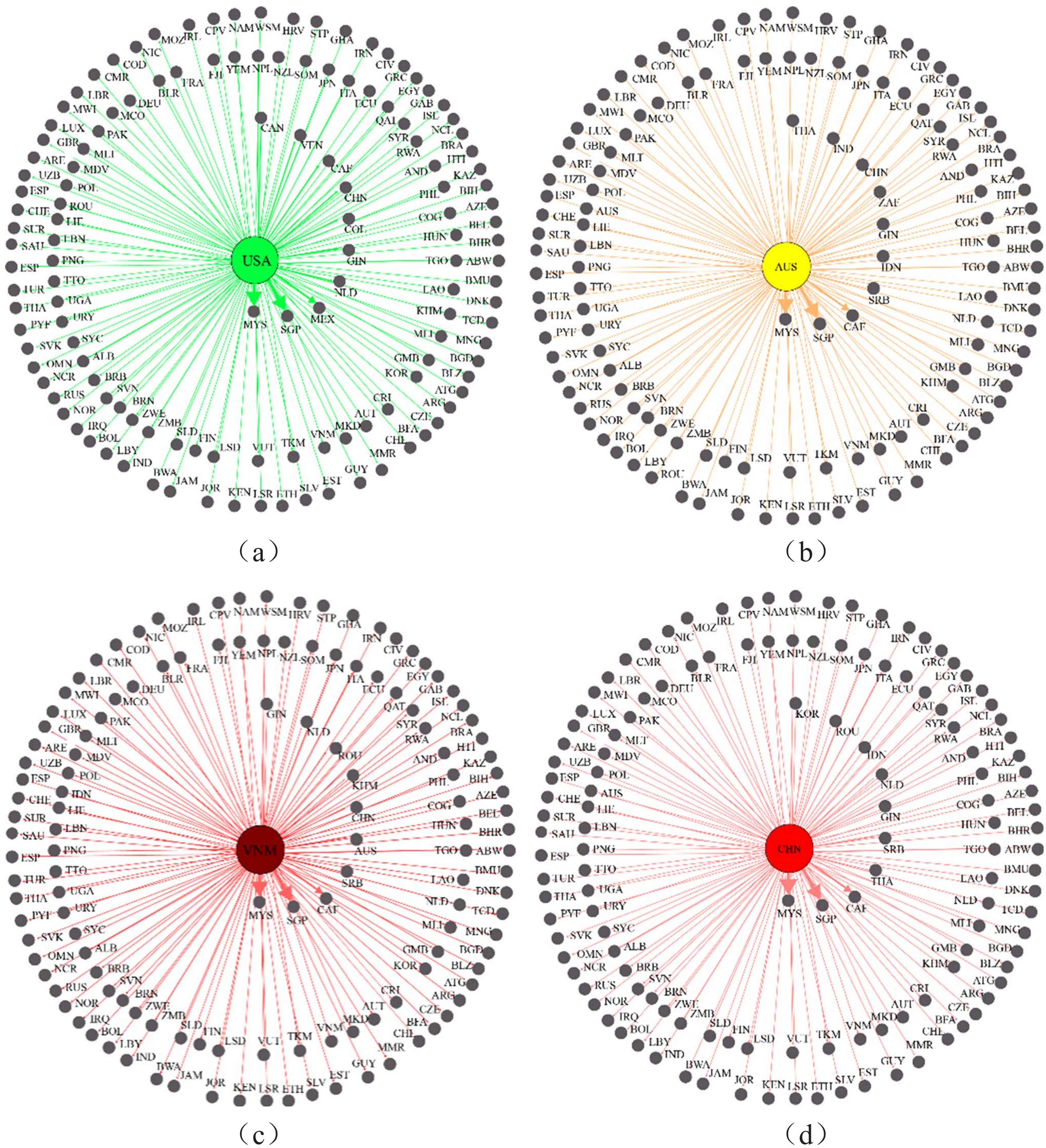


**Fig. 2** Top four countries with embodied carbon outflows in global trade in 2016 (**a** USA; **b** Australia; **c** Vietnam; **d** China)

relationships inside the plate and 1581 relationships between plates. The number of relationships between plates is much higher than that inside plates. It can be concluded that the spatial correlation network is dominated by the spillover effect between plates.

The first plate mainly includes Vietnam, Iran, Iraq, and other countries or regions. The actual and expected internal relationships of this plate are 4.13% and 70.65%, respectively. This plate not only receives the spillover relationship to other plates, but also issues the relationship to other plates.

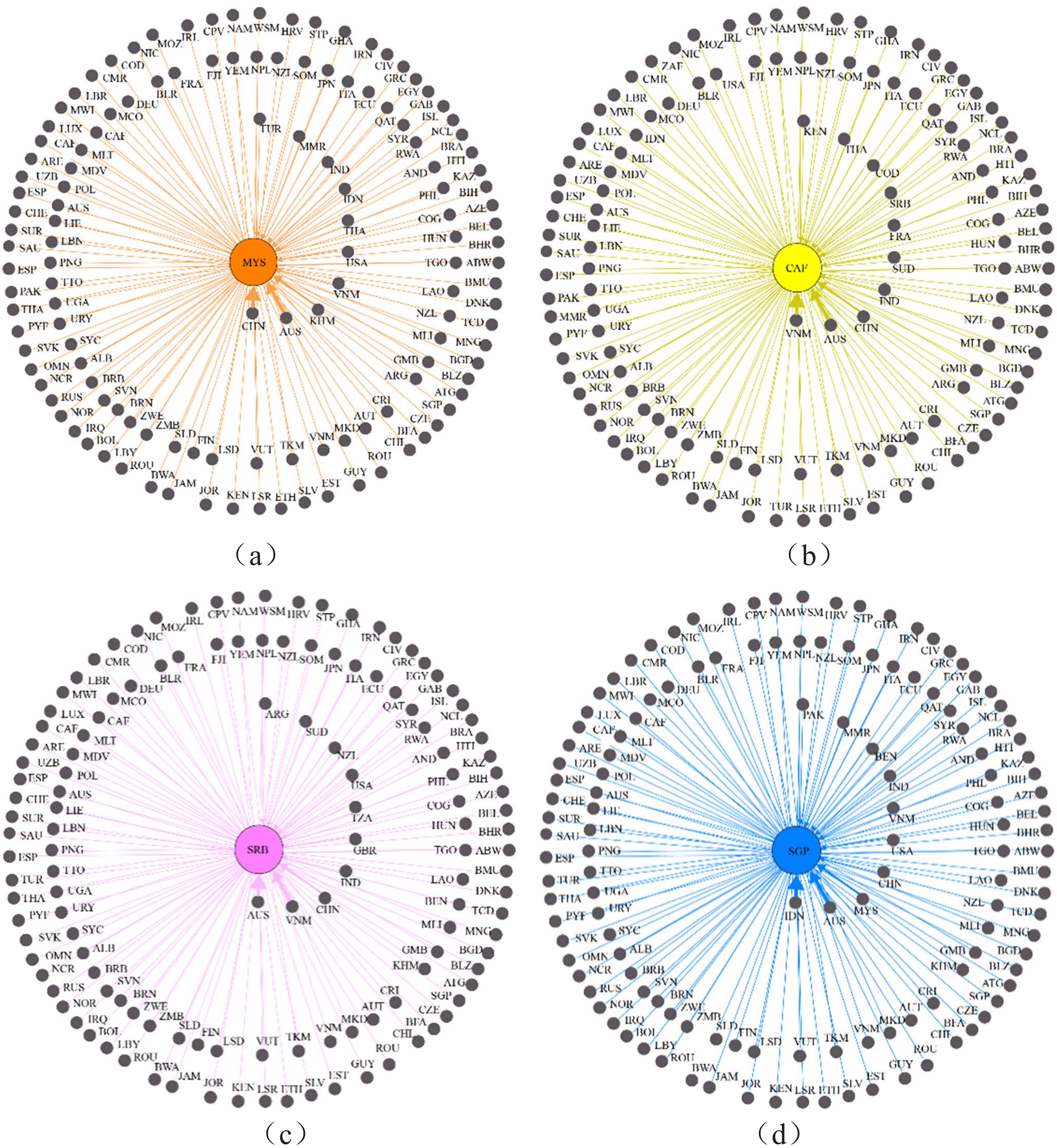


**Fig. 3** Top four countries with embodied carbon inflows in global trade in 2016 (**a** Malaysia; **b** Central Africa; **c** Singapore; **d** Serbia)

However, the number of internal relationships in the plate is small, which has the characteristics of broker plate. The second plate mainly contains Austria, Syria, and other countries or regions. The ratio of actual internal relationships within the plate is 3.80%, which is lower than the expected ratio of 7.36%. There are many connections between the internal and external plates of the whole one, which belongs to a two-way spillover plate. The nodes of countries or regions in the plate not only issue many relationships to the external plate, but also have relationships to the internal plate. Its members have a two-way relationship and have a factor radiation relationship between the internal members of the plate

**Table 2** Centrality results of carbon transfer network in global agricultural trade in 2016

| Ranking | Outdegree centrality | | Indegree centrality | | In-proximity centrality | | Out-proximity centrality | | Intermediary centrality | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Country | Degrees | Country | Degrees | Country | Degrees | Country | Degrees | Country | Degrees |
| 1 | USA | 46,932.289 | MYS | 110,641.5 | NGA | 0.791 | CAF | 3.327 | KHM | 3.525 |
| 2 | CHN | 45,573.316 | CAF | 101,214.961 | NER | 0.778 | SRB | 1.993 | NLD | 3.068 |
| 3 | AUS | 41,492.504 | SGP | 85,057.969 | ARE | 0.777 | GIN | 1.31 | VNM | 2.874 |
| 4 | VNM | 31,384.236 | SRB | 45,573.016 | ARG | 0.773 | ROU | 1.227 | GHA | 2.596 |
| 5 | IDN | 27,615.377 | NLD | 42,822.059 | GTM | 0.773 | PRT | 1.173 | ZAF | 2.371 |
| 6 | IND | 26,460.15 | ROU | 31,285.076 | CRI | 0.773 | COD | 1.166 | TUR | 2.2 |
| 7 | KHM | 18,236.576 | GIN | 28,888.41 | CIV | 0.768 | NOR | 1.155 | SGP | 1.974 |
| 8 | FRA | 17,326.314 | EST | 22,986.889 | PAK | 0.767 | LBY | 1.151 | CHN | 1.77 |
| 9 | THA | 16,256.767 | COD | 21,940.654 | CAN | 0.767 | KWT | 1.142 | EST | 1.68 |
| 10 | TUR | 16,145.207 | ZAF | 12,679.468 | MDG | 0.767 | MLT | 1.139 | FRA | 1.377 |
| 11 | NLD | 15,421.784 | THA | 11,974.756 | PNG | 0.767 | KOR | 1.135 | AUS | 1.242 |
| 12 | ZMB | 13,406.473 | NOR | 10,810.436 | CHL | 0.767 | NAM | 1.133 | IND | 0.98 |
| 13 | ARG | 11,977.296 | CHN | 9803.72 | TZA | 0.767 | MUS | 1.133 | USA | 0.878 |
| 14 | DEU | 11,956.539 | BRA | 9532.612 | DOM | 0.767 | NLD | 1.131 | TCD | 0.737 |
| 15 | ESP | 10,864.051 | IND | 9526.77 | USA | 0.763 | SGP | 1.131 | COL | 0.723 |

and the external nodes of countries or regions. The overall function of the plate is the diffusion, radiation, and transmission of factors. The third plate includes the USA, China, Australia, India, Indonesia, Cambodia, and other countries or regions. The actual and expected internal relationships of this plate are 9.55% and 15.22%, respectively. The plate not only receives the spillover relationship of other plates, but also issues the relationship to other plates. The number of relationships outside the plate is much greater than that inside the plate. The third plate has obvious net overflow characteristics. The fourth sector mainly contains Central Africa, Malaysia, Guinea, South Korea, and other countries or regions. The actual relationship ratio within the plate is 10.80%, higher than the expected ratio of 8.70%, and the spillover effect of the plate is limited. The number of relationships received from other plates is much higher than the number of relationships issued by them, which belongs to the main beneficiary plate. More embodied carbon spillovers from other plates are received in the network (Table 3).

To further investigate the embodied carbon transfer relationship between the plates, the density matrices of four plates are calculated and their image matrices are summarized. The element values of the image matrix are 0 and 1. When the density matrix of the plate is greater than the overall network density, the corresponding position in the image matrix is 1; otherwise, it is 0 (Table 4). From the perspective of the degree of spillover plate, the main beneficiary plate of the fourth plate has a certain spillover effect on itself, the first plate (broker plate), and the second plate (two-way spillover plate); and the two-way spillover plate of the second plate is mainly subject to spillover from the first plate (broker plate), itself, and the fourth plate (main beneficiary plate). In addition, the first plate has a significant effect of embodied net carbon spillover of agricultural trade on the second plate. From the perspective of the self-reflexive relationship, the diagonal position of the second plate (two-way spillover plate) and the fourth plate (main beneficiary plate) in the matrix is 1, indicating that the two plates have a high degree of reflexivity and obvious internal clustering characteristics.

## Discussion

Based on this paper's research, the following insights are obtained. In the process of global agricultural trade, the USA, Australia, China, Malaysia, and Central Africa, which are typical agricultural countries, have long been in an unbalanced state of embodied carbon outflow and inflow. The core nodes in global agricultural net embodied carbon network are mainly concentrated in Central Africa (Fig. 1), Serbia, the Netherlands, Singapore, Malaysia, the USA, China, India, Brazil, and other countries. These countries, as the core of agricultural trade, have spatial heterogeneity in the relationship between net carbon transfer and its inflow and outflow. From a global perspective, the embodied carbon emissions in agricultural trade need to be planned scientifically and cooperated globally to reduce the embodied carbon emissions.

The global agricultural trade has typical small world characteristics. In the global agricultural trade process, the major spillovers, including the USA, Australia, and China, need

**Table 3** Spillover effect of relevant plates in global agricultural trade in 2016

| | Plate I | Plate II | Plate III | Plate IV |
|---|---|---|---|---|
| Members | AFG; ALB; DZA; AND; AGO; ATG; ARG; ARM; ABW; MWI; ERI; AZE; BHS; BHR; BGD; BRB; BLR; BLZ; BEN; BMU; BTN; BOL; BIH; BWA; BRA; VGB; BRN; BFA; BDI; CMR; CPV; CYM; MCO; NCL; NGA; PSE; TCD; CHL; COL; COG; HRV; CYP; PRK; COD; DJI; DOM; ECU; SLV; FJI; FRA; PYF; GAB; GMB; GEO; JPN; MDV; NPL; PAN; PRT; SMR; SRB; SLE; SVK; SOM; ZWE; GRL; HTI; HND; ISL; IRN; IRQ; IRL; ISR; JAM; KAZ; KEN; KWT; KGZ; LAO; LSO; LBR; MDG; MLI; NAM; OMN; MDA; WSM; SUR; SWZ; TJK; TGO; TKM; TZA; URY; UZB; LIE; LTU; LUX; MLT; MRT; MUS; MNG; MNE; MAR; MOZ; NCL; NIC; NER; PNG; PRY; PHL; QAT; RWA; STP; SAU; SEN; SYC; SVN; SDS; SUD; MKD; TGO; TUN; UGA; UKR; ARE; GBR; VUT; VNM; YEM | AUT; BGR; CZE; ETH; JOR; LBN; SYR; TJK | AUS; BEL; KHM; CAN; CHN; CRI; CIV; DNK; EGY; FIN; DEU; GHA; GRC; GTM; HUN; IND; IDN; ITA; LVA; MMR; PAK; POL; RUS; ESP; LKA; SWE; THA; TUR; USA | CAF; EST; GIN; GUY; LBY; MYS; MEX; NLD; ANT; NOR; PHL; KOR; ROU; SGP; ZAF; CHE; VEN |
| Issued inside the plate | 5 | 3 | 64 | 89 |
| Issued outside the plate | 84 | 115 | 565 | 26 |
| Received inside the plate | 5 | 3 | 64 | 89 |
| Received outside the plate | 32 | 9 | 41 | 709 |
| Ratio of expected internal relationships | 70.65% | 3.80% | 15.22% | 8.70% |
| Ratio of actual internal relationships | 4.13% | 7.36% | 9.55% | 10.80% |
| Types of plate | Broker plate | Two-way spillover plate | Main overflow plate | Main beneficiary plate |

**Table 4** Density and image matrices of transfer network in global agricultural trade in 2016

| Plate | Density matrix | | | | Average network density | Image matrix | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Plate I | Plate II | Plate III | Plate IV | | Plate I | Plate II | Plate III | Plate IV |
| Plate I | 0.006 | 0.031 | 0 | 0.008 | 0.026 | 0 | 1 | 0 | 0 |
| Plate II | 0.008 | 0.059 | 0 | 0.001 | | 0 | 1 | 0 | 0 |
| Plate III | 0 | 0 | 0 | 0 | | 0 | 0 | 0 | 0 |
| Plate IV | 0.148 | 0.372 | 0 | 0.058 | | 1 | 1 | 0 | 1 |

to pay more attention and take responsibility for the hidden carbon emissions. Besides, the two-way spillover plate should exploit the potential of energy saving and emission reduction to reduce the embodied carbon emissions at source (Irfan et al. 2022). The plate should serve as a key hub and influence plate in agricultural trade, which is conducive to the overall emission reduction of global agricultural trade, while promoting more countries or regions to implement green and low-carbon production pattern. The USA, China, Australia, Vietnam, and Indonesia play an active role in the embodied net carbon transfer of agricultural trade, which has a major impact on other countries. In addition, Malaysia, Central Africa, Singapore, Serbia, and the Netherlands, these countries are more affected by other countries in the carbon transfer process embodied in agricultural trade.

Central Africa, Serbia, Guinea, Romania, and Portugal have low independence in receiving specific net carbon inflows, strong restrictions from other countries or regions, and weak influence on other countries. Cambodia, the Netherlands, Vietnam, Ghana, and South Africa have a strong influence and bridge role in spatial correlation, and have a strong ability to control the spatial correlation of other countries. For different countries or regions in agricultural trade, we should start from the two levels of inflow and outflow. Specifically, when cooperating with other countries or regions, priority can be given to the countries or regions with their embodied net carbon inflow relationship, trading partners can be selected that are conducive to the green development of their agriculture, and the further expansion of embodied carbon in trade can be increased. When it comes to the embodied carbon emission of agricultural products, it is necessary to increase the export proportion of value-added products and reduce the carbon content of export products.

## Conclusions

This paper constructs the embodied carbon transfer network of global agricultural trade in 185 countries in 2016, comprehensively measures the status and role of the embodied carbon transfer of global agricultural trade, as well as the characteristics of the pattern of global embodied carbon inflow and outflow, identifies the plates of different countries based on the block model, and reveals the roles and functions of different plates. The main research conclusions of this paper are as follows.

Firstly, from the perspective of the embodied carbon transfer outflow end of global agricultural products, the top four countries with the largest embodied carbon transfer outflow of agricultural products in 2016 were the USA, Australia, Vietnam, and China. From the perspective of the embodied carbon transfer inflow end of global agricultural trade, the top four countries with the largest embodied carbon transfer inflow of agricultural products in 2016 were Malaysia, Central Africa, Singapore, and Serbia.

Secondly, from the perspective of the characteristics of the embodied carbon transfer network of global agricultural products trade, the spatial spillover characteristics of the net transfer network are obvious, the core edge characteristics of global agricultural products trade are clear, the connections of the embodied net carbon transfer network of global agricultural products are dense, and the number of network relationships reaches 17,700. The embodied carbon transfer of global agricultural products trade has obvious spatial correlation characteristics. Moreover, the relevance of the embodied carbon network of global agricultural trade is 1, which shows that the global agricultural trade transfer network has good accessibility and obvious spatial spillover effect. The network density is 0.496, and the links between nodes are close, indicating that with the economic development, the links between various countries or regions gradually tend to be close, resulting in more frequent transfer of agricultural trade.

Thirdly, from the perspective of outdegree centrality, the USA, China, Australia, Vietnam, and Indonesia are in an active position in the embodied net carbon transfer of agricultural trade, which has a major impact on other countries. From the perspective of indegree centrality, Malaysia, Central Africa, Singapore, Serbia, and the Netherlands are more influenced by other countries in the embodied carbon transfer in agricultural trade. What is more, in terms of proximity centrality, the average embodied net carbon transfer path of other countries or regions to Nigeria, Niger, UAE, Argentina, and Guatemala is longer. In terms of intermediary centrality, Cambodia, the Netherlands, Vietnam, Ghana, and South Africa have a strong influence and bridge role in spatial correlation. These countries or regions are in the central position in the spatial correlation network of embodied net carbon transfer in global agricultural trade and have strong control over the spatial correlation of other countries or regions.

Fourthly, from the block model results, the embodied carbon transfer network of global agricultural trade can be divided into four plates: net spillover, two-way spillover, broker, and main beneficiary. The main spillover plate is the main carbon emission plate of the global agricultural trade transfer network, which mainly includes the USA, India, Germany, China, etc. Besides, these countries play an important role in the supply of labor and energy resources in the global agricultural production network, and have a significant embodied carbon spillover effect on other plates within the plate. Furthermore, the main beneficiary plate mainly contains Central Africa, Malaysia, the Netherlands, Singapore, etc. These plates mainly produce highly polluting agricultural products, receive more embodied carbon spillover from other plates, and play the main beneficiary characteristics of the embodied net carbon transfer network in the global trade.

Last but not least, the USA, China, Australia, Indonesia, and other major agricultural countries should actively improve the export structure of agricultural products and effectively change the mode of agricultural development. Efforts should be made to optimize the export structure of agricultural products, strengthen the export of green and low-carbon agricultural products, appropriately limit the export of agricultural products with high carbon intensity, and increase the import of intermediate products with high energy consumption for agricultural production input (Irfan et al. 2021b). Relying on the upgrading of the export structure of agricultural products to promote the upgrading of agricultural industrial structure, and realize the low-carbon development of agriculture. Countries should reasonably allocate the responsibility of carbon reduction according to the trading embodied carbon transfer. Additionally, countries should promote technological innovation in agriculture and intensify research and development of low-carbon energy (Irfan et al. 2021c; Irfan et al. 2021d). In the process of promoting modern agriculture, on the basis of the development of ecological agriculture, organic agriculture, and circular agriculture, the application of low-carbon agricultural technology should be actively promoted. However, due to the complexity of multi-regional input–output database construction, the latest data of Eora database is only updated to 2016, so subsequent scholars can continue to track and update relative research.

**Supplementary Information** The online version contains supplementary material available at https://doi.org/10.1007/s11356-022-22337-w.

**Acknowledgements** We are grateful for anonymous reviewers for the helpful comments.

**Author contribution** Fan Zhang: conceptualization, methodology, formal analysis. Qinyang Guo: writing—original draft, writing—review and editing. Xinsheng Zhou: formal analysis, writing—original draft. Guofeng Wang: software, visualization, writing—review and editing.

**Funding** This research was funded by the National Natural Science Foundation of China, grant numbers 72003111 and 71903117.

**Data availability** Provided according to the needs of the applicant.

## Declarations

**Ethics approval** The authors approve principles of ethical and professional conduct.

**Consent to participate** The authors consent to participate in the preparation of this article.

**Consent for publication** The authors consent to publish this article in *Environmental Science and Pollution Research*.

**Competing interests** The authors declare no competing interests.

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