Land Use Policy 125 (2023) 106464

Contents lists available at ScienceDirect

Land Use Policy

journal homepage: www.elsevier.com/locate/landusepol

Tele-connection of global agricultural land network: Incorporating complex network approach with multi-regional input-output analysis

Mengyao Cheng [a], Jialu Wu [a], Chaohui Li [c], Yuanxin Jia [a], Xiaohua Xia [a,b,*]

[a] School of Applied Economics, Renmin University of China, Beijing 100872, China
[b] Institute of China's Economic Reform and Development, Renmin University of China, Beijing 100872, China
[c] Laboratory of Systems Ecology and Sustainability Science, College of Engineering, Peking University, Beijing 100871, China

ARTICLE INFO

Keywords:
Embodied agricultural land use
System input-output analysis
Complex network approach
Tele-connections

ABSTRACT

The geographical distribution imbalance of global agricultural land has been reduced as a result of increasing globalization, which accelerates land redistribution through global supply networks. In turn, interregional trade extends the control of land resources beyond of local borders. However, the specific structural features of agricultural land flow patterns embodied in international trade remain unclear from the perspective of a complex network. In this paper, we integrate multi-regional input-output model and complex network theory to reveal the structural characteristics of the global embodied land flow network (GELFN) in multiple dimensions. Globally, GELFN exhibits small-world nature, indicating that embodied land transfer interconnects economies at a high level. Regionally, GELFN has a basic community structure of seven groups, and economies in the same regional economic cooperation organizations, such as NAFTA, EU and AU, are more likely to cluster in the same community, implying that GELFN embodies the characteristics of multi-polarization and intra-region aggregation. Nationally, by introducing resource endowments and network-based measurements, we classify seven groups of key economies ('connection clusters') to identify different land use patterns. Moreover, the core-periphery structure of GELFN confirms that a few economies act as hubs associated with a large amount of land transfer. The results emphasize the importance of multi-regional cooperation on global agricultural land management and well-targeted policies in key economies and sectors.

1. Introduction

Land is one of the most basic resources needed for human survival and economic development. 35.4% of the global total land area is used for agricultural production (OECD, 2015). The rapid growth of population has brought surging food demand in the past few decades, while urbanization and industrialization have led to large scale land encroachment, soil erosion, and soil degradation. The fierce competition between land use and global food demand is one of the most daunting challenges human faces in the 21st century. As the scarcity of land resources continue to increase, conflict in demand for land resources will not only arise from different productive sectors, i.e., livestock, cropland use, urban sprawl, etc., but will also arise in regional competition. While land is constrained within a geographical scope, the use of such land resource is able to re-allocate to other regions through the trade of land-use intensive goods and services. Improving the utilization efficiency of agricultural land resources through rational allocation under the condition of scarce land resources and unbalanced geographical distribution is therefore an important topic of sustainable development research (Chen and Wu, 2020), and strengthening trans-regional resource management on a global scale (Voss et al., 2013) has become a hot issue of academic and political attention.

With the in-depth development of globalization and industrialization, the nature of a highly integrated global economy has become more evident. The economic activities of regions are increasingly connected to one another, a phenomenon widely known as "teleconnections". This concept of "teleconnections" is highly valued in explaining how consumption in one region affects other remote regions (Friis et al., 2016). Many past studies have shown that resources are transferred between economies in large quantities through trans-regional trade of goods and commodities (Han et al., 2018; Chen et al., 2021). For the analysis of the global economic system, the multi-regional input-output model (MRIO) has been widely used to capture the embodied resource or emission flows within and between economies, so that the cumulative effect of

* Corresponding author at: School of Applied Economics, Renmin University of China, Beijing 100872, China.
E-mail addresses: chengmengyao@ruc.edu.cn (M. Cheng), xiaxh.email@gmail.com (X. Xia).

https://doi.org/10.1016/j.landusepol.2022.106464
Received 21 May 2022; Received in revised form 7 November 2022; Accepted 16 November 2022
Available online 30 November 2022
0264-8377/

environmental burden upstream in global supply chains can be effectively analyzed. Various resource and pollutions embodied in trade have been well-documented through MRIO analysis, such as energy consumption (Zhang et al., 2016; Xia et al., 2017; Wu and Chen, 2018), greenhouse gas emissions (Peters et al., 2012; Li et al., 2018; Han et al., 2020), water use (Lenzen et al., 2013a; Wu et al., 2019), including land use (Han et al., 2019; Ji et al., 2020a). The concurring conclusion of the above studies indicates that both producers and consumers of resources or emissions are responsible for the allocation of resource consumption and environmental degradation arising from trade activities. In view of this, MRIO presents a valid method to capture the flow of agricultural land reflected in production and consumption activities along with the flow of global supply chains from a perspective of embodiment in order to rationally allocate land resources and equally distribute the responsibility of resource consumption and environmental degradation.

In terms of land resources, the sum of direct and indirect land resources used to produce a certain product or service is defined as embodied land (Chen and Han, 2015; Han and Chen, 2018). Existing research focused more on measuring the allocation of embodied land among economies and used by different sectors. Specific in-depth analysis is made for different types of land resources, such as arable land (Han and Chen, 2018; Ji et al., 2020b), pastureland (Guo et al., 2019; Li et al., 2021), built-up land (Guo et al., 2020; Chuai et al., 2021), agricultural land (Wu et al., 2018; Chen et al., 2018a; b; Han and Li, 2021). As the contradiction between a region's economic development and resource constraints or environmental sustainability becomes more prominent and the relationship becomes closer, the calculation of land embodiment at different scales (global, national, regional and urban) has also been taken into account (Rulli et al., 2013; Guo et al., 2016; Han et al., 2019).

The above studies provide valuable insights into understanding the tripartite relationship between intermediate producers, final producers, and final consumers. However, the current economic system is too fragmented that global economic activities could not be fully captured by this simplified model. The present circumstance is more similar to a flow of an interconnected network that is made up of multitudinous economic agents. Given this, the combination of embodied land transfer network with international trade network based on complex network theory presents a strong and effective measure to study the complex intertwining relationship among numerous global economic agents. Complex network analysis is an effective tool to reflect the characteristics of global economic network based on a series of specific indicators, which can supplement and summarize the traditional multi-regional input-output analysis method. The structural characteristics of the land flow network are deeply revealed from the perspective of network topology in a comprehensive global dimension, which is of great significance to better detect and regulate the global land transfer and put forward policy suggestions. Among a range of indicators, degree and strength analysis helps to identify economies in the network with a large number of land transfer partners and a large volume of land inflow or outflows; Centrality analysis measures the direct and indirect influence of a particular economy on other economies in the network; Community detection divides economies with high correlation into the same community through a measure of modularity density. The analysis of these indicators is of great significance for the implementation of cross-regional land management cooperation (Liu et al., 2021). Previous studies have used complex network theory to analyze global embodied flows of natural resources, such as CO_2 emissions (Kagawa et al., 2015; Li et al., 2020; López et al., 2020), CH_4 emissions (Zhao et al., 2020; Liu et al., 2021), mercury emissions (Chen et al., 2019), air pollutants from oil refining (Wu et al., 2022), etc. However, it is worth noting that a comprehensive analysis of land transfer network embodied in global supply chains from the perspective of complex network is still lacking.

In order to fill this gap, this study aims to conduct an analysis of MRIO through complex network theory, so as to summarize and reveal the structural characteristics of global embodied land transfer network in a more comprehensive and in-depth way. Through the calculation and analysis of complex network indicators, we identify the key economies, key sectors and key paths in the network from multiple dimensions. By means of multi-method cluster analysis, we are able to identify differences in the roles and importance of economies in the network by combining agricultural land resource endowments and direct agricultural land use. These conclusions are of great help to propose effective policies targeted at key economies and sectors to strengthen trans-regional cooperation in global land management, so as to alleviate land shortage in some areas, improve the utilization efficiency of global land resources, and contribute to sustainable land use.

2. Methods and data

2.1. System MRIO model

For the analysis of resource flows in the global economy, MRIO model is adopted, which incorporates both direct resource flows and monetary flows. The original design was created by Leontief in the 1930 s, and IOA was extended by incorporating pollution emissions into the conventional model later in 1970 s (Leontief, 1970). On the basis of embodiment theory in systems ecology, we assume that the global economy comprises m economies, with n sectors and k kinds of final demand in each economy. c_{ij}^{st} is the monetary value of goods or services as intermediate inputs imported from Sector i in Economy s to Sector j in Economy t. f_{il}^{st} represents the monetary value of goods or services as final demand l imported from Sector i in Economy s to Economy t, which is an end-point of the global supply chains of goods or services. Meanwhile, d_i^s stands for the direct land exploitation of Sector i in Economy s, representing the volume of resources entering from the natural ecological system into the economic system. The total output of Sector *i* in Economy *s* is represented as x_i^s.

Eq. (1) can be used to express the monetary input-output balance:

$$x_i^s = \sum_{t=1}^{m}\sum_{j=1}^{n} c_{ij}^{st} + \sum_{t=1}^{m}\sum_{l=1}^{k} f_{il}^{st} \tag{1}$$

Biophysical input-output balance can be calculated as follows:

$$d_i^s + \sum_{t=1}^{m}\sum_{j=1}^{n} \varepsilon_j^t c_{ji}^{ts} = \varepsilon_i^s x_i^s \tag{2}$$

Where ε_i^s is defined as the embodied land use intensity of goods or services measured by Sector *i* in Economy *s*, representing the total (direct and indirect) agricultural land for producing one unit of goods or services, including exogenous input from natural ecological system for direct land use and endogenous feedback generated by the economic system itself for indirect land use.

Eq. (2) can be rewritten as follows by introducing the matrix:

$$\mathbf{D} + \mathbf{EC} = \mathbf{E}\widehat{\mathbf{X}} \tag{3}$$

Therefore, on account of the condition matrix $(\widehat{\mathbf{X}} - \mathbf{C})^{-1}$ is invertible, the embodied land intensity matrix can be calculated by:

$$\mathbf{E} = \mathbf{D}(\widehat{\mathbf{X}} - \mathbf{C})^{-1} \tag{4}$$

Therefore, in the global complex network, the agricultural land embodied in trade flows from Economy *s* to Economy *t* can be acquired through:

$$q^{st} = \sum_{i=1}^{n}\left(\sum_{j=1}^{n}\left(\varepsilon_i^s c_{ij}^{st}\right) + \sum_{l=1}^{k}\left(\varepsilon_i^s f_{il}^{st}\right)\right) \tag{5}$$

Agricultural land embodied in exports (LEE) of Economy *s* is equal to the amount of land transferred from Economy *s* to meet the intermediate use and final consumption of all other economies in global supply chains, as derived as:

$$LEE^S = \sum_{i=1}^{n}\sum_{t=1(t\neq s)}^{m}\left(\sum_{j=1}^{n}\left(\varepsilon_i^s c_{ij}^{st}\right) + \sum_{l=1}^{k}\left(\varepsilon_i^s f_{il}^{st}\right)\right) \quad (6)$$

The total imported embodied land (LEI) of Economy s is equal to the amount of land transferred from all other economies in global supply chains driven by the intermediate use and final demand of Economy s, as expressed by:

$$LEI^S = \sum_{t=1(t\neq s)}^{m}\sum_{j=1}^{n}\left(\sum_{i=1}^{n}\left(\varepsilon_j^t c_{ji}^{ts}\right) + \sum_{l=1}^{k}\left(\varepsilon_j^t f_{ji}^{ts}\right)\right) \quad (7)$$

The embodied land net imports (LENI) of Economy s, denoting the balance of land transfer in international trade, is defined as below:

$$LENI^S = LEI^S - LEE^S \quad (8)$$

A positive LENI indicates that the Economy is a net importer, which expressed as a net land inflow. A negative LENI indicates that the Economy is a net exporter, which expressed as a net land outflow.

2.2. Complex network analysis

An embodied land trade relationship between economies can be visualized graphically through a collection of nodes and edges in a complex network system perspective. In the case of Global Embodied Land Flow Network (GELFN), it can be represented as a set $N = (E, F)$, in

Table 1
Parameters for GELFN analysis.

Category	Variable	Character	Calculation formula	Explanation
Small-world nature	Average clustering coefficient	Clustering coefficient is a measure of the possibility of connecting two nodes in the network. Average clustering coefficient is the average of all clustering coefficients, which is used to evaluate the clustering degree of nodes in the network (Holme et al., 2007).	$C_s = \frac{E_s}{m_s \times (m_s - 1)} C(k) = \frac{1}{n_k}\sum_{s=\{t\mid k_t=k\}} C_s$	m_s is the number of neighbors adjacent to node s, then $m_s \times (m_s - 1)$ represents all the possible connections between the m_s neighbors; E_s stands for the actual number of edges among m_s neighbors; $C(k)$ represents the average clustering coefficient over the n_k nodes.
	Average path length	The average number of steps in the shortest paths of all possible pairs of nodes in the network (Brandes, 2001).	$L = \frac{1}{n(n-1)}\sum_{t=1}^{n}\sum_{s=1}^{n} d_{st}(s \neq t)$	d_{st} is the shortest path between node s and r, in weighted network which is defined as: $d_{st} = \min\left(\frac{1}{q_{sr}} + \ldots + \frac{1}{q_{rt}}\right)$
	Small-world quotient	A network's small-world nature is testified by SWQ. SWQ is greater than 1, implying network presenting a small-world nature (Zhu et al., 2013).	$SWQ = \left[\frac{C_{actual}}{L_{actual}}\right] * \left[\frac{L_{random}}{C_{random}}\right]$	$C_{random} = \frac{\bar{k}}{n}$ and $L_{random} = \frac{\ln(n)}{\ln\bar{k}}$ are the average clustering coefficient and characteristic path length of random network with the same number of economies n and average degree k as GELFN, respectively.
Degree analysis	In-degree	A specific node's in-degree refers to the number of total inflows from nodes that are connected to it (Vespignani et al., 2004).	$k_s^{in} = \sum_{t=1(t\neq s)}^{n} a_{ts}$	
	Out-degree	A specific node's out-degree refers to the number of total outflows from nodes that are connected to it.	$k_s^{out} = \sum_{t=1(t\neq s)}^{n} a_{st}$	
Strength analysis	In-strength	In-strength is the volume of inflows from one node within the network and represents its impact power (Vespignani et al., 2004).	$S_s^{in} = \sum_{t=1(t\neq s)}^{n} w_{ts}$	
	Out-strength	Out-strength indicates the volume of outflows of one node in the network.	$S_s^{out} = \sum_{t=1(t\neq s)}^{n} w_{st}$	
Core-periphery structure	Core degree	Core-periphery structure is usually defined as a closely connected and cohesive core and a sparsely connected and disconnected periphery. Core degree investigates the degree of proximity between economies and the core in GELFN (Borgatti and Everett, 1999).	$\rho_c = \sum_{s,t} A_{st} C_{s,t} C_{st} = \left\{\begin{array}{c} 1, if C_s = C_t = 1 \\ a \in [0,1], if C_s = 1 or C_t = 1 \\ 0, otherwise \end{array}\right\}$	$C_{st} = C_s \times C_t = a$The adjacency-matrix element A_{st} represents the weight of flows between nodes s and t.
Centrality analysis	Degree centrality	Degree centrality is defined as the number of nodes directly connected to a specific node, including links relating to inflows and outflows. Degree centrality reflects the extensive external contacts of a node in the network.	$k_s = k_s^{in} + k_s^{out}$	
	Betweenness centrality	A node's betweenness centrality indicates the degree to which it acts as an intermediary in the network, which reflects its regulatory role in GELFN (Opsahl et al., 2010).	$b_a = \sum_s\sum_t \frac{g_{sat}}{g_{st}}$	b_a is the betweenness centrality of node a, g_{st} is the number of shortest paths between node s and t, and g_{sat} represents the number of shortest paths that pass through node a.
	Closeness centrality	Closeness centrality is a measure of the average weighted distance between a node and other nodes in the network, which indicates how central the node is within the network (Freeman, 1978).	$CC_s = \frac{n-1}{\sum_t w_{st}}$	
Community detection	Modularity	A measure of modularity is the density within communities as compared to intercommunity links, which is based on the community partition introduced by Newman and Girvan (Blondel et al., n.d.).	$Q = \frac{1}{2m}\sum_{s,t}\left[q_{s,t} - \frac{h_s h_t}{2m}\right]\delta(c_s, c_t)$	$q_{s,t}$ is the weight of the edge from node s to t; $h_s = \sum_t q_{s,t}$ is the sum of weights of edges attached to node s; c_s is the community in which node s is assigned; the $\delta(c_s, c_t)$ is 1 if $c_s = c_t$ and 0 otherwise and $m = \frac{1}{2}\sum_{s,t} q_{s,t}$
	Core community	Clustering coefficients, correlation density coefficients, diffusion coefficients, and adhesion coefficients provide an understanding of a community's core structure (He et al., 2017).	$H_{G_i} = \alpha CSC(G_i) + \beta CSD(G_i) + \gamma CST(G_i) + \delta CSL(G_i)$	H_{G_i} is the core community structure coefficient, $H_{(G)\max}$ is the core community.

which the network nodes set $E = \{e_1, e_2 \ldots e_n\}$ represent economies, and embodied land flows set F donate the network edges:

$$F = \{f_{st}\} = \{q^{st} \times a^{st}\} where a_{st} = \left\{ \begin{array}{c} 1 if q^{st} > 0 \\ 0 otherwise \end{array} \right\} \tag{9}$$

which the weight of edges has been taken into consideration, representing the trade relationships between economies. f_{st} denotes embodied land flows in exports from economy e_s to e_t. To describe the global embodied land flows, a directed weighted network is constructed using the network above. Therefore, we modify a complete network with 188 nodes and 35344 edges. Considering the amount of embodied land flows between some economies are too small, GELFN was streamlined to include 30,500 edges. A series of parameters are used to describe the characteristics and laws of current embodied land flow system. The definitions and accounting methods of each indicator in detail are demonstrated in Table 1. Ultimately, this paper explores small-world nature, degree, strength, centrality, community and the core-periphery model to provide a synthesis of land connections in global economy system systematically and dynamically from multiple dimensions and perspectives.

2.3. Cluster analysis

To identify the pattern of global embodied land transfer, our study utilizes an agglomerative hierarchical cluster analysis (Ward's cluster) (Ward et al., 2016) to recognize 'connection clusters' to classify 188 economies. Our clustering technique utilizes six variables, which can be used to identify the different groups of economies that display similar characteristics of tele-connected embodied land use: (1) embodied land imports, (2) embodied land exports, (3) embodied land net-imports, (4) embodied land competitive advantage index, (5) land stress index, (6) direct agricultural land use.

2.3.1. Embodied land competitive advantage index

Resource Allocation Process (RAP) approach indicates the limited amount of resources that participant nodes can obtain from target nodes, so that the complete target subgraph obtained through projection can clearly show the competition relations between participants (Xing et al., 2018). By introducing RAP method in this paper, resources are allocated to each participant and object in the network, with w_{st}^P representing the proportion of resources distributed to the participant t through the object from the participant s, also representing the competitive strength of economies s against t, while w_{ts}^P is that of the opposite. Thus, the total of competitive strengths (w_{st}^P) can be defined as Competitive Advantage Index (CAI) of an economy. Corresponding to complex network theory, CAI equals to out-strength of nodes in GELFN, which can be expressed as followed:

$$CAI(s) = S_s^{out} = \sum_{t=1}^{N} w_{st}^P \tag{10}$$

2.3.2. Land stress index

Water pressure is generally defined as the ratio between total annual freshwater withdrawal and hydrological availability. Pfister et al. (2009) proposed a concept of Water Stress Index (WSI), ranging from 0 (no pressure) to 1 (maximum pressure) to measure water stress. Similar to WSI, Land Stress Index (LSI) has been advanced (Liu et al., 2018a; b) to reveal the impact of land occupation and quantitatively evaluate land pressure in each region. The scarcity of a resource or factor in the market can be measured by the ratio of supply and demand. In case of land demand data cannot be obtained directly, other indicators are used instead. In this paper, LSI refers to the land pressure caused by the occupation of land for agricultural and construction activities in each region. Agricultural land includes arable, pasture, and other agricultural land, while construction land is used for residential, industrial, mining, transportation, and water conservancy facilities. LSI can be expressed as:

$$LSI_i = \frac{L_i^A + L_i^C}{L_i^T} \tag{11}$$

where LSI_i is the land stress index of region i, L_i^A is the agricultural land in region i, L_i^C is the construction land of region i, L_i^T is the total area of region i. Table 2 shows the classification of land stress index in different grades.

2.4. Data sources

For the calculation of global agricultural land embodiment, monetary MRIO table for the year of 2015 is collected from Eora Global MRIO database (current version: v199.82) (Lenzen et al., 2012, 2013b), which contains 190 economies with 26 sectors and 6 final-demand coupled systems. We choose the Eora database due to its relatively high resolution of economies (190 economies) and the coverage of most recent data (up to 2015), compared with other MRIO databases. There are significant differences between several major MRIO databases, and for comprehensive discussion of comparisons based on source data and results in detail, see Steen-Olsen et al. (2016).

Regional agricultural land exploitation is directly derived from Food and Agriculture Organization (FAO) (FAO, 2015), while agricultural land and construction land data can be approximated from land cover data in the Organization for Economic Co-operation and Development (OECD) (OECD, 2015). Statistically, agricultural land exploitation is assigned into Sector 1 (Agriculture). The reference year 2015 is chosen as the Eora Global MRIO database has updated to 2015, though the newest data available for the agricultural land exploitation is the year of 2019.

3. Results

3.1. Agricultural land embodied in interregional trade

Economies play different roles in global supply chains at the same time, not only as suppliers of agricultural land to provide intermediate inputs to downstream producers, but also as consumers to meet their own final demand. In terms of final demand, China is the largest consumer, followed by the United States, Brazil, Russia and Australia. The top 5 economies account for 38.43% of the global embodied agricultural land for final demand. In terms of total agricultural direct land use in 2015, the top 5 economies are China, the United States, Australia, Brazil and Kazakhstan, accounting for 32.97% of the total agricultural direct land (DL) in the world. While in terms of total arable land resources, the top 5 economies with the largest area are the United States, India, China, Russia and Brazil. These economies mainly serve as suppliers of agricultural land, using original agricultural land resources to provide products or services related to agriculture, so as to meet the demand of global economies for land resources. Fig. 1 reflects the difference between agricultural land use embodied in final demand (LEF) and total direct agricultural land use (DL), as well as the total arable land resources for 188 economies in 2015. LEF are the agricultural land needed for final demand, while DL are the actual agricultural land exploitation

Table 2
Land Stress Level.

Land Stress Index	Level
No stress	< 0.20
Slight stress	0.20–0.40
Moderate	0.40–0.60
Severe	0.60 – 0.80
Extreme	> 0.80

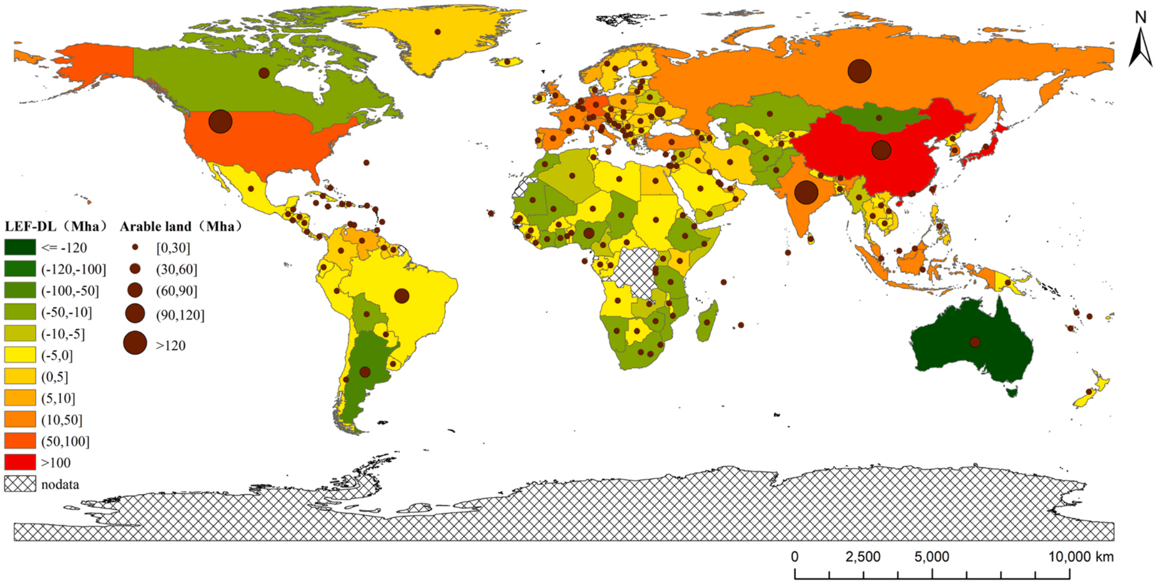

Fig. 1. Difference between land use embodied in final demand (LEF) and DL.

of an economy. The difference between the two reflects whether an economy can meet its final demand through its own agricultural land use, and to some extent, reflects whether an economy needs to conduct global trade of agricultural land in order to meet its final demand. Due to the uneven geographical distribution of agricultural land supply and demand, the imbalance between LEF and DL is transferred through the inter-regional trade of agricultural land. To some extent, the difference reflects the value of the net export or import of agricultural land for an economy to meet its final needs. Among of 188 economies, 95 economies show deficits in the use of agricultural land, with Japan, China, Germany, the United States and Russia showing the largest deficits. While 93 economies have surpluses, led by Australia, Mongolia, Argentina, Madagascar, Ethiopia and Ethiopia.

Fig. 2 reflects the difference between per capita agricultural land use embodied in final demand (LEF) and total direct agricultural land use (DL) per capita, as well as the total arable land resources per capita for 188 economies in 2015. In per capita terms, the overall picture has changed dramatically. The top 5 economies with the largest per capita DL are Mongolia, Australia, Namibia, Kazakhstan and Botswana. The largest areas of arable land per capita are Australia, Kazakhstan, Canada, Argentina and Russia. The top 5 economies with largest LEF per capita are SAN Marino, Mongolia, Botswana, Kazakhstan and Australia. From the perspective of per capita LEF and per capita DL, 95 economies show a deficit of per capita agricultural land use, with SAN Marino, Hong Kong, Guyana, Monaco and Bermuda experiencing the largest deficits. 93 economies have surpluses in agricultural land use per head, led by Mongolia, Namibia, Australia, Mauritania and Iceland. Comparing the statistics of total volume and per capita, it is worth noting that Mongolia and Australia, the two economies with the largest total surpluses, also show high surpluses in per capita use, which the ranking may change but remain high.

Fig. 3 shows the imports, exports and net imports of embodied agricultural land of 188 economies. Among them, 99 economies have a surplus in embodied land imports, while another 89 economies suffer a deficit. The largest net embodied land exporters are Australia, followed by Mongolia, Argentina, Madagascar and Ethiopia, while the top 5 net

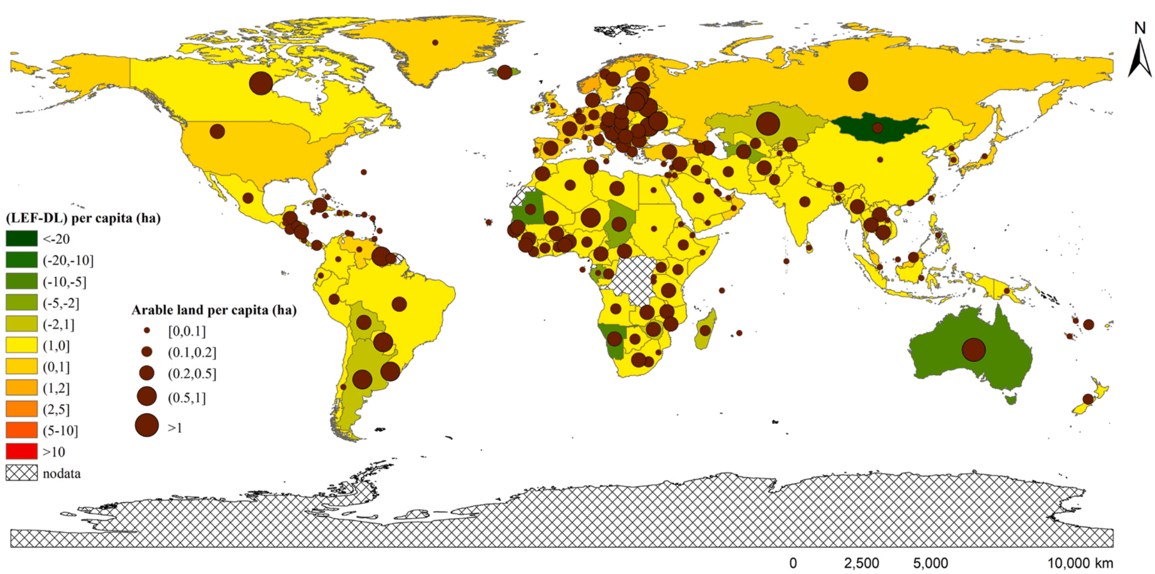

Fig. 2. Difference between land use embodied in final demand (LEF) per capita and DL per capita.

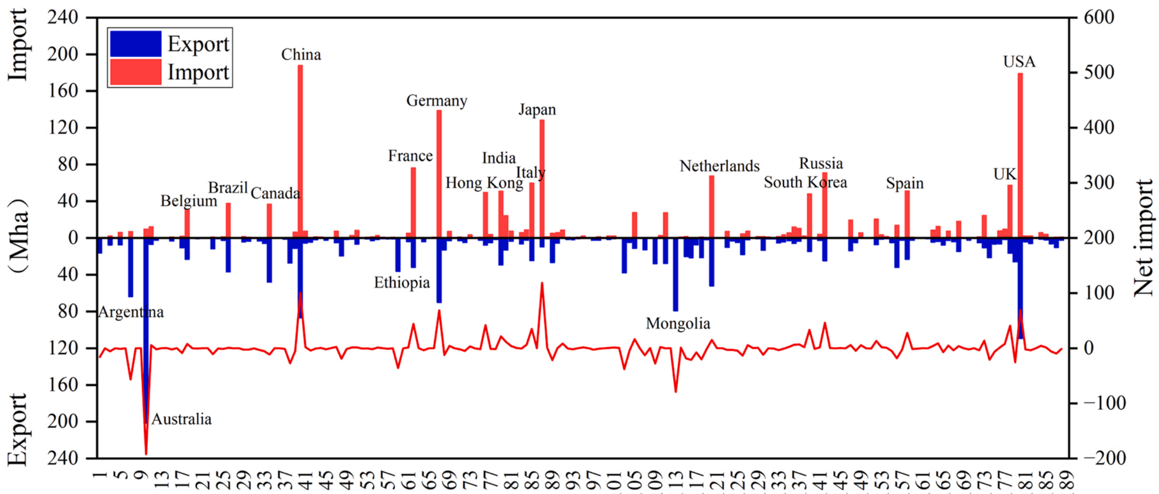

Fig. 3. Imports, exports and net imports of embodied agricultural land.

embodied land importers are Japan, China, Germany, the United States and Russia. As a whole, the United States, China and Germany occupy the leading position in the import and export of embodied agricultural land resources, which indicates that these economies are at the center of trade activities with rich inflow and outflow of agricultural land resources.

3.2. Complex network analysis

3.2.1. Structural characteristics of GELFN

A small-world network is one in which the majority of nodes are not neighbors, but it takes only a few steps to connect any two randomly selected nodes, which is demonstrated mathematically by a high average clustering coefficient and a short characteristic path length. The clustering coefficient of GELFN is calculated to be 0.88, indicating that almost all of the neighbors of a specific economy tend to have connections with each other, most economies are highly clustered among themselves. Analogous to social network, it takes 1.13 steps, i.e., the characteristic path length, in order for embodied land to move from one economy to another in GELFN, indicating that the network has good connectivity.

The small-world quotient is estimated to be 4.32 in GELFN, confirming GELFN presents a small-world nature. Accordingly, it confirms the existence of a close relationship between economies in terms of embodied land flows, and the impact on an economy may quickly spread to others, which is very fragile under some circumstances, providing an important opportunity for collaborative land management.

3.2.2. Key economies analysis

In GELFN constructed in this paper, every sector of each economy is interconnected to varying degrees and interdependent with other sectors of other economies, with direct or indirect connections. Globally, it is essential to capture these direct or indirect links among economies, providing a key to observe global embodied land flows using complex network theory. To measure the trade liquidity of each economy in GELFN, degree is used to analyze the number of nodes connected to the target node in the network. The higher the nodal degree, the more trade activities the economy has with other economies. Degree includes in-degree and out-degree, representing the number of import and export partners of each economy in the network.

Analogously, strength analysis focuses on the volume of embodied land transfer among various economies. By analyzing the weights of the edges connecting nodes in the network, we compare the trade shares of each economy in the international trading market of GELFN, and measure their competitiveness. Strength includes in-strength and out-strength, representing the quantity of import and export embodied land, also reflecting the influence of import and export industries of each economy.

Fig. 4 shows the cumulative probability distribution of the weighted degree and the strength of nodes in GEFLN, indicating the characteristics of a scale-free network. As shown in Fig. 4, the top 44 nodes (23%) account for 90% of the cumulative weighted in-degrees and the top 62 nodes (33%) account for 90% of the cumulative weighted out-degree, while the top 44 nodes (22%) carry 90% of the cumulative in-strengths and the top 67 nodes (36%) carry 90% of the cumulative out-strengths, both indicating heterogeneity of the network. This means that a small number of key economies determine most of the land flow in GEFLN. If the nodes with large amounts of agricultural land change their trading activities, it can have a huge impact on the entire flow in GEFLN. Moreover, the cumulative distribution curves of the in-degree and in-strength are higher than that of the out-degree and out-strength, which indicates the key nodes in the import flow network play a more important role. As a result, consumer economies are more concentrated than producer economies in agricultural land transfer.

The combination of degree analysis and strength analysis identifies the key economies in GELFN. Fig. 5 shows the joint relationship of degree and strength analysis which helps to identify key nodes of GELFN. Regions with large amount of embodied land imports (with high in-strength, represented as consumer economies), i.e. the United States, China, Germany, Japan, etc., also tend to have a large weighted in-degree, indicating that the import source is very scattered; Specifically, the in-degree of China and the United States are far higher than other economies, indicating that China and the United States have a greater pulling effect on the embodiment of land use compared with others, and serve as the aggregation center of embodied land flows in GELFN. Regions with large amount of embodied land exports (with high out-strength, represented as producer economies): Australia, the United States, China, Mongolia, etc., meanwhile, these economies also have a large weighted out-degree, indicating that the export destination is relatively scattered. Among the economies mentioned above, the out-degree and out-strength of Australia is much higher than that of other economies, indicating that Australia has a greater restriction to reflect land use, and acts as the aggregation center of embodied land flows in GELFN. Economies with top 10 weighted in-strength account for 55% of the total embodied land imports, and the top 10 weighted out-strength economies account for 43% of the total embodied land exports, indicating that the consumption center of embodied land is more concentrated than the production center.

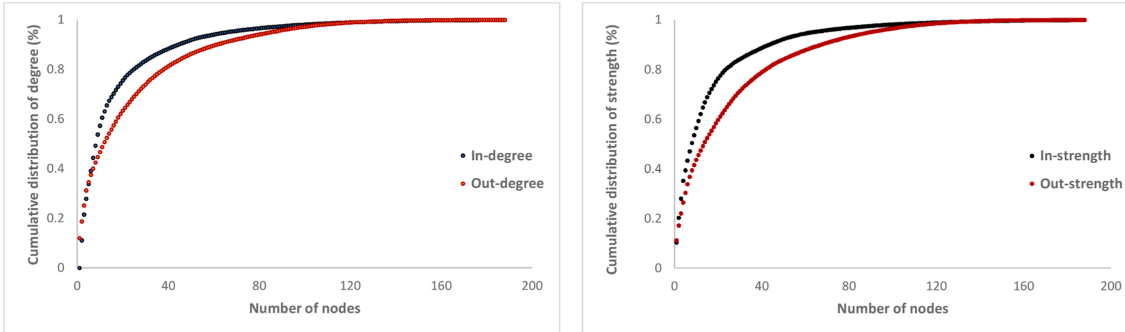

Fig. 4. The cumulative distribution of weighted degree and strength in GELFN.

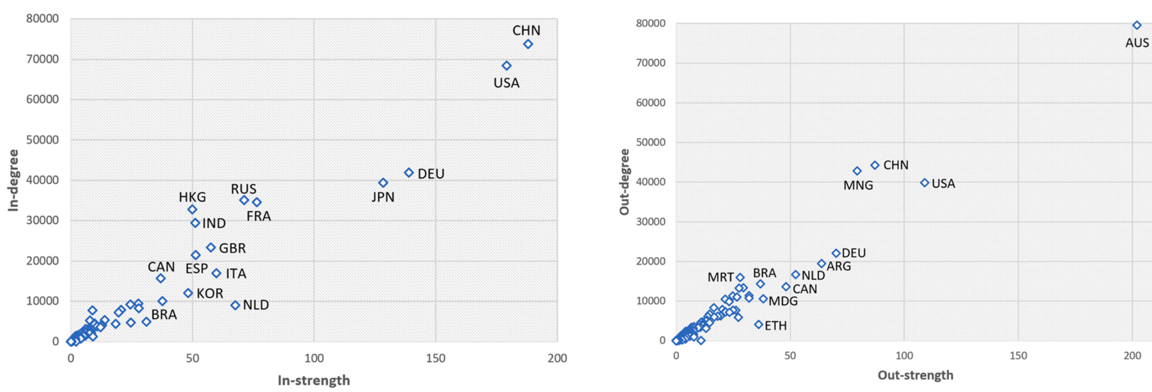

Fig. 5. Relationship between degree and strength analysis.

3.2.3. *Key path analysis*

In GELFN, a weighted edge indicates a high volume of flows between nodes. Edges with a higher weight carry more embodied land and have an increasing impact on global trading activities. The importance of identifying key edges with high weights therefore cannot be overstated. The cumulative distribution of the weighted edges of GELFN is shown in Fig. 6, with 0.45% of the flows accounting for 90% of total embodied land flows, showing that a small part of edges control most of the land flows. Probability distribution of weighted links indicates that GELFN is highly heterogeneous, in the way that a few links are disproportionally larger or stronger than the majority of links.

The embodied land flows across 188 economies including domestic transfers and excluding domestic transfers are shown in Fig. 7(a) and Fig. 7(b) respectively, in which the prominent color blocks show the main embodied land trade routes in GELFN. Table 3 shows the top 10 weighted edges of GELFN among different economies. The top 10 weighted edges account for about 17.6% of total volume of embodied land flows, and 5 edges from China occupy half of the top 10. Among these 10 edges containing large amount of embodied land transfer between economies, the main exporters are Mongolia, China and Australia, which account for 4.98%, 3.87% and 3.7% of global embodied land transfer respectively. Correspondingly, the main importers are China, USA, and Hong Kong, which account for 7.01%, 4.12%, 2.96% of total embodied land transfer respectively.

3.2.4. *Key sector analysis*

It is noteworthy to capture the key flows across economies from a sectorial perspective. Fig. 8(a) and Fig. 8(b) show the import and export

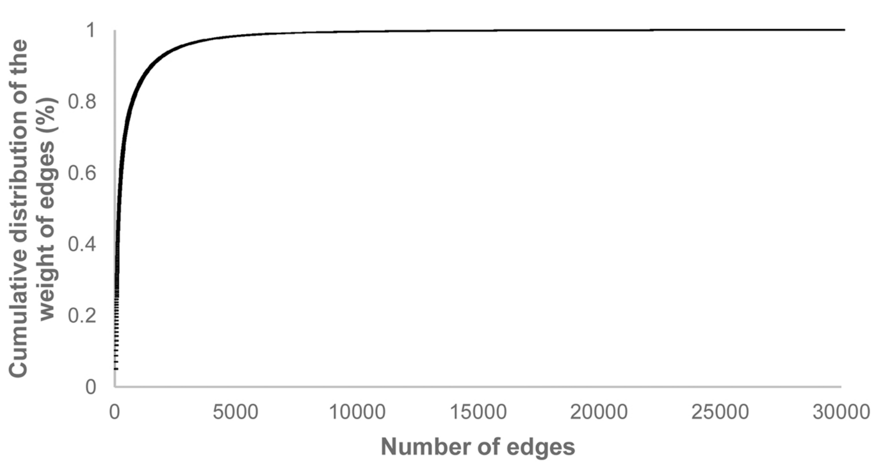

Fig. 6. The cumulative distribution of GELFN edges.

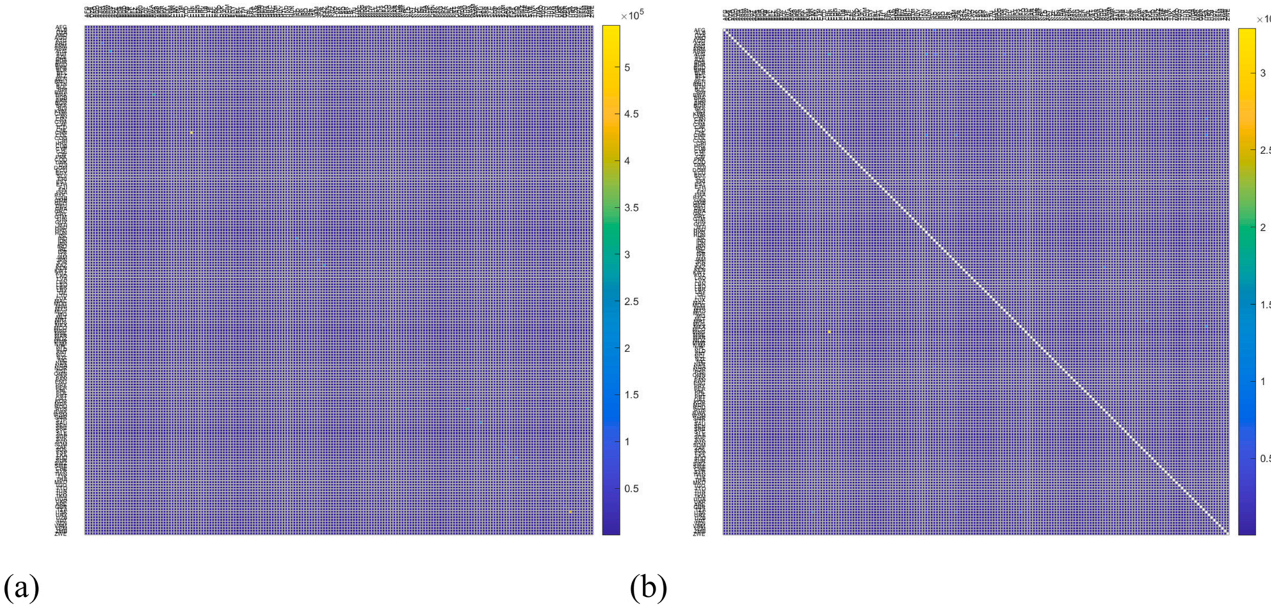

Fig. 7. Embodied land flows across 188 economies.

Table 3
Top 10 edges in weight of GELFN among different economies.

Source	Target	Embodied land consumption	Proportion (%)
MNG	CHN	32891.87	4.98
AUS	CHN	13416.78	2.03
AUS	HKG	11021.30	1.67
MEX	USA	10422.22	1.58
CHN	USA	9289.60	1.41
CHN	HKG	8547.92	1.29
KAZ	RUS	8321.52	1.26
CHN	JPN	7704.40	1.17
CAN	USA	7449.22	1.13
USA	CAN	7338.02	1.11

volume of the top 20 global embodied agricultural land transfer economies by 26 sectors in Eora database respectively. Specifically, we can infer from the results that most land-intensive flows take place among the sector of agriculture. There is no doubt that the sector of agriculture is the most important part of the embodied agricultural land transfer, which is related to the fact that agricultural land resources are widely needed in agricultural land processing and agricultural production process. Food and beverage production is closely related to agriculture, so this sector ranks only second to the largest amount of embodied agricultural land transfer. In individual economies, agricultural land transfers are also more frequently embodied in the sectors of textiles and wearing apparel, electrical and machinery, other manufacturing, hotels and restaurants, but the amount of transfer is not comparable to the sector of agriculture.

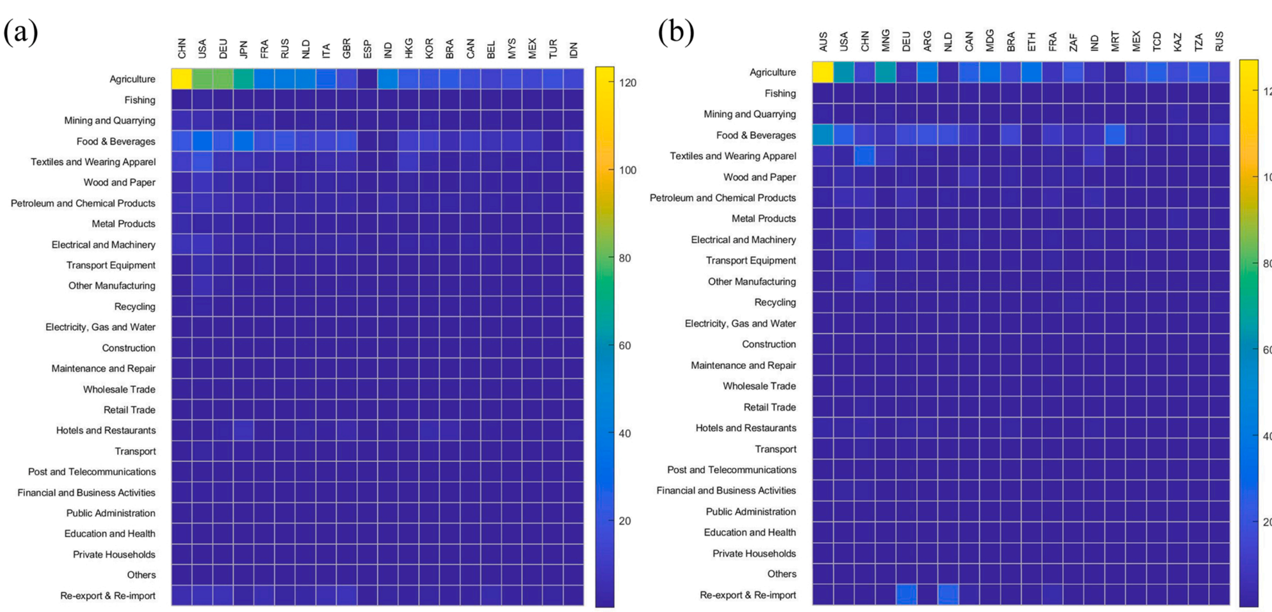

Fig. 8. Top 20 import-based and export-based embodied agricultural land transfer economies by 26 sectors.

3.2.5. Community detection

Community detection is a method that divides the nodes according to the density of their connections, which is used for investigating the spatial distribution of GELFN. To identify major economy clusters causing global embodied land flows, we divide GELFN into seven communities by the modularity maximization approach, with the modularity value calculated as 0.36, implying a distinct separation of amounts appears to exist among communities. Fig. 9(a) shows the results of community detection (community structure of GELFN) and Fig. 9(b) depicts the global distribution pattern of communities, in which economies in the same community are marked by the same color. Approximately 65% of the economies cluster into the two largest communities (C6 and C5), while C7 includes only 8 regions. The C6, dominated by Germany, accounts for 36% of total through-flows of GELFN. The second-largest community C5, mainly consisting of the USA and Australia, contributes to 23% of total through-flow, followed by C2, which is led by China. C4, C3, C1and C7 are insignificant compared with other communities. The major embodied land suppliers of C6 and C5 are from the corresponding community itself, while only a small number of embodied land receivers are dominated by other communities themselves. Generally, more than half of the total through-flows are attributed to intra-community flows, highlighting the regional integration of GELFN. However, economies not only actively engage themselves into the intensive land transfers within located community but also contribute a lot to inter-community flows in GELFN, accounting for 48.6% of total through-flows. Fig. 10 shows the flows of embodied land within intra-community and between inter-community, drawing the compositions of a community's land inflows, outflows and total flows, also illustrates the point above.

Each community represents a cluster of economies that are strongly connected with one another by embodied land leakages, which affects one another's land use more dramatically than economies outside this community. Some communities are divided exactly in line with geographical boundaries, such as the economies in C1 are geographically adjacent perfectly, suggesting the occurrence of an ongoing process of regionalization of embodied land transfer. Whereas, the division of most communities has a correlation with geographical proximity in some way, but not limited by geographic constraint, which includes economies located on different sides of the world. It has shown that geographic proximity only partly explains the community structure of embodied land trade, but the drivers of the embodied land flows are yet to be adequately identified.

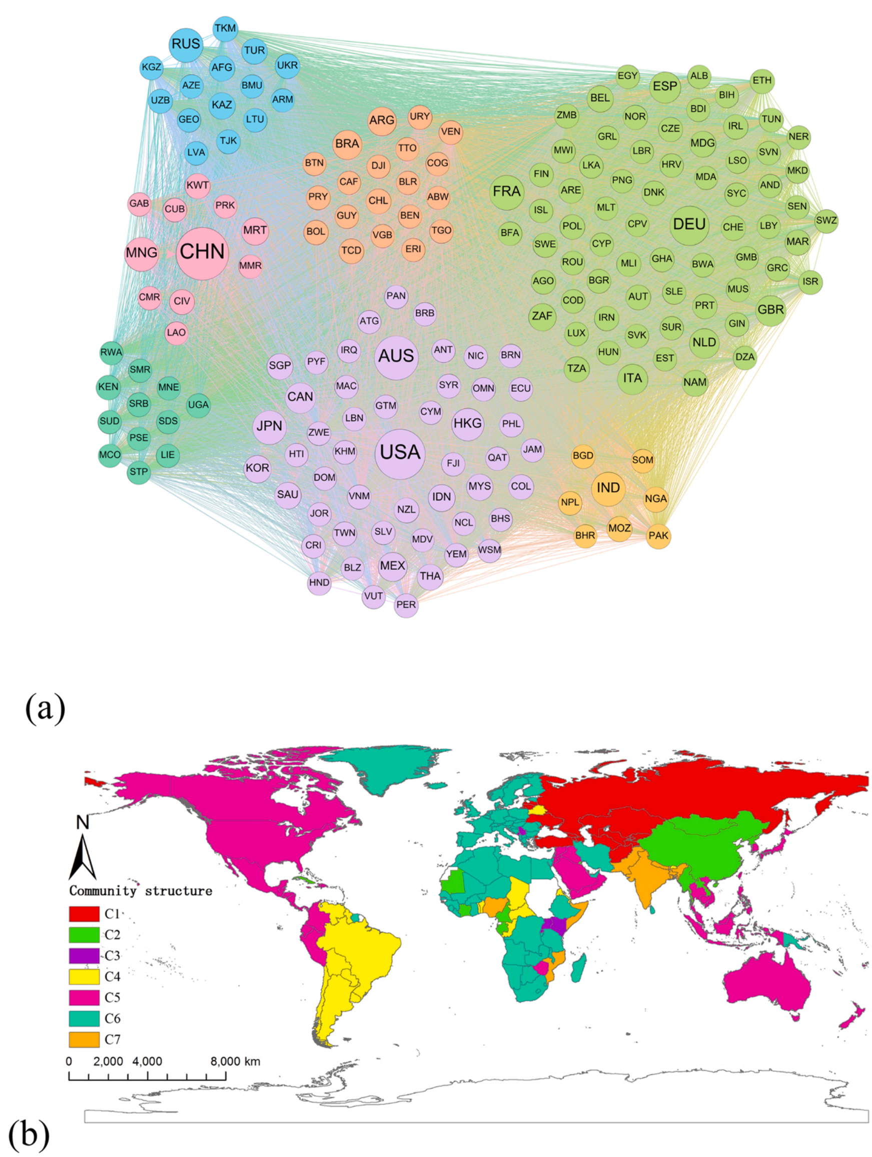

Fig. 9. Community structure and community division of GELFN. (Node size in Fig. 9(a) is proportional to core degree, and connection thickness is positively correlated with embodied land flows.) .

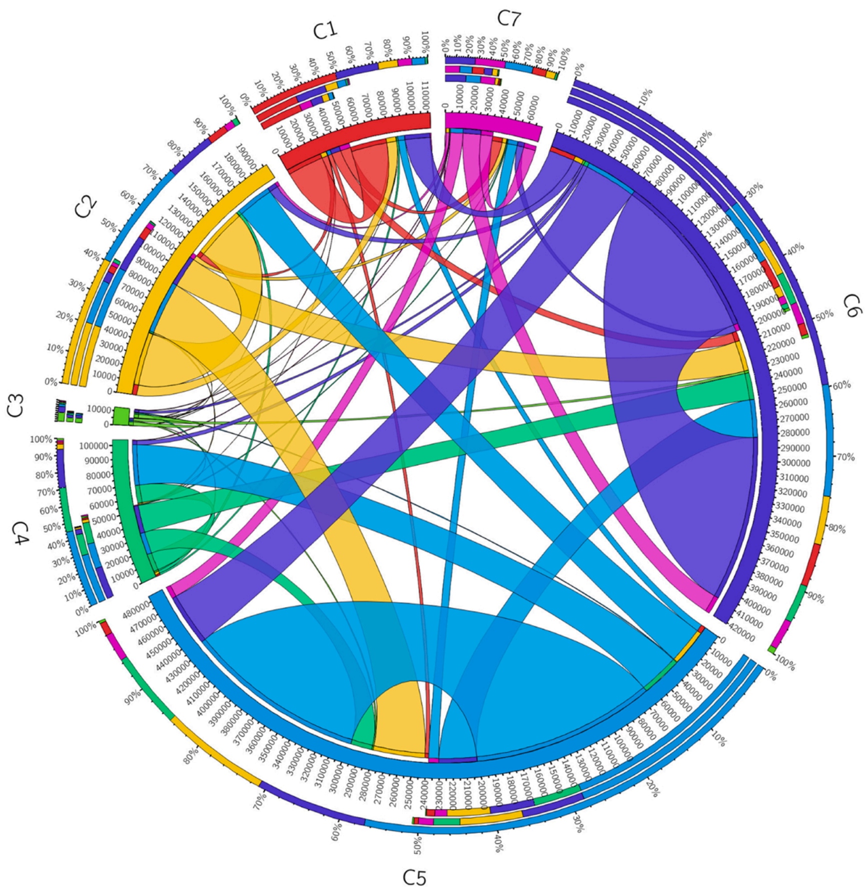

Fig. 10. The intra-community and inter-community flow mapping.

Additionally, a detailed examination of communities reveals that the distribution of communities is strongly influenced by the division of regional organization for economic cooperation. Economies in the same region economic cooperation organization are more likely to be divided into the same community, such as EU and AU in C6, NAFTA in C5, MERCOSUR in C4, CIS in C1 and SAARC in C7. On the whole, the outcome of community detection is consistent with the physical geographic connections and virtual administration divisions that exist within agglomeration economies approximately. Such cross relation between geographical regionalization and administrative regionalization demonstrates the results of economic operation and resource allocation under the influence of government-led policy regulation.

The results shown in Table 4 demonstrated that there is a necessary relationship between the core structure and the number of economies in the community. The number of economies for DEU's core community, USA's core community, CHN's core community, BRA&ARG's core community, KEN's core community, RUS's core community, and IND's core community were 71, 51, 20, 15, 12, 11 and 8 respectively. The result indicates that DEU's core community is the largest community in GELFN, which means the homogeneous competition is high.

3.2.6. *Core-periphery structure analysis*

3.2.6.1. Relative position of core trading economies. When trading economies are clustered into four categories by using K-Means clustering method according to four categories of network structure indicators (Core degree, degree centrality, betweenness centrality, closeness centrality), each cluster center stably reflects the coupling and convergence among the indicators. Statistical summary of four structural indicators in GELFN are shown in Table 5, reflecting clear comprehensive grade characteristics in the competition and cooperation relationship of embodied land flows. Accordingly, each trading economy can be divided into four levels: core trading economy, major trading economy, general trading economy and marginal trading economy. Among them, four indexes of core trading economies are all at the highest level, followed by the indexes of major trading economies, the indexes of general trading economies are moderately low, and all the indexes of marginal trading economies are at the lowest level.

Core degree reflects the degree to which an economy is closely connected with core flows. Economies in the same category are ranked according to their core degrees, so the division of economies based on K-

Table 4
Core community of GELFN.

Community	Number of economies	$CSC(G_i)$	$CSD(G_i)$	$CST(G_i)$	$CSL(G_i)$	H_{G_i}
C6 (DEU)	71	0.38	0.16	0.15	0.15	0.21
C5 (USA)	51	0.27	0.18	0.16	0.17	0.20
C2 (CHN)	20	0.06	0.08	0.09	0.06	0.07
C4 (BRA&ARG)	15	0.11	0.03	0.04	0.02	0.05
C3 (KEN)	12	0.06	0.00	0.00	0.12	0.05
C1 (RUS)	11	0.08	0.04	0.04	0.03	0.05
C7 (IND)	8	0.04	0.03	0.03	0.02	0.03

Table 5
Statistical summary of four structural indicators in GELFN.

	Category	Core Degree	Degree Centrality	Closeness Centrality	Betweenness Centrality
Cluster Central Value	Core	6.90E-02	3.66E+ 02	9.88E-01	5.70E+ 01
	Major	1.20E-02	3.42E+ 02	9.72E-01	1.94E+ 01
	General	2.70E-03	2.86E+ 02	8.15E-01	6.37E+ 00
	Marginal	1.00E-04	2.13E+ 02	6.04E-01	1.82E+ 00
Description Statistics	Maximum Value	6.38E-01	3.74E+ 02	1.00E+ 00	7.42E+ 01
	Minimum Value	0.00E+ 00	1.70E+ 02	5.47E-01	0.00E+ 00
	Mean Value	2.34E-02	3.24E+ 02	9.10E-01	2.48E+ 01
	Standard Deviation	6.90E-02	4.87E+ 01	1.38E-01	2.15E+ 01

means clustering analysis is shown in Appendix. The global geographic distribution of economies by core degree is shown in Fig. 11. The relative status of each economy can be reflected by the closeness between core trading economies. The higher the ranking, the higher the core status. The centralization or differentiation degree of economies in the same geographical region from the core of the flow are indicated at the same time.

In this paper, according to geographical distribution of import and export trade of embodied agricultural land, combing with global geographical division, the land flows are divided into Asia Pacific (except west Asia), West Asia, Oceania, North America, South America, Africa, Europe, and other agricultural land geographical areas. The four geographic boundaries of Oceania, West Asia, South America and Africa are designated as export geographic regions, and the three geographic regions of Europe, North America and Asia-Pacific are designated as import geographic regions.

From the perspective of the overall competition and cooperation situation, the subjects of GELFN are still a few economies with large amount of embodied agricultural land imports and exports. It is still a seller's market dominated by main export geographic regions. Therefore, the relative status at the two levels of core and major trading economies are mainly considered.

The core trading economies are the world's most active land import and export trading economies. The total amount of agricultural land transfer is large, and there are extensive direct trade links all over the world, so the degree centrality is high. Their trading partners are mostly major trading economies, so they generally have high intermediate centrality and high coreness degree. There are two-way trade links, overlapping partners and interwovening forces among core trading economies, making each core trading economy condensed into a closer polar core. They not only control the main competition and cooperation relations, but also tend to have direct or close flow relations with the majority of trading economies, showing high closeness centrality. Accordingly, core trading economies play the highest level of flow control and influence in GELFN.

Australia and Mongolia are typical export-oriented cores. As the largest producer of agricultural land in the world today, Australia is an important pole in GELFN, with a wide range of agricultural land trade, covering North America, Asia Pacific and Africa, and North American economies are the main ones. Therefore, Australia and Mongolia have a overall correlation, regulation and influence on the world's agricultural land flows, demonstrating the dominance of major agricultural land exporting economies in GELFN.

The United States and China form an import-leading core. The United States and China are the world's largest land trading economies, which have a close relation with the Middle East, Africa, Western Europe and the Asia-pacific zone at the inlet and outlet of agricultural land. The importing flows are greater than exporting flows, showing the leading role of importing cores is stronger. The United States and China become the world's agricultural land import and export hubs and mixed leaders, regulating and influencing land flows widely and directly. In view of the interlacing of core position of China and the United States, they have always been competing with each other in GELFN.

Germany has become the core of mid-transition. As an core trading economy, Germany carries out trade with the world's major agricultural land importers and exporters, especially with most of the European economies to maintain two-way trade, belonging to the core of mid-transition. This further reflects that the large inflows and outflows of agricultural land, especially the two-way trade with major trading economies, improve the extent of an economy's external agricultural land connection and enhance its mediating power and spreading influence on land flows.

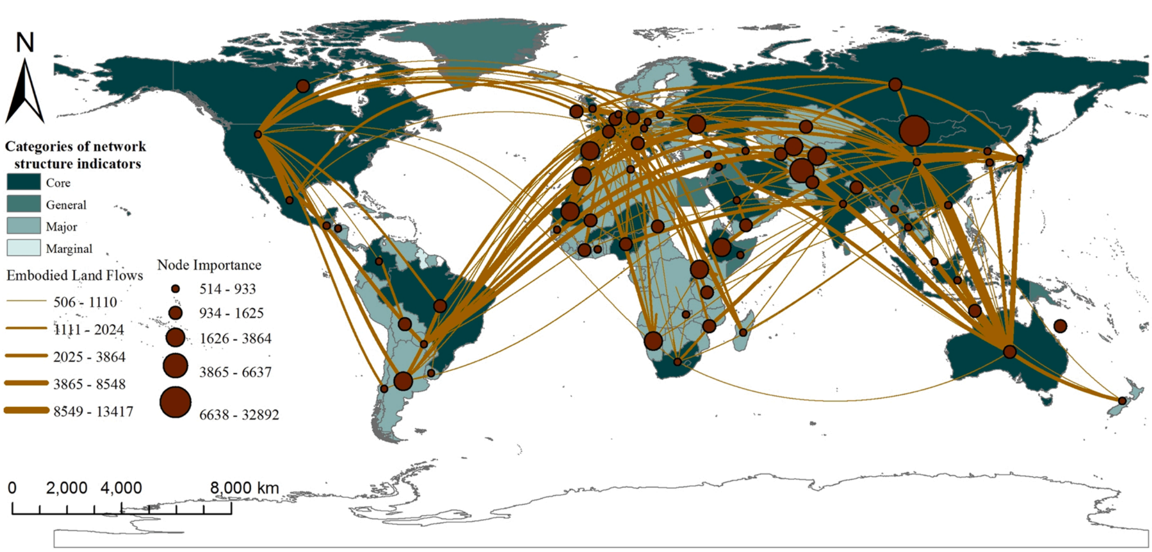

Fig. 11. Global geographic distribution of economies by core degree.

3.2.6.2. Overall competition and cooperation situation interpretation. The diversification of export regions brings opportunities for the optimization of import cooperation. Australia, China - Mongolia, the United States, and Germany have gradually evolved into the four main embodied agricultural land export regions in the world. Among them, the most significant feature of Germany export regions driven by multi-cores is that it plays a mediating role of large import and export among the world's vast trading economies, especially among major trading economies. The main advantage of China - Mongolia and the United States export regions is that supply regions are extremely extensive, almost including all trading economies above the general level. Especially, through the close connection with European economies, strengthen the ability of competition and cooperation in the flows of European agricultural land. Unlike the former two regions, Australia still exerts a great influence on the balance of supply and demand in the world's agricultural land market due to its huge export scale and market share.

The regulation and influence of Africa and South America on agricultural land flows are more regional, highlighted by the fact that Africa's export region is highly dependent on European market, while South America's export region is mainly dependent on North America and its own market. Nowadays they are still the important concurrence and cooperation forces in the pattern of global agricultural land flows, although the core status of the two is not at the top of the list. As the trade roles of Western Europe and the United States will change over time, Africa and South America also need to seek replace markets and export diversification actively in the future. It is the diversification and relative change of export regions that brings opportunities for import regions to adjust flow relations and enhance their core status.

North America and Western Europe are not only fully connected with exporting economies, but also compete with each other for agricultural land resources. However, the import source structure of the two regions has a certain dislocation, and the competition conflict is controllable. Among them, Western Europe prefers West Asia and Africa, which are two major export regions near the region, while North America region focuses more on the South America and Oceania. It is worth mentioning that the major importers in Asia-Pacific region seek to develop trade with the general or even marginal trading economies in global scope in order to avoid competitive edge.

The Asia-Pacific region, as the import region with the largest growing demand for agricultural land, has become a competitive place for export regions such as Oceania, West Asia, South America and Africa, which urgently need to expand new markets, creating space for Asia-Pacific region to enhance its core position and influence in GELFN. However, the Asia Pacific importing economies have been fighting with each other for a long time in the cooperation with each export region, and the lack of mutual exchange thus causing the fiercest importing competition between economies in GELFN. It can be seen that the Asia-Pacific region has become the focus of the competition and cooperation in GELFN, and whether it can make full use of the status changes and export competition opportunities of each export region will greatly depend on whether the major agricultural land importing economies can fully cooperate and resolve competition contradictions.

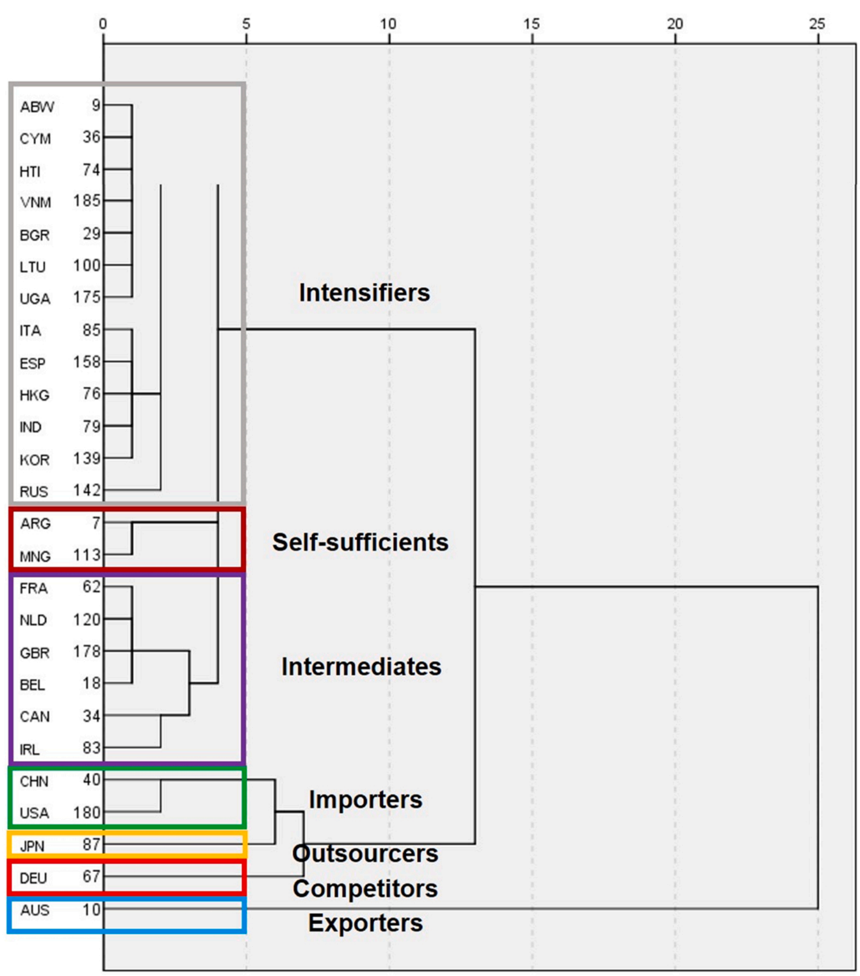

Fig. 12. Dendrogram of hierarchical cluster analysis using an average between groups.

3.3. Analysis of hierarchical cluster results

In order to identify global agricultural land use patterns, we use Ward's hierarchical clustering analysis which groups economies into clusters of similar characteristics. The statistical clustering analysis identified seven groups of economies ('connection clusters') (clustering coefficient 0.81) following the principle of minimum intra-cluster (within-group) variance and maximum inter-cluster (between-group) variance. Dendrogram as the result of hierarchical cluster analysis is shown in Fig. 12. The global geographic distribution of economies' classifications is shown in Fig. 13. The definitions and characteristics of each cluster are as follows:

1) 'Exporters'. The 'exporters' cluster consists of one economy, Australia, characterized by a high level of embodied land exports, exhibits as a net exporter of embodied land. Additionally, 'exporters' has a higher value of agricultural land endowments, showing as a lower value of LSI compared to other clusters.
2) 'Outsourcers'. The 'outsourcers' cluster (consists of Japan) exhibits a high dependence on imported land, giving evidence of high values for embodied land imports and net imports. The characteristic of 'outsourcers' cluster - high embodied land net-imports reveals that 'outsourcers' could not meet its relatively high demand of agricultural land for domestic consumption and production without international trade, showing a dependency on both domestic and imported embodied land to meet its domestic need. In the 'outsourcers' cluster, the amount of direct agricultural land application maintains at a relatively low level, while indirect land embodied in imported products is still required at a relatively large scale.
3) 'Importers'. The cluster of 'importers' includes two core of land imports regions (China, the USA), indicates high value of embodied land net imports, attributed to relatively low domestic land input and the import of agricultural products from economies with higher direct land inputs.
4) 'Intermediates'. Other major exporters, like Canada or Netherlands, which were classified as 'intermediates', involve dramatically lower amount of embodied land exports compared to the ones classified here as 'exporters'. Among these six economies (Netherlands, the UK, Belgium, France, Ireland and Canada) are many European economies with high level of exports, imports, LCAI and LSI.
5) 'Self-sufficients'. The 'self-sufficients' cluster covers two economies-Argentina and Mongolia, mainly in Africa and Asia. It is not only characterized as a strong self-sufficiency due to high value of direct agricultural land use, but act as a minor net-exporter of embodied land with a considerable amount of land devoted directly in agriculture.
6) 'Competitors'. The cluster of 'competitors' (consists of Germany) shows the characteristic of strong competitive advantage index.
7) 'Intensifiers'. The 'intensifiers' cluster is characterized by general amounts in every variates, it is not characterized by distinct patterns in the dataset.

4. Discussions and policy implications

The shortage of agricultural land resources has inevitably become a common problem faced by most economies. Most of the existing land suitable for farming has been reclaimed. Blind expansion is obviously not the right way to solve the problem, so improving the efficiency of global land use is an inevitable solution. The importance of redistributing agricultural land resources along global supply chains through interregional trade flows is becoming increasingly evident. Through a unified framework of multi-regional input-output quantification of embodied land use incorporating complex network approach, reflecting the characteristics of global land transfer network, the global land consumption and land pressure caused by regional trade of specific economies can be evaluated. Thus, the sustainable management of land resources is fully considered from a global perspective.

Firstly, different complex network indicators reveal the multi-dimensional characteristics of GELFN from different perspectives. Under the reality of diversified international trade and globalized production and consumption, GELFN shows the characteristics of multi-polarization and clustering. The results of community detection demonstrate the clustering characteristics of global land use, which is of great significance to better understand how to optimize land utilization by strengthening collaborative management of agricultural land in specific regions. Since economies within the same community are closely linked, land use interventions within one economy are not limited to itself, but have spillover effects within the community. Therefore, positive externalities are reflected in the fact that policy interventions in one economy can alleviate land shortage in other economies within the same community. Alleviating global land shortage can be more effectively addressed by implementing strategies within the community. Negative externalities are reflected in the fact that policy intervention in one economy may also lead to more severe land shortage within the community, and thereby further reduce the efficiency of global land use. On account of policy intervention in one economy has a

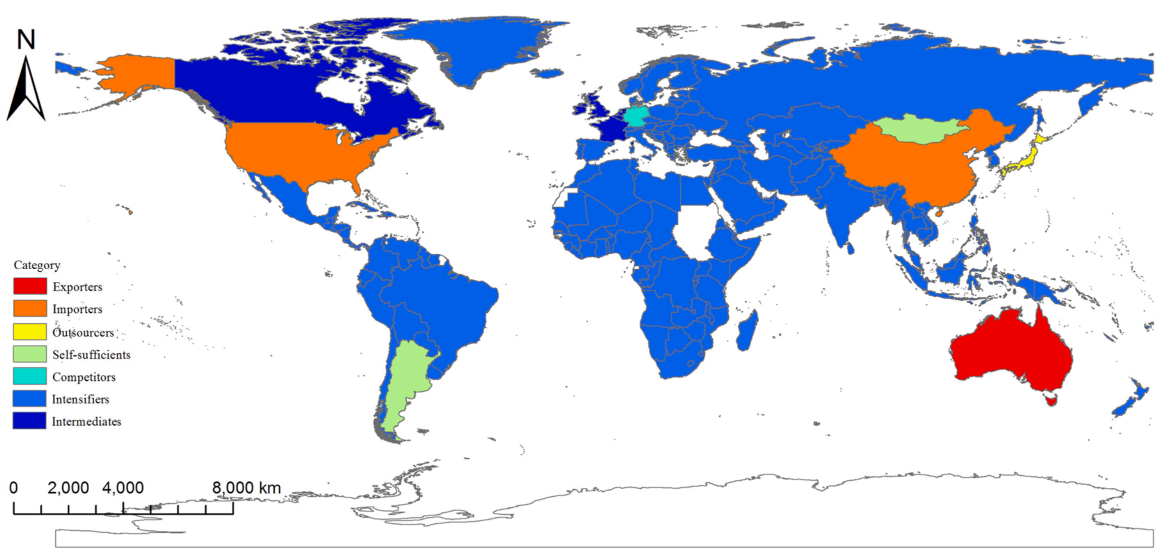

Fig. 13. Global geographic distribution of hierarchical cluster analysis.

stronger externality to land use within the community than in different communities, at the same time, economies within the same community usually have the advantage of geographical proximity, so trade transfers within the same community have a relatively stronger trade cost advantage generally. Therefore, priority should be given to embodied land flows within communities in formulating land collaborative management strategies. Economies located in the same community or even geographically adjacent communities should constitute a cooperative group, make joint decisions, develop cross-region cooperation schemes, and balance land management policies in order to maximize policy effects, which reduces the planning scope and provides more concrete implementation ideas.

Secondly, core-periphery structure analysis shows that most economies are on the periphery of GELFN, with little impact on the overall network. The nodes that play a central role in GELFN are only concentrated in a few economies. In consequence, we regard GELFN as a multilevel heterogeneous structure with a dense core and inter-connected periphery. The highly heterogeneous land flow network is robust but fragile, and it is vulnerable to change in the trade pattern of key nodes. Therefore, another key of global land collaborative management is to capture these key nodes and establish a collaborative management system centered on them. The centrality analysis makes a more detailed elaboration on the role of core economies. First of all, focus should be paid to core economies in GELFN to strengthen trade links and consolidate trade partnerships with them. At the same time, major economies, general economies, and peripheral economies should not be ignored, and trade links with these economies should be widely established to prevent land shortage and food crisis when the trade network with core economies is interrupted.

Thirdly, trade flows between economies also conform to the characteristics of scale-free network, bilateral trade with large trade flows also play an important role in GELFN. The specific sectors that reflect the transfer and aggregation of embodied agricultural land also have a significant impact on the whole network. In consequence, the importance of grasping the critical paths and key sectors in GELFN cannot be ignored. Trade quotas and policies should be negotiated among several economies with specific large trade flows to coordinate transfers from critical flows. Producing economies should continue to improve production techniques in agriculture and other related sectors and use agricultural land resources in more environmentally friendly ways for production and processing. For consuming economies with large agricultural land embodied in final demand, the government should adopt to use less land intensive goods/services of consumer behavior, and provide tax cuts or price subsidies to products with smaller environmental impact. This would encourage consumers to choose these products, and further make the upstream suppliers to minimize its product sales to the end consumer's environmental impact, achieve the cooperation between national land use.

Fourthly, land use structure of an economy is jointly determined by its land resource endowment and international trade relations. Therefore, we put land resource endowment and direct land use into the framework of cluster analysis, combined with the characteristics of embodied land transfer flows to identify agricultural land use patterns more comprehensively. Ultimately, specific agricultural land use policy recommendations are put forward for economies with different agricultural land use patterns. In general, the imbalance of global agricultural land geographical distribution and the gap between land supply and demand among economies are alleviated in the trade of embodied land transfer. The general trend is that embodied land transfers from land-abundant, competitive advantage in land utilization and less developed economies to land-poor, relatively weak competitive advantage in land utilization and more developed economies.

Specifically, for 'competitors' (such as Germany), the international division of labor should be used to further improve the efficiency of land use and give full play to the hub role of intermediary economies. As hubs in the network, these regions are the medium connecting influential nodes in GELFN. Large amount of embodied land flows may not exist in the final demand of these economies, but reflected in the production of intermediate goods. Trade policies of land transfer should be adjusted to play its role as an intermediary center to minimize land input from upstream economies and maintain land supply to downstream economies of global supply chains. Indirectly affecting the pattern of land transfer through the interconnected GELFN is of great significance for strengthening scarce agricultural land use.

For 'importers' (such as China and the USA), attention should be paid to adjust the industrial and trade structure, rationally distribute land intensive industries and import more land intensive products to further ease land tension. It is worth noting that for 'outsourcers' (such as Japan), trade may be an effective method to alleviate land shortage, but relying solely on importing embodied land is not only detrimental to global land economization, but also a damage to independence of the economy itself. For 'importers' and 'outsourcers', the final demand for agricultural land as final consumers creates land scarcity not only for themselves but also for other economies. It is crucial to improve the productivity of land acquired upstream from the supply chains and to select economies with low intensity of scarce land use as embodied land suppliers. For example, depending on local environmental conditions, import embodied land from Australia, where land pressures are relatively low. Therefore, Australia can encourage land exports to meet the demand of land-poor economies such as Japan, and obtain economic benefits through land exports. As a whole, optimizing land consumption behavior in these economies alleviates land scarcity and sustainable land use upstream of the supply chains. Coordinated management can be implemented through price subsidies and taxes on traded goods. Price subsidies should be imposed on high-value-added goods with high land use efficiency, while taxes should be imposed on low-value-added land-intensive products, so as to optimize the structure of GELFN and increase emphasis on sustainable land use.

For 'exporters' (such as Australia), the network is vulnerable at these nodes, and the changes of trade structure at these nodes will reshape the overall network pattern. Therefore, it is of great significance to play the role of globally integrated land management from the upstream of supply chains by integrating resources to strengthen domestic agricultural land supply, improving production efficiency and reducing the demand for external land-intensive products. For 'exporters' and 'self-sufficients' (such as Mongolia and Argentina), emphasis must be placed on land constraints to reduce unnecessary resource consumption. There are still a considerable number of land-poor and less developed economies (such as Ethiopia) tend to become large net exporters of embodied agricultural land. When the cost of economic development is excessive consumption of local scarce land resources, it is bound to cause irreversible damage to the local environment. These economies should take full consideration of balancing the economic gains of interregional trade with the corresponding resource consumption, and design policies to limit land-intensive exports, such as raising export tariffs. In addition, land exporting economies (such as the African Union) usually have fragile land systems due to land degradation, widespread poverty and mismanagement. Land importing economies (such as the European Union) can also establish a compensation mechanism to provide financial and technical support for land exporting economies to transform their economic development mode and realize sustainable development of land resources.

5. Conclusions

At present, embodied land transfer network through global supply chains has received extensive attention from the academic and political circles. The inter-regional management of agricultural land resources under the global dimension provides an effective way to alleviate land shortage and sustainable development of agricultural land. In this paper, GELFN is regarded as a comprehensive system based on the complex network method to supplement and summarize the result of MRIO analysis. Combining the resources endowment of clustering analysis, this paper depicts the overall structure of land use characteristics, regional characteristics and the role of key economies assumed in 2015. This study provides a new perspective to better understand agricultural land-use patterns of different economies and a theoretical support for targeted inter-regional land use management policies.

However, an analysis of characteristics of GELFN in just one year (2015 - the most recent data available) does not fully reflect evolutionary trends, nor do laws reflect the changing importance and roles of different economies as the network changes over time. In consequence, continuous time series analysis is needed in the future. In addition, specific sectors of certain economies also play a prominent role in global land transfer, requiring further analysis from the perspective of sectors and micro policymaking.

Declaration of Interest statement

Declarations of interest: none.

Data Availability

Data will be made available on request.

Acknowledgements

This study has been supported by the National Natural Science Foundation of China (Grant Nos. 72273143 and 71974192).

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.landusepol.2022.106464.

Appendix B. Supporting information

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References

Blondel, V.D., Guillaume, J., Lefebvre, E., n.d. Fast unfolding of communities in large networks 1–12.
Borgatti, S.P., Everett, M.G., 1999. Models Core R. Peripher. Struct. 375–395.
Brandes, U., 2001. A Faster Algorithm Between Cent. * 25, 163–177.
Chen, B., Han, M.Y., Peng, K., Zhou, S.L., Shao, L., Wu, X.F., Wei, W.D., Liu, S.Y., Li, Z., Li, J.S., Chen, G.Q., 2018a. Global land-water nexus: agricultural land and freshwater use embodied in worldwide supply chains. Sci. Total Environ. 613–614, 931–943. https://doi.org/10.1016/j.scitotenv.2017.09.138.
Chen, B., Li, J.S., Wu, X.F., Han, M.Y., Zeng, L., Li, Z., Chen, G.Q., 2018b. Global energy flows embodied in international trade: a combination of environmentally extended input–output analysis and complex network analysis. Appl. Energy 210, 98–107. https://doi.org/10.1016/J.APENERGY.2017.10.113.
Chen, B., Wang, X.B., Li, Y.L., Yang, Q., Li, J.S., 2019. Energy-induced mercury emissions in global supply chain networks: structural characteristics and policy implications. Sci. Total Environ. 670, 87–97. https://doi.org/10.1016/J.SCITOTENV.2019.03.215.
Chen, G.Q., Han, M.Y., 2015. Virtual land use change in China 2002–2010: internal transition and trade imbalance. Land Use Policy 47, 55–65. https://doi.org/10.1016/J.LANDUSEPOL.2015.03.017.
Chen, J., Wu, F., 2020. Housing and land financialization under the state ownership of land in China. Land Use Policy 104844. https://doi.org/10.1016/J.LANDUSEPOL.2020.104844.
Chen, W., Kang, J.N., Han, M.S., 2021. Global environmental inequality: evidence from embodied land and virtual water trade. Sci. Total Environ. 783, 146992 https://doi.org/10.1016/J.SCITOTENV.2021.146992.
Chuai, X., Gao, R., Huang, X., Lu, Q., Zhao, R., 2021. The embodied flow of built-up land in China's interregional trade and its implications for regional carbon balance. Ecol. Econ. 184, 106993 https://doi.org/10.1016/j.ecolecon.2021.106993.
FAO, 2015. Statistics Division. Food and Agriculture Organization of the United Nations.
Freeman, L.C., 1978. Cent. Soc. Netw. Concept. Clarification 1, 215–239.
Friis, C., Nielsen, J.Ø., Otero, I., Haberl, H., Niewöhner, J., Hostert, P., 2016. From teleconnection to telecoupling: taking stock of an emerging framework in land system science. J. Land Use Sci. 11, 131–153. https://doi.org/10.1080/1747423X.2015.1096423.
Guo, S., Shen, G.Q., Peng, Y., 2016. Embodied agricultural water use in China from 1997 to 2010. J. Clean. Prod. 112, 3176–3184. https://doi.org/10.1016/j.jclepro.2015.09.123.
Guo, S., Jiang, L., Shen, G.Q.P., 2019. Embodied pasture land use change in China 2000-2015: from the perspective of globalization. Land Use Policy 82, 476–485. https://doi.org/10.1016/J.LANDUSEPOL.2018.12.031.
Guo, S., Wang, Y., Shen, G.Q.P., Zhang, B., Wang, H., 2020. Virtual built-up land transfers embodied in China's interregional trade. Land Use Policy 94. https://doi.org/10.1016/j.landusepol.2020.104536.
Han, M., Chen, G., 2018. Global arable land transfers embodied in Mainland China's foreign trade. Land Use Policy 70, 521–534. https://doi.org/10.1016/J.LANDUSEPOL.2017.07.022.
Han, M., Li, S., 2021. Transfer patterns and drivers of embodied agricultural land within china: based on multi-regional decomposition analysis. Land 10, 1–16. https://doi.org/10.3390/land10020213.
Han, M., Yao, Q., Lao, J., Tang, Z., Liu, W., 2020. China's intra- and inter-national carbon emission transfers by province: a nested network perspective. Sci. China Earth Sci. 63, 852–864. https://doi.org/10.1007/s11430-019-9598-3.
Han, M.Y., Chen, G.Q., Li, Y.L., 2018. Global water transfers embodied in international trade: tracking imbalanced and inefficient flows. J. Clean. Prod. 184, 50–64. https://doi.org/10.1016/j.jclepro.2018.02.195.
Han, M.Y., Chen, G.Q., Dunford, M., 2019. Land use balance for urban economy: a multi-scale and multi-type perspective. Land Use Policy 83, 323–333. https://doi.org/10.1016/J.LANDUSEPOL.2019.01.020.
He, X., Dong, Y., Wu, Y., Wei, G., Xing, L., Yan, J., 2017. Structure analysis and core community detection of embodied resources networks among regional industries. Phys. A Stat. Mech. Appl. 479, 137–150. https://doi.org/10.1016/J.PHYSA.2017.02.068.
Holme, P., Min, S., Jun, B., Edling, C.R., 2007. Korean university life in a network perspective. Dyn. a Large Affil. Netw. 373, 821–830. https://doi.org/10.1016/j.physa.2006.04.066.
Ji, X., Han, M., Ulgiati, S., 2020a. Optimal allocation of direct and embodied arable land associated to urban economy: understanding the options deriving from economic globalization. Land Use Policy 91, 104392. https://doi.org/10.1016/J.LANDUSEPOL.2019.104392.
Ji, X., Han, M., Ulgiati, S., 2020b. Optimal allocation of direct and embodied arable land associated to urban economy: understanding the options deriving from economic globalization. Land Use Policy 91. https://doi.org/10.1016/j.landusepol.2019.104392.
Kagawa, S., Suh, S., Hubacek, K., Wiedmann, T., Nansai, K., Minx, J., 2015. CO_2 emission clusters within global supply chain networks: Implications for climate change mitigation. Glob. Environ. Chang 35, 486–496. https://doi.org/10.1016/J.GLOENVCHA.2015.04.003.
Lenzen, M., Kanemoto, K., Moran, D., Geschke, A., 2012. Mapping the structure of the world economy. Environ. Sci. Technol. 46, 8374–8381. https://doi.org/10.1021/es300171x.
Lenzen, M., Moran, D., Bhaduri, A., Kanemoto, K., Bekchanov, M., Geschke, A., Foran, B., 2013a. International trade of scarce water. Ecol. Econ. 94, 78–85. https://doi.org/10.1016/J.ECOLECON.2013.06.018.
Lenzen, M., Moran, D., Kanemoto, K., Geschke, A., 2013b. Building Eora: a global multi-region input-output database at high country and sector resolution. Econ. Syst. Res 25, 20–49. https://doi.org/10.1080/09535314.2013.769938.
Leontief, W., 1970. Environmental repercussions and the economic structure: an input-output approach. Rev. Econ. Stat. 52, 262–271. https://doi.org/10.2307/1926294.
Li, C., Wu, X., Chen, G., Han, M., Chen, K., Yangzong, C., Lo, D., Alsaedi, A., Hayat, T., 2021. Pastureland use of China: accounting variations from different input-output analyses. Land Use Policy 109, 105597. https://doi.org/10.1016/j.landusepol.2021.105597.
Li, Y., Chen, B., Li, C., Li, Z., Chen, G., 2020. Energy perspective of Sino-US trade imbalance in global supply chains. Energy Econ. 92, 104959 https://doi.org/10.1016/J.ENECO.2020.104959.
Li, Y.L., Chen, B., Han, M.Y., Dunford, M., Liu, W., Li, Z., 2018. Tracking carbon transfers embodied in Chinese municipalities' domestic and foreign trade. J. Clean. Prod. 192, 950–960. https://doi.org/10.1016/J.JCLEPRO.2018.04.230.
Liu, Y., 2018a. Introduction to land use and rural sustainability in China. Land Use Policy 74, 1–4. https://doi.org/10.1016/J.LANDUSEPOL.2018.01.032.
Liu, Y., Wang, S., Chen, B., 2018b. Water – land S carcity R isk N exus in the N ational T rade S ystem B ased on M ultiregional I nput – output and E cological N etwork A nalyses 2–5.
Liu, Y., Ma, R., Guan, C., Chen, B., Zhang, B., 2021. Global trade network and CH4 emission outsourcing. Sci. Total Environ. 803, 150008 https://doi.org/10.1016/j.scitotenv.2021.150008.
López, L.A., Arce, G., Jiang, X., 2020. Mapping China's flows of emissions in the world's carbon footprint: a network approach of production layers. Energy Econ. 87, 104739 https://doi.org/10.1016/J.ENECO.2020.104739.
OECD, 2015. Organization for Economic Co-operation and Development: Data Insights.
Opsahl, T., Agneessens, F., Skvoretz, J., 2010. Node centrality in weighted networks: generalizing degree and shortest paths. Soc. Netw. 32, 245–251. https://doi.org/10.1016/j.socnet.2010.03.006.
Peters, G.P., Davis, S.J., Andrew, R., 2012. A synthesis of carbon in international trade. Biogeosciences 9, 3247–3276. https://doi.org/10.5194/bg-9-3247-2012.
Pfister, S., Koehler, A., Hellweg, S., 2009. Assessing the environmental impacts of freshwater consumption in LCA. Environ. Sci. Technol. 43, 4098–4104. https://doi.org/10.1021/es802423e.
Rulli, M.C., Saviori, A., D'Odorico, P., 2013. Global land and water grabbing. Proc. Natl. Acad. Sci. 110, 892–897. https://doi.org/10.1073/PNAS.1213163110.

Steen-Olsen, K., Owen, A., Barrett, J., Guan, D., Hertwich, E.G., Lenzen, M., Wiedmann, T., 2016. Accounting for value added embodied in trade and consumption: an intercomparison of global multiregional input–output databases. Econ. Syst. Res. 28, 78–94. https://doi.org/10.1080/09535314.2016.1141751.

Vespignani, A., Barrat, A., Barthe, M., Data, W.N., 2004. The architecture of complex weighted networks.

Voss, K.A., Famiglietti, J.S., Lo, M., De Linage, C., Rodell, M., Swenson, S.C., 2013. Groundwater depletion in the Middle East from GRACE with implications for transboundary water management in the Tigris-Euphrates-Western Iran region. Water Resour. Res. 49, 904–914. https://doi.org/10.1002/wrcr.20078.

Ward, J.D., Sutton, P.C., Werner, A.D., Costanza, R., Mohr, S.H., Simmons, C.T., 2016. Is decoupling GDP growth from environmental impact possible. PLoS One 11, 1–14. https://doi.org/10.1371/journal.pone.0164733.

Wu, J., Jia, Y., Cheng, M., Xia, X., 2022. A complex network perspective on embodiment of air pollutants from global oil refining industry. Sci. Total Environ. 824, 153740 https://doi.org/10.1016/J.SCITOTENV.2022.153740.

Wu, X.D., Guo, J.L., Han, M.Y., Chen, G.Q., 2018. An overview of arable land use for the world economy: from source to sink via the global supply chain. Land Use Policy 76, 201–214. https://doi.org/10.1016/J.LANDUSEPOL.2018.05.005.

Wu, X.D., Guo, J.L., Li, C.H., Shao, L., Han, M.Y., Chen, G.Q., 2019. Global socio-hydrology: an overview of virtual water use by the world economy from source of exploitation to sink of final consumption. J. Hydrol. 573, 794–810. https://doi.org/10.1016/J.JHYDROL.2019.03.080.

Wu, X.F., Chen, G.Q., 2018. Coal use embodied in globalized world economy: from source to sink through supply chain. Renew. Sustain. Energy Rev. 81, 978–993. https://doi.org/10.1016/J.RSER.2017.08.018.

Xia, X.H., Chen, B., Wu, X.D., Hu, Y., Liu, D.H., Hu, C.Y., 2017. Coal use for world economy: provision and transfer network by multi-region input-output analysis. J. Clean. Prod. 143, 125–144. https://doi.org/10.1016/J.JCLEPRO.2016.12.142.

Xing, L., Guan, J., Dong, X., Wu, S., 2018. Understanding the competitive advantage of TPP-related nations from an econophysics perspective: influence caused by China and the United States. Phys. A Stat. Mech. Appl. 502, 164–184. https://doi.org/10.1016/j.physa.2018.02.126.

Zhang, B., Qiao, H., Chen, Z.M., Chen, B., 2016. Growth in embodied energy transfers via China's domestic trade: evidence from multi-regional input–output analysis. Appl. Energy 184, 1093–1105. https://doi.org/10.1016/J.APENERGY.2015.09.076.

Zhao, X., Wu, X., Guan, C.H., Ma, R., Nielsen, C.P., Zhang, B., 2020. Linking agricultural GHG emissions to global trade network. Earth's Futur 8. https://doi.org/10.1029/2019EF001361.

Zhu, D., Wang, D., Hassan, S.-U., Haddawy, P., 2013. Small-world phenomenon of keywords network based on complex network. Scientometrics 97, 435–442. https://doi.org/10.1007/s11192-013-1019-3.