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Network Effects in Global Carbon Transfer: New Evidence from a Carbon-Connectedness Network Centered on China

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Abstract: There is plenty of evidence to suggest that global carbon emission transfer has evolved into a mutually related system, where a realistic and complex network is formed. To profile the structures and features in the global carbon emission transfer network, a carbon-connectedness network model is adapted and combined with the multiregional input–output analysis framework, on the basis of massive and multi-layer global carbon flow data. This study formulates the topological features, spatio-temporal features, dynamic features and core–periphery features from a brand-new perspective on China. Meanwhile, this study identifies the network effects in the global carbon transfer network, including spillover, spillin and spillback effects. In general, an increase in China’s carbon emission transfer would lead to significant spillover effects on most economies worldwide, especially on developing economies and those with weaker tertiary industry or situated at the upstream of the global value chain. Simultaneously, China itself would also face substantial spillback effects. Spillovers and spillbacks underscore a broader negative impact that exceeds its initial magnitude. Focused on the connectedness network centered on China, this study is complementary to traditional insights, helping to comprehend the connections and relationships of carbon emissions among economies. This understanding is of substantive significance for the formulation of multi-national mitigation strategies and fostering global climate governance cooperation.

Keywords: carbon transfer; trade embodied carbon; connectedness network; MRIO analysis; network effect; spillover effect



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1. Introduction

“Humanity has a choice: cooperate or perish. It is either a Climate Solidarity Pact, or a Collective Suicide Pact”. The Climate Solidarity Pact mentioned above was proposed by UN Secretary-General António Guterres at the opening of the UN Climate Change (COP27), which is the largest and the most influential climate-related conference worldwide. It is a historic pact between developed and developing economies, which calls for an extra effort from all economies over the world to reduce emissions under the 1.5-Degree Goal and a tighter union between developed and developing economies in financial and technical assistance.

The 1.5-Degree Goal came to light during the Paris Agreement. The contracting parties pledged their national contribution to reducing carbon emissions, also known as Intended Nationally Determined Contributions (INDCs), to ensure global warming stays well below 2 degrees Celsius, and ideally at 1.5 degrees Celsius. This is also one of the key targets for climate action under the Sustainable Development Goals (SDGs) adopted by the United Nations in 2015 [1,2]. Scientific evidence is clear that any hope of limiting the temperature rise to 1.5 degrees means achieving global net zero emissions by 2050, while the Global Carbon Project (GCP, 2022) [3] warns that the remaining carbon budget will be depleted in just 6.5 to 9 years if emissions persist at their current levels. In this case, no economy can escape from the ravages of climate change; the only way forward is to rebuild trust between

nations. More precisely, developed economies should take the lead, while developing economies are also critical in bending the global emissions curve.

In fact, a fair amount of measures have been implemented by both developed and developing countries to address climate change. For instance, China, as the largest current emitter of greenhouse gases worldwide [4], has committed to achieving the “Double Carbon” target through the strict implementation of the “Double Control” policy on energy consumption and intensity, which entails reaching the carbon peak in 2030 and attaining carbon neutrality by 2060 [5,6]. These policies exemplify China’s role as a major developing country [7]. Meanwhile, the European Union, as one of the largest cumulative emitters and a pioneering economy in proposing carbon neutrality plans, has established a comprehensive roadmap for carbon neutrality, encompassing the “European Green Deal”, the “European Climate Law” and the “Fit for 55” package. Under these efforts, the EU Emissions Trading System (EU-ETS) and its carbon price mechanism are considered to be the most effective market economy means in global practice.

In addition to individual efforts, international cooperation is more crucial, but numerous international negotiations have stalled without any real progress. The Kyoto Protocol in 1997 and the Paris Agreement in 2015 are the only two legally binding agreements worldwide. Both of them define the shared responsibilities under the principle of production-based accounting (PBA) emissions. The PBA principle calculates the emissions physically occurring within an economy. It is based on territorial scope and national boundaries, also called territorial emissions.

However, the intensifying globalization and ever-changing international trade connections accelerate the fragmentation of the global supply chain, whereby the spatial separation of production and consumption is ubiquitous. The original “Great Triangle” pattern of division has been gradually fragmented, giving rise instead to a new cluster structure of “Three-Way” communities centered on North America, Europe and Asia [8–10]. The “intra-regional” circulation and economic links among them have been greatly strengthened.

Therefore, the PBA principle ignores some key issues. Firstly, PBA adheres to the Grandfathering Principle of carbon allowances, which disregards historical emissions. This Grandfathering Principle allocates the right to carbon emissions under the “preemption rule”, providing an emissions advantage to historical polluters at the expense of future polluters. Secondly, PBA leads to the problem of carbon leakage, which is inconsistent with the SDGs, especially carbon transfer through international trade channels. A clear example can be seen in the relationship between developed and developing economies. Developed economies import highly polluting commodities from developing economies while producing low-polluting goods domestically and exporting them to the latter, resulting in an unfair allocation of shared responsibilities: there is a rise in developing economies’ carbon emission responsibility and a corresponding drop in those of developed economies.

Considering the limitations and inadequacies of the PBA principle, constructing a more equitable and effective new international climate regime becomes the top priority. Obviously, consumption-based accounting (CBA) is a better way out. It takes into account the “Embodied Carbon” in international goods, which is a derived concept of “Embodied Flow” (Brown & Herendeau, 1996) [11]. Embodied carbon is defined as carbon dioxide emitted directly or indirectly in the production chain from producers to consumers, reporting the total emissions associated with the final demand in each economy. In the former example, the gap between PBA and CBA is the amount of carbon emission responsibility that developed economies transfer to developing economies. This is exactly what this paper is interested in.

Additionally, under the framework of modern international trade, the production chain has become increasingly complex, being interconnected across four dimensions: value chain, enterprise chain, supply-demand chain and space chain, covering the whole process of production, including raw material provision, technology research and development, intermediate goods manufacturing and circulation, terminal goods consumption, etc. Consequently, the extensive interdependence among economies through trade challenges the

way we redistribute global carbon emission responsibility, especially within this complex interacting system, which consists of a multitude of producers and consumers, rather than the oversimplified structure.

Given this, this paper has extensively reviewed the existing literature and identified three areas in which previous research could be enhanced. Firstly, in terms of research subjects, the existing literature primarily focuses on the application of the CBA principle within specific countries or regional alliances, with a lack of studies involving global samples. Secondly, in terms of research methods, it would be more appropriate to investigate international trade, especially the carbon transfer embodied in it, by utilizing a complex network model, which is absent in existing studies. Thirdly, the existing literature solely concentrates on embodied carbon emission itself without considering its role as an environmentally negative externality, which could cause significant global contagion.

To make some improvement in these areas, this paper aims to clarify the evolution of the structure and functions of global carbon transfers within a complex network. A connectedness network model is employed, which integrates massive time-series carbon flow supported by multiregional input–output analysis. This model not only formulates the topological structure of global carbon emission responsibility redistribution, together with their in-depth bilateral, multilateral and overall patterns and correlated relationships, but also captures the spatio-temporal characteristics of the global carbon transfer network, including the trends, directions, and weights that are invisible in traditional input–output analysis. Furthermore, this model enunciates the core–periphery structure and dynamic structure when centered on China. Comprehensively, this connectedness network of carbon transfers provides additional insights for redistributing global responsibility for carbon emissions and mitigates China’s increasing physical carbon dioxide emission responsibilities. It may offer accurate forecasts for evolution that could be considered for future policy formulation to promote global collective and inclusive governance.

This paper innovatively contributes to existing research in the following areas: (1) It highlights the principle of consumption-based accounting (CBA), which is distinguished from the principle of production-based accounting (PBA) in current international communities, elucidating the apportionment of responsibility for carbon emissions resulting from production supplies between producing economies and consuming economies. Supported by multiregional input–output analysis (MRIO-A) and the world input–output table (WIOT), we are able to calculate the bilateral carbon emission flows embodied in international trade and formulate a massive matrix of global carbon transfer. (2) It profiles the global carbon transfer, as well as its spillover effects and spillback effects through a carbon-connectedness network model. By adapting the global carbon transfer flows to a trade-connectedness network model, it portrays a visualized global carbon transfer network with trends, weights and directions. Moreover, it simultaneously uncovers both the static and dynamic properties, topological structure and core–periphery structure of this network. (3) It emphasizes the necessity and inevitability of China’s global radiance. By identifying the spillover effects and spillback effects in the global carbon transfer network centered on China, this paper not only focuses on China’s significant global influence, but also explores the reciprocal impacts of international periphery on China. This might provide substantial evidence for China and the international community to reassess a fairer mechanism for allocating and distributing carbon emission responsibility.

The remainder of the paper proceeds as follows. Section 2 overviews the existing literature, Section 3 introduces the methodology, model, and data, Section 4 demonstrates the result analysis, Section 5 depicts the heterogeneity analysis, Section 6 discusses the robustness of the model compared to the context of US as the epicenter and Section 7 concludes and explores the policy implications of this study.

2. Literature Review

On reviewing the existing literature, we have found some gaps in related fields that could be further improved. Specifically, our focus lies on addressing three practical issues:

(1) the appropriate application of optimal principle of responsibility; (2) the selection of a comprehensive methodology for calculating embodied carbon emission; (3) the construction of a more adaptable model for network analysis. Motivated by these potential areas for enhancement, we reviewed and summarized previous literature on these three aspects, aligning them with the marginal innovations mentioned in the introduction.

2.1. Principle of Responsibility

Previous research has investigated multiple principles for accounting for “Embodied Carbon” within trade, including international trade, inter-regional trade and sub-national trade. These principles are the following: (i) Production-based accounting (PBA) (WBGU, 2009 [12]; IPCC, 2014 [13]) reports, on the production side, the carbon dioxide physically emitted within an economy’s geographical boundaries, regardless of the consumption activities abroad, and is widely used in the Paris Agreement, the Kyoto Protocol and other negotiations worldwide. (ii) Consumption-based accounting (CBA) was first proposed by scholars such as Peters (2007 [14], 2008 [15]), Hertwich (Peters & Hertwich, 2008 [16]), etc. However, it has made waves in ecological economics in recent years with the efforts of Kanemoto et al. (2012 [17], 2014 [18], 2016 [19]), Kander et al. (2015 [20], 2020 [21]) and Jiborn et al. (2018) [22], etc. On the consumption side, it reports the emissions caused both directly and indirectly by an economy’s final consumption demand. Carbon dioxide physically emitted by the producer is regarded as the responsibility of the consumer. This principle breaks the barrier of geographical boundaries and is considered to be a better principle (Peters et al., 2011 [23]; Van et al., 2019 [24]). (iii) Other principles, beyond CBA and PBA, divide the responsibilities between producers and consumers. The biggest challenge is how to conceptualize them consistently and quantitatively (Gallego & Lenzen, 2005 [25]; Lenzen et al., 2007) [26]. The simplest scheme is on a basis of 50%–50% allocation (Gallego and Lenzen, 2005 [25]), while more complex and precise schemes have been proposed. For example, income-based accounting (IBA) (Lenzen and Murray, 2010 [27]; Liang et al., 2017 [28]) assigns trade-related emissions to primary suppliers, which might help inform supply-side policymaking. Csutora and Vetóné mózner (2014) [29] proposed the beneficiary-based shared responsibility. This principle assumes that consumers should take responsibility for the value of the material throughputs of the goods, while the producer should be responsible for value-added gains. Jakob et al. (2021) [30] proposed the economic benefit shared responsibility (EBSR), which allocates the responsibilities between productions and consumers according to the economic benefits they derived from trade-related emissions. However, these principles remain at the stage of theoretical construction with few empirical studies because of less policy acceptability or inconsistent standards. The CBA principle is still the top choice at present (Fullerton and Muehlegger, 2019 [31]; Tukker et al., 2020 [32]).

The CBA and PBA principles are two mainstream schemes in the international community. For large exporting economies, carbon emissions on the production side are always much higher than those on the consumption side. On the contrary, for large importing economies, carbon emissions on the production side are always much lower than those on the consumption side (Moran and Wood, 2014) [33]. The gap between the production side and the consumption side is exactly the carbon emission transfer embodied in international trade, which is the focus of this research.

2.2. Calculation of Embodied Carbon

Based on a more equitable principle of CBA, the selection of an appropriate analysis for calculating the underlying data in practice under the guidance of the CBA principle is worth considering. Life cycle assessment (LCA) is first used (e.g., Chojnacka et al., 2019) [34]. However, LCA has a narrow scope of application and is difficult to collect complete data, which presents an opportunity for Input–Output (IO) analysis (Leontief, 1936 [35], 1970 [36]). Recently, IO analysis has been constantly improved under the efforts of scholars. From the domestic technology hypothesis model of single-regional input–output

(SRIO) (e.g., Wieland et al., 2020 [37]; Xu et al., 2021 [38]), which focuses on sub-national trade and domestic carbon flow, to the bilateral trade input–output model (BTIO) (e.g., Li et al., 2020 [39]), which reflects the import and export relations between two economies, and then to the multiregional input–output model (MRIO) (e.g., Cheng et al., 2018 [40]; Long et al., 2018 [41]; Yuan et al., 2022 [42]), which takes into account the technical differences among economies and the intermediate inputs in the whole process of products.

In comparison, MRIO analysis depicts the inextricable relationship between economies through import and export trade and an in-depth relationship interwound with demand and supply. Therefore, it is considered to be a better tool for analyzing carbon emissions in international trade (Kanemoto et al., 2012 [17]), accompanied by the appearance of some new hybrid methods; for example, Zafrilla et al. (2014) [43] adopted a new method, called LCA-MRIO.

2.3. Economics of Spillovers and Complex Network Analysis

Existing research has confirmed that the widely expanding carbon flow embodied in international trade has evolved into an increasingly complex network, where individual economies are not on-site producers (PBA perspective), consumers (CBA perspective) or upstream suppliers (IBA perspective), but play multiple roles in the global production chain and demand–supply chain. A coherent framework of complex network analysis is needed to untangle the intricate relationships among economies.

Currently, there are three prevailing network models in the field of trade and carbon emissions, including social network analysis, global vector autoregressive modeling (GVAR) and spatial econometric modeling. For example, Smith and White (1992) [44] employed social network analysis to examine the dynamics of international trade in order to assess its structural properties. Fang et al. (2024) [45] employed social network analysis to map the intensity of carbon emissions in individual economies. Wang and Han (2021) [46] used the GVAR model to reveal how energy, the economy and the environment are affected in multiple countries. Bu et al. (2022) [47] investigated the impact factor of carbon emissions on the basis of a spatial econometric model in China. These studies have significantly contributed to the advancement of utilizing network methodology for the analysis of carbon emissions. However, all three models mentioned above are static. It is important to note that the pattern of carbon transfer embodied in international trade exhibits a dynamic evolutionary process; therefore a dynamic network is needed.

While the application of dynamic networks in the field of carbon emissions is limited, potential solutions have been identified in other sectors of the economy. The most widely used methods include the VAR methods. For example, Tan et al. (2022) [48] depicted the transmission among global financial markets using the TVP-VAR-Connectedness model; Zhou et al. (2022) [49] accomplished the analysis of global policy uncertainty spillovers through the LASSO-VAR model. Always combined with the methods above, structural econometric models have become popular in recent years, particularly in global general equilibrium models. For instance, Chin and Li (2019) [50] revealed the relations among various economic variables and constructed an effective forecasting VAR-DSGE model by combining the VAR model with the DSGE model. In addition, it is worth mentioning the DY model based on the VAR method. Diebold and Yilmaz (2009 [51], 2012 [52], 2014 [53]) developed a spillover network model which could grasp both the directions and the dynamics in the process of spillovers, known as the DY model. Scholars often combined it with other models, including the TVP-VAR-DY model (Antonakakis et al., 2020 [54]), the MS-VAR-DY model (Lien et al., 2022 [55]), etc. Fewer complex network studies are found in the ecology field. Li et al. (2020) [56] place global carbon flows into a complex network, depicting common evolution and heterogeneous characteristics, such as coreness and cumulative/weighted degree, across global, regional and national dimensions. However, they are confined to a single-layer network which contains only the current balance of international flows and considers the spillovers temporally through a single round.

There exists a multi-layer network, known as the connectedness network model, which was proposed by Leonidov and Kireyev (2015) [57]. The network can capture higher-round network effects through the interactions of each balance of international flows. This model is more adaptable for international spillovers, with a more detailed identification of network effects consecutively, directionally and asymmetrically. Leonidov and Kireyev (2015 [57], 2016 [58]) constructed a connectedness network of international trade, which simulates the whole process of spillover, spillins and spillbacks under repeated occurrence of an initial shock. This is exactly the model selected in this research. However, a multi-layer network such as the connectedness network calls for higher data requirements; bilateral data on each balance of flows are needed.

Motivated by the carbon flow data supported by MRIO analysis, this paper builds upon these previous studies and proposes the carbon-connectedness network model for the first time. We have adapted the trade-connectedness network model into a carbon-connectedness network model to better suit research on climate governance. To cope with the extremely high requirements for data, we then combined the connectivity model with multiregional input–output analysis, depicting the extensive and complete carbon flow among economics driven by international trade with trends, directions and weights. Focusing on this carbon-connectedness network, we analyze its common features and heterogeneous characteristics from a static perspective. Further, we take into account its network effects from a dynamic perspective, a factor which has long been disregarded in the existing literature. Finally, we compare China with USA when each is regarded as the epicenter, respectively.

3. Methodology, Model and Data

3.1. Consumption-Based Embodied Carbon with MRIO

The input–output analysis, firstly proposed by Leontief in 1970, serves as a clear reflection of the flow of commodities between economies through trade. The derivation of the concept of “embodied flow” (such as embodied air pollution emission, embodied water pollution, etc.) has led to the increasing application of the input–output analysis in the environmental field, and it has become a basic paradigm for studying the carbon transfer embodied in trade [52]. Referring to the methods of Moran and Wood (2014) and Jiborn et al. (2018) [22,33], this paper employs a multiregional input–output model (MRIO) (Miller and Blair, 2009) [59] to estimate the carbon emissions embodied in international trade. The MRIO framework can be referenced in Appendix A (see Table A1).

On the basis of the MRIO framework, we employed a world input–output table (WIOT) provided by the Eora database for the following research. There are N economies (or regions) in the world, and each economy (or region) has m sectors within it. In this paper, to ensure the integrity and uniformity of the data, we employed the simplified Eora26 model recommended by the Eora database, where $N = 177$ and $m = 26$. See Tables A2 and A3 in the Appendix A for a specific list of 26 sectors and 177 economies. Z is the matrix of intermediate consumption combined by individual input–output tables; the term $Z_{ij}(i, j = 1, 2, \dots, N \text{ and } i \neq j)$ is the intermediate input from economy i to economy j ; Y is the matrix of final demand, which includes six variables: household final consumption, non-profit institutions serving households, government final consumption, gross fixed capital formation, changes in inventories and acquisitions less disposals of valuables; the term $Y_{ij}(i, j = 1, 2, \dots, N \text{ and } i \neq j)$ is the final demand of economy j produced by economy i ; VA is the matrix of added value, which includes six variables: compensation of employees, taxes on production, subsidies on production, net operating surplus, net mixed income and consumption of fixed capital; X is the matrix of total outputs; the term

$X_i (i = 1, 2, \dots, N)$ is the total output vector of the economy i . According to MRIO rules, Equation (1) can be obtained from Table 1.

$$\begin{bmatrix} Z_{11} + Z_{12} + \dots + Z_{1N} \\ Z_{21} + Z_{22} + \dots + Z_{2N} \\ \vdots \\ Z_{N1} + Z_{N2} + \dots + Z_{NN} \end{bmatrix} + \begin{bmatrix} Y_{11} + Y_{12} + \dots + Y_{1N} \\ Y_{21} + Y_{22} + \dots + Y_{2N} \\ \vdots \\ Y_{N1} + Y_{N2} + \dots + Y_{NN} \end{bmatrix} = \begin{bmatrix} X_1 \\ X_2 \\ \vdots \\ X_N \end{bmatrix} \quad (1)$$

Table 1. Description of pass-through coefficients (β).

	Amplifiers	Absorbers	Blockers
Number of economies	34	94	49
Millennium Development Goals (MDGs) (Data source: https://mdgs.un.org/ , accessed on 26 March 2024)			
Developed	7	24	20
Developing	27	70	29
Pass-through coefficients			
Average	1.36	0.74	−0.01
S.e.	0.31	0.19	0.77
Max	2.01	0.99	0.77
Min	1.00	0.19	−4.75

Define a new matrix $A_{n \times n}$, where $A(A^{ij} = Z^{ij} / \hat{X}^j)$ is the matrix of the direct consumption coefficient, which reveals the technical and economic relations among various sectors. $\hat{X}^j$ is a diagonalized matrix constructed by the total output of economy, j . Scilicet, Equation (1) can be written as Equations (2) and (3).

$$AX + Y = X \quad (2)$$

$$X = (1 - A)^{-1}Y = LY \quad (3)$$

In Equation (3), $(1 - A)^{-1}$ is the global Leontief inverse matrix. By multiplying it by the carbon emission factor coefficient matrix, a matrix of carbon emissions embodied in international trade can be obtained, as illustrated by Equation (4).

$$E = \hat{e}LY \quad (4)$$

This is rewritten in matrix form as Equation (5):

$$\begin{bmatrix} c_{11} & \dots & c_{1j} \\ \vdots & \ddots & \vdots \\ c_{i1} & \dots & c_{ij} \end{bmatrix} = \begin{bmatrix} e_1 & \dots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \dots & e_i \end{bmatrix} \times \begin{bmatrix} l_{11} & \dots & l_{1j} \\ \vdots & \ddots & \vdots \\ l_{i1} & \dots & l_{ij} \end{bmatrix} \times \begin{bmatrix} Y_{11} & \dots & Y_{1j} \\ \vdots & \ddots & \vdots \\ Y_{i1} & \dots & Y_{ij} \end{bmatrix} \quad (5)$$

Thus, carbon emissions embodied in the export trade and import trade for economy i are shown, respectively, in Equations (6) and (7). Vector CEX_i is the carbon emissions embodied in the export activities of economy i , the term CEX_{ij} is the carbon emissions caused by products produced in economy i and ultimately consumed in economy j , i.e., the embodied carbon emissions inflow from economy j to i . Therefore, the total inward carbon flow for economy i can be aggregated as Equation (8), which means that the carbon emitted by economy i should be the responsibility of economy j . Vector CM_i is the carbon emissions embodied in the import activities of economy i , the term CM_{ji} is the carbon emissions caused by products produced in economy j and ultimately consumed in economy i , i.e., the embodied carbon emission outflow from economy i to j . Therefore, the total out-

ward carbon flow for economy i can be aggregated as Equation (9), which means that the carbon emitted by economy j should be the responsibility of economy i .

$$CEX_i = \begin{pmatrix} CEX_{i1} \\ CEX_{i2} \\ \vdots \\ CEX_{iN} \end{pmatrix} = \begin{pmatrix} c_{i1} \\ c_{i2} \\ \vdots \\ c_{iN} \end{pmatrix} = \begin{pmatrix} \hat{e}LY^{i1} \\ \hat{e}LY^{i2} \\ \vdots \\ \hat{e}LY^{iN} \end{pmatrix} \quad (6)$$

$$CM_i = \begin{pmatrix} CM_{1i} \\ CM_{2i} \\ \vdots \\ CM_{Ni} \end{pmatrix} = \begin{pmatrix} c_{1i} \\ c_{2i} \\ \vdots \\ c_{Ni} \end{pmatrix} = \begin{pmatrix} \hat{e}LY^{1i} \\ \hat{e}LY^{2i} \\ \vdots \\ \hat{e}LY^{Ni} \end{pmatrix} \quad (7)$$

$$Total_CEX_i = \sum_{j \neq i}^N c_{ij} = \sum_{j \neq i}^N \hat{e}(1 - A)^{-1} Y^{ij} \quad (8)$$

$$Total_CM_i = \sum_{j \neq i}^N c_{ji} = \sum_{j \neq i}^N \hat{e}(1 - A)^{-1} Y^{ji} \quad (9)$$

3.2. Connectedness Network Model

Referring to the approach of Leonidov and Kireyev (2015 [57], 2016 [58]), we will construct a connectedness network for carbon emissions transfer and describe the spillover effects, spillin effects and spillback effects under an initial shock in the epicenter economy.

1. Step 1: constructing the carbon-connectedness network.

Based on the data of carbon flows embodied in international trade, a carbon emissions inflow–outflow matrix $W = \{w_{ij}\}$ is formed, expressed as Equation (10) (we consider transfers between distinct economies only, so the diagonal elements of matrix W are set to zero). In this matrix, rows show carbon emissions inflow of an economy from all other economies, and columns show carbon emissions outflow of one economy to all other economies. The term w_{ij} stands for carbon emissions transfer from economy j to economy i . For a fixed $i = i_0$, w_{i_0j} is the vector of carbon emissions inflow into economy i_0 , and for a fixed $j = j_0$, vector w_{ij_0} is the vector of carbon emissions outflow of economy j_0 .

$$W = \begin{pmatrix} w_{11} & \cdots & w_{1j} & \cdots & w_{1N} \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ w_{N1} & \cdots & w_{Nj} & \cdots & w_{NN} \end{pmatrix} \quad (10)$$

In Equations (11) and (12), $I = (I_1, \dots, I_N)$ is the total inflow vector, which represents the total carbon emissions inflow into economy i ; $O = (O_1, \dots, O_N)$ is the total outflow vector, which represents the total carbon emissions outflow of economy j . Consequently, a global carbon emissions transfer network with directions and weights is formed.

$$I_i = \sum_{j=1}^N w_{ij} \quad (11)$$

$$O_i = \sum_{i=1}^N w_{ij} \quad (12)$$

Next, we simulate a process of repeated occurrence of an initial shock. An initial shock in the epicenter economy will be passed through to the first neighbor economy, and then to the second and even the n th neighbor economy in the connectedness network. In this paper, we regard China as the epicenter economy, and assume a positive change in China's

total outflow $O \rightarrow O + \Delta O$, which is exactly the initial shock. For each of its first neighbor economies, the positive carbon emissions outflow shock ΔO of China is equivalent to an increase in their carbon emissions inflow shock $\{\Delta w_{ij}\}$, which is assumed to be shared proportionally, as Equations (13) and (14).

$$\Delta O_j = \sum_{i=1}^N \Delta w_{ij} \quad (13)$$

$$\Delta w_{ij} = \frac{w_{ij}}{\sum_{k=1}^N w_{kj}} \Delta O_j = \frac{w_{ij}}{O_j} \Delta O_j \quad (14)$$

Then, the carbon emissions inflow–outflow matrix transforms from W to $\tilde{W} = W + \Delta W$, where

$$\Delta W = \begin{pmatrix} \Delta w_{11} & \cdots & \Delta w_{1j} & \cdots & \Delta w_{1N} \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ \Delta w_{N1} & \cdots & \Delta w_{Nj} & \cdots & \Delta w_{NN} \end{pmatrix} \quad (15)$$

Additionally, the total inflow vector of the first neighbors changes from I to $I + \Delta I$, where

$$\Delta I_i = \sum_{j=1}^N \Delta w_{ij} = \sum_{j=1}^N \frac{w_{ij}}{O_j} \Delta O_j \quad (16)$$

After receiving such a carbon emissions inflow shock, the first neighbor economies will convert it into a new outflow shock, while the pass-through coefficients differ because of their different responses and sensitivities. Since carbon emission inflow and outflow data are calculated based on trade, we believe that the pass-through coefficients estimation model between the import and export trade of an economy is also applicable to the carbon emission inflow and outflow to some extent. Therefore, following the estimation method of Leonidov and Kireyev (2015) [57], the pass-through coefficients are estimated by Equation (17). Considering the lagged response, we improve the model by adding a lag term.

$$\ln O_{i,t} = \partial_i + \beta_i \ln I_{i,t} + \gamma_i \ln I_{i,t-1} + \varepsilon_i \quad (17)$$

Considering the simplest case, a linear relation exists between ΔI and ΔO , so that a new outflow shock is generated, as Equations (18) and (19) show.

$$\ln \left(\frac{O_{i,t} + \Delta O}{O_{i,t}} \right) = \beta_i \ln \left(\frac{I_{i,t} + \Delta I}{I_{i,t}} \right) \quad (18)$$

$$\Delta \tilde{O}_i = O_i \left(\left(1 + \frac{\Delta I_i}{I_i} \right)^{\beta_i} - 1 \right) \quad (19)$$

The newly generated outflow shock $\Delta \tilde{O}_i$ will be passed through to the second to the n th round in the same process as above. The complete process is shown in Figure 1. The initial shock in the epicenter economy is defined as an increase of its outward carbon transfer driven by any reasons, such as its ongoing, but not yet successful, low-carbon production. Specifically, ΔO is the initial shock. The inflow shocks of neighbor economies are defined as the increase in their inward carbon transfer caused by the initial shock, and the outflow shocks of neighbor economies are defined as the increase in their outward carbon transfer, which would be passed through to the next neighbor. Specifically, $\Delta \tilde{I}_i$ of the first, second, third and the n th neighbor economies are representative of inflow shocks, whereas $\Delta \tilde{O}_i$ of the first, second, third and the n th neighbor economies are representative of outflow shocks.

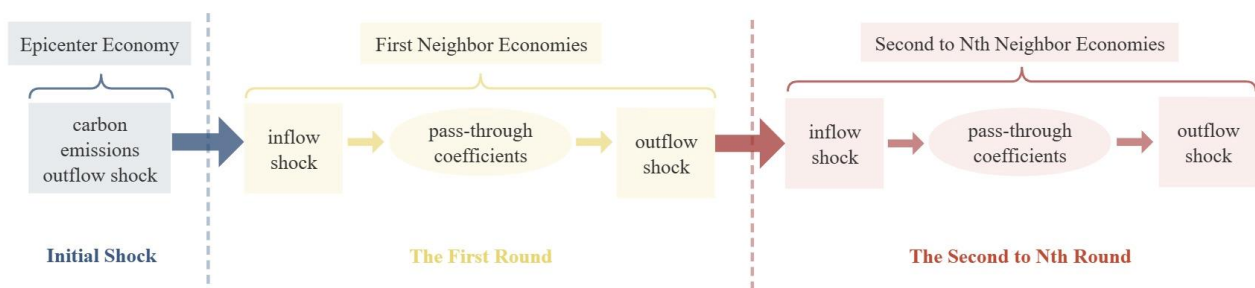


Figure 1. The process of shock occurrence.

The low-carbon transition will take decades, rather than occurring suddenly. Based on the current production estimates, once an initial shock occurs, an inflow shock will be received by the first neighbor economies and an outflow shock will be generated domestically and will be received by the second to the n th neighbor economies. In this way, once the initial shock is nonzero, it may continue to be transmitted and received, as shown in Figure 1. The scale of the shock will also be amplified, absorbed or blocked through the process.

2. Step 2: spillover, spillin and spillback effects.

After multiple rounds of delivery, the shock gradually weakens until it disappears. In the entire process of dynamic evolution, we regard China as the core, which proactively generates the initial shock, and other economies as the periphery, which passively receives the shock. Through this core–periphery structure, there are complex and assignable network effects in the carbon-connectedness network, including spillover effects of the initial shock in China to the rest of the world, spillin effects among economies other than China, spillback effects from the rest of the world on China itself, caused by its initial potential shock.

Figure 2 describes the simplest context of a connectedness network with 3 economies. Economy A is the epicenter economy and economies B and C are two neighboring economies. A change in economy A, known as the initial shock, will directly spillover on economies B and C, with the direct spillover effects equaling the inflow shocks received by B and C from A. Over the n th round of propagation, B and C will spillback on economy A, with the spillback effects equaling the inflow shocks received by A. In addition, economies B and C will spillin into each other in the process, with the spillin effects equaling the inflow shocks received by B from C, as well as by C from B.

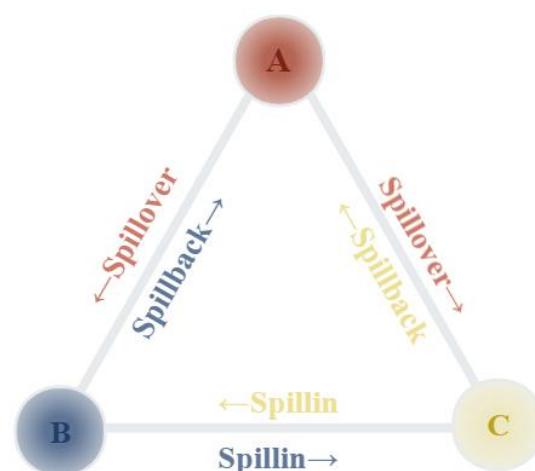


Figure 2. Spillovers, spillins and spillbacks in the network.

Further expanded into a multinational context, spillover effects can be defined as the effects transmitted from an initial shock in the epicenter to its first neighbors; it can also be called *direct spillovers*. Spillin effects can be defined as the effects received by the

n th neighbors from the first neighbors, and can also be called indirect spillovers. Direct and indirect spillovers add up to the total spillovers from the epicenter to its peripheries. Conversely, spillback effects can be defined as the effects transmitted from any neighbors to the epicenter. The appendix includes an illustrative example of calculating spillover effects (see Appendix B).

In the follow-up research, we regard China as the epicenter and investigate how its context spills over to other economies. The selection of China is reasonable and sensible for several reasons. First, China is one of the largest developing economies worldwide. Traditional studies regard developed countries as the center of the world, while research centered on developing countries is lacking, which is necessary. The impact of developing countries on the world should not be ignored, and that is why the Climate Solidarity Pact was proposed. Second, China is the world's largest carbon emitter and energy consumer, as well as the biggest trade partner globally. China has undertaken too much foreign carbon emission transfer, which is one of the main reasons for the rapid increase in China's carbon emissions.

3.3. Data Sources

The input–output table selected for calculating the carbon emissions embodied in international trade is from the Eora database, released by UNCTAD (data source: <https://worldmrio.com>, accessed on 26 March 2024). The Eora dataset provides a complete global MRIO table in a harmonized 26-sector classification and covers the matching environmental accounts for 190 economies, from 1990 to 2021. Therefore, we regard it as more suitable compared to other MRIO databases, such as WIOD, EXIOBASE, etc. After calculation, the final dataset contains the trade-embodied carbon emission transfer data among 177 sample economies, covering the period from 1990 to 2021. Other data sources, including Emissions Database for Global Atmospheric Research (EDGAR) (data source: <https://edgar.jrc.ec.europa.eu/>, accessed on 26 March 2024), UN Comtrade Database (data source: <https://comtradeplus.un.org/>, accessed on 26 March 2024), UNSDG (data source: <https://unstats.un.org/sdgs/dataportal>, accessed on 26 March 2024), IMF data (data source: <https://www.imf.org/external/datamapper/PPPGDP@WEO/OEMDC/ADVEC/WEOWORLD>, accessed on 26 March 2024), the World Bank database (data source: <https://data.worldbank.org/topic/economy-and-growth>, accessed on 26 March 2024), World Development Indicators (WDI) (data source: <https://databank.worldbank.org/source/world-development-indicators>, accessed on 26 March 2024), OECD-TIVA database (data source: OECD-TIVA database-2021edition, <https://stats.oecd.org>, accessed on 26 March 2024).

4. Result Analysis

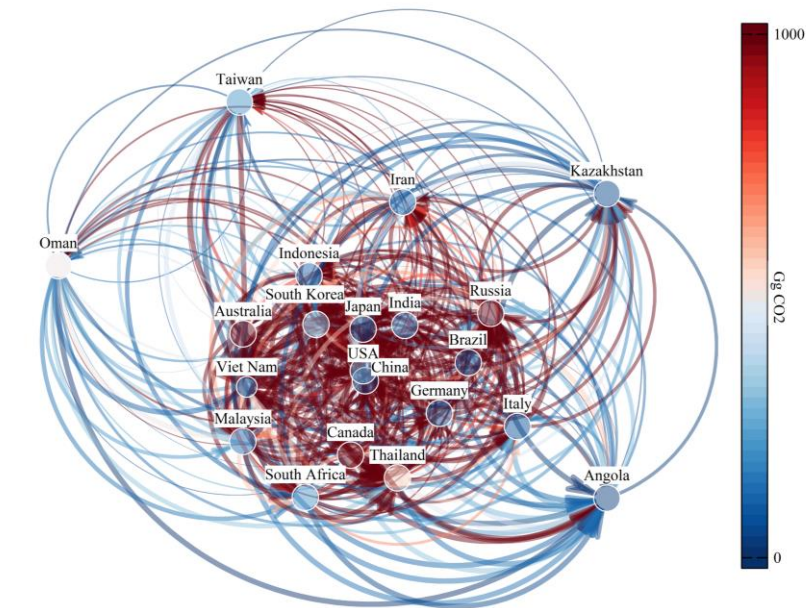
4.1. China in the Network of Carbon Emission Transfers

China's international trade is closely intertwined with the majority of economies, resulting in the global transfer of embodied carbon emissions. To ensure data integrity, we focus on 177 economies that have international trade links with China. By employing a MRIO model, we construct an inflow–outflow matrix for carbon emission transfers, providing a comprehensive and intuitive representation of the multilateral relationships among these economies. Moreover, this extensive matrix forms a complex system, and we numerically simulate it using the Force-Directed Placement Algorithm (Fruchterman and Reingold, 1991) [60].

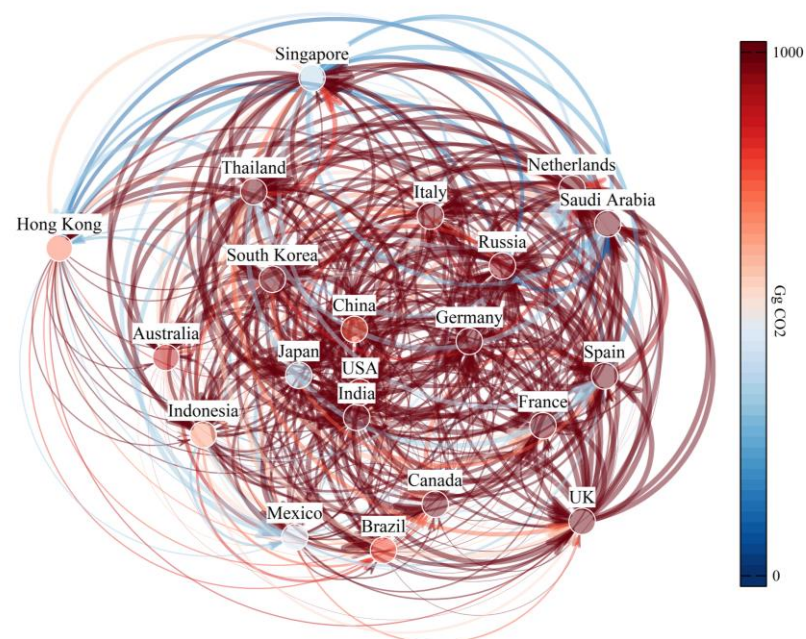
Force-Directed Placement is a widely adopted algorithm in graph layout for any type of schematic diagram. It simulates the motion of nodes and edges by incorporating attraction and repulsion forces, resulting in a stable layout through automatic clustering and iterative refinement, commonly referred to as the force-directed layout graph. In such a force-directed layout graph, each node within the system is regarded as an electric charge, with repulsive forces acting between any two charges representing their connecting edges. Under the interaction of attraction and repulsion, charges move continuously from an initial random and disordered state until they reach a balanced and organized configuration. The

final layout effectively visualizes the relationships among nodes, as well as the overall structure, providing an intuitive representation of complex networks.

Comprehensively analyzing the data of carbon emission transfers derived from MRIO, we find that China exhibits significant carbon inflows and outflows with 177 economies worldwide, indicating its central role in the global carbon transfer network. We visualize the stable layout of the carbon transfer network, with China as the epicenter economy in 2021, shown in Figure 3. These two stable layouts are weighted, directed and asymmetrical, which leads to their inconsistencies in transmitting shocks. We have identified the common and heterogeneous features between the two stable layouts.



(a) Network of China's carbon emission outflows



(b) Network of China's carbon emission inflows

Figure 3. The network of China's carbon emission transfer, 2021.

Note: (1) Figure 3a,b show a complex network of carbon emission transfer among China and its top 20 target economies and origin economies, respectively. The nodes are individual economies involved in this network, and the edges are carbon emission transferred among these economies. (2) The colors of the edges show the absolute scale of carbon emission transfer from/into China, where blue represents 0, and red represents 1000 Gg CO₂. (3) The colors of the nodes show the average scale of carbon emission transfer into/from individual economies, following the same color standard as above.

1. Feature 1: the carbon transfer network is scattered and ubiquitous.

In Figure 3a, the sum of the top 20 economies accounts for 44.7% of China's total carbon emission outflow, and in Figure 3b, the sum of the top 20 economies accounts for 52.2% of China's total carbon emission inflow. About half of the carbon emission transfer outflows and inflows are associated with the remaining 157 economies, indicating a relatively scattered network of global carbon emission transfer, with China as the epicenter. The phenomenon of carbon emission transfer is not solely observed within individual major trading partners, but it is tightly interwound with most economies worldwide.

2. Feature 2: a carbon deficit in China.

When comparing Figure 3a,b, it becomes evident that the inflow network exhibits a significantly higher degree of redness than the outflow network, both in terms of node colors and edge colors. What is more, we observe that 12 economies (these 12 countries are the United States, South Korea, Russia, Japan, India, Thailand, Germany, Indonesia, Australia, Brazil, Canada and Italy) consistently appear in both figures, all of which are included in China's top 15 trading partners list. Upon comparing the performances of these 12 economies, it is evident that their carbon inflows into China generally surpass the outflows from China. The "redder" inflows of carbon emission transfer into China indicate a carbon deficit, underlying China's trade surplus, which would exacerbate the burden of net carbon emission transfer on China.

3. Feature 3: carbon inflows' origin is different from the outflows' target.

In addition to the 12 economies that appear repeatedly in the top origin list and target list, we are more interested in their differences.

We find that Malaysia, Vietnam, Iran, Kazakhstan, Taiwan, Angola, Oman and South Africa are the main targets of carbon emission outflows from China. From the perspective of developing level and geographical distribution, they are all developing economies in Asia and Africa, with a medium or low GDP level, especially in east to south Asia, Central or South Africa, and Angola is even the least developed country. From the perspective of energy consumption, industrial structure and carbon productivity, they are more dependent on fossil energy and weaker in the tertiary industry compared to China, with relatively lower productivity under a unit of carbon dioxide. More importantly, these economies are all in a huge carbon deficit in terms of bilateral carbon transfer with China, which means that their carbon inflows from China are far larger than the outflows into China, resulting in a state of high imbalance.

France, Hong Kong, the United Kingdom, Singapore, Spain, Mexico, the Netherlands and Saudi Arabia are the main sources of carbon emission inflows into China. From the perspective of their development level and geographical distribution, these economies are more developed, with medium-to-high GDP levels concentrated mainly in Europe and America. From the perspective of energy consumption, industrial structure and carbon productivity, they are less dependent on fossil energy and stronger in the tertiary industry compared to China, with relatively higher productivity under a unit of carbon dioxide. Diametrically opposed, these economies all have a huge carbon surplus in terms of bilateral carbon transfer with China, which means that their carbon outflows into China are far larger than the inflows from China. China has taken responsibility for their net carbon outflows.

To conclude, in this section, we substantiate the gravity of global carbon emission transfer, which has long been neglected by the international community. Specifically, our

findings align with the Climate Solidarity Pact proposed during COP27. They not only unveil a substantial carbon emission transfer from developed economies into developing economies, but also underscore China's massive responsibility for peripheral economies.

4.2. Estimation of Pass-Through Coefficients for Various Economies

Based on the stable layout above, we adopt the connectedness network model proposed by Kireyev and Leonidov (2015) [57] to capture the projection of the network's future response to subsequent endogenous shock. Centered on China, each individual economy in the carbon-connectedness network might augment, absorb or block the initial shock through a sequential transformation of its inflow–outflow matrices in higher rounds. The estimated pass-through coefficients, that is β , may lead to three scenarios of shock diffusion, and, correspondingly, β also determines the three different roles that individual economies may play in the network. The roles of 177 economies in our sample are shown in Table A4 (see Appendix A).

A total of 34 economies are spillover amplifiers. In this case, β is statistically significant and $\beta > 1$. This suggests that a change in carbon emission inflow from first neighbors will lead to a proportionally larger change in their outflow. As a result, these economies will amplify the impact on other economies when passing through the initial shock impulse. Amplifiers consist of three types of economies: (i) China's main trading partners, e.g., Indonesia, Pakistan, etc., are highly dependent on China's foreign trade and are more sensitive to shocks in China. (ii) China's geographical neighbor, e.g., Mongolia, Japan, Kazakhstan, Kyrgyzstan, etc., are more vulnerable to China due to geographical proximity. (iii) Major fossil energy exporters are more dependent on China, e.g., Algeria, Australia, Iraq, Nigeria, etc. The high-carbon structure of export products determines their role as amplifiers.

A total of 94 economies are spillover absorbers. In this case, β is statistically significant and $0 < \beta \leq 1$, indicating that a change in carbon emission inflow from first neighbors will lead to a proportionally smaller change in their outflow. As a result, these economies will absorb a partial impact on other economies when passing through the initial shock impulse. Most economies in the world are shock absorbers.

A total of 49 economies are spillover blockers. In this case, $\beta \leq 0$ or is not statistically significant, indicating that a change in carbon emission inflow from first neighbors will not lead to any change in their outflow. As a result, these economies will completely block all impacts on other economies when passing through the initial shock impulse. Blockers consist of three types of economies. (i) The least-developed economies or middle-to-low level developing countries, e.g., Ethiopia, Liberia, Ethiopia, etc., are less dependent on foreign trade because of backward economic level. Thus, they are at a relatively low status in the global carbon transfer network. (ii) Some powerful developed economies, e.g., the United States, Canada, the United Kingdom, etc., are in leading positions in the global economy and thus are hardly affected by China's carbon outflows.

4.3. Network Effects Centered on China

Given the network structure above, we regard China as the epicenter economy. The spillovers from an initial shock in China will affect its direct and indirect trading partners in several rounds of transmission. According to the data on China's carbon emission outflows and inflows from 1990 to 2021, there is an increasing trend in both directions. Meanwhile, inflow data are significantly higher than outflow data. The outflows increase at 5.33% per year on average, with the highest growth rate of 12.5% being recorded in 2003. Considering the convenience and comparison in estimation, the initial shock is presented as a 10% positive increase in China's total carbon outflows in 2021, which is equivalent to a 0.3426 kt CO₂/hundred million USD GDP increase when compared to GDP. Due to the large differences in developing levels, trade volume and the scale of carbon emissions embodied among different economies, network effects are expressed compared to GDP. After simulating n rounds of transmission of the initial shock, we observe its passage

through the economies in the network for several rounds before it disappears after the sixth round. Therefore, we will take into account six rounds of shock spillovers.

4.3.1. Spillover Effects

As a direct consequence of the initial shock, spillovers would be experienced by China's trading partners (first neighbors). Considering only the 30 economies where the impact felt would be the largest, the first round of China's direct spillover effects is shown in Figure 4. Figure 4a represents the absolute scale of spillovers, while Figure 4b represents the spillovers compared to GDP, which provides more informative insights.

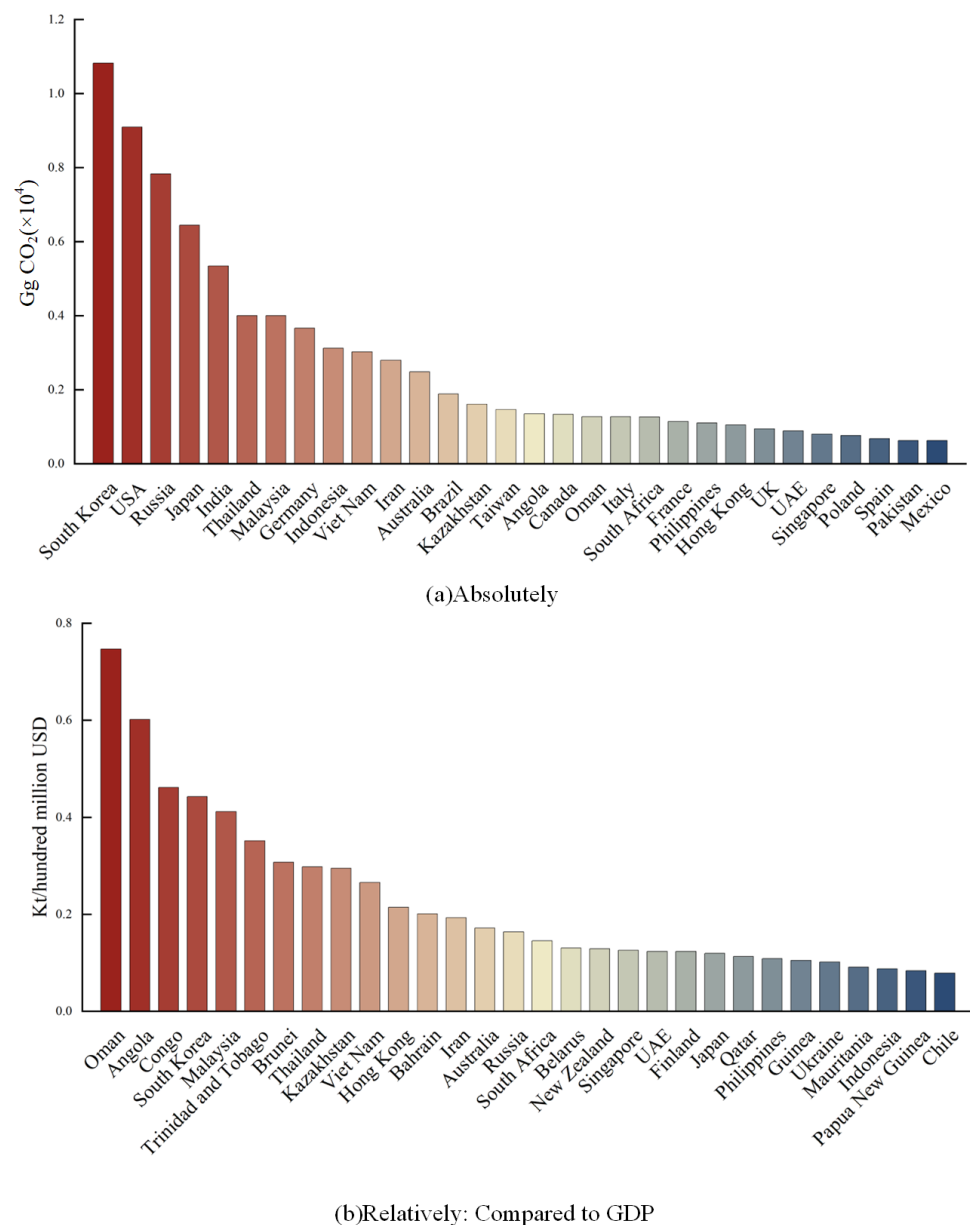


Figure 4. China's direct spillover effects in the first round.

From the perspective of absolute spillovers in Figure 4a, the economies most affected by China are consistent with China's major trading partners. However, when compared to the GDP of individual economies, the result differs markedly. In Figure 4b, an average impact (kt CO₂/hundred million USD GDP) of 0.0622 would be felt by all the peripheries, with some countries experiencing even higher impacts, such as Oman at 0.747, Angola

at 0.602 and Congo at 0.462. A large burden of carbon emission responsibility would be transferred to these economies.

We find some similarities among economies that suffer more direct spillover effects from China. (i) Most of them are located in the East to South Asia and Africa, few of them are located in Europe and America, meanwhile, most of them are countries of the Belt and Road Initiative. These economies are closely tied with China in economics, trade, politics, or geopolitics, resulting in more carbon emission responsibility transfer. For example, China is one of the largest trading partners of South Africa, and is also the main trading partner of Indonesia, Thailand, Philippines, etc. (ii) Most of them are rich in natural resources such as oil, natural gas, coal, minerals, etc., meanwhile, they are dependent on fuel energy in economic growth. The exploitation and use of fuel energy resources lead to large amounts of fuel energy exports and imports, together with lagged clean energy technology. Therefore, they experience more spillovers from global carbon emission transfer. For example, Oman, Angola, Russia, Indonesia and Kazakhstan are abundant in fossil energy resources and are also large users of fossil fuels, China imports considerable amounts of fossil energy from them.

4.3.2. Spillin Effects

Spillovers in the second to sixth round are indirect spillovers passed through by peripheral economies, also called spillin effects in the carbon-connectedness network, shown in Figure 5. China would apply a spillin effect (kt CO₂/hundred million USD GDP) of 0.1404 to Peripheral economies on average, as high as 1.381 in Brunei, 1.152 in Trinidad and Tobago, 0.910 in Oman.

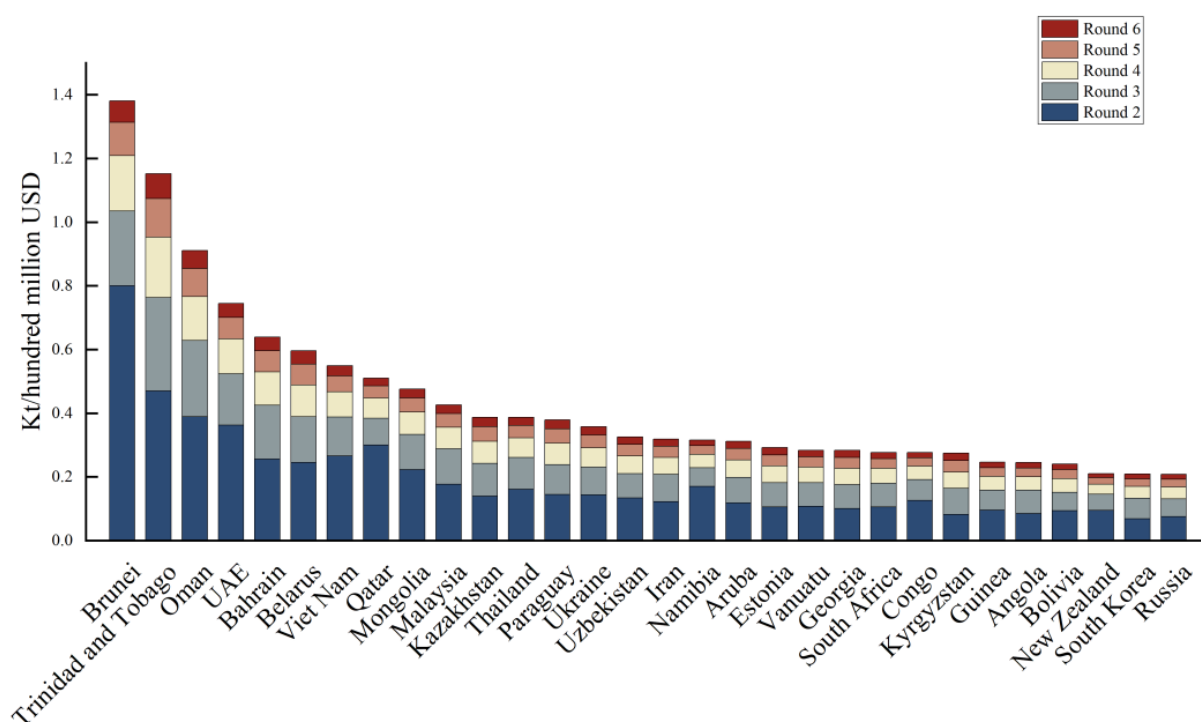
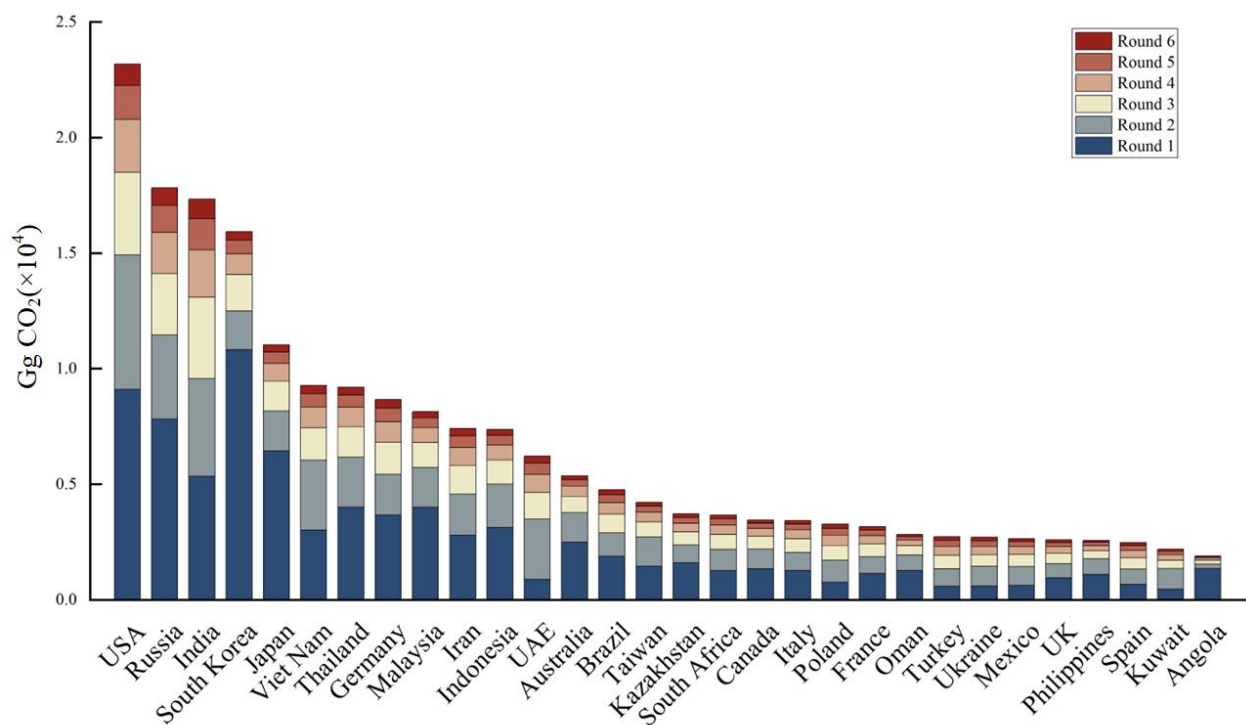
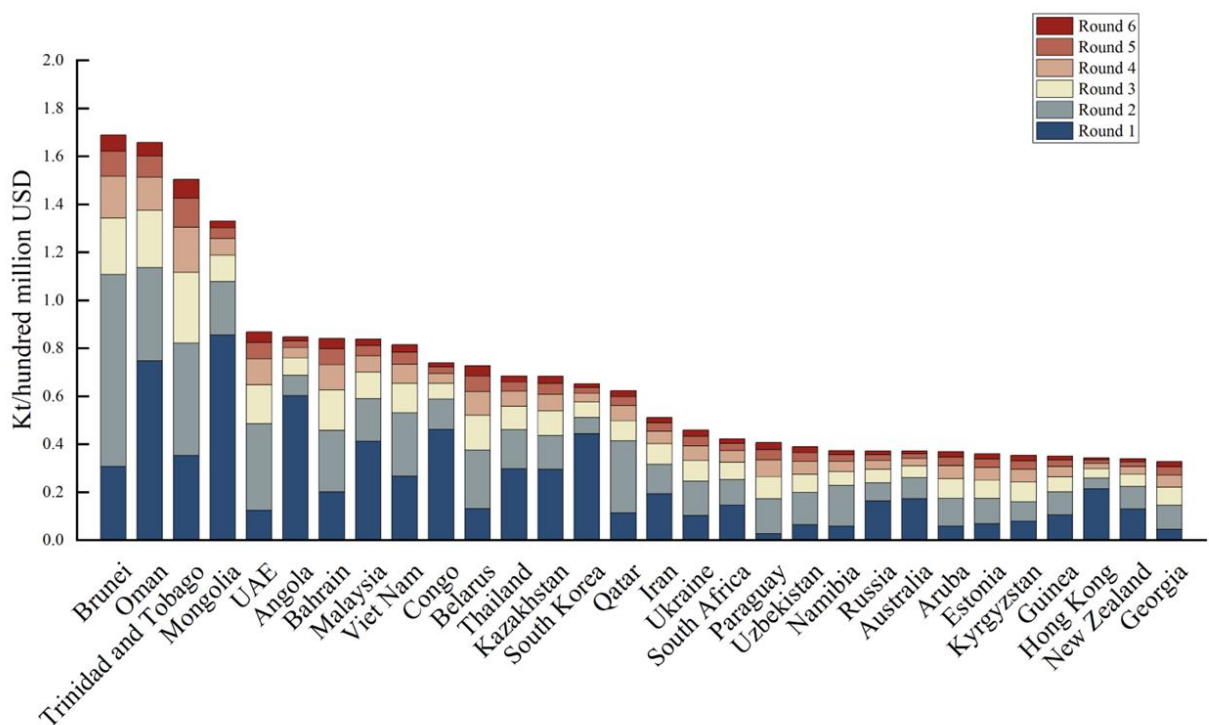


Figure 5. China's spillin effects in the second to sixth round: compared to GDP.

Taking into account six rounds of shock's total spillovers, the negative impact caused by an initial shock in the global network is substantially higher, as depicted in Figure 6a,b. The largest total spillovers (kt CO₂/hundred million USD GDP) would be experienced by economies such as Brunei at 1.688, Oman at 1.657, Trinidad and Tobago at 1.504.



(a) Absolutely



(b) Relatively: Compared to GDP

Figure 6. China's total spillover effects in six rounds: spillovers and spillins.

Contrast Figures 4b and 6b, economies most affected by China are basically consistent, 23 economies appear repeatedly. Economies such as Paraguay, Uzbekistan, Namibia, Aruba, Estonia, Kyrgyzstan, Georgia are more affected by spillovers in the first round, while less by cumulative spillovers. On the opposite, Singapore, Finland, Japan, Philippines, Mauritania,

Indonesia, Papua New Guinea, and Chile are less affected by spillovers in the first round, while more by cumulative spillovers.

In addition, through the ratio of first-round spillovers to cumulative spillovers in Figure 6b, we find that most economies have received less than half of the total spillovers from China, and received more spillins from other economies in the network, which means tight connectedness among economies in the network. All these findings can also be proved by comparing Figures 4a and 6a, where 27 economies appear repeatedly.

4.3.3. Spillback Effects

In addition to the spillover and spillin effects, China would receive spillback effects from its initial shock, shown in Figure 7. China receives no spillback in the first round and the largest spillback in the second round. In round 2, China would suffer a 0.1109 kt CO₂/hundred million USD GDP spillback with a 10% change of carbon emission outflow (equal to a 0.3426 kt CO₂/hundred million USD GDP change compared to GDP) from itself, 32.4% of the initial shock would be back to China itself. Subsequently, the spillbacks diminish round by round and gradually disappear, it drops to 0.0143 in round 6.

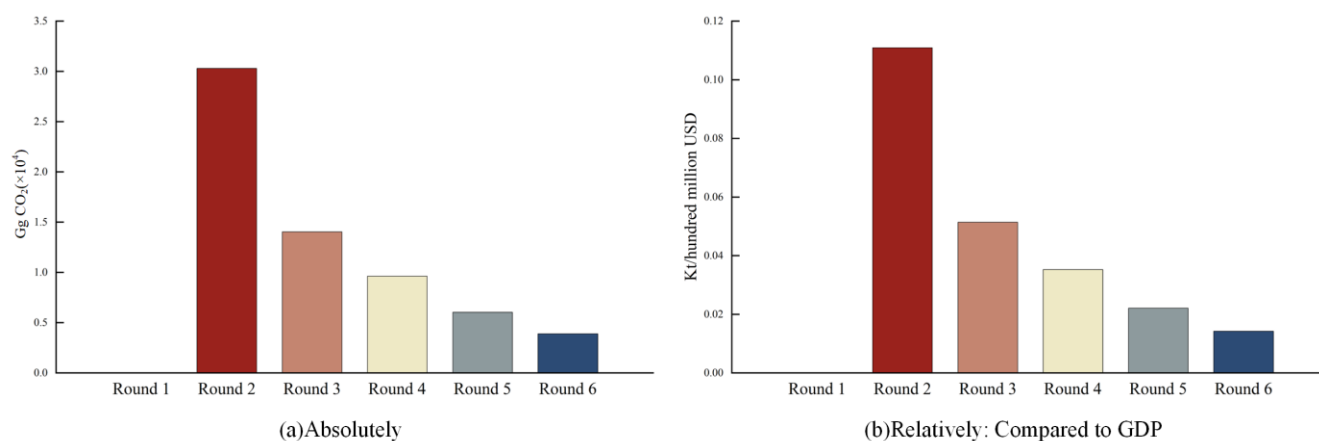


Figure 7. China's spillback effects.

The existence of spillback effects is of great significance, a change in China's carbon emission outflow would not only affect other economies in the global carbon-connectedness network, but also affect itself on a considerable scale. Therefore, the existence of a carbon emission transfer network is not conducive to achieving either the 1.5-Degree Goal or the Climate Solidarity Pact.

In this section, we substantiate the existence of spillover effects, spillin effects and spillback effects in global carbon emission transfer network. The work is scientific and quite important. Mainstream research is based on original carbon emission data or transfer data, few focus on the network effects from a global perspective. The existence of network effects would amplify the negative shock and cannot be observed by traditional methods. In our carbon-connectedness network, with China as the epicenter, an average level of 0.0622 kt CO₂/hundred million USD GDP in direct spillover effect and 0.1404 kt CO₂/hundred million USD GDP in spillin effect would be received by all peripheries, and more total spillover effects would be received by economies located in Asia and Africa or those with rich fossil energy resources. Additionally, a spillback effect as high as 0.1109 kt CO₂/hundred million USD GDP would soon be received by China, and more spillbacks would be received in the long term.

5. Heterogeneity Analysis

5.1. Differences among Economies at Different Levels of Development

A total of 177 economies in the sample are divided into five groups according to the United Nations Millennium Development Goals: (i) developed regions; (ii) least developed regions; (iii) landlocked developing regions; (iv) small island developing regions; (v) other developing regions, as shown in Table A5 in the Appendix A (the groups (iii), (iv) and (v) are consolidated into one group called “developing regions” in the results).

Spillover effects received and transmitted by economies with different levels of development are shown in Figure 8a,b. Whether spillovers are received or transmitted, the value of developing economies is the highest, while that of the least developed economies is the lowest. This indicates that developing economies are not only the biggest “victims” in the global carbon emission transfer network, but also the biggest potential “transmitters” and “perpetrators” in the next round of shocks.

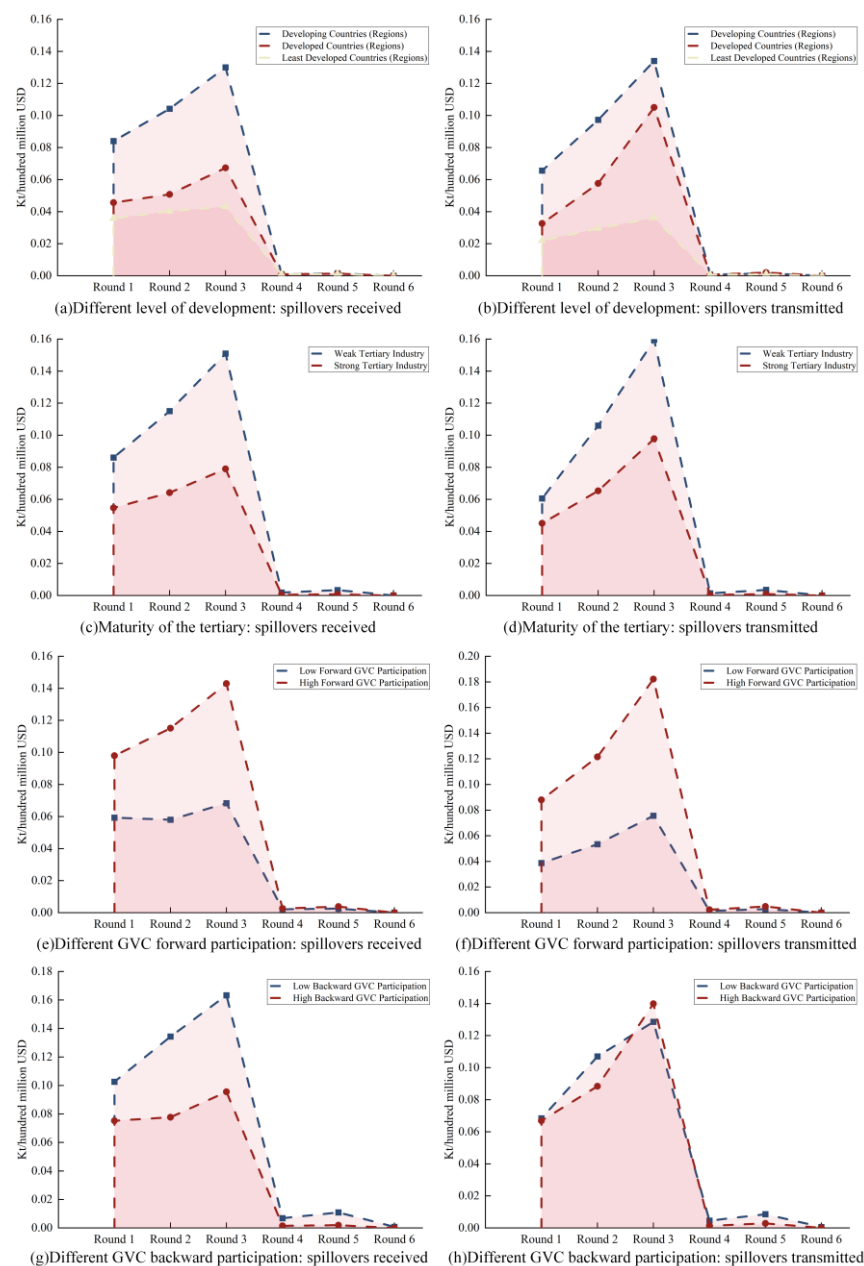


Figure 8. Results of heterogeneity analysis.

There may be three reasons for this. First, developed economies go far faster than developing economies in the low-carbon development process. According to the statistical research released by WRI in 2017 (Levin and Rich, 2017) [61], 53 economies have peaked, or would peak their carbon emissions by 2020. Nearly all developed economies are to bend their carbon emission curve. Second, it is closely related to the different industrial structures between developed and developing economies, which would be elaborated on in Section 5.2. Third, it is also connected with their status in the global value chain, which would be elaborated on in Section 5.3.

5.2. Differences among Economies of Different Industrial Structure

The development level of an economy usually improves alongside with the optimization of its industrial structure. For example, the majority of developed economies have gone through the following change in their industrial structure: the pillar industry of economic activity transitions from the primary industry to the secondary industry and finally to the tertiary industry, corresponding to the stages of traditional agriculture, industrialization and comprehensive development with high efficiency. Meanwhile, there is a clear consistency and correlation between the trade structure and domestic industrial structure. Consequently, international trade will shift from labor-intensive products to capital-intensive and technology-intensive products, resulting in reduced carbon emission transfer and greater environmental sustainability. We believe that the industrial structure may lead to heterogeneous results among economies.

In developed counties, the tertiary industry accounts for more than 50% of their economic activities. By contrast, China's primary, secondary and tertiary industries accounted for 7.2%, 39.43% and 53.31% of GDP, respectively, in 2021. Therefore, taking China as a reference, we classify the sample economies into two groups: economies with strong tertiary industries and economies with weak tertiary industries, according to the added value of the primary, secondary and tertiary industry provided by the World Bank database (data source: <https://data.worldbank.org/topic/economy-and-growth>, accessed on 26 March 2024). Due to incomplete data from a few countries, 155 countries in the sample are finally matched, as shown in Table A6 in the Appendix A.

Spillover effects received and transmitted by economies with different industrial structures are shown in Figure 8c,d. In the first to the sixth rounds, spillover effects received by economies with weak tertiary industries are all larger than those with strong tertiary industries. In the meanwhile, there is almost no difference of spillover effects produced by the two groups of economies. This result indicates that the industrial structure is of great significance to the position of an economy in the carbon emission transfer network. Developing economies should optimize their industrial structure as much as possible to avoid undertaking excessive transfer of carbon emissions that do not belong to them.

5.3. Differences among Economies of Different Positions in GVC

In recent years, China has been playing an increasingly active and important role in the global value chain (GVC), as have other developing economies in the process of globalization. However, developing economies are still struggling in the dilemma of "Low-end manufacturing lock-in" and "high carbon burden". We wonder if the GVC position is significant for explaining the heterogeneity among economies.

The GVC position can be measured by two important indicators: forward participation and backward participation. Forward GVC participation indicates the proportion of intermediate goods in exports. An economy is dependent on the GVC on the supply side if its forward GVC participation is high. Backward GVC participation indicates the proportion of intermediate goods in imports. An economy(region) is dependent on the GVC on the demand side if its backward GVC participation is high. It is generally viewed that, if an economy's(region's) forward GVC participation is high, then it is upstream of GVC and provides more raw materials, technology or intermediate goods to other economies. On the contrary, if an economy's backward GVC participation is high, then it is downstream of

the GVC and uses more intermediate goods from other economies or mainly engages in assembly work, as shown in Figure 9.



Figure 9. Upstream and downstream relationships in GVC.

In this sector, we adopt the forward(backward) GVC participation (data source: OCED-TIVA database-2021 edition, <https://stats.oecd.org>, accessed on 26 March 2024). Due to incomplete data from some countries, 64 countries in the sample are finally matched) in China as the classification criterion. The ample economies are divided into two groups: (i) low forward(backward) GVC participation; (ii) high forward(backward) GVC participation, as Table A7 in the Appendix A.

Spillover effects received and transmitted by economies with different GVC participation are shown in Figure 8e–h. In the first to the sixth rounds, spillover effects received and transmitted by economies with higher forward and lower backward GVC participation are all larger compared to those with lower forward and higher backward GVC participation. This is consistent with reality. Economies with higher forward or lower backward GVC participation are upstream of China, exporting a large number of raw materials and intermediate goods to the latter; therefore, carbon emission transfer from China to them on a large scale.

6. Robustness Check and Comparative Study: US as the Epicenter

Current discussions predominantly revolve around a global economy with the United States as the focal point. Thus, we further discuss this sector by taking the United States as the center. Additionally, there are other reasons supporting the suitability of the United States as a choice. Firstly, China is the largest developing country, while the United States is the largest developed country. The contradiction between developing countries and developed countries regarding carbon emissions is a major concern in the international community, which aligns with the “Climate Solidarity Pact” in the introduction. Secondly, China is currently the biggest emitter, while the US is the biggest emitter historically (BP global, the 72nd edition of the Statistical Review of World Energy. Available at: <https://www.bp.com/en/global/corporate/energy-economics/statistical-review-of-world-energy.html>, accessed on 6 October 2023). Meanwhile, the US is one of the first countries to achieve carbon peak. The contrast could reflect the future efforts of China and other developing countries.

The result shows that the United States would apply a direct spillover effect (kt CO₂/hundred million USD GDP) of 0.123 and a spillin effect of 0.1934 to peripheral economies on average, both of which are apparently larger than spillovers and spillins of China apparently. Additionally, the United States would feel a spillback effect of 0.058 from the peripheries, which is smaller than the spillbacks felt by China.

Taking into account the whole process of spillovers in six rounds, we come to exactly the same conclusions (see Appendix C). Table 2 shows the comparison with China and the United States as the epicenter, respectively. The spillovers represented absolutely by the change of carbon flows are listed on the line above, while the spillovers represented relatively compared to the GDP are listed on the line below. We find that the United States would receive and transmit larger network effects than China either absolutely or relatively compared to GDP. Table 3 shows the comparison of spillovers on economies of different developing levels when centered on China and the United States, respectively. We find that the United States is more influential than China whether on developing economies, or developed economies, but the fact that developing economies will receive more spillovers than developed economies is consistent (most economies worldwide are weaker than the US in the tertiary industry and are upstream of US in GVC. Thus, the discussion of

heterogeneity in these two aspects is removed.). These findings substantiate the gravity and heterogeneity of global carbon emission transfer, both in terms of scale and distribution. The fundamental relationship between “victims” and “perpetrators” remains consistent. Moreover, despite being the largest emitter globally, China exhibits a lower level of carbon emission transfer and would generate fewer network effects compared to the US. These results support the validity of the model and verify the rationality of choosing the United States and China as focal points from the perspective of post-inspection. Meanwhile, these results highlight the urgent need for developed countries to provide assistance and support in addressing carbon emission transfer, aligning with the Climate Solidarity Pact.

Table 2. Contrast between China and US.

Central Economy	Target Economy	Spillovers		Round 1	Round 2	Round 3	Round 4	Round 5	Round 6	Accumulated
China	US	received	(1)	9095.169	5823.477	3566.014	2290.701	1462.074	940.787	23,178.221
			(2)	0.00396	0.0285	0.0200	0.0172	0.0191	0.0257	0.1500
China	US	transmitted	(3)	4656.697	2945.052	1793.947	1148.681	731.625	470.143	11,746.144
			(4)	0.0081	0.0058	0.0041	0.0035	0.039	0.053	0.307
US	China	received	(5)	77,349.763	32,154.373	21,636.975	13,404.396	8545.026	5451.968	158,542.501
			(6)	0.2832	0.1177	0.0792	0.0491	0.0313	0.0200	0.5805
US	China	transmitted	(7)	13,023.163	5285.961	3568.815	2207.963	1406.775	897.194	26,389.871
			(8)	0.1234	0.0807	0.0496	0.0374	0.0381	0.0492	0.3785

Note: (1) Row (1)–(4) are spillovers received or transmitted by US if the epicenter economy is China. Row (5)–(8) are spillovers received or transmitted by China if the epicenter economy is US. (2) We list the absolute and relative spillovers in the table. (3) The unit of row (1) (3) (5) (7) is Gg CO₂, and the unit of row (2) (4) (6) (8) is Kt/hundred million USD.

Table 3. Difference in development levels: contrast between China and US.

		Spillovers Received		Spillovers Transmitted	
Epicenter Economy		China	US	China	US
Development level	Developing	0.3208	0.4014	0.2993	0.3225
	Developed	0.1661	0.2111	0.1981	0.1845
	Least developed	0.1213	0.1543	0.0892	0.1289

Note: (1) We list relative spillovers compared to GDP only, and the unit is Kt/hundred million USD. (2) Data in Table 3 represent the average spillovers received and transmitted by different groups of economies. (3) Due to US's mature industrial structure and absolute upstream position in GVC, we ignore the contrast between US and China in these fields.

7. Conclusions and Policy Implications

This paper adapts a numerical model rooted in the theory of complex networks to climate governance, the so-called carbon-connectedness network. It aims to profile the global carbon transfer network from the perspective of China. Concretely, we combine the multiregional input–output analysis with the connectedness network model in adaptation to integrate massive global carbon flows and formulate the topological structure, spatio-temporal structure, dynamic structure and core–periphery structure in the network when centered on China. We find the following: (1) Firstly, in view of the topological structure, the global carbon transfer network is scattered and ubiquitous, with China's carbon flows closely tied with the majority of the economies worldwide. It suggests that carbon leakage through international trade is worldwide and serious, and should be paid timely attention to by inter-country associations, regional international organizations and the international community. (2) Secondly, in view of the spatio-temporal structure, China has been in a huge carbon deficit for decades, and this situation will continue in the near future. Economies located in East to South Asia, Central or South Africa, with medium to low GDPs, are main targets of China's carbon outflows. Economies located in Europe and America, with a medium-to-high GDP level are the main sources of China's carbon inflows. Under

the “Double Carbon” target, China should prioritize optimizing its trade structure and adjusting the import and export activities in accordance with the carbon inflow and outflow characteristics. (3) Thirdly, in view of the dynamic structure, the negative impact caused by an initial shock of carbon transfer growth on the global network is substantially high. Direct and indirect spillovers would be more received by economies that are located in East to South Asia and Africa and are rich in natural resources. In addition, spillback effects would be received by the epicenter economy which is also notable. The presence of spillover effects enhances our previous estimates of carbon transfer. Under the guidance of the Climate Solidarity Pact, economies in different regions and at varying levels of development should collaborate in mitigating such adverse spillovers. (4) Fourthly, in view of the core–periphery structure, we simulated the context by taking China as an example. In fact, the increase in outward carbon transfer of each economy would cause a greater negative impact through the network, and each country will experience the spillover or spillback effects in the meantime. We also compared the context when US is placed as the epicenter. We found that the US would generate more negative effects through the network. Further, the peripheries of developing economies, economies with weaker tertiary industry, and those with higher forward and lower backward GVC participation are more affected by the shock of carbon transfer when centered on either China or US, which means that they are more sensitive to carbon transfer problems. Spillover effects warrant attention from these relatively weak economies. Meanwhile, other economies are also responsible to help mitigate the transmission of spillovers.

These findings provide additional comprehensive insights for global climate governance, which is comprehensive and all-encompassing. First and foremost, present mitigation strategies only provide a traditional overview of direct emissions or geographical emissions, leading to local reductions but an overall increase. These traditional rules are insufficient to track the carbon leakage effects induced by international trade. Therefore, a fairer principle of consumption-based accounting for responsibilities requires wider application in the international community. Simultaneously, it is urgent to establish explicit policies targeting the issue of carbon emission transfer, such as EU’s carbon tariffs policy and the implementation of carbon markets in select economies. These measures should be refined for widespread adoption among economies.

Next, reductions and mitigations cannot be achieved by unilateral or bilateral policies. What is needed is collective and inclusive global governance, with all economies’ participation in policy formulation, under the guidance of a fairer principle of “common but differentiated” carbon emissions responsibility. Currently, there exist several climate collaborations among developing economies, such as the Green Belt and Road initiative and South–South cooperation on climate change. However, there is a lack of cooperation between developed and developing economies. This is exactly what the “Climate Solidarity Pact” proposed. In terms of inter-country relations, it is imperative to establish systematic policies for emission reduction, drawing lessons from advanced experiences, such as the European Green Deal. Mitigating goals can be achieved by the development of green finance, green technology innovation and the establishment of green industry chains within external linkages. In terms of multi-national alliances, it is crucial to accurately recognize the characteristics of public goods and externalities associated with carbon emissions. Building upon voluntary cooperation and mutual benefits, various forms of collaboration, including capital investment, technological exchange, equipment sharing, and resource allocation, should be employed to synchronize emission reduction endeavors among all parties involved. Through these measures, a truly global carbon neutral alliance should be established by 2050.

Further, the profile of spillover effects depends on the presentation of carbon emissions embodied in the trade matrix and is closely linked to the sensibility and capacity of peripheral economies to amplify, absorb or block the shock. As the epicenter, China should adhere to the “Double Control” of energy consumption and expedite achieving the “Double Carbon” target, in order to mitigate the initial shocks and minimize the transmission

through the network. As the peripheries, pursuing environmental sustainability does not mean hindering development; instead, it is imperative to foster harmony between economic growth and sustainability. Measures such as industrial structure transformation and increased core participation in GVC are a potentially feasible direction for enhanced efforts. Moreover, both central and peripheral economies need to focus on the domestic structure of low-carbon production and consumption while considering carbon balance and carbon distribution by changing the weights, origins and targets during imports and exports. This is crucial for the transmission of carbon transfer.

Last but not least, China is playing a considerably important role in the global carbon transfer network, with a long-term carbon deficit. The international community should involve China more in discussions about climate change. Meanwhile, the heterogeneous characteristics identified in this paper could support significant references for monitoring global carbon transfer and the achievement of the 1.5-Degree Goal, as well as the Climate Solidarity Pact.

Notably, several limitations still exist, so the model could be further improved. Firstly, our analysis was based on a partial equilibrium and was abstracted from various endogenous responses in face of an increase in China's outward carbon emission transfer, such as policy adjustment. Secondly, we consider carbon emission transfer through international trade only, which is the biggest channel, and do not incorporate other channels that might also contribute to carbon emission transfer, such as foreign investment and industrial migration. These limitations provide clear directions for further research.

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Data Availability Statement: The data that support the findings of this study will be openly available on request.

Conflicts of Interest: The authors declare no conflicts of interest.

Appendix A. Complementary Data

Table A1. MRIO framework.

Inputs		Outputs	Intermediate Demand			Final Demand			Output
			Economy A	...	Economy N	Economy A	...	Economy N	
			1, ..., m	...	1, ..., m	1, ..., n	...	1, ..., m	
Intermediate inputs	Economy A	Z ₁₁	...	Z _{1N}	Y ₁₁	...	Y _{1N}	X ₁	
	Economy B	Z ₂₁	...	Z _{2N}	Y ₂₁	...	Y _{2N}	X ₂	
			...			...			
	Economy N	Z _{N1}	...	Z _{NN}	Y _{N1}	...	Y _{NN}	X _N	
Value-added Inputs		VA ₁	...	VA _N	—	—	—	—	
		X ₁	...	X _N	—	—	—	—	

Table A2. List of 26 sectors included in Eora26 model.

Num.	Sector Name	Num.	Sector Name
1	Agriculture	14	Construction
2	Fishing	15	Maintenance and Repair
3	Mining and Quarrying	16	Wholesale Trade
4	Food and Beverages	17	Retail Trade
5	Textiles and Wearing Apparel	18	Hotels and Restaurants
6	Wood and Paper	19	Transport
7	Petroleum, Chemical and Non-Metallic Mineral Products	20	Post and Telecommunications
8	Metal Products	21	Financial Intermediation and Business Activities
9	Electrical and Machinery	22	Public Administration
10	Transport Equipment	23	Education, Health and Other Services
11	Other Manufacturing	24	Private Households
12	Recycling	25	Others
13	Electricity, Gas and Water	26	Re-export and Re-import

Table A3. All the sample economies and their abbreviated code.

Num.	English Name	Abbreviated Code	Num.	English Name	Abbreviated Code	Num.	English Name	Abbreviated Code
1	Afghanistan	AFG	60	Gambia	GMB	119	Nigeria	NGA
2	Albania	ALB	61	Germany	DEU	120	Norway	NOR
3	Algeria	DZA	62	Georgia	GEO	121	Monaco	MCO
4	Andorra	AND	63	Oman	OMN	122	Panama	PAN
5	Angola	AGO	64	Ghana	GHA	123	Papua New Guinea	PNG
6	Antigua	ATG	65	Greece	GRC	124	Paraguay	PRY
7	Azerbaijan	AZE	66	Kuwait	KWT	125	Peru	PER
8	Argentina	ARG	67	Guatemala	GTM	126	Philippines	PHL
9	Australia	AUS	68	Haiti	HTI	127	Poland	POL
10	Austria	AUT	69	Honduras	HND	128	Portugal	PRT
11	Bahamas	BHS	70	Hungary	HUN	129	Guyana	GUY
12	Bahrain	BHR	71	Macao SAR	MAC	130	Togo	TGO
13	Bangladesh	BGD	72	Iceland	ISL	131	Qatar	QAT
14	Armenia	ARM	73	India	IND	132	South Korea	KOR
15	Barbados	BRB	74	Indonesia	IDN	133	Romania	ROU
16	Belgium	BEL	75	Iran	IRN	134	Russia	RUS
17	Bhutan	BTN	76	Iraq	IRQ	135	Rwanda	RWA
18	Bolivia	BOL	77	Ireland	IRL	136	Samoa	WSM
19	Bosnia and Herzegovina	BIH	78	Italy	ITA	137	Sao Tome and Principe	STP
20	Botswana	BWA	79	Jamaica	JAM	138	Saudi Arabia	SAU
21	Brazil	BRA	80	Croatia	HRV	139	Senegal	SEN
22	Belize	BLZ	81	Japan	JPN	140	Serbia	SRB
23	Somalia	SOM	82	Kenya	KEN	141	Seychelles	SYC
24	British Virgin Islands	VGB	83	Kazakhstan	KAZ	142	Sierra Leone	SLE
25	Brunei	BRN	84	DR Congo	COD	143	Singapore	SGP
26	Bulgaria	BGR	85	Moldova	MDA	144	Slovakia	SVK
27	Namibia	NAM	86	Kyrgyzstan	KGZ	145	Slovenia	SVN
28	Burundi	BDI	87	Laos	LAO	146	South Africa	ZAF
29	Belarus	BLR	88	Latvia	LVA	147	Spain	ESP

Table A3. Cont.

Num.	English Name	Abbreviated Code	Num.	English Name	Abbreviated Code	Num.	English Name	Abbreviated Code
30	Cambodia	KHM	89	Lesotho	LSO	148	Sri Lanka	LKA
31	Cameroon	CMR	90	Liberia	LBR	149	Suriname	SUR
32	Canada	CAN	91	Lebanon	LBN	150	Swaziland	SWZ
33	Cape Verde	CPV	92	Libya	LBY	151	Sweden	SWE
34	Central African Republic	CAF	93	Liechtenstein	LIE	152	Switzerland	CHE
35	Chad	TCD	94	Lithuania	LTU	153	Syria	SYR
36	China	CHN	95	Luxembourg	LUX	154	Tajikistan	TJK
37	Hong Kong	HKG	96	Madagascar	MDG	155	Thailand	THA
38	Taiwan	TWN	97	Colombia	COL	156	TFYR Macedonia	MKD
39	Congo	COG	98	Malawi	MWI	157	Trinidad and Tobago	TTO
40	Mexico	MEX	99	Malaysia	MYS	158	Tunisia	TUN
41	Denmark	DNK	100	Maldives	MDV	159	UK	GBR
42	Costa Rica	CRI	101	Mali	MLI	160	Turkey	TUR
43	Cote d'Ivoire	CIV	102	Malta	MLT	161	Turkmenistan	TKM
44	Cuba	CUB	103	Mauritania	MRT	162	Uganda	UGA
45	Cyprus	CYP	104	Mauritius	MUS	163	Ukraine	UKR
46	Czech Republic	CZE	105	Mongolia	MNG	164	UAE	ARE
47	North Korea	PRK	106	Montenegro	MNE	165	El Salvador	SLV
48	Benin	BEN	107	Morocco	MAR	166	Tanzania	TZA
49	Djibouti	DJI	108	Mozambique	MOZ	167	Chile	CHL
50	Dominican Republic	DOM	109	Myanmar	MMR	168	Guinea	GIN
51	Ecuador	ECU	110	Pakistan	PAK	169	Jordan	JOR
52	Egypt	EGY	111	Nepal	NPL	170	Israel	ISR
53	Eritrea	ERI	112	Netherlands	NLD	171	USA	USA
54	Estonia	EST	113	Netherlands Antilles	ANT	172	Uruguay	URY
55	Ethiopia	ETH	114	Aruba	ABW	173	Burkina Faso	BFA
56	Fiji	FJI	115	New Zealand	NZL	174	Uzbekistan	UZB
57	Finland	FIN	116	Venezuela	VEN	175	Vanuatu	VUT
58	France	FRA	117	Nicaragua	NIC	176	Viet Nam	VNM
59	Gabon	GAB	118	Niger	NER	177	San Marino	SMR

Table A4. Roles of economies in the carbon-connectedness network.

Amplifiers	Algeria; Australia; Armenia; Brazil; Costa Rica; Cuba; Czech Republic; North Korea; Dominican Republic; Ecuador; Estonia; Kuwait; Iceland; Indonesia; Iraq; Japan; Kazakhstan; Kyrgyzstan; Latvia; Luxembourg; Madagascar; Mongolia; Pakistan; Nepal; Niger; Nigeria; Philippines; Qatar; Sri Lanka; Tajikistan; Thailand; Turkey; Chile; Uzbekistan
Absorbers	Afghanistan; Albania; Angola; Azerbaijan; Argentina; Bahamas; Bahrain; Bhutan; Bolivia; Bosnia and Herzegovina; Botswana; Belize; Somalia; Namibia; Burundi; Cambodia; Cameroon; Central African Republic; Chad; China; Taiwan; Congo; Mexico; Denmark; Cote d'Ivoire; Cyprus; Benin; Egypt; Eritrea; Fiji; Finland; France; Gabon; Gambia; Germany; Ghana; Greece; Guatemala; Haiti; Honduras; Hungary; India; Iran; Italy; Jamaica; Croatia; Kenya; DR Congo; Lebanon; Lithuania; Colombia; Malawi; Maldives; Mali; Malta; Mauritania; Mauritius; Montenegro; Mozambique; Myanmar; Netherlands Antilles; Nicaragua; Panama; Papua New Guinea; Paraguay; Peru; Portugal; Togo; South Korea; Romania; Russia; Saudi Arabia; Senegal; Serbia; Sierra Leone; Singapore; Slovenia; South Africa; Spain; Suriname; Syria; TFYR Macedonia; Tunisia; Turkmenistan; Uganda; Ukraine; UAE; El Salvador; Guinea; Jordan; Israel; Uruguay; Burkina Faso; Viet Nam

Table A4. *Cont.*

Blockers	Andorra; Antigua; British Virgin Islands; Ethiopia; Ireland; Liberia; Liechtenstein; New Zealand; Monaco; Guyana; Samoa; Sao Tome and Principe; Slovakia; Tanzania; Vanuatu; San Marino; Andorra; Antigua; Austria; Bangladesh; Barbados; Belgium; British Virgin Islands; Brunei; Bulgaria; Belarus; Canada; Cape Verde; Hong Kong; Djibouti; Ethiopia; Georgia; Oman; Macao SAR; Ireland; Moldova; Laos; Lesotho; Liberia; Libya; Malaysia; Morocco; Netherlands; Aruba; New Zealand; Venezuela; Norway; Poland; Guyana; Rwanda; Samoa; Sao Tome and Principe; Seychelles; Slovakia; Swaziland; Sweden; Switzerland; Trinidad and Tobago; UK; Tanzania; USA; Vanuatu; San Marino
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Table A5. Classification by different levels of development.

developed regions	Albania; Andorra; Australia; Austria; Belgium; Bosnia and Herzegovina; Bulgaria; Belarus; Canada; Denmark; Cyprus; Czech Republic; Estonia; Finland; France; Germany; Greece; Hungary; Iceland; Ireland; Italy; Croatia; Japan; Moldova; Latvia; Liechtenstein; Lithuania; Luxembourg; Malta; Montenegro; Netherlands; Netherlands Antilles; New Zealand; Norway; Monaco; Poland; Portugal; Romania; Russia; Serbia; Slovakia; Slovenia; Spain; Sweden; Switzerland; TFYR Macedonia; UK; Ukraine; Israel; USA; San Marino	
least developed regions	Afghanistan; Angola; Bangladesh; Bhutan; Somalia; Burundi; Cambodia; Central African Republic; Chad; Benin; Djibouti; Eritrea; Ethiopia; Gambia; Haiti; DR Congo; Laos; Lesotho; Liberia; Madagascar; Malawi; Mali; Mauritania; Mozambique; Myanmar; Nepal; Niger; Togo; Rwanda; Samoa; Sao Tome and Principe; Senegal; Sierra Leone; Uganda; Tanzania; Guinea; Burkina Faso; Vanuatu	
developing regions	landlocked developing regions	Azerbaijan; Armenia; Bolivia; Botswana; Kazakhstan; Kyrgyzstan; Mongolia; Paraguay; Swaziland; Tajikistan; Turkmenistan
	small island developing regions	Antigua; Bahamas; Barbados; Belize; British Virgin Islands; Cape Verde; Cuba; Dominican Republic; Fiji; Jamaica; Maldives; Mauritius; Aruba; Papua New Guinea; Guyana; Seychelles; Singapore; Suriname; Trinidad and Tobago
	other developing regions	Algeria; Argentina; Bahrain; Brazil; Brunei; Namibia; Cameroon; China; Hong Kong; Taiwan; Congo; Mexico; Costa Rica; Cote d'Ivoire; North Korea; Ecuador; Egypt; Gabon; Georgia; Oman; Ghana; Kuwait; Guatemala; Honduras; Macao SAR; India; Indonesia; Iran; Iraq; Kenya; Lebanon; Libya; Colombia; Malaysia; Morocco; Pakistan; Venezuela; Nicaragua; Nigeria; Panama; Peru; Philippines; Qatar; South Korea; Saudi Arabia; South Africa; Sri Lanka; Syria; Thailand; Tunisia; Turkey; UAE; El Salvador; Chile; Jordan; Uruguay; Uzbekistan; Viet Nam

Table A6. Classification by different industrial industry.

Weak tertiary industry	Angola; Azerbaijan; Bangladesh; Bhutan; Brunei; Burundi; Cambodia; Chad; Cote d'Ivoire; Benin; Egypt; Ethiopia; Gabon; Oman; Ghana; India; Indonesia; Iran; Iraq; Kenya; DR Congo; Kyrgyzstan; Laos; Lesotho; Liberia; Mali; Mauritania; Mongolia; Mozambique; Myanmar; Nicaragua; Niger; Nigeria; Paraguay; Guyana; Togo; Qatar; Rwanda; Sierra Leone; Tajikistan; Uganda; Tanzania; Guinea; Burkina Faso; Uzbekistan
Strong tertiary industry	Afghanistan; Albania; Algeria; Andorra; Antigua; Argentina; Australia; Austria; Bahamas; Bahrain; Armenia; Belgium; Bolivia; Bosnia and Herzegovina; Botswana; Brazil; Belize; Bulgaria; Namibia; Belarus; Cameroon; Cape Verde; China; Hong Kong; Mexico; Denmark; Costa Rica; Cuba; Cyprus; Czech Republic; Djibouti; Dominican Republic; Ecuador; Estonia; Fiji; Finland; France; Gambia; Germany; Georgia; Greece; Kuwait; Guatemala; Haiti; Honduras; Hungary; Iceland; Ireland; Italy; Jamaica; Croatia; Japan; Kazakhstan; Moldova; Latvia; Lebanon; Lithuania; Luxembourg; Madagascar; Colombia; Malawi; Malaysia; Maldives; Malta; Mauritius; Montenegro; Morocco; Pakistan; Nepal; Netherlands; Norway; Monaco; Panama; Peru; Philippines; Poland; Portugal; South Korea; Romania; Russia; Samoa; Sao Tome and Principe; Saudi Arabia; Senegal; Serbia; Seychelles; Singapore; Slovakia; Slovenia; South Africa; Spain; Sri Lanka; Suriname; Swaziland; Sweden; Switzerland; Thailand; TFYR Macedonia; Trinidad and Tobago; Tunisia; UK; Turkey; Ukraine; UAE; El Salvador; Chile; Jordan; Israel; USA; Uruguay

Note: the classification is based on the ratio of value-added of tertiary industry to GDP. We define an individual economy as weak/strong if it is higher/lower than China.

Table A7. Classification by different status in GVC.

Low forward GVC participation	Argentina; Bulgaria; Cambodia; Canada; Mexico; Denmark; Costa Rica; Cyprus; Estonia; Greece; Iceland; India; Ireland; Croatia; Luxembourg; Malta; Morocco; New Zealand; Portugal; Singapore; Slovakia; Slovenia; Spain; Thailand; Tunisia; Turkey; Viet Nam
High forward GVC participation	Australia; Austria; Belgium; Brazil; Brunei; Hong Kong; Taiwan; Czech Republic; Finland; France; Germany; Indonesia; Italy; Japan; Kazakhstan; Laos; Latvia; Lithuania; Colombia; Malaysia; Myanmar; Netherlands; Norway; Peru; Philippines; Poland; South Korea; Romania; Russia; Saudi Arabia; South Africa; Sweden; Switzerland; UK; Chile; Israel; USA
Low backward GVC participation	Argentina; Australia; Brazil; Brunei; Cambodia; Indonesia; Kazakhstan; Colombia; New Zealand; Norway; Peru; Russia; Saudi Arabia; Chile; USA
High backward GVC participation	Austria; Belgium; Bulgaria; Canada; Hong Kong; Taiwan; Mexico; Denmark; Costa Rica; Cyprus; Czech Republic; Estonia; Finland; France; Germany; Greece; Iceland; India; Ireland; Italy; Croatia; Japan; Laos; Latvia; Lithuania; Luxembourg; Malaysia; Malta; Morocco; Myanmar; Netherlands; Philippines; Poland; Portugal; South Korea; Romania; Singapore; Slovakia; Slovenia; South Africa; Spain; Sweden; Switzerland; Thailand; Tunisia; UK; Turkey; Israel; Viet Nam

Appendix B. Calculation of Spillovers: An Example

Considering the simplest context of 3 economies here with a carbon emission inflow-outflow matrix W as follow:

$$\begin{array}{c} \begin{array}{ccc} & A & B & C \\ \begin{array}{c} A \\ B \\ C \end{array} & \begin{pmatrix} 0 & 30 & 50 \\ 10 & 0 & 60 \\ 20 & 40 & 0 \end{pmatrix} \end{array} W = \begin{pmatrix} 0 & 30 & 50 \\ 10 & 0 & 60 \\ 20 & 40 & 0 \end{pmatrix} \quad (A1)$$

Carbon emission outflows are shown in columns and inflows are shown in rows. For example, $O_A = 0 + 10 + 20 = 30$ and $I_A = 0 + 30 + 50 = 80$.

Now we assume an initial shock of 10% increase on O_A , it is a shock on the aggregate consists of $\Delta O_{BA} = 1$ from B and $\Delta O_{CA} = 2$ from C. Thus, the initial shock leads to a transformation of W : $\tilde{W} = \begin{pmatrix} 0 & 30 & 50 \\ 10 & 0 & 60 \\ 20 & 40 & 0 \end{pmatrix} + \begin{pmatrix} 0 & 0 & 0 \\ 1 & 0 & 0 \\ 2 & 0 & 0 \end{pmatrix} = \begin{pmatrix} 0 & 30 & 50 \\ 11 & 0 & 60 \\ 22 & 40 & 0 \end{pmatrix}$.

The direct spillover effects from A to its first neighbors (B and C) is $\begin{pmatrix} 0 & 0 & 0 \\ 1 & 0 & 0 \\ 2 & 0 & 0 \end{pmatrix}$, where the direct spillovers received by B is 1, and C is 2.

Then, in $\tilde{W}$, ΔI_B , ΔI_C have changed, $\Delta I_B = 1 + 0 + 0$, $\Delta I_C = 2 + 0 + 0$ (the sum of the second and third row). Then, ΔO_B , ΔO_C will also change because of ΔI_B , ΔI_C . We consider a context involving three roles that passes through shocks to different extents: A is a shock blocker, B is a shock absorber with a pass-through coefficient of 0.5, and C is a shock amplifier with a pass-through coefficient of 1.5.

$$\Delta O_B = O_B \left(\left(1 + \frac{\Delta I_B}{I_B} \right)^{0.5} - 1 \right) = (0 + 30 + 40) \left(\left(1 + \frac{1}{10 + 60} \right)^{0.5} - 1 \right) \approx 0.5 \quad (A2)$$

$$\Delta O_C = O_C \left(\left(1 + \frac{\Delta I_C}{I_C} \right)^{1.5} - 1 \right) = (0 + 50 + 60) \left(\left(1 + \frac{2}{20 + 40} \right)^{1.5} - 1 \right) \approx 5.5 \quad (A3)$$

Therefore, the newly generated shock in the second round is $\Delta O_B = 0.5$, $\Delta O_C = 5.5$. That is to say, in the second round, a new shock of $(0 \ 0.5 \ 5.5)$, the same as $\begin{pmatrix} 0 & 0.5 \times \frac{30}{30+40} & 5.5 \times \frac{50}{50+60} \\ 0 & 0 & 5.5 \times \frac{60}{50+60} \\ 0 & 0.5 \times \frac{40}{30+40} & 0 \end{pmatrix}$ will be applicated in $\begin{pmatrix} 0 & 30 & 50 \\ 11 & 0 & 60 \\ 22 & 40 & 0 \end{pmatrix}$.

In the second to n th rounds, shocks will be passed through by similar way above, and spillin effects and spillback effects will appear from the second round.

Appendix C. Complementary Results

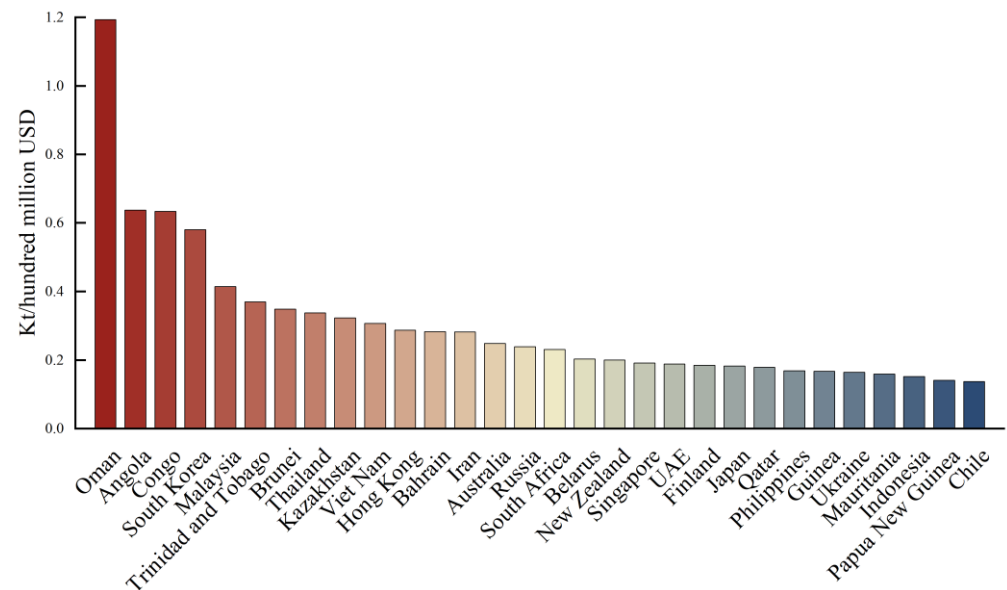


Figure A1. US's spillovers in the first round.

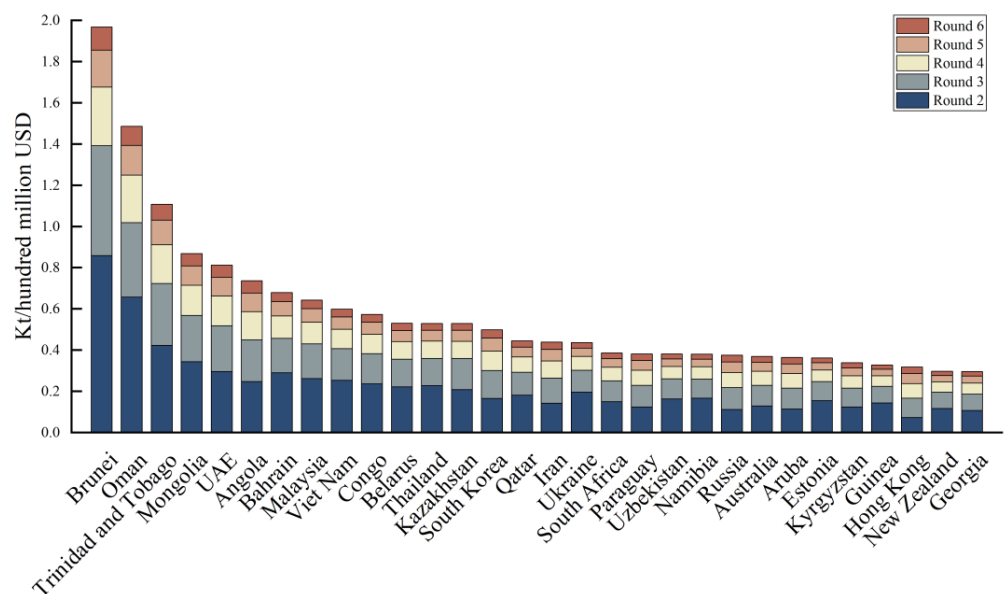


Figure A2. US's spillins in the second to sixth round.

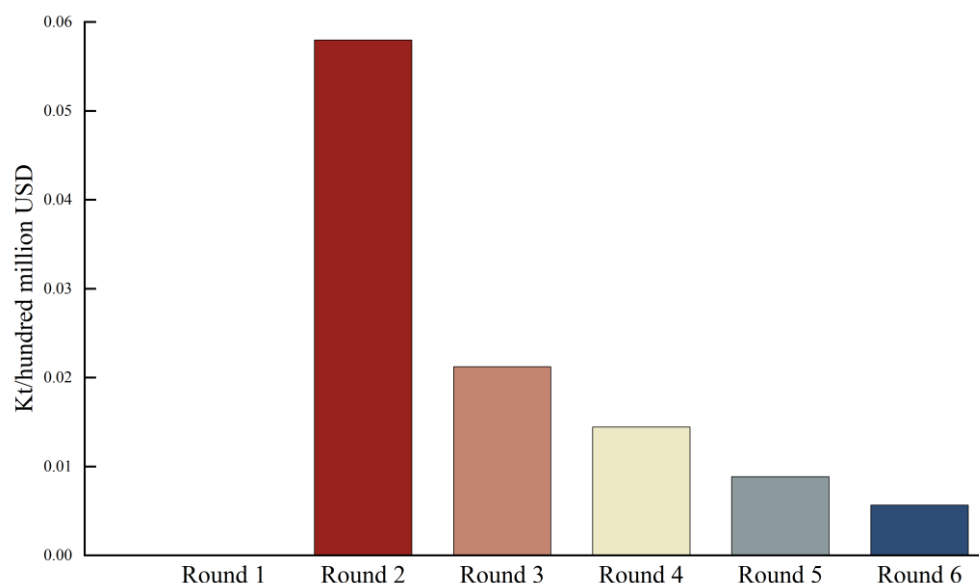


Figure A3. US's spillbacks in six rounds.

References

- Manioudis, M.; Meramveliotakis, G. Broad Strokes towards a Grand Theory in the Analysis of Sustainable Development: A Return to the Classical Political Economy. *New Political Econ.* **2022**, *27*, 866–878. [CrossRef]
- Meramveliotakis, G.; Manioudis, M. History, Knowledge, and Sustainable Economic Development: The Contribution of John Stuart Mill's Grand Stage Theory. *Sustainability* **2021**, *13*, 1468. [CrossRef]
- GCP (Global Carbon Project). Carbon Budget and Trends 2022. 2022. Available online: www.globalcarbonproject.org/carbonbudget (accessed on 10 June 2023).
- Chen, C.; Liu, W. Advances and future trends in research on carbon emissions reduction in China from the perspective of bibliometrics. *PLoS ONE* **2023**, *18*, e0288661. [CrossRef] [PubMed]
- State Council of the PRC. *The State Council's Opinions on the Complete, Accurate and Comprehensive Implementation of the New Development Concept to Do a Good Job in Carbon Peak Carbon Neutrality*; The State Council of the People's Republic of China: Beijing, China, 2021. Available online: http://www.gov.cn/zhengce/2021-10/24/content_5644613.htm (accessed on 5 March 2023).
- State Council of the PRC. *Plan for Improving the Dual Control Degree of Energy Consumption Intensity and Total Volume*; The State Council of the People's Republic of China: Beijing, China, 2021. Available online: https://www.gov.cn/zhengce/zhengceku/2021-09/17/content_5637960.htm (accessed on 5 March 2023).
- Li, R.Y.M.; Wang, Q.; Zeng, L.; Chen, H. A Study on Public Perceptions of Carbon Neutrality in China: Has the Idea of ESG Been Encompassed? *Front. Environ. Sci.* **2023**, *10*, 949959. [CrossRef]
- HSBC Global Banking and Markets. Asia Supply Chains: A New Era. 2021. Available online: <https://www.gbm.hsbc.com/-/media/media/gbm-global/pdf/campaign/hsbc-asia-supply-chains-a-new-era-external.ashx> (accessed on 12 June 2023).
- KPMG. Rethinking Supply Chain in Asia Pacific: A study on Supply Chain Realignment and Competitiveness across High Growth Markets. 2021. Available online: <https://assets.kpmg.com/content/dam/kpmg/xx/pdf/2021/11/rethinking-supply-chains-in-asia-pacific.pdf> (accessed on 12 June 2023).
- Doheny, M.; Gómez, M.; Nolasco, O.C. *To Regionalize or Not? Optimizing North American Supply Chains*; McKinsey&Company: New York, NY, USA, 2022; Available online: <https://www.mckinsey.com/capabilities/operations/our-insights/to-regionalize-or-not-optimizing-north-american-supply-chains> (accessed on 12 June 2023).
- Brown, M.T.; Herendeen, R.A. Embodied Energy Analysis and Energy Analysis: A Comparative View. *Ecol. Econ.* **1996**, *19*, 219–235. [CrossRef]
- WBGU (German Advisory Council on Global Change). Solving the Climate Dilemma: Carbon Budget Approach. 2009. Available online: https://www.researchgate.net/publication/259472131_Solving_the_climate_dilemma_The_budget_approach (accessed on 15 June 2023).
- IPCC (Intergovernmental Panel on Climate Change). Climate Change 2014: Mitigation of Climate Change. 2014. Available online: https://www.ipcc.ch/site/assets/uploads/2018/02/ipcc_wg3_ar5_frontmatter.pdf (accessed on 15 June 2023).
- Peters, G.P. Opportunities and Challenges for Environmental MRIO Modelling: Illustrations with the GTAP Database, IIOA Conference. 2007. Available online: https://www.iioa.org/conferences/16th/files/Papers/Peters_LP.pdf (accessed on 15 June 2023).
- Peters, G.P. From Production-Based to Consumption-Based National Emission Inventories. *Ecol. Econ.* **2008**, *65*, 13–23. [CrossRef]
- Peters, G.P.; Hertwich, E.G. CO₂ Embodied in International Trade with Implications for Global Climate Policy. *Environ. Sci. Technol.* **2008**, *42*, 1401–1407. [CrossRef] [PubMed]

17. Kanemoto, K.; Lenzen, M.; Peters, G.P.; Moran, D.; Geschke, A. Frameworks for Comparing Emissions Associated with Production, Consumption and International Trade. *Environ. Sci. Technol.* **2012**, *46*, 172–179. [[CrossRef](#)] [[PubMed](#)]
18. Kanemoto, K.; Moran, D.; Lenzen, M.; Geschke, A. International Trade Undermines National Emissions Targets: New Evidence from Air Pollution. *Glob. Environ. Chang.* **2014**, *24*, 52–59. [[CrossRef](#)]
19. Kanemoto, K.; Moran, D.; Hertwich, E.G. Mapping the Carbon Footprint of Nations. *Environ. Sci. Technol.* **2016**, *50*, 10512–10517. [[CrossRef](#)]
20. Kander, A.; Jiborn, M.; Moran, D.; Thomas, O.W. National Greenhouse-Gas Accounting for Effective Climate Policy on International Trade. *Nat. Clim. Chang.* **2015**, *5*, 431–435. [[CrossRef](#)]
21. Kanemoto, K.; Shigetomi, Y.; Hoang, N.T.; Okuoka, K.; Moran, D. Spatial Variation in Household Consumption-Based Carbon Emission Inventories for 1200 Japanese Cities. *Environ. Res. Lett.* **2020**, *15*, 114053. [[CrossRef](#)]
22. Jiborn, M.; Kander, A.; Kulionis, V.; Nielsen, H.; Moran, D. Decoupling or Delusion? Measuring Emissions Displacement in Foreign Trade. *Glob. Environ. Chang.* **2018**, *49*, 27–34. [[CrossRef](#)]
23. Peters, G.P.; Minx, J.C.; Weber, C.L.; Edenhofer, O. Growth in emission transfers via international trade from 1990 to 2008. *Proc. Natl. Acad. Sci. USA* **2011**, *108*, 8903–8908. [[CrossRef](#)] [[PubMed](#)]
24. Van den Berg, N.J.; van Soest, H.L.; Hof, A.F.; den Elzen, M.G.; van Vuuren, D.P.; Chen, W.; Drouet, L.; Emmerling, J.; Fujimori, S.; Höhne, N.; et al. Implications of various effort-sharing approaches for national carbon budgets and emission pathways. *Clim. Chang.* **2020**, *162*, 1805–1822. [[CrossRef](#)]
25. Gallego, B.; Lenzen, M.A. A Consistent Input-Output Formulation of Shared Producer and Consumer Responsibility. *Econ. Syst. Res.* **2005**, *17*, 365–391. [[CrossRef](#)]
26. Lenzen, M.; Murray, J.; Sack, F.; Wiedmann, T. Shared Producer and Consumer Responsibility: Theory and Practice. *Ecol. Econ.* **2007**, *61*, 27–42. [[CrossRef](#)]
27. Lenzen, M.; Murray, J. Conceptualising Environmental Responsibility. *Ecol. Econ.* **2010**, *70*, 261–270. [[CrossRef](#)]
28. Liang, S.; Qu, S.; Zhu, Z.; Guan, D.; Xu, M. Income-Based Greenhouse Gas Emissions of Nations. *Environ. Sci. Technol.* **2017**, *51*, 346–355. [[CrossRef](#)]
29. Csutora, M.; Vetőné mózner, Z. Proposing a beneficiary-based shared responsibility approach for calculating national carbon accounts during the post-Kyoto era. *Clim. Policy* **2014**, *14*, 599–616. [[CrossRef](#)]
30. Jakob, M.; Ward, H.; Steckel, J.C. Sharing responsibility for trade-related emissions based on economic benefits. *Glob. Environ. Chang.* **2021**, *66*, 102207. [[CrossRef](#)]
31. Fullerton, D.; Muehlegger, E. Who bears the economic burdens of environmental regulations? *Rev. Environ. Econ. Policy* **2019**, *13*, 62–82. [[CrossRef](#)]
32. Tukker, A.; Pollitt, H.; Henkemans, M. Consumption-based carbon accounting: Sense and sensibility. *Clim. Policy* **2020**, *20* (Suppl. 1), S1–S13. [[CrossRef](#)]
33. Moran, D.; Wood, R. Convergence Between the Eora, WIOD, EXIOBASE, and Open EU's Consumption-Based Carbon Accounts. *Econ. Syst. Res.* **2014**, *26*, 245–261. [[CrossRef](#)]
34. Chojnacka, K.; Kowalski, Z.; Kulczycka, J.; Dmytryk, A.; Górecki, H.; Ligas, B.; Gramza, M. Carbon Footprint of Fertilizer Technologies. *J. Environ. Manag.* **2019**, *231*, 962–967. [[CrossRef](#)] [[PubMed](#)]
35. Leontief, W.W. Quantitative Input and Output Relations in The Economic Systems of The United States. *Rev. Econ. Stat.* **1936**, *18*, 105–125. [[CrossRef](#)]
36. Leontief, W.W. Environmental Repercussions and The Economic Structure: An Input-output Approach. *Rev. Econ. Stat.* **1970**, *52*, 262–271. [[CrossRef](#)]
37. Wieland, H.; Giljum, S.; Eisenmenger, N.; Wiedenhofer, D.; Bruckner, M.; Schaffartzik, A.; Owen, A. Supply Versus Use Designs of Environmental Extensions in Input-Output Analysis: Conceptual and Empirical Implications for the Case of Energy. *J. Ind. Ecol.* **2020**, *24*, 548–563. [[CrossRef](#)] [[PubMed](#)]
38. Xu, W.; Xie, Y.; Xia, D.; Ji, L.; Huang, G. A Multi-Sectoral Decomposition and Decoupling Analysis of Carbon Emissions in Guangdong Province, China. *J. Environ. Manag.* **2021**, *298*, 113485. [[CrossRef](#)]
39. Li, J.; Chandio, A.A.; Liu, Y. Trade Impacts on Embodied Carbon Emissions-Evidence from the Bilateral Trade between China and Germany. *Int. J. Environ. Res. Public Health* **2020**, *17*, 5076. [[CrossRef](#)]
40. Cheng, H.; Dong, S.; Li, F.; Yang, Y.; Li, S.; Li, Y. Multiregional Input-Output Analysis of Spatial-Temporal Evolution Driving Force for Carbon Emissions Embodied in Interprovincial Trade and Optimization Policies: Case Study of Northeast Industrial District in China. *Environ. Sci. Technol.* **2018**, *52*, 346–358. [[CrossRef](#)] [[PubMed](#)]
41. Long, R.; Li, J.; Chen, H.; Zhang, L.; Li, Q. Embodied Carbon Dioxide Flow in International Trade: A Comparative Analysis Based on China and Japan. *J. Environ. Manag.* **2018**, *209*, 371–381. [[CrossRef](#)] [[PubMed](#)]
42. Yuan, X.; Sheng, X.; Chen, L.; Tang, Y.; Li, Y.; Jia, Y.; Qu, D.; Wang, Q.; Ma, Q.; Zuo, J. Carbon Footprint and Embodied Carbon Transfer at the Provincial Level of the Yellow River Basin. *Sci. Total Environ.* **2022**, *803*, 149993. [[CrossRef](#)] [[PubMed](#)]
43. Zafrilla, J.E.; Cadarso, M.; Monsalve, F.; de la Rúa, C. How Carbon-Friendly is Nuclear Energy? A Hybrid MRIO-LCA Model of a Spanish Facility. *Environ. Sci. Technol.* **2014**, *48*, 14103–14111. [[CrossRef](#)] [[PubMed](#)]
44. Smith, D.A.; White, D.R. Structure and Dynamics of the Global Economy: Network Analysis of International Trade 1965–1980. *Soc. Forces* **1992**, *70*, 857–893. [[CrossRef](#)]

45. Fang, G.; Huang, M.; Zhang, W.; Tian, L. Exploring Global Embodied Carbon Emissions Transfer Network—An Analysis Based on National Responsibility. *Technol. Forecast. Soc. Chang.* **2024**, *202*, 123284. [\[CrossRef\]](#)
46. Wang, Q.; Han, X. Spillover Effects of the United States Economic Slowdown Induced by COVID-19 Pandemic on Energy, Economy, and Environment in Other Countries. *Environ. Res.* **2021**, *196*, 110936. [\[CrossRef\]](#) [\[PubMed\]](#)
47. Bu, Y.; Wang, E.; Qiu, Y.; Möst, D. Impact Assessment of Population Migration on Energy Consumption and Carbon Emissions in China: A Spatial Econometric Investigation. *Environ. Impact Assess. Rev.* **2022**, *93*, 106744. [\[CrossRef\]](#)
48. Tan, X.; Ma, S.; Wang, X.; Feng, C.; Xiang, L. The Impact of the COVID-19 Pandemic On the Global Dynamic Spillover of Financial Market Risk. *Front. Public Health* **2022**, *10*, 963620. [\[CrossRef\]](#)
49. Zhou, Y.; Liu, Z.; Wu, S. The Global Economic Policy Uncertainty Spillover Analysis: In the Background of COVID-19 Pandemic. *Res. Int. Bus. Financ.* **2022**, *61*, 101666. [\[CrossRef\]](#)
50. Chin, K.; Li, X. Bayesian Forecast Combination in VAR-DSGE Models. *J. Macroecon.* **2019**, *59*, 278–298. [\[CrossRef\]](#)
51. Diebold, F.X.; Yilmaz, K. Measuring Financial Asset Return and Volatility Spillovers, with Application to Global Equity Markets. *Econ. J.* **2009**, *119*, 158–171. [\[CrossRef\]](#)
52. Diebold, F.X.; Yilmaz, K. Better to Give Than to Receive: Predictive Directional Measurement of Volatility Spillovers. *Int. J. Forecast.* **2012**, *28*, 57–66. [\[CrossRef\]](#)
53. Diebold, F.X.; Yilmaz, K. On the Network Topology of Variance Decompositions: Measuring the Connectedness of Financial Firms. *J. Econom.* **2014**, *182*, 119–134. [\[CrossRef\]](#)
54. Antonakakis, N.; Chatziantoniou, I.; Gabauer, D. Refined Measures of Dynamic Connectedness Based on TVP-VAR. *J. Risk Financ. Manag.* **2020**, *13*, 84. [\[CrossRef\]](#)
55. Lien, D.; Zhang, J.; Yu, X. Effects of Economic Policy Uncertainty: A Regime Switching Connectedness Approach. *Econ. Model.* **2022**, *113*, 105879. [\[CrossRef\]](#)
56. Li, Y.L.; Chen, B.; Chen, G.Q. Carbon Network Embodied in International Trade: Global Structural Evolution and Its Policy Implications. *Energy Policy* **2020**, *139*, 111396. [\[CrossRef\]](#)
57. Leonidov, A.; Kireyev, A.P. *Network Effects of International Shocks and Spillovers*; IMF Working Papers 2015, 2015/149; International Monetary Fund: Washington, DC, USA, 2015.
58. Leonidov, A.; Kireyev, A.P. *China's Imports Slowdown: Spillovers, Spillins, and Spillbacks*; IMF Working Papers 2016/051; International Monetary Fund: Washington, DC, USA, 2016.
59. Miller, R.E.; Blair, P.D. *Input–Output Analysis: Foundations and Extensions*, 2nd ed.; Cambridge University Press: Cambridge, UK, 2009; ISBN 9780521517133.
60. Fruchterman, T.M.J.; Reingold, E.M. Graph Drawing by Force-Directed Placement. *Softw. Pract. Exp.* **1991**, *21*, 1129–1164. [\[CrossRef\]](#)
61. Levin, K.; Rich, D. Turning Point: Which Countries' GHG Emissions Have Peaked? Which Will in the Future? 2017. Available online: <https://www.wri.org/insights/turning-point-which-countries-ghg-emissions-have-peaked-which-will-future> (accessed on 12 October 2023).

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