



Temporal Changes and Environmental Imbalance of Carbon Transfer in China–Belt and Road Trade

Yinuo Jiang

Guizhou University, Guiyang, China
2239013419@qq.com

Abstract. Against the backdrop of deepening trade integration within the Belt and Road Initiative (BRI), this study investigates the evolution of embodied carbon transfers among BRI economies between 2015 and 2023. Using the EMERGING V2 multi-regional input-output database, we construct and analyze both total and net embodied carbon transfer matrices, with a focus on China's role in the network. The results show that China consistently functions as the dominant net embodied carbon exporter, with its net carbon outflows to BRI partners more than doubling over the period, alongside a rising carbon leakage rate. These findings reveal a growing imbalance in the distribution of environmental pressures, where expanding trade volumes have been accompanied by a disproportionate concentration of production-side emissions in China. This study highlights the need for targeted policies to address uneven environmental impacts and advance equitable low-carbon development in the BRI region.

Keywords: Belt and Road Initiative, Multi-Regional Input-Output, Carbon Leakage, China's Trade-Related Emissions

1 Introduction

Since its launch, the Belt and Road Initiative has developed into a broad international cooperation platform focused on infrastructure connectivity, trade liberalization, investment facilitation, and people-to-people exchanges. For many developing economies, the BRI has promoted industrialization, expanded employment, improved public infrastructure, and contributed to poverty reduction. At a time of sluggish global growth and rising trade fragmentation, the initiative has upheld multilateralism and win-win cooperation, becoming an important practice for building a community with a shared future for mankind. Nevertheless, closer economic integration has accelerated cross-border factor flows and reshaped the geographic distribution of environmental pressures. Under the global value chain system, countries specialize in different production stages. Economies with relatively lower technological levels often engage in carbon-intensive manufacturing and processing, while high-income economies concentrate on R&D, design, brand services, and other low-carbon, high-value-added activities. Such a division leads to substantial transfers of embodied carbon from consuming nations to producing nations through trade [1][2][3]. When final consumption in one country

drives substantial emissions in another, carbon leakage occurs, creating a decoupling between consumption benefits and environmental costs.

For BRI economies, this mismatch directly challenges sustainable development goals. While economic gains are widely shared, environmental costs are disproportionately concentrated in a small number of manufacturing economies. This imbalance not only hinders national carbon neutrality targets but also erodes the coordinated development of environment, economy, and society. In the era of high-quality BRI development and global climate governance, it is both theoretically meaningful and practically urgent to clarify the scale, structure, and evolution of embodied carbon transfers and carbon leakage among BRI economies and to assess their impacts on EES synergy [4][5].

The idea of environmental-economic-social synergy originates from the classical sustainable development theory, which requires harmony between economic growth, social progress, and ecological protection. Real sustainable development does not pursue single-dimensional expansion but balanced improvement across three systems. In regional cooperation, EES synergy means that economic activities boost social welfare without imposing excessive or unbalanced environmental burdens [6]. Existing literature widely confirms the positive economic and social impacts of the BRI. Trade expansion has improved income levels; infrastructure construction has enhanced accessibility; investment flows have created jobs and reduced poverty. However, environmental dimensions are often understudied. Many researchers overlook the environmental externalities embedded in trade linkages. In reality, overly concentrated or unfairly distributed environmental costs can restrain long-term growth, damage public health, and reduce overall social welfare. Without environmental sustainability, EES synergy cannot be achieved [7][8].

Embodied carbon refers to the total CO₂ emissions generated throughout the production chain of a good, including direct emissions from production and indirect emissions from raw material and energy inputs [2][9]. In international trade, exporting embodied carbon means that the producing country bears emissions generated for the consuming country's final demand [1][3]. Carbon leakage typically occurs when strict climate policies in advanced economies lead to reduced domestic production and increased imports of carbon-intensive goods from countries with laxer regulations. As a result, global emissions may not decline; they simply relocate. For the BRI region, wide gaps in development levels, industrial structures, and environmental policies make such leakage particularly pronounced. High-income economies rely on imports to satisfy demand for steel, chemicals, construction materials, and other energy-intensive goods, leaving developing economies to bear heavier emission burdens.

This paper takes the Belt and Road economies as the research object, selects the two key years of 2015 and 2023, and adopts the multi-regional input-output method to systematically measure the total embodied carbon transfer and net embodied carbon transfer between China and BRI economies. On this basis, it constructs carbon transfer matrix and net carbon transfer matrix to comparatively analyze the temporal evolution characteristics of carbon flow patterns. Meanwhile, this study further calculates the corresponding carbon leakage rate and net carbon leakage rate, clarifies China's role as a net carbon exporter in BRI trade, and reveals the unbalanced characteristics of

environmental burden sharing behind trade links. The research results can provide empirical reference for coordinating trade cooperation and low-carbon sustainable development among Belt and Road economies.

2 Research Methods and Data Sources

2.1 Multi-Regional Input-Output Model

The MRIO [10] model describes the interdependencies among sectors across different countries (or regions), linking intra-regional production activities, inter-regional trade flows, and final consumption demand. Therefore, this paper adopts the multi-regional input-output model to calculate production-side and consumption-side embodied carbon emissions under the global value chain division of labor, and to characterize the cross-border carbon transfer pattern. Within the analytical framework of the MRIO model, the relationship among total output X , intermediate input AX , and final demand F can be expressed as:

$$X = AX + F \quad (1)$$

The matrix form of the MRIO model is:

$$\begin{pmatrix} X^1 \\ X^2 \\ \vdots \\ X^m \end{pmatrix} = \begin{pmatrix} A^{11} & A^{12} & \dots & A^{1m} \\ A^{21} & A^{22} & \dots & A^{2m} \\ \vdots & \vdots & \ddots & \vdots \\ A^{m1} & A^{m2} & \dots & A^{mm} \end{pmatrix} \begin{pmatrix} X^1 \\ X^2 \\ \vdots \\ X^m \end{pmatrix} + \begin{pmatrix} F^1 \\ F^2 \\ \vdots \\ F^m \end{pmatrix} \quad (2)$$

Rearranging Equation (1) and Equation (2) yields:

$$X = (I - A)^{-1}F \quad (3)$$

where: I is the identity matrix; $L = (I - A)^{-1}$ is the Leontief inverse matrix, representing the sum of direct and indirect inputs required to satisfy one unit of final demand; A is the direct input coefficient matrix.

2.2 Carbon Transfer Matrix Construction and Calculation

This study constructs the multi-regional input-output (MRIO) model to calculate the embodied carbon transfer matrix among BRI economies. First, the original dataset including 245 economies and 133 sectors is aggregated into 60 BRI countries and one rest of the world (ROW) region using a spatial mapping matrix. Based on the aggregated MRIO table, the direct consumption coefficient matrix and the Leontief inverse matrix are constructed to capture the full industrial chain effects including both direct and indirect impacts. Then, the carbon emission intensity of each sector is calculated as the ratio of sectoral CO₂ emissions to total output. By multiplying the diagonalized carbon emission intensity matrix, the Leontief inverse matrix, and the final demand matrix, the sector-level embodied carbon flow matrix is obtained. Finally, the sectoral carbon flows are summed up to the national level, forming the 61×61 national-level

carbon transfer matrix G , in which each element $G(r,s)$ represents the total embodied carbon emissions produced in region r to meet the final consumption of region s . The net carbon transfer matrix is further derived as the difference between the carbon transfer matrix and its transpose, which identifies net carbon exporters and importers across BRI economies.

2.3 Dataset Source

This study uses the EMERGING V2 [11] multi-regional input-output (MRIO) database and its corresponding CO₂ emission inventory for analysis. The database covers 245 economies and 133 sectors, with optimized and calibrated data on intermediate inputs, trade volumes, and total outputs, particularly for the energy, electricity, and transportation sectors. The CO₂ inventory, derived from IEA and CEADs data, provides sector-level fossil fuel combustion emissions across seven energy types. For this study, we use core MRIO data including intermediate input matrices, gross output matrices, final demand data, and sectoral CO₂ emissions, along with country codes to aggregate the sample into Belt and Road economies.

3 Results and Discussion

3.1 Changes in China-BRI Embodied Carbon Flows and Carbon Leakage Rates

Table 1 reveal that China has consistently been a net embodied carbon exporter to Belt and Road economies during 2015–2023. In 2015, the total carbon emissions generated in China to meet export demand from Belt and Road countries stood at 482.01 Mt CO₂, while emissions generated in Belt and Road economies to satisfy China's final demand amounted to 270.53 Mt CO₂, yielding a net carbon outflow of 211.48 Mt CO₂. By 2023, both directions of embodied carbon flows had increased significantly: China's export-related emissions rose to 792.08 Mt CO₂, and Belt and Road countries' emissions driven by Chinese demand reached 358.47 Mt CO₂. As a result, the net carbon outflow more than doubled to 433.62 Mt CO₂, indicating that China has borne a growing share of the environmental pressures associated with consumption in other Belt and Road economies.

From the perspective of carbon leakage rates, the proportion of China's production-side emissions driven by Belt and Road exports increased from 6.87% in 2015 to 8.86% in 2023, and the net carbon leakage rate rose from 3.01% to 4.85%. These trends suggest that, as trade volumes expanded, the environmental cost imbalance in China–Belt and Road trade has become more pronounced. While deeper economic integration has brought shared development benefits, the uneven distribution of embodied carbon emissions—with China bearing a rising share of the production-side pollution—poses growing challenges to the coordinated advancement of environmental, economic, and social goals in the Belt and Road region.

Table 1. China's embodied carbon transfers and carbon leakage rates with BRI economies (2015 vs. 2023)

Indicator	2015	2023	Change
China's embodied carbon exports to BRI economies (Mt CO ₂)	482.01	792.08	+310.07
BRI economies' embodied carbon exports to China (Mt CO ₂)	270.53	358.47	+87.94
Net embodied carbon transfer from China to BRI economies (Mt CO ₂)	211.48	433.62	+222.14
Production-side carbon leakage rate (% of China's total production emissions)	6.87	8.86	+1.99
Net carbon leakage rate (% of China's total production emissions)	3.01	4.85	+1.84

3.2 Total Embodied Carbon Transfer Patterns Among BRI Economies (2015 vs. 2023)

The total embodied carbon transfers among Belt and Road economies in 2015 and 2023 are presented in Figure 1 and Figure 2, respectively.

The total embodied carbon transfer matrices highlight China's dominant role in cross-border carbon flows among Belt and Road economies, with a clear intensification between 2015 and 2023. In both years, the highest-intensity flows are concentrated in China's row (producing side), indicating that China acts as the primary carbon exporter in the network. By 2023, the peak carbon transfer from China to a single BRI economy more than doubled, and the number of significant cross-border flows originating from China expanded to include more partners across Southeast Asia, Central Asia, and Eastern Europe. In contrast, China's column (consuming side) shows only moderate increases in emissions driven by its own demand, confirming it remains a net carbon exporter bearing a growing share of the region's environmental costs.

Other major economies show far smaller and more stable roles in the carbon transfer network. India's carbon exports remain modest despite a slight increase, while Russia's flows to key partners are visible but do not challenge China's dominance. Saudi Arabia appears primarily as a carbon importer, with its column showing growing flows from producing countries, likely tied to its demand for manufactured goods. Together, these patterns reinforce that the BRI's embodied carbon network is highly uneven, with China as the clear core of export-side environmental pressure.

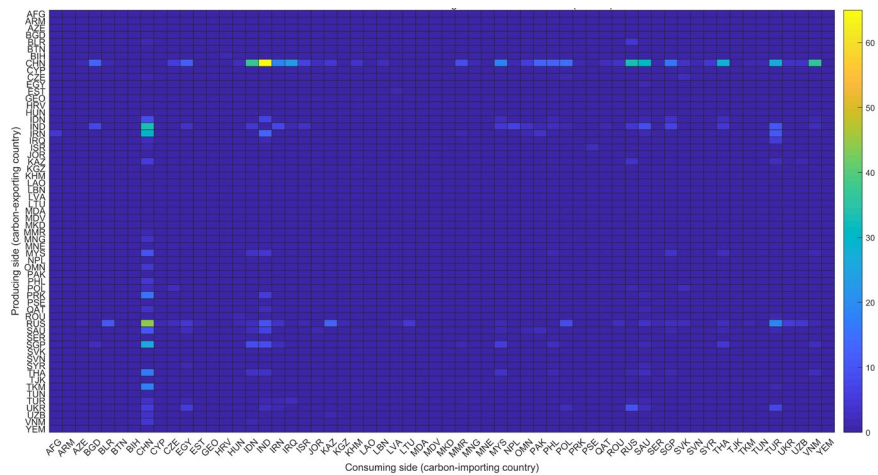


Fig. 1. Total embodied carbon transfers among Belt and Road economies, 2015 (Mt CO₂)

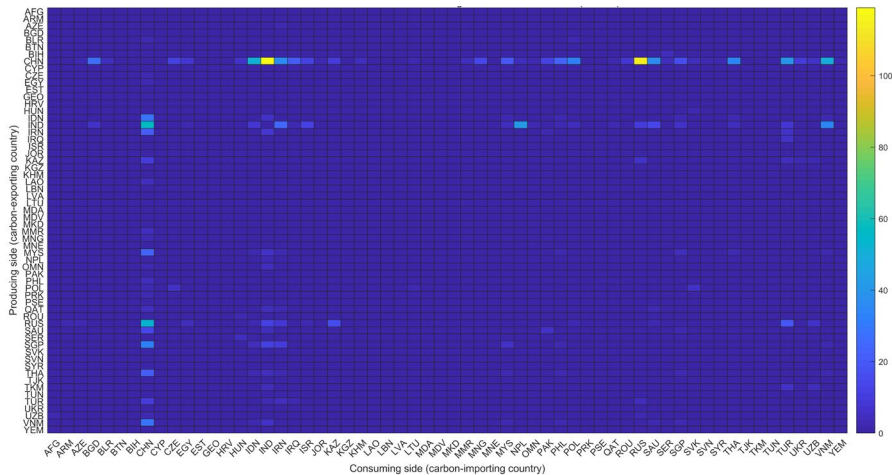


Fig. 2. Total embodied carbon transfers among Belt and Road economies, 2023 (Mt CO₂)

3.3 Net Embodied Carbon Transfer Patterns Among BRI Economies (2015 vs. 2023)

The net embodied carbon transfers among Belt and Road economies in 2015 and 2023 are presented in Figure 3 and Figure 4, respectively.

The net embodied carbon transfer matrices clearly illustrate China’s persistent and growing role as the dominant net carbon exporter among Belt and Road economies. In both 2015 and 2023, the most intense red cells (indicating positive net carbon outflows) are concentrated in China’s row, reflecting that China bears far more production-side emissions for other BRI countries than it generates as a result of their demand. By 2023, the magnitude of China’s largest net carbon outflows nearly doubled, and the number

of significant net export relationships expanded across the network, reinforcing China’s position as the primary carrier of the region’s environmental costs.

In contrast, blue cells (indicating net carbon inflows to China) remain sparse and small in both years, showing that no single BRI economy generates enough emissions to offset China’s net carbon outflows. India, for example, appears as a minor net carbon exporter to some partners but remains a net importer in its relationship with China, as indicated by the blue cell in India’s row for China. The widening gap between China’s red and blue cells from 2015 to 2023 confirms that the imbalance in China-BRI trade-related carbon flows has intensified, with China’s net carbon exports rising significantly faster than any countervailing flows from other economies.

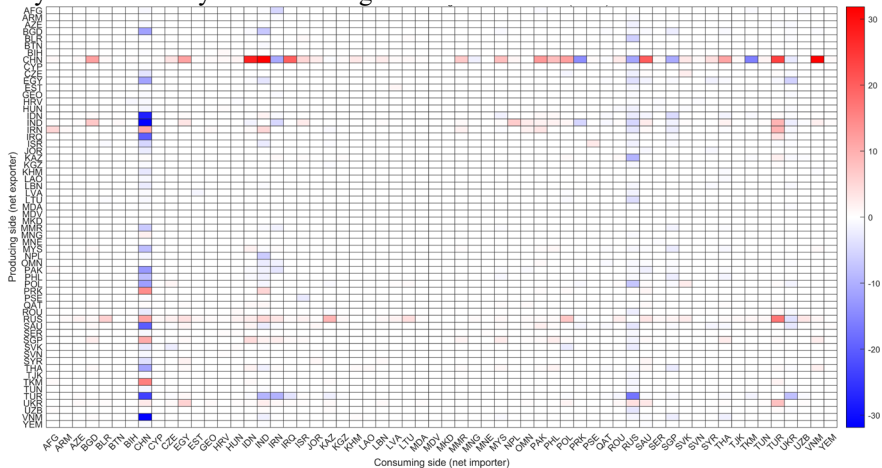


Fig. 3. Net embodied carbon transfers among Belt and Road economies, 2015 (Mt CO₂)

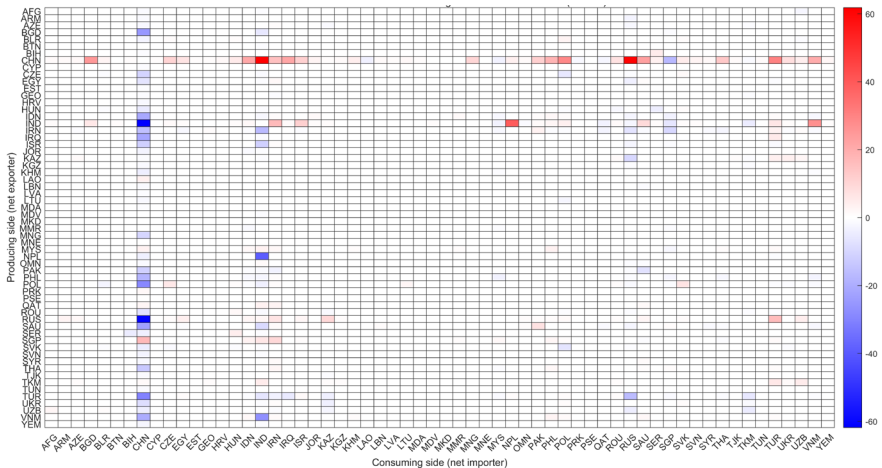


Fig. 4. Net embodied carbon transfers among Belt and Road economies, 2023 (Mt CO₂)

4 Conclusion

This study analyzed embodied carbon transfers among Belt and Road (BRI) economies using the EMERGING V2 multi-regional input-output database for 2015 and 2023. The results reveal that China consistently acts as the primary net embodied carbon exporter in the network, with its net carbon outflows to BRI partners more than doubling over the period. The carbon leakage rate also rose significantly, indicating that China has borne an increasing share of the environmental costs associated with regional trade. Meanwhile, the net transfer matrices show a growing imbalance in carbon distribution, with few other economies contributing significantly to offsetting China's role. These findings highlight the need for coordinated policy efforts to address the uneven environmental impacts of trade integration, promote low-carbon industrial transformation, and advance more equitable and sustainable development within the Belt and Road framework. This study covers only two years and does not conduct sectoral decomposition. Future research may use longer panel data, industry-specific analysis, and econometric testing of driving mechanisms to provide more detailed insights for green BRI development.

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