Reconciling Producer and Consumer Responsibilities: A Parameter-Free Shared Model Based on Production Layer Decomposition

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Abstract: As the world's first substantially implemented unilateral carbon tariff tool, the implementation of the European Union's Carbon Border Adjustment Mechanism (CBAM) marks a new stage in global climate governance. Currently, the academic community has yet to reach a unified consensus on carbon emission responsibility accounting schemes. This paper innovatively proposes a parameter-free carbon emission responsibility-sharing model based on structural production layer decomposition. The model precisely segments the embodied carbon emissions of products undergoing direct trade into first-tier (direct export), second-tier (direct intermediate input), third-tier (first-round indirect input), and higher-tier carbon emission responsibilities from the buyer's perspective. Research findings indicate that, from a product dimension, the CBAM default values for U.S. products are highly concentrated within the first-tier buyer carbon emission intensity indicators. In contrast, the CBAM default values for Chinese products accumulate far beyond the carbon emission intensity indicators of the complete industrial chain. This phenomenon highlights the systemic discrimination of the EU's Carbon Border Adjustment Mechanism against countries possessing complete industrial chains. From a national dimension, major developing countries represented by China and India have long transitioned from a shallow processing trade model to an internalized model with complete industrial chains. Conversely, developed economies represented by the EU and the United States exhibit a trend of manufacturing hollowing-out and the outsourcing of high-carbon emission stages

Keywords: CBAM Parameter-free Production layer decomposition Responsibility-sharing model

1.Introduction

The legitimacy and effectiveness of carbon emission reduction policies fundamentally depend on the scientific nature of national carbon emission responsibility accounting. Currently, there are primarily three methods for accounting carbon emission responsibility: producer responsibility, consumer responsibility, and shared responsibility. The signing of the *United Nations Framework Convention on Climate Change* and the *Kyoto Protocol* marked the emergence of producer responsibility based on the "territorial responsibility principle," meaning that whoever generates carbon emissions on their territory bears the responsibility. Building upon this, Eder & Narodoslawsky (1999) and Peters (2008) proposed replacing territorial emissions with complete production emissions and final production emissions. However, this carbon emission responsibility accounting system based on the territorial principle not only ignores the transnational flow of embodied carbon in international trade but also provides an institutional loophole for developed countries to transfer highly polluting enterprises to developing countries through FDI to achieve "paper" emission reductions. Consequently, the "consumer responsibility principle," which advocates "whoever consumes is responsible," took the stage, requiring that carbon emissions from the entire industrial chain be entirely attributed to the final consuming country. Eder & Narodoslawsky (1999) proposed the concept of "unlimited benefit responsibility," requiring a region to be responsible for the carbon emissions generated by its residents satisfying their final demands; subsequent scholars such as Munksgaard & Pedersen (2001) and Peters et al. (2008; 2011) further advanced the development of this theory. However, the consumer responsibility principle completely exempts exporting countries from environmental constraints during the profitable production process, which is obviously unfair to consuming countries. Against this backdrop, the "shared responsibility principle" has gradually become the focus of attention. Kondo et al. (1998) explicitly proposed weighting producer responsibility and consumer responsibility, selecting the "territorial responsibility" followed by the Kyoto Protocol as the emission indicator representing producer responsibility; Ferng (2003), Peters (2008), and Rodrigues et al. (2006; 2008) used complete production emissions, final production emissions, and income-side emissions as emission indicators for producer responsibility; building on this, Gallego & Lenzen (2005) and Lenzen et al. (2007) proposed responsibility allocation coefficients based on value-added. However, reviewing the existing literature, most shared responsibility schemes heavily rely on exogenously given empirical weight coefficients, lacking an endogenous consideration of the topological structure of production processes and the depth of the industrial chain within the supply chain.

With the official implementation of the European Union's Carbon Border Adjustment Mechanism (CBAM) on January 1, 2026, global climate governance began to evolve from multilateral negotiations to unilateral trade rules. The policy constraints of carbon reduction crossed national borders for the first time, directly impacting international trade itself. The EU claims that CBAM, as a unilateral climate trade tool that extends and complements the EU Emissions Trading System (EU ETS), was introduced to rectify a series of issues arising during the operation of the EU ETS; it aims to curb the risk of "carbon leakage" by levying border adjustment taxes on imported high-carbon products while simultaneously protecting the competitiveness of domestic high-carbon enterprises within the EU. However, in the context of the continuously evolving global value chains today, the implementation of this mechanism has sparked widespread controversy. A major point of contention is that there is currently no unified global standard for accounting product carbon footprints; although the EU asserts that the default carbon emission values for products are based on authoritative data from its Joint Research Centre (JRC) and that the calculation methods are public, it has neither released the raw data nor the specific methodologies used to calculate default values for products from different countries. In fact, we have found that within existing public CBAM documents, there are significant discrepancies in the default carbon emission values assigned to similar products from different countries, raising the question of whether there is systemic discrimination against specific countries.

To address this issue, this paper proposes a parameter-free carbon emission responsibility-sharing model based on structural production layer decomposition. By decomposing the production tiers along the value chain, this model ingeniously avoids the flaw of traditional carbon emission responsibility accounting, which can only rely on fixed parameters. Simultaneously, by linking this with the CBAM default values for products from different countries, empirical findings reveal that CBAM exhibits clear systemic discrimination against the vast number of developing countries led by China. At the same time, we have also measured total carbon emissions at the national level, finding that major developing countries represented by China and India have long transitioned from a shallow processing trade model to an internalized model of complete industrial chains. Conversely, developed economies represented by the EU and the United States demonstrate a trend characterized by the hollowing-out of manufacturing and the outsourcing of high-carbon emission stages.

The remainder of this paper is organized as follows. Section II primarily introduces CBAM and the literature review. Section III introduces the model construction and data sources. Section IV presents the empirical analysis. Section V serves as the conclusion.

2.Literature review

As the world's first climate trade instrument with substantive punitive binding force, the Carbon Border Adjustment Mechanism (CBAM) was initially established to prevent "carbon leakage" resulting from rising environmental costs in domestic industries and to safeguard the international competitiveness of local enterprises (Zhong & Pei, 2022; 2024). However, the product emission default values mandated by CBAM have sparked immense controversy. CBAM stipulates that when EU importers are unable to provide compliant actual carbon emission data, the system will compulsorily apply predetermined default values as substitute carbon emissions in the carbon tax calculation. A working paper by the OECD (2025) points out that this default value accounting mechanism will cause downstream supply chains not covered by CBAM to suffer negative shocks due to rising input costs. Utilizing a Computable General Equilibrium (CGE) model, Bellora and Fontagné (2023) further confirm that this mechanism will exert highly complex impacts on industries across different countries. Fundamentally, the academic community has not yet reached a unified consensus on a carbon emission responsibility accounting scheme, and CBAM completely overlooks the heterogeneity of production network depths across countries, thereby resulting in systemic discrimination against developing countries deeply embedded at the bottom of the supply chain.

Accurately defining the allocation of carbon emission responsibility forms the foundation of all climate trade policies. Referring to the systematic review of national carbon responsibility accounting schemes by Peng Shuijun et al. (2016), these can be broadly categorized into three types: production-based carbon emission responsibility (Eder & Narodoslawsky, 1999; Ferng, 2003; Peters, 2008; Gallego & Lenzen, 2005; Rodrigues et al., 2006; Marques et al., 2012), consumption-based carbon emission responsibility (Eder & Narodoslawsky, 1999; Munksgaard & Pedersen, 2001;

Peters, 2008; Peters et al., 2011), and shared responsibility (Kondo et al., 1998; Ferng, 2003; Peters, 2008; Rodrigues et al., 2006; Rodrigues & Domingos, 2008; Gallego & Lenzen, 2005; Lenzen et al., 2007). The production-based carbon emission accounting principle established by the early *Kyoto Protocol* faces increasingly severe challenges; international industrial relocation has shifted a substantial proportion of carbon emissions from developed to developing countries, and national emission reduction policies are simultaneously offset by transnational production (Wiedmann & Lenzen, 2018). Although consumption-based carbon accounting better reflects "common but differentiated rights to carbon consumption" (Fan Gang et al., 2010), due to issues such as technical complexity and political acceptability, consumption-based accounting may lack universal binding force (Afionis et al., 2017; Wiedmann & Lenzen, 2018). To address this issue, Lenzen et al. (2007) first systematically proposed a mathematical model of shared responsibility within an input-output framework. Xu Yingzhi et al. (2014) conducted quantitative research on producers, consumers, and shared responsibility, demonstrating the fairness of the shared principle. Temursho & Miller (2020) broke through the traditional weight allocation method relying on value-added, proposing an upstream-downstream shared responsibility model based on the distances of the "input requirement chain" and "output supply chain". Zhang et al. (2023) proposed a shared responsibility model based on the benchmark approach. Du et al. (2024) broke the limitations of single economic indicators and constructed a CVAT comprehensive allocation coefficient method encompassing direct carbon emissions (C), value-added (VA), and technological level (T).

In fact, with the high fragmentation of global value chains today, multinational corporations facilitate the flow of massive amounts of embodied carbon across different countries through cross-border investment, global subcontracting, and offshore production (Zhang et al., 2020). Particularly in the context of foreign direct investment (FDI), Li et al. (2026) formally incorporated multinational investors into the shared responsibility system and proposed an optimized shared responsibility framework.

Traditional environmentally extended multi-regional input-output (EE-MRIO) models utilize the complete Leontief inverse matrix for aggregate measurements, which can easily obscure the true carbon footprints of intermediate production stages (Gao et al., 2021). Zhang et al. (2017) ingeniously conducted a cross-border expansion of the Leontief inverse matrix by introducing the cross-border frequency of carbon footprints. Crucially, Wieland et al. (2018) formally introduced the Structural Production Layer Decomposition (SPLD) method, tracking discrete production layers through a Taylor series expansion of the Leontief inverse matrix.

3. Theoretical Model and Data Sources

3.1 Model Construction

This paper utilizes the multi-regional input-output (MRIO) model spanning 1995 to 2022 published by the OECD. Let us assume there are *N* countries globally, with each country comprising *M* sectors. The figure below presents the basic structure of a standard global multi-regional input-output table.

投入＼产出			中间使用													最终使用				总产出
			国家1				国家2				⋯	国家N				国家1	国家2	⋯	国家N	
			1	2	⋯	M	1	2	⋯	M		1	2	⋯	M					
中间投入	国家1	1	Z_{11}^{11}	Z_{11}^{12}	⋯	Z_{11}^{1M}	Z_{12}^{11}	Z_{12}^{12}	⋯	Z_{12}^{1M}	⋯	Z_{1N}^{11}	Z_{1N}^{12}	⋯	Z_{1N}^{1M}	Y_{11}^{1}	Y_{12}^{1}	⋯	Y_{1N}^{1}	X_{1}^{1}
		2	Z_{11}^{21}	Z_{11}^{22}	⋯	Z_{11}^{2M}	Z_{12}^{21}	Z_{12}^{22}	⋯	Z_{12}^{2M}	⋯	Z_{1N}^{21}	Z_{1N}^{22}	⋯	Z_{1N}^{2M}	Y_{11}^{2}	Y_{12}^{2}	⋯	Y_{1N}^{2}	X_{1}^{2}
		⋮	⋮	⋮	⋱	⋮	⋮	⋮	⋱	⋮	⋯	⋮	⋮	⋱	⋮	⋮	⋮	⋯	⋮	⋮
		M	Z_{11}^{M1}	Z_{11}^{M2}	⋯	Z_{11}^{MM}	Z_{12}^{M1}	Z_{12}^{M2}	⋯	Z_{12}^{MM}	⋯	Z_{1N}^{M1}	Z_{1N}^{M2}	⋯	Z_{1N}^{MM}	Y_{11}^{M}	Y_{12}^{M}	⋯	Y_{1N}^{M}	X_{1}^{M}
	国家2	1	Z_{21}^{11}	Z_{21}^{12}	⋯	Z_{21}^{1M}	Z_{22}^{11}	Z_{22}^{12}	⋯	Z_{22}^{1M}	⋯	Z_{2N}^{11}	Z_{2N}^{12}	⋯	Z_{2N}^{1M}	Y_{21}^{1}	Y_{22}^{1}	⋯	Y_{2N}^{1}	X_{2}^{1}
		2	Z_{21}^{21}	Z_{21}^{22}	⋯	Z_{21}^{2M}	Z_{22}^{21}	Z_{22}^{22}	⋯	Z_{22}^{2M}	⋯	Z_{2N}^{21}	Z_{2N}^{22}	⋯	Z_{2N}^{2M}	Y_{21}^{2}	Y_{22}^{2}	⋯	Y_{2N}^{2}	X_{2}^{2}
		⋮	⋮	⋮	⋱	⋮	⋮	⋮	⋱	⋮	⋯	⋮	⋮	⋱	⋮	⋮	⋮	⋯	⋮	⋮
		M	Z_{21}^{M1}	Z_{21}^{M2}	⋯	Z_{21}^{MM}	Z_{22}^{M1}	Z_{22}^{M2}	⋯	Z_{22}^{MM}	⋯	Z_{2N}^{M1}	Z_{2N}^{M2}	⋯	Z_{2N}^{MM}	Y_{21}^{M}	Y_{22}^{M}	⋯	Y_{2N}^{M}	X_{2}^{M}
	⋮		⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋱	⋮	⋮	⋮	⋮	⋮	⋮	⋱	⋮	⋮
	国家N	1	Z_{N1}^{11}	Z_{N1}^{12}	⋯	Z_{N1}^{1M}	Z_{N2}^{11}	Z_{N2}^{12}	⋯	Z_{N2}^{1M}	⋯	Z_{NN}^{11}	Z_{NN}^{12}	⋯	Z_{NN}^{1M}	Y_{N1}^{1}	Y_{N2}^{1}	⋯	Y_{NN}^{1}	X_{N}^{1}
		2	Z_{N1}^{21}	Z_{N1}^{22}	⋯	Z_{N1}^{2M}	Z_{N2}^{21}	Z_{N2}^{22}	⋯	Z_{N2}^{2M}	⋯	Z_{NN}^{21}	Z_{NN}^{22}	⋯	Z_{NN}^{2M}	Y_{N1}^{2}	Y_{N2}^{2}	⋯	Y_{NN}^{2}	X_{N}^{2}
		⋮	⋮	⋮	⋱	⋮	⋮	⋮	⋱	⋮	⋯	⋮	⋮	⋱	⋮	⋮	⋮	⋯	⋮	⋮
		M	Z_{N1}^{M1}	Z_{N1}^{M2}	⋯	Z_{N1}^{MM}	Z_{N2}^{M1}	Z_{N2}^{M2}	⋯	Z_{N2}^{MM}	⋯	Z_{NN}^{M1}	Z_{NN}^{M2}	⋯	Z_{NN}^{MM}	Y_{N1}^{M}	Y_{N2}^{M}	⋯	Y_{NN}^{M}	X_{N}^{M}
增加值			V_{1}^{1}	V_{1}^{2}	⋯	V_{1}^{M}	V_{2}^{1}	V_{2}^{2}	⋯	V_{2}^{M}	⋯	V_{N}^{1}	V_{N}^{2}	⋯	V_{N}^{M}					
总投入			$(X_{1}^{1})'$	$(X_{1}^{2})'$	⋯	$(X_{1}^{M})'$	$(X_{2}^{1})'$	$(X_{2}^{2})'$	⋯	$(X_{2}^{M})'$	⋯	$(X_{N}^{1})'$	$(X_{N}^{2})'$	⋯	$(X_{N}^{M})'$					

Here, *Z* represents the intermediate consumption relationship matrix among sectors across all countries. Z_{rs}^{ij} denotes the direct consumption by sector *j* in country *s* of the products from sector *i* in country *r*. We define $Z_{rs} = \begin{pmatrix} Z_{rs}^{11} & Z_{rs}^{12} & \cdots & Z_{rs}^{1M} \\ Z_{rs}^{21} & Z_{rs}^{22} & \cdots & Z_{rs}^{2M} \\ \vdots & \vdots & \ddots & \vdots \\ Z_{rs}^{M1} & Z_{rs}^{M2} & \cdots & Z_{rs}^{MM} \end{pmatrix}$.Let $a_{rs}^{ij} = \frac{Z_{rs}^{ij}}{X_s^i}$ represent the direct consumption of products from sector *i* in country *r* required by sector *j* in country *s* to produce one unit of product. Thus, the direct consumption coefficient matrix can be expressed as $A_{rs} =$

$\begin{pmatrix} a_{rs}^{11} & a_{rs}^{12} & \cdots & a_{rs}^{1M} \\ a_{rs}^{21} & a_{rs}^{22} & \cdots & a_{rs}^{2M} \\ \vdots & \vdots & \ddots & \vdots \\ a_{rs}^{M1} & a_{rs}^{M2} & \cdots & a_{rs}^{MM} \end{pmatrix}$, where A_{rr} is the direct consumption coefficient matrix among domestic sectors within country *r*. Y_{rs}^{i} indicates the products produced by sector *i* in country *r* to satisfy the final demand of country *s*, and $Y_{rs} = \begin{pmatrix} Y_{rs}^{1} \\ Y_{rs}^{2} \\ \vdots \\ Y_{rs}^{M} \end{pmatrix}$. f_r^i is the direct emission intensity of sector *i* in country *r*, which is the amount of carbon emissions generated per unit of total output of the sector. $f_r = \begin{pmatrix} f_r^1 \\ f_r^2 \\ \vdots \\ f_r^M \end{pmatrix}$ is the column vector of direct carbon emission intensity for country *r*, and $\widehat{f_r}$ represents the diagonal matrix of f_r. e is a summation column vector with all elements equal to 1, and e^T denotes the transpose of e.

We define W_{rs}^{i} as the carbon emission column vector generated by all sectors within country *r* during the process of sector *i* in country *r* exporting goods and services to country *s*. The calculation formula is as follows:

$$W_{rs}^{i} = \widehat{f_r} * (I - A_{rr})^{-1} * (Z_{rs} * e + Y_{rs})$$

In this formula, $(I - A_{rr})^{-1}$ is the well-known domestic intermediate Leontief inverse matrix. It represents the total domestic output required within country *r* to satisfy one unit of final demand after undergoing countless domestic cycles. To achieve a structural penetration of the production layers of carbon emissions, under the condition of ensuring matrix convergence, we utilize the Taylor series to perform a power matrix expansion on the domestic intermediate Leontief inverse matrix:

$$(I - A_{rr})^{-1} = I + A_{rr} + {A_{rr}}^2 + \cdots$$

3.1.1 Carbon Emissions from the Perspective of First-Tier Buyers

Here, we attribute the carbon emissions generated from direct exports during the process of country *r* exporting goods and services to country *s*, to country *s*.

$${}_{s}^{1}W_{rs}^{i} = \widehat{f_r} * I * (Z_{rs} * e + Y_{rs})$$

Similarly, we attribute the carbon emissions generated from direct exports during the process of country *s* exporting goods and services to country *r*, to country *r*.

$$ {}_{r}^{1}W_{sr}^{i} = \widehat{f_s} * I * (Z_{sr} * e + Y_{sr}) $$

Consequently, we obtain the carbon emission column vector from the perspective of a first-tier buyer, attributed to country *r* in the direct international trade between country *r* and country *s*:

$$ {}_{r^1}E_{rs}^{i} = W_{rs}^{i} - {}_{s}^{1}W_{rs}^{i} + {}_{r}^{1}W_{sr}^{i} $$

By performing column summation on ${}_{r^1}E_{rs}^{i}$, we can obtain the total carbon emissions from the perspective of a first-tier buyer attributed to country *r* in the direct international trade between country *r* and country *s*:

$$ {}_{r^1}E_{rs} = e^T * {}_{r^1}E_{rs}^{i} $$

Simultaneously expanding the model to a global scale yields the total carbon emissions from the perspective of a first-tier buyer attributed to country *r* in its direct trade with the world:

$$ {}_{r^1}E_{r} = \sum_{s \neq r} {}_{r^1}E_{rs} $$

3.1.2 Carbon Emissions from the Perspective of Higher-layer Buyers

Due to space constraints, the following only derives the carbon emissions from the perspective of a higher-layer buyer.

Here, during the process of country *r* exporting goods and services to country *s*, we calculate backwards from the direct trade across borders to the *k*-th layer and attribute these carbon emissions to country *s*.

$$ {}_{s}^{k}W_{rs}^{i} = \widehat{f_r} * (I + \sum_{\alpha=1}^{k-1} A_{rr}{}^{\alpha}) * (Z_{rs} * e + Y_{rs}) $$

Similarly, during the process of country *s* exporting goods and services to country *r*, we calculate backwards from the direct trade across borders to the *k*-th tier and attribute these carbon emissions to country *r*.

$$ {}_{r}^{k}W_{sr}^{i} = \widehat{f_s} * (I + \sum_{\alpha=1}^{k-1} A_{ss}{}^{\alpha}) * (Z_{sr} * e + Y_{sr}) $$

Consequently, we obtain the carbon emission column vector from the perspective of a *k*-th tier buyer, attributed to country *r* in the direct international trade between country *r* and country *s*:

$$ {}_{r^k}E_{rs}^{i} = W_{rs}^{i} - {}_{s}^{k}W_{rs}^{i} + {}_{r}^{k}W_{sr}^{i} $$

By performing column summation on ${}_{r^k}E_{rs}^{i}$, we can obtain the total carbon emissions from the perspective of a *k*-th tier buyer attributed to country *r* in the direct international trade between country r and country s.

$$ {}_{r^k}E_{rs} = e^T * {}_{r^k}E_{rs}^i $$

Simultaneously expanding the model to a global scale yields the total carbon emissions from the perspective of a k-th tier buyer attributed to country r in its direct trade with the world:

$$ {}_{r^k}E_r = \sum_{s \neq r} {}_{r^k}E_{rs} $$

3.1.3 Column Vector of Carbon Emission Intensity from the Buyer's Perspective

Constrained by the granularity of macroeconomic data, this study is based on the homogeneity assumption within the field of input-output analysis: it assumes that all products manufactured within the same sector share identical production technologies and emission intensities.

To precisely anchor the default values of the EU's CBAM, we will process the previously obtained ${}_{r^k}E_{rs}^i$. Here, country s defaults to the EU, and H_r^i represents the total export volume of various sectors in country r to the 27 EU member states. V_r^i denotes the total trade volume between country r and various sectors of the EU, and G_r^i is the total product weight between country r and various sectors of the EU. Consequently, the column vector of carbon emission intensity for products exported by sector i of country r to the EU can be expressed as:

$$ {}_r^kL = \frac{{}_{r^k}E_{rs}^i}{H_r^i} * \frac{V_r^i}{G_r^i} $$

3.2 Data Sources and Processing

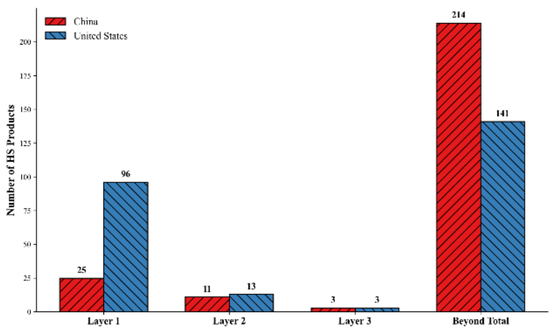
The data utilized in this paper are primarily sourced from the 1995-2022 Global Multi-Regional Input-Output (MRIO) tables published by the Organization for Economic Co-operation and Development (OECD), the Greenhouse Gas Footprints (GHGFP): Emissions embodied in production by scope, the HS 8-digit code trade data released by Eurostat, and the latest official CBAM document published by the EU on December 31, 2025, which announces the default emission values for different HS 8-digit commodities imported from various countries. Among these, the 1995-2022 global MRIO tables published by the OECD cover 81 economies, with each economy consisting of 50 sectors, whereas the carbon footprint accounts published by the OECD only cover 77 economies, with each economy consisting of 45 sectors. Therefore, during data processing, a dimensionality reduction approach was adopted; the 4 countries not covered by the carbon footprint accounts in the global MRIO table were compressed into the ROW (Rest of World) category, and the 50 sectors were aggregated into 45 sectors according to the rules of the carbon footprint accounts to ensure dimensional consistency.

Simultaneously, we mapped the HS 8-digit codes to the sectors of the global MRIO table. However, constrained by the granularity of the macroeconomic data, we could only employ the homogeneity assumption, postulating that one unit of different products manufactured within each sector shares the same emission intensity, so as to project the carbon emissions of different products into carbon emission intensities. The official CBAM document published by the EU contains highly detailed data on direct emissions, indirect emission default values, and free allowances. For the convenience of comparison, we solely extracted the default direct carbon emission value for each product, without considering the more complex calculation rules.

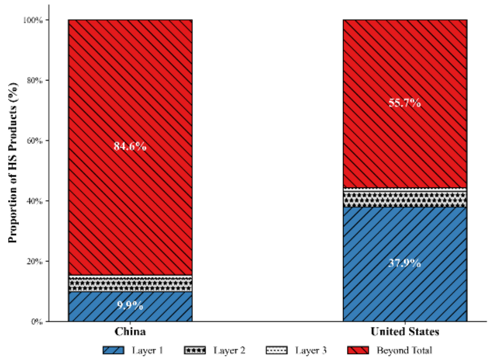
4. Empirical Analysis

4.1 Comparison of CBAM Default Values Between Chinese and U.S. Products

To verify whether the Carbon Border Adjustment Mechanism (CBAM) practically exhibits differentiated discrimination against various economies (particularly between developing and developed countries) in its actual implementation, this study, grounded on the homogeneity assumption, strictly controlled for the heterogeneity of product categories and rigorously screened 253 completely overlapping 8-digit HS code products exported by both China and the United States to the EU. Concurrently, utilizing the global multi-regional input-output table, the carbon emissions of distinct production layers across different sectors in both countries were converted into carbon emission intensities, and these were projected onto the product level of their corresponding sectors, thereby facilitating an asymmetric comparative study of the default product emission values between the nations. The figure below illustrates the distribution results of Chinese and American products across different production tiers under the CBAM default system.

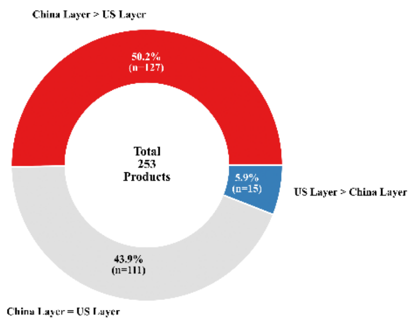


(a) Number of HS Products Distribution

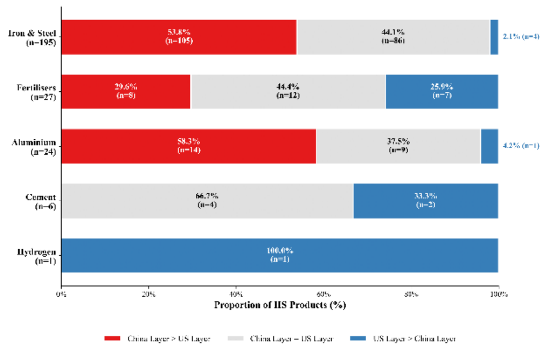


(b) Proportion of HS Products Distribution

Empirical data demonstrate that the CBAM default value system manifests a significant "preferential emission treatment" for U.S. export products; among the 253 evaluated products, up to 37.9% of U.S. products are matched with default carbon emission intensities only up to the first tier, which covers exclusively the direct export emissions of the production stage. This implies that when facing the EU's carbon tariff scrutiny, the carbon footprints of the complex upstream supply chains for a considerable number of high-value-added American products have been substantially underestimated. In stark contrast, the carbon reviews imposed on China are significantly more stringent. Within the same 253 evaluated products, a mere 9.9% of Chinese products match the first tier, whereas a staggering 84.6% of the products are assigned default values that far exceed the "entire-industrial-chain carbon emission intensity" deduced via the Leontief inverse matrix. This finding indicates that when the EU reviews the carbon emissions of products originating from China, it not only traces all carbon emissions along the entire industrial chain but also forcibly imposes an additional "punitive emission".



(c) Comparison of CBAM Accounting Boundaries:
China vs. United States



(d) Asymmetry of CBAM Accounting Boundaries by Industry

To further investigate the extent of the asymmetric accounting by the EU's CBAM regarding identical products from China and the United States, this paper conducted a detailed subcategory and industry-specific examination of the 253 corresponding products. Figure (c) above represents the comparison of tiers between the CBAM default values for China and the US concerning products with the exact same 8-digit HS code. The chart reveals that 127 Chinese products have default emission tiers greater than those of the US products, accounting for over half at approximately 50.2%; conversely, only 15 US products have default emission tiers greater than those of Chinese products, representing a mere 5.9%.

Figure (d) above subsequently conducts a heterogeneity analysis of the products from an industry dimension. The research finds that in high-value-added metals industries (such as the iron and steel industry and the aluminum industry), the differentiated discrimination of the EU's CBAM is particularly pronounced. In the iron and steel sector, over half of the Chinese products possess default emission tiers greater than those of the US, at a proportion of approximately 53.8%, while only 2.1% of the US products have default emission tiers greater than those of Chinese products. Similarly, in the aluminum industry, over half of the Chinese products also exhibit default emission tiers greater than those of the US, at a proportion of about 58.3%, with only 4.2% of the US products having default emission tiers greater than the Chinese products. In contrast, in the cement and fertilizer sectors, which are two industries with relatively lower value-added, the differentiated discrimination is significantly reduced.

The disparate treatment encountered by China and the United States regarding subdivided products profoundly exposes the systemic discrimination inherent in the CBAM default value system. The accounting system established by CBAM is by no means an impartial environmental regulatory tool; rather, it constitutes a novel green trade barrier characterized by overt differentiated discrimination and high asymmetry. Substantively, it constructs a protective threshold favorable to the industrial systems of developed countries and, through concealed manipulations of accounting boundaries, imposes punitive carbon tariffs on key metal industries in China that possess strong processing attributes, high price elasticity, and high value-added.

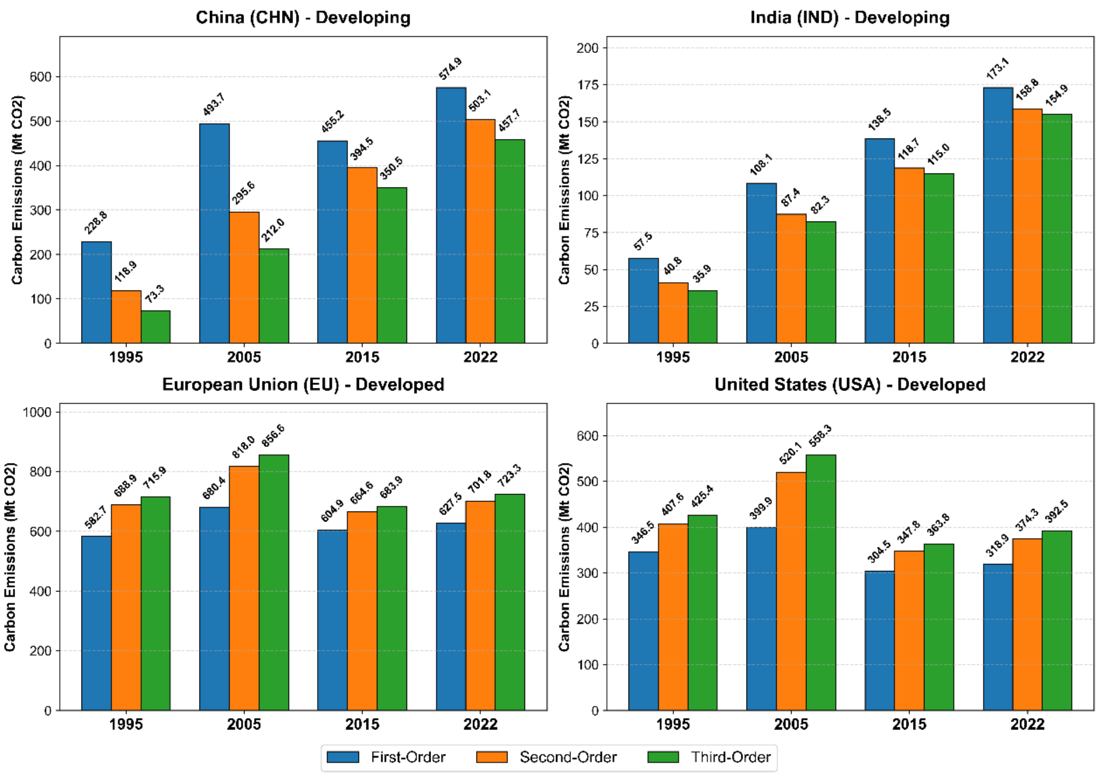
4.2 Historical Evolution Trends of Carbon Emissions in Different Countries

To explore the evolutionary patterns of carbon emissions across different countries during various historical periods, this paper conducts an in-depth analysis of the total carbon emissions at each production layer for major economies from 1995 to 2022. The data in the chart below intuitively reveals the reconstruction and development of the global industrial chain landscape over the past nearly three decades, as well as the historical shift in embodied carbon emission responsibilities.

Trajectories of Carbon Emissions by Order (1995-2022)

Economy Type	Country/Region	Year	First-Order	Second-Order	Third-Order
Developing	CHN	1995	228.76	118.90	73.28
		2005	493.71	295.55	212.04
		2015	455.17	394.46	350.54
		2022	574.86	503.15	457.73
	IND	1995	57.55	40.84	35.85
		2005	108.09	87.43	82.28
		2015	138.49	118.69	115.02
		2022	173.07	158.81	154.91
Developed	EU	1995	582.73	688.89	715.90
		2005	680.38	818.04	856.56
		2015	604.89	664.65	683.94
		2022	627.47	701.75	723.26
	USA	1995	346.48	407.57	425.37
		2005	399.95	520.10	558.30
		2015	304.46	347.81	363.77
		2022	318.86	374.33	392.48

Comparison of Carbon Emission Structures by Order (1995-2022)



As can be observed from the chart, for developing countries represented by China and India, the structure of carbon emissions at various tiers exhibits an "inverted pyramid" characteristic of successive decrement; that is, lower-tier carbon emissions are progressively higher than higher-tier carbon emissions. Taking China as an example, first-tier carbon emissions dominated in 1995 (228.8 Mt CO_2), which was almost more than three times the third-tier carbon emissions (73.3 Mt CO_2) in the same year. This massive data disparity profoundly corroborates the production model of "putting both ends of the production process on the world market and maintaining large-scale imports and exports" adopted by China in the early stages of its reform and opening-up. At that time, China primarily undertook the lowest-end and cheapest labor-intensive industrial stages in the global value chain, relying heavily on imported raw materials, while its domestic supply chain was predominantly concentrated in the final assembly and production stages. However, as time progressed, China's first-tier carbon emissions reached approximately 574.9 Mt in 2022, representing a growth rate of 151% compared to 1995, while its second-tier and third-tier carbon emissions reached about 503.1 Mt and 457.7 Mt, with staggering growth rates of 323% and 524%, respectively. This exponential expansion of embodied carbon indicates that China has successfully broken away from the model relying on shallow processing, manufacturing, and assembly, and has begun to form complete internal industrial chain clusters, thoroughly extending its domestic supply chain. India, similar to China, is also undergoing a protracted period of industrial ascent.

Conversely, for developed economies represented by the European Union and the United States, the structure of carbon emissions across different tiers presents an ascending "pyramid" characteristic, meaning that higher-tier carbon emissions are progressively greater than lower-tier emissions. Among these developed economies, the third-tier carbon emissions, which represent the deep industrial chain, have consistently remained at a "high level," whereas the first-tier carbon emissions, representing low-end manufacturing, have consistently marked the lowest point. This phenomenon demonstrates that, in order to satisfy their own demands for high value-added industries and low on-paper emission reductions, these developed economies have extensively outsourced highly energy-consuming low-end manufacturing to developing countries, thereby spatially transferring high emissions and environmental costs along the global value chain.

In summary of the comparative data, the globalization process over the past few decades has not merely been a process of distributing value activities; rather, it is a microcosm of carbon flows. Developed economies have maintained superficial, on-paper emission reduction data through "deindustrialization," while developing countries, in the process of absorbing production capacity from developed economies, have inevitably borne the cost of paying for the embodied carbon generated by ultimate global consumption. Therefore, when defining national carbon reduction responsibilities, one must not merely focus on the data within financial and environmental statements, but should instead comprehensively consider the structural roles of different countries within the global industrial chain landscape.

5. Conclusion

Against the backdrop of the deep integration of global value chains, scientific and equitable carbon emission responsibility accounting has emerged as the core focus of international green trade. Breaking away from traditional responsibility accounting schemes that rely on fixed parameters, this study innovatively proposes a parameter-free shared responsibility model based on the cross-scale linkage between global multi-regional input-output models and micro-trade data; rather than depending on fixed weight parameters, this model utilizes topological distances along the production chain to allocate carbon emission responsibilities. Furthermore, an in-depth empirical test of the CBAM default value system using this model reveals that the EU has not applied a uniform accounting depth to the carbon footprints of different countries. Relying on the high export unit prices of their products, developed countries successfully conceal the carbon footprints of complex supply chains behind "high premiums"; conversely, developing countries relying on cost advantages are assigned exorbitant "punitive" carbon emissions. This asymmetric carbon responsibility accounting system—characterized by "identical goods subject to differentiated rights"—not only severely deviates from the true levels of carbon footprints but also fundamentally deprives developing countries of legitimate trade space for low-value-added goods.

From the macro perspective of global governance, the asymmetric carbon responsibility accounting system of CBAM is essentially a strategic tool utilized by the EU to facilitate trade protectionism via its rule-making power over carbon emissions. By implementing "shallow protection" for developed nations and "deep punishment" for developing nations, it practically exacerbates inequalities in global climate governance. Even if a developing country achieves low-carbon upgrades in its domestic production technologies, as long as it maintains an export strategy characterized by low product unit prices, it will persistently suffer from carbon tariff exploitation brought about by asymmetric accounting.

In summary, a singular carbon pricing mechanism will inevitably engender structural inequalities. Future climate governance frameworks must be founded on multi-national participation to jointly establish internationally credible carbon emission databases, completely discarding "black-box" default carbon emission systems. Only under an accounting framework that is transparent, symmetrical, and fully considers the specific circumstances of each nation, can the unification of environmental emission reduction and international trade be truly realized, thereby propelling global substantive low-carbon transitions.

6. References

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