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论文题目：国际贸易间碳不平等四象限模型构建与碳补偿核算（Four-quadrant Modelling of Carbon Inequality in International Trade and Accounting for Carbon Compensation）

TITLE： Four-quadrant modelling of carbon inequality in international trade and accounting for carbon compensation

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ABSTRACT: In global trade, there is a phenomenon that the "economic gains" and "ecological damages" of some countries and regions are not consistent. Using the multi-regional input-output model (MRIO) and the EXIOBASE database, this study measures the transfer of embodied carbon and value-added in trade among 16 countries or regions, including the European Union, the United States and other countries from 1995 to 2022. On this basis, we adopts the four-quadrant analysis method to classify the carbon inequality phenomenon in international trade, and constructs the carbon inequality index to quantify the carbon inequality situation in bilateral trade. The results indicate that carbon inequality between international trade can be divided into three categories: victims of absolute carbon inequality, relative carbon equality and beneficiaries of absolute carbon inequality. Carbon inequality in bilateral trade exists between developed and developing countries, as well as between developing countries. Finally, a carbon compensation accounting model is constructed to measure the monetary value of cross-regional carbon offset, which provides data support for international carbon emission reduction cooperation.

KEY WORDS: Trade embodied carbon, Carbon inequality, Carbon compensation, Multi-regional input-output analysis

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1 Introduction

Since the 1990s, global trade has achieved rapid growth with the wave of economic globalization. According to the World Bank database, world merchandise exports increased significantly from 1990 ($3.46 trillion) to 2022 ($25.03 trillion), with merchandise trade's share of GDP rising to 50.5%in 2022. The development of international trade is accompanied by international transfers of energy flows such as goods, services, capital, and costs, which consequently can have wide-ranging economic, social, and environmental impacts on all regions of the globe (Wiedmann, T. and M. Lenzen, 2018). International trade is based on domestic production and oriented to foreign demand. The production process, which relies on the consumption of fossil energy, leads to the emission of greenhouse gases. So the rapid development of international trade will inevitably lead to a large amount of greenhouse gas emissions (Peters, G.P. and E.G. Hertwich, 2008; Peters, G.P., et al., 2011;Liang, X., et al.,2020). The embodied carbon of international trade accounts for an increasing share of carbon emissions. According to the measurement[1], the embodied carbon of international trade in 1995 was 3896.88Mt, and this value became 8467.80Mt in 2022, an increase of 117.30%, meanwhile, the embodied carbon of trade accounted for 22.2% of the total carbon emissions in 1995, and then showed an increasing trend, reaching a peak (28%) in 2008, and then in 2009 there was a sharp decline (the financial crisis in 2008 led to a decline in global trade), followed by a gradual rebound in 2010, and has maintained a favorable trend to 2022, accounting for a share of about 25%. In recent years, as the impact of CO2 emissions on global warming has attracted strong global attention (IPCC, 2023), global cooperation on carbon emission reduction has been

[1] Author's calculations using EXIOBASE data

deepening, and inter-regional games in the areas of carbon emission responsibility and reduction goals have become increasingly intense. How to distinguish the share of carbon emissions between trading partners and the division of responsibility for emission reduction has an important impact on inter-country cooperation to cope with global climate change, so the embodied carbon emissions transferred between countries has become a hot research topic.

There has been a large body of research on the measurement of total carbon emissions supported by producer-based (Harris, S., et al., 2020; Wu S , et al., 2020), consumer-based (Serrano, A., et al., 2016; Franzen, A., et al., 2018) and sharing-based (Jakob, M., et al., 2021) among other measurements. However, considering only the total amount of emissions cannot further advance the process of global carbon emission reduction. Due to the differences between different countries in terms of total population, level of economic development, resource endowment, etc., resulting in significant variations in each nation's overall and per-person carbon emissions, when the total carbon emissions are limited, the differences in carbon emissions among countries and different groups may be solidified, which will lead to inequity in carbon emissions among countries or groups. At the same time, with the in-depth study of the carbon embodied by international trade, it has been discovered that various locations engage in the global division of labor and incur various environmental costs, resulting in the inconsistent "economic benefits" and "ecological damage" of some countries and regions（Golgeci, I., et al., 2021), and they are at a disadvantage in international trade. There is carbon inequality. Categorizing and analyzing carbon inequalities can help to gain a deeper understanding of the relationship between carbon emissions and economic benefits of trade on a global scale, reduce carbon inequalities, and provide insights for advancing concerted emission reductions across countries.

This paper focuses on two main issues by clarifying the structure and flow of embodied carbon in international trade. The first is to explore whether carbon inequality exists in different economies in global trade; the second is to construct accounting standards and models for carbon compensation among different countries or regions. Based on this, the Multi-Regional Input-Output(MRIO)analysis is used in this study to examine the demand for carbon embodied by global trade and the flow and structure of carbon embodied by global trade from the perspective of the global industrial chain, so as to clarify the structure of carbon transfer from the major economies in the world, and to clarify the different roles of the regions with closely interrelated economies and significantly different patterns of carbon emission in the process of emission reduction. This will provide a basis for cooperation between economic development and carbon emission reduction. On this basis, we construct a model to measure carbon inequality in international trade and carbon inequality index for bilateral trade, and combine it with the average CER clearing price from the European Climate Exchange to construct a carbon compensation model and measure the amount of international carbon compensation. Exploring the issue of carbon inequality and accounting for carbon offsets can provide data support for the negotiation of carbon offsets between developed and developing countries, which is of great theoretical and practical significance for global equity and sustainable development.

The remaining parts of this paper are organized as follows. Section 2 provides an overview of the literature on trade-embodied carbon. Section 3 outlines the model and data used. Section 4 presents the empirical results and analysis. Finally， Section 5 concludes.

2. Literature review

With the development of global trade, economically developed regions will transfer high carbon emission products from economically backward regions through international trade, and the backward regions, based on their resource endowment and industrial foundation, will produce such products for a long time for the sake of economic development, which results in the phenomenon that although the emission reduction in the developed regions is effective, the pressure on the carbon emission reduction in the underdeveloped regions has been aggravated. Scholars have launched a series of studies on this situation, and found that there is a problem of carbon transfer in inter-regional trade, which is called embodied carbon. In order to study the total amount of a resource directly and indirectly consumed in the production of a product or service, "embodied" can be added to the name of the resource (Amaral, L.P., et al., 2016). Embodied carbon emissions differ from direct carbon emissions resulting from direct energy use, and refer to carbon emissions generated throughout the life cycle of goods and services consumed by the population, including carbon emissions from production and final decomposition processes (Fan J., 2012).

Scholars have found that the carbon emissions of economically developed countries themselves are very small, but their trade-induced correlated energy consumption and carbon emissions may be large (Peters.et al.,2008;Jakob, M and Marschinski, R.,2012； Wiedmann, T.et al.,2018). Based on this, scholars have carried out a large number of studies on the issue of embodied carbon transfer in international trade, starting from the perspective of a single country or region (Mi, Z.,et al., 2017;Wilting, H.C.,et al., 2021； Bruckner, B., et al., 2023), or a comprehensive exploration of the issue of embodied carbon in trade among the major countries or regions of the world, and the study of embodied carbon in trade among the major countries or regions of the world. Carbon issues are comprehensively explored in a wider range of studies (Brizga, J., et al., 2017; Franzen, A. and S. Mader, 2018; Zhao, L., et al., 2023). From the perspective of the amount and direction of embodied carbon transfer, although the carbon emissions of developed countries and the relevant territories required by the Kyoto Protocol decreased during the period 1990-2011, the embodied carbon emissions from trade increased, and the net transfer of carbon emissions from developed countries to developing countries through trade has already exceeded the emission reductions required by the Kyoto Protocol (Darwill,2023). From a geospatial perspective, in international trade consumers and producers of pollutants (e.g., CO2 emissions) are geographically and spatially separated, and a country can transfer pollutant emissions related to its consumption to other countries or regions through international trade, which also transfers part of the carbon emission reduction obligations originally belonging to consumers to producers, making it particularly difficult to reach a consensus on carbon emission reductions by the countries or regions in the middle of the trade (Hertwich,2020). This makes it particularly difficult for trading countries or regions to reach a consensus on carbon emissions reduction. International trade may have important implications for national emissions accounting and the estimation of responsibility for pollutant emissions in global climate policy. Whether from the perspective of global patterns or regional development, the impact of trade-embodied carbon on regional carbon emissions is not only broad in scope, long in duration, and deep in degree, but also an important influence factor that must be taken into account when studying the issue of regional carbon emissions.

Owing to differences in the stages of economic development and economic structures of various regions, global trade may lead to an asymmetric relationship between economic benefits and carbon emissions, ultimately generating carbon inequality. The international discussion on carbon inequality is mainly based on the sharing of responsibility for climate change between nations that are developed and those that are not. Due to the unequal international division of labor and different levels of technological progress, there is a huge gap between developed and underdeveloped countries in terms of production structure, consumption structure, and environmental regulation, so there is also a "carbon" inequality in international trade exchanges between the two. As Mörsdorf, G. (2022) points out, EU countries believe that other emitters within the framework of the Paris Agreement are allowed to increase their emissions until 2030, which results in Carbon Leakage outside the EU, i.e., firms move production to areas where carbon emissions are less regulated or non-existent in order to avoid stringent carbon emission reduction measures and high carbon emission reduction costs. In the end, carbon dioxide that should have been controlled in one country or region is emitted in another, and global carbon emissions are not reduced and may even increase. Differences in economic and carbon emissions between countries and regions not only raise the issue of inequity in carbon responsibility, but also exacerbate the disparities in economic development between regions, leading to deeper environmental inequities (Hickel, J., et al., 2022).

To address the issue of carbon inequality, research has mainly focused on clarifying the inequality of CO2 emissions between countries and its correlation with the differences in the level of economic development (gross domestic product per capita) and the reasons for its formation, and has found that there is a disparity between carbon emissions and economic development, income (economic efficiency), etc. (Sinha, A.,, 2015; Tomás, M., 2020; Huang , R. and L. Tian, 2021). For the measurement of carbon inequality emission problem in the international context often follows the analytical framework of income inequality. For example, the Gini coefficient (Lorenz curve) is used, and CO2 emissions are used to replace income to establish a carbon Lorenz curve reflecting the inequality of carbon emissions (Groot, L., 2010; Liu, G. and F. Zhang, 2022). However, there is no clear definition of the concept of "carbon inequality". Carbon inequality is not only a regional carbon dioxide emission issue, but also relates to economic development and public welfare. With the increasing complexity of global trade networks, the embodied transfer of carbon emissions between countries (regions) has gradually attracted the attention of researchers. Different regions participate in the international and domestic division of labor differently, and pay different environmental costs, which will produce the phenomenon that the "economic gains" and "ecological damage" of some countries and regions are not consistent. At present, there are few studies on the equivalence between trade-embodied carbon transfer and economic growth (value added) and economic welfare. Based on this, this paper aims to construct a model to measure carbon inequality, covering the transfer of trade-embodied carbon and trade-added value, with the aim of measuring whether the transfer of embodied carbon due to international trade matches the value added.

In light of the issue of "inequitable carbon emission reduction" among different regions, scholars have begun to explore ways to ensure the fairness of regional carbon emission reduction cooperation through the implementation of inter-regional financial or technical compensation. "Carbon offsetting" is a new area of ecological compensation research. As early as in the 1990s, in order to encourage worldwide reduction of greenhouse gas emissions, the Kyoto Protocol stipulates that six types of greenhouse gas emission reductions can be traded, which is the earliest international level of "carbon trading compensation". Combined with the concept and connotation of eco-compensation, carbon compensation can be defined as "the behavior of carbon emitting subjects giving certain compensation to carbon sink subjects or ecological protectors in an economic or non-economic way" (Zhao R., et al. 2015). Carbon compensation is the behavior of carbon emission subject to eliminate carbon emission externality through economic means. The purpose of carbon compensation is to promote carbon emission reduction and realize regional equity and sustainable development, which is essentially a mode and means of regional low-carbon development with carbon as a link. Research on carbon offsetting can be traced back to inter-regional resource interest coordination and compensation research and ecological compensation research. Internationally, exploratory studies have been conducted on regional carbon emission quota allocation mechanism (Yu, B., L. Xu and Z. Yang, 2016), forest carbon compensation (Galik, C.S. et al; 2009), and carbon compensation technology (Lovell, H. and D. Liverman; 2010). Accounting methods on carbon offset credits mainly include the carbon balance method (Yang, G., et al., 2019) and the ecosystem value method (Arowolo er al., 2018). But these compensation methods only consider territorial emissions and do not incorporate trade-embodied carbon into the carbon offset accounting system, which may further lead to the exacerbation of carbon inequality and be not conducive to the fair global development. Based on this, we construct an accounting model for measuring trade-embodied carbon compensation under the framework of carbon inequality, so as to provide research direction for existing carbon compensation programs and promote the development of carbon compensation.

3 Methods and Data

3.1 Trade-embodied carbon transfer modeling and data

This paper uses the MRIO model to measure carbon flows in international trade, which is frequently used to analyze environmental resource flows in global supply chains. A large number of articles have used the MRIO model to assess emissions associated with international trade (Rama, M., et al.,2021; Huo, J., et al.,2021; Zhong, S., et al.,2022) and trade-related natural resource flows such as water and land (Serrano et al., 2016; Dorninger, C., et al.,2021). EXIOBASE is a comprehensive，multi-regionally extended supply-use table (MR-SUT) and input-output Table (MR-IOT).The current latest version is Exiobase V3.8.2[2]. EXIOBASE was

[2] https://zenodo.org/record/5589597

chosen for a number of reasons: (1) EXIOBASE has the most accurate statistics, containing 44 countries (28 EU member states and 16 major economies) and 5 other world regions, with a high degree of data completeness, no missing data, and the most detailed sectoral breakdown (163 sectors) (Bjelle, E.L., et al., 2020); (2) the data years range from 1995-2022, which is suitable for analyzing trends over time;(3) EXIOBASE covers environmental footprint data, with input-output tables and environmental data synchronized and continuously updated to more recent years (to 2022) (Stadler, K., et al., 2021).

By creating a global input-output table and determining the input-output relationship between each industry in each nation， the Multi-Regional Input-Output(MRIO)analysis can be used to assess the inputs and emissions of a country's final consumer goods in each country along the manufacturing chain. Combined with the carbon emission coefficients of each industry in each country, it can completely and accurately reflect the embodied carbon flow of global trade.The MRIO analysis is shown below:

$$\mathrm{x} = \mathbf{A}\mathrm{x} + \mathrm{y} \tag{1}$$

where the vector x is the output of each sector in each country or region, and A is the matrix of technical coefficients, the $\mathrm{A} = \mathrm{Z}/\mathrm{x}^{\mathrm{T}}$, and Z is the matrix of intermediate inputs. The vector y is the final demand of each sector in each country or region, and the total output can also be represented by the Leontief inverse matrix as shown in Eq. (2).

$$\mathrm{x} = (\boldsymbol{I} - \boldsymbol{A})^{-1} y = \boldsymbol{L} y \tag{2}$$

Where I is the unit matrix, and L is the Leontief inverse matrix. Expanding Eq. (2), the impact of economic activities on natural resources can be quantified to obtain Eq. (3).

$$\mathbf{C} = \hat{c}\mathbf{L}\hat{y} \tag{3}$$

In equation (3) $\hat{\mathrm{c}}$ is the diagonal matrix of direct carbon emission intensity for each sector and the vectory is denoted as the diagonal matrix $\hat{\mathrm{y}}$. By summing matrix $\mathbf{C}$ in columns, the direct and indirect carbon emissions of each sector can be obtained.

According to Serrano, A.,et al., (2016), MRIO can be parsimoniously represented as follows:

$$\begin{bmatrix} \boldsymbol{C}_{11} & \boldsymbol{C}_{12} & \cdots & \cdots & \boldsymbol{C}_{1r} \\ \boldsymbol{C}_{21} & \boldsymbol{C}_{22} & \cdots & \cdots & \boldsymbol{C}_{2r} \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ \boldsymbol{C}_{s1} & \vdots & \boldsymbol{C}_{ss} & \cdots & \boldsymbol{C}_{sr} \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ \boldsymbol{C}_{r1} & \boldsymbol{C}_{r2} & \cdots & \cdots & \boldsymbol{C}_{rr} \end{bmatrix} = \begin{bmatrix} \hat{c}_{11} & 0 & \cdots & \cdots & 0 \\ 0 & \hat{c}_{22} & \cdots & \cdots & 0 \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ 0 & 0 & \hat{c}_{ss} & \cdots & 0 \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ 0 & 0 & \cdots & \cdots & \hat{c}_{rr} \end{bmatrix} \begin{bmatrix} \boldsymbol{L}_{11} & \boldsymbol{L}_{12} & \cdots & \cdots & \boldsymbol{L}_{1r} \\ \boldsymbol{L}_{21} & \boldsymbol{L}_{22} & \cdots & \cdots & \boldsymbol{L}_{2r} \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ \boldsymbol{L}_{s1} & \vdots & \boldsymbol{L}_{ss} & \cdots & \boldsymbol{L}_{sr} \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ \boldsymbol{L}_{r1} & \boldsymbol{L}_{r2} & \cdots & \cdots & \boldsymbol{L}_{rr} \end{bmatrix} \begin{bmatrix} \hat{y}_{11} & \hat{y}_{12} & \cdots & \cdots & \hat{y}_{1r} \\ \hat{y}_{21} & \hat{y}_{22} & \cdots & \cdots & \hat{y}_{2r} \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ \hat{y}_{s1} & \vdots & \hat{y}_{ss} & \cdots & \hat{y}_{sr} \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ \hat{y}_{r1} & \hat{y}_{r2} & \cdots & \cdots & \hat{y}_{rr} \end{bmatrix} \tag{4}$$

Where $\mathbf{C_{rs}}$ is the matrix and each element $\mathrm{C_{rs}^{ij}}$ represents the carbon emitted by sector i in region r (directly and indirectly) to satisfy the final demand of sector j in region s. $\hat{\mathrm{c}}_{\mathrm{rr}}$ represents the direct carbon intensity of region r ,$\mathrm{L_{rs}}$ represents the Leontief inverse matrix, $\hat{\mathrm{y}}_{\mathrm{rs}}$ represents region r as the diagonal matrix that satisfies the final demand of the region.The embodied carbon transfer from region s to region r (embodied carbon from import trade TC_s^r) and from region r to region s (embodied carbon from export trade TC_r^s) can be obtained from $\mathbf{C_{rs}}$.

Similar to the embodied carbon measure, introducing the diagonal matrix of value added $\hat{\mathrm{v}}$ generated per unit of output per sector in each region gives the matrix $\mathbf{V_{rs}}$ to obtain the transfer of value added from region s to region r (import trade value added TV_s^r) and from region r to region s (export trade value added TV_r^s).

Thus, the net carbon transfer (Nc_s^r)and net value added transfer (Nv_s^r)from region s to region r is:

$$Nc_s^r = TC_r^s - TC_s^r \tag{5}$$

$$Nv_s^r = TV_r^s - TV_s^r \tag{6}$$

Further the net carbon transfer $\mathrm{Nc_s}$ and net value added $\mathrm{Nv_s}$ in international trade for region s can be obtained as:

$$Nc_s = \sum_{r \neq s} Nc_s^r \tag{7}$$

$$Nv_s = \sum_{r \neq s} Nv_s^r \tag{8}$$

3.2 Four-quadrant model of carbon inequality between international trades

International trade in goods and services leads not only to a transfer of carbon emissions but also to a transfer of value added, i.e. international trade brings not only environmental but also economic impacts. The comparison of net carbon emissions from trade and net value added from trade for a country or region can be categorized into four scenarios, as shown in Figure 1.

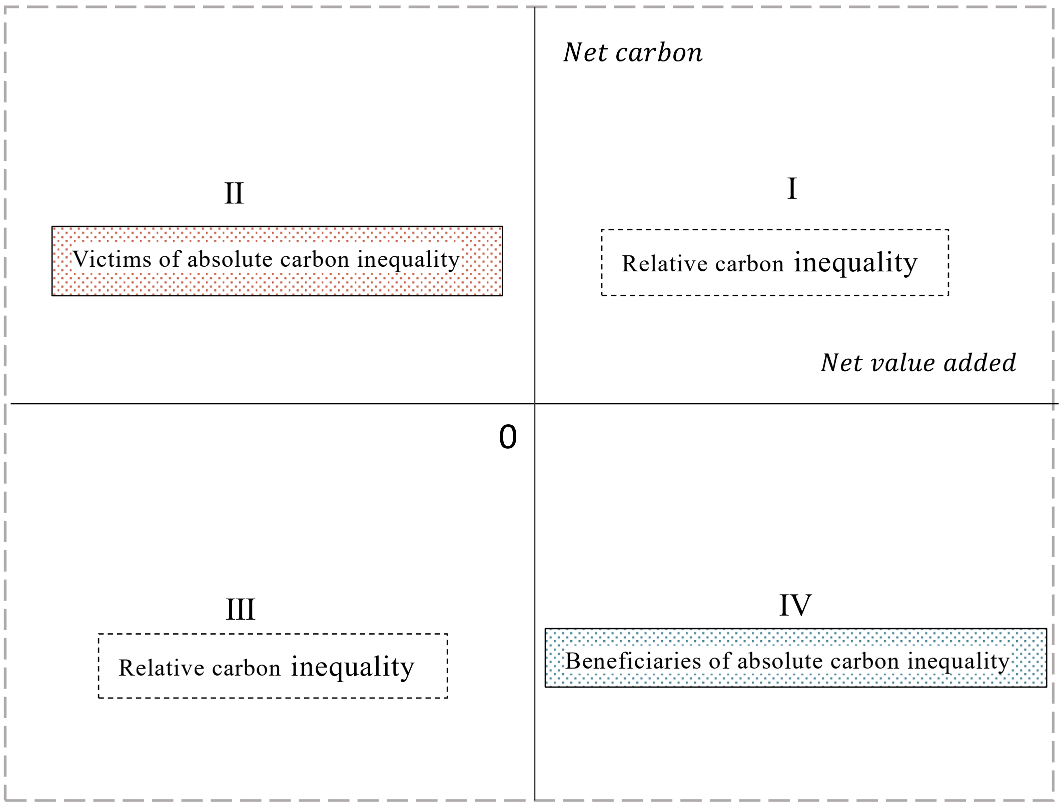

Figure 1 Quadrant Distribution of Net Carbon Emissions and Net Value Added from Trade in a Country or Region

A country or region in quadrant I with net carbon emissions greater than 0 and net value added greater than 0. This indicates that the carbon embodied by its exports is greater than the carbon embodied by its imports, and the corresponding value added by its exports is greater than the value added by its imports, and that other regions are transferring carbon to the region but also value added. This situation is unfavorable for the region's carbon mitigation environment but beneficial for the region's economy.

Quadrant II countries or regions with net carbon emissions greater than 0 and net value added less than 0. This indicates that the carbon embodied by their export trade is greater than the carbon embodied by their import trade, while the value added by their export trade is less than the value added by their import trade, and that other regions are transferring carbon to the region, while at the same time transferring value added from the region to other regions. This situation is detrimental to the carbon reduction environment of the region, as well as to the economy of the region.

Quadrant III countries or regions with net carbon emissions less than 0 and net value added less than 0. This indicates that the carbon embodied by their export trade is less than the carbon embodied by their import trade, while the value added by their export trade is less than the value added by their import trade, and that the region is transferring carbon to other regions, while it is transferring value added to other regions. This situation is good for the region's carbon abatement environment, but not good for the region's economy.

Quadrant IV countries or regions with net carbon emissions less than 0 and net value added greater than 0. This indicates that the embodied carbon from exports is less than the embodied carbon from imports, while the value added from exports is less than the value added from imports, and that the region is transferring carbon to other regions, while other regions are transferring value added to the region. This situation is beneficial to the carbon reduction environment of the region, as well as to the economy of the region.

Based on this, this paper defines carbon inequality as the mismatch between economic gains and environmental impacts caused by a country or region's international trade. From the analysis of the above four quadrants, it can be seen that the countries in the quadrant II are in a disadvantageous position, its international trade in both environmental damage, but also did not get economic stimulation, they are victims of absolute carbon inequality. On the other hand, countries in the quadrant IV are in an advantageous position, as they benefit their environment and boost their economy in international trade, which are beneficiaries of absolute carbon inequality. Countries in quadrants I and III are in a position to benefit only one of their own economies or the environment in international trade, implying relatively fair regional trade and relative carbon equality.

For the measurement of carbon inequality between two regions in bilateral trade, the carbon inequality index (CII_s^r) can be constructed to quantify the carbon inequality caused by bilateral trade, drawing on the REI index (Zhang, et al. ,2016). Take the trade between region s and region r as an example.

Firstly, normalizeNc_s^r， Nv_s^r， taking Nc_s^r as an example,as shown in (9):

$$f(Nc_s^r) = \frac{Nc_s^r - Nc_{s\,min}^r}{Nc_{s\,max}^r - Nc_{s\,min}^r} \qquad (9)$$

Next, the carbon inequality index for the four quadrants, as shown in (10):

$$CII_s^r = \begin{cases} -f\left(Nc_s^r/Nv_s^r\right), if\ Nc_s^r > 0, Nv_s^r > 0 \\ -f(Nc_s^r) - f(Nv_s^r) - 1, if\ Nc_s^r > 0, Nv_s^r < 0 \\ f\left(Nc_s^r/Nv_s^r\right), if\ Nc_s^r < 0, Nv_s^r < 0 \\ f(Nc_s^r) + f(Nv_s^r) + 1, if\ Nc_s^r > 0, Nv_s^r > 0 \end{cases} \qquad (10)$$

In bilateral trade, when $Nc_s^r > 0, Nv_s^r > 0$，-1<CII_s^r<0，or when $Nc_s^r < 0, Nc_s^r < 0, Nv_s^r < 0$，0<$CII_s^r$<1，it means relatively fair regional trade and belongs to relative carbon equality. When $Nc_s^r > 0, Nv_s^r < 0, CII_s^r$<-1, global trade is not favorable to the region's carbon abatement environment (net carbon input), but also to the region's economy (net value added output), which is an victim of absolute carbon inequality. When $Nc_s^r > 0, Nv_s^r > 0$， CII_s^r>1， global trade is beneficial to the region's carbon abatement environment (net carbon output) as well as to the region's economy (net value added input), which are beneficiaries of absolute carbon inequality.

3.3 Carbon Compensation Accounting Model

Carbon inequality exists among international trade, and it is necessary to consider not only the embodied carbon transfer among trade, but also the economic gains from trade when constructing the trade-embodied carbon compensation model (Jakob, M., et al., 2021). Based on the principle of fair sharing with equal benefits and responsibilities, i.e., region s and region r determine their respective responsibilities for trade-embodied carbon emissions according to their respective economic gains, and the total trade-embodied carbon emissions between them are apportioned to these two provinces, as shown in the following formula:

Taking the measurement of carbon offset between region s and region r as an example, the carbon transfer from region s to region r under the principle of fair sharing is first calculated $\overline{TC}_s^r$:

$$\overline{TC}_s^r = (TC_s^r + TC_r^s) \times \frac{TV_s^r}{TV_s^r + TV_r^s} \tag{11}$$

whereTC_s^r is the actual carbon transfer from region s to region r, and TC_r^s is the real carbon transfer from region r to region s, and TV_s^r is the value added transfer from region s to region r, and TV_r^s is the value added transfer from region r to region s.

The carbon offset between regions s and r is then:

$$CO_s^r = (TC_s^r - \overline{TC}_s^r) \times P \tag{12}$$

Similarly, the carbon transfer from region r to region s on an equitable sharing basis $\overline{TC}_r^s$ for:

$$\overline{TC}_r^s = (TC_s^r + TC_r^s) \times \frac{TV_r^s}{TV_s^r + TV_r^s} \tag{13}$$

Then the carbon offset between regions r and s is:

$$CO_s^r = (TC_r^s - \overline{TC}_r^s) \times P \tag{14}$$

Carbon offsets between regions s and r are valued monetarily using the average CER settlement price from the European Climate Exchange (ECE)[3], which reflects the carbon price level of the year. In this study, the average CER settlement price of the European Climate Exchange is used, which is 81 EUR/tCO2 equivalent in 2022.

4 Empirical results and analysis

4.1 Analyzing the dynamics of carbon inequality among international traders based on a four-quadrant model

The study shows that there is indeed carbon inequality among international trade. Therefore, data from 1995 - 2022 are selected to specifically analyze carbon inequality in international trade. Figures 2.a, 2.b, 2.c and 2.d show the distribution of net carbon transfers and net value added transfers in the four quadrants for 16 countries or regions, including the EU (28 countries, including the UK), the US, China and India, for the period 1995-2022.

Changes in carbon inequality in international trade in different countries or regions can be classified into four categories: (1) from absolute inequality to relative equality, such as Russia and India; (2) from relative equality to absolute inequality, such as South Africa and Canada; (3) from absolute equality to relative equality, such as Norway; and (4) no change in inequality status.

Specifically, in 1995, China, Russia and India were located in Quadrant II (Figure 1.a), which took on the carbon transfer from other countries or regions, but at the same time transferred the value added to other countries or regions, and were in a disadvantageous position in international trade. They took on the responsibility of carbon emissions in trade and did not boost the local economy and they were victims of absolute carbon inequality. And by 2004, 2013 and 2022, China is still located in Quadrant II, has been

[3] https://www.ice.com/index

victims of absolute carbon inequality and in an extremely unfavourable position. Russia and India have moved to Quadrant I, indicating that international trade has led to increased carbon emissions and value added in these two regions, implying relatively fair regional trade. These two regions have moved from victims of absolute carbon inequality to relative carbon equality. South Africa and Canada were in quadrant I in 1995 and have been in quadrant II ever since, moving from relative equality to absolute inequality. Both have changed from an economic gain at the expense of an environmental loss to neither an environmental nor an economic gain.

As can be seen from Figure 2, EU28, Japan and Switzerland have been in Quadrant IV, which is a favorable position in international trade, not bearing the responsibility for carbon emissions in trade, but also promoting the development of their own economies. Although a few developed countries (South Korea, Turkey, etc.) moved to quadrant IV in 2004, they then moved to other quadrants, and the overall trend has not yet changed to beneficiaries of absolute carbon inequality. In 1995, there were a number of developed or developing countries in quadrant III, such as Brazil, South Korea, the United States, Australia, etc., which have made the reduction of local carbon emissions and value added through international trade, and belong to the relative carbon equality. After that, there are countries with victims of absolute carbon inequality (Brazil, Indonesia, Mexico), and there are also countries with beneficiaries of absolute carbon inequality and then relative carbon equality (South Korea, Turkey). The position of these countries in international trade has also changed due to their economic development, transformation of industrial structure and technological progress. It is noteworthy that the United States, Australia, and Mexico have been in Quadrant III, where they have been trading less economic gains in international trade for domestic emission reductions, and are in relative carbon equality. From the analysis, it can be seen that no country can change from victims of absolute carbon inequality to beneficiaries of absolute carbon inequality. It is very difficult for developing countries to change their status in international trade, and some countries are always in an unfavorable position. While some developed countries occupy a favorable position in the national trade, and enjoy the economic and environmental benefits of the country. Therefore, it should be considered that developed countries should provide compensation to some developing countries to promote equitable development in the world.

Notes: a. 1995; b. 2004; c. 2013; d. 2022

Figure 2 Distribution of carbon inequality across 16regions in 1996-2022

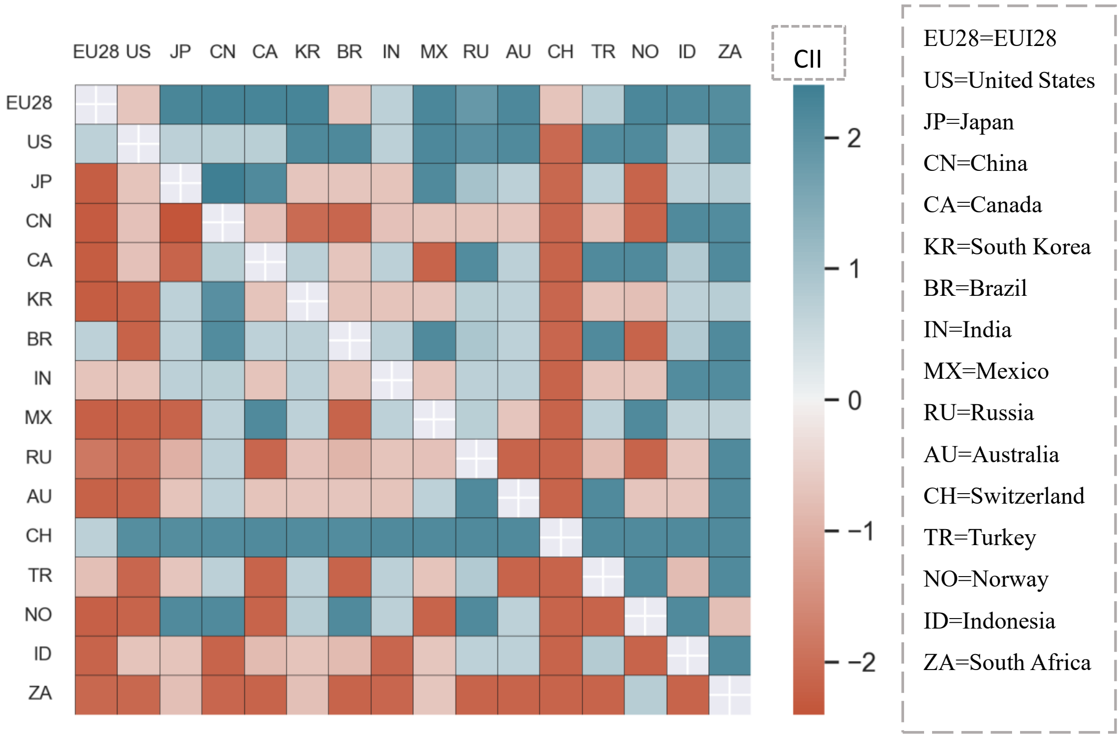

Figure 3 Carbon Inequality Index (CII) of bilateral trade of 16 countries or regions (Horizontal view indicates the CII of the focal region with respect to other regions. when CII<-1 means that the focal region are victims of absolute carbon inequality in bilateral trade; when -1<CII<0 or 0<CII<1, it means that the relative carbon equality experienced by the focal region in bilateral trade; and when CII>1, it means that focal regions are beneficiaries of absolute carbon inequality in bilateral trade. The colour from red to blue indicates increasing inequality.)

We use the Carbon Inequality Index (CII) to measure whether the environmental losses associated with international trade match the economic gains between two regions or countries in 2022 (Figure 3).Horizontally, developed countries such as the EU, Switzerland, Japan and the United States are beneficiaries of absolute carbon inequality in their bilateral trade with most other countries, while developing countries such as China, Indonesia and South Africa are victims of absolute carbon inequality in their bilateral trade with most other countries. While developing countries such as China, Indonesia, and South Africa are victims of absolute carbon inequality in their bilateral trade with most other countries, and North American countries such as Canada and Mexico are in a position of relative carbon equality in their bilateral trade. The higher values of CII are for EU-China (CII=2.29), US-Mexico (CII=2.21), Switzerland-India (2.15), and China- Indonesia (2.14), implying that the EU has not only made economic gains in its bilateral trade with China, but has also reduced the pressure on local carbon emission reduction. Similarly for the US with Mexico, Switzerland with India, and China with Indonesia. Overall net carbon transfers are shifted from importing regions (mainly developed countries) to exporting regions (mainly developing countries), while net value added is simultaneously shifted from exporting to importing regions. However, there are also carbon inequalities among developing countries, such as Indonesia bearing carbon transfers from China without a corresponding value added, and South Africa bearing carbon transfers from Indonesia without a corresponding economic gain.

4.2 Analysis of spatial flows of trade-embodied carbon in typical regions

From the analysis in 4.1, it can be seen that Russia in Quadrant I and China in Quadrant II have obvious carbon inequality, while the U.S. in Quadrant III and the EU in Quadrant IV are in an advantageous position in international trade. Therefore, this section focuses on analyzing the quantity, flow and spatial distribution of trade-embodied carbon in these four countries or regions using the data of 2022 as an example.

First of all, let's analyze the quantity and structure of carbon emissions of these four countries or regions. From Table 1, we can see that the amount of carbon emissions based on the consumer principle in the EU and the US is much larger than the amount of carbon emissions based on the producer principle, while the situation in China and Russia is the opposite.The embodied carbon emissions from EU imports are greater than the embodied carbon emissions from exports, which means that the EU's final demand leads to more carbon emissions elsewhere than other regions' final demand leads to the EU's emissions, and that the EU transfers carbon to other regions through trade. The same is true for the US. China and Russia, on the other hand, import more carbon than they export, which means that China and Russia's final demand leads to more carbon emissions in other regions than other regions' final demand leads to in China and Russia, and other regions transfer carbon to China and Russia through trade. At the same time, the EU's local carbon emissions account for 50% of the total consumer-based carbon emissions and 60% of the total producer-based carbon emissions, with nearly half of the carbon emissions being transferred to other regions through trade. On the other hand, China's local carbon emissions account for 90% of the total carbon emissions based on the consumer principle and 84 % of the total carbon emissions based on the producer principle. It can be seen that no matter what principle to calculate the total carbon emissions, the developed countries such as the EU have a high proportion of embodied carbon from trade, while developing countries such as China have not transferred too much embodied carbon through trade. Developed countries such as the EU have announced that they have reached peak carbon a long time ago, and it is easy to suspect that they have achieved this goal by transferring embodied carbon to developing countries.

Table 1 Quantitative and structural analysis of carbon emissions in four regions

Unit: Mt

region	EU28	United States	China	Russia
Domestic emissions	1841.80	3263.16	9758.72	1020.66
export embodied	1221.17	452.71	1850.08	544.89
import embodied	1837.20	1337.73	980.50	148.32
emissions-consumption	3679.00	4600.89	10739.22	1168.98
emissions-production	3062.97	3715.86	11608.80	1565.55

Let's first analyze the characteristics of the EU's、the US, China and Russia trade-embodied carbon (Figures 4 and 5) . The EU28 transfers -616.03 Mt net to other countries or regions in 2022, with the most carbon transferred to China (165.39 Mt), followed by Russia (157.59Mt), and India (44.42Mt). The EU transferred some carbon to developing countries

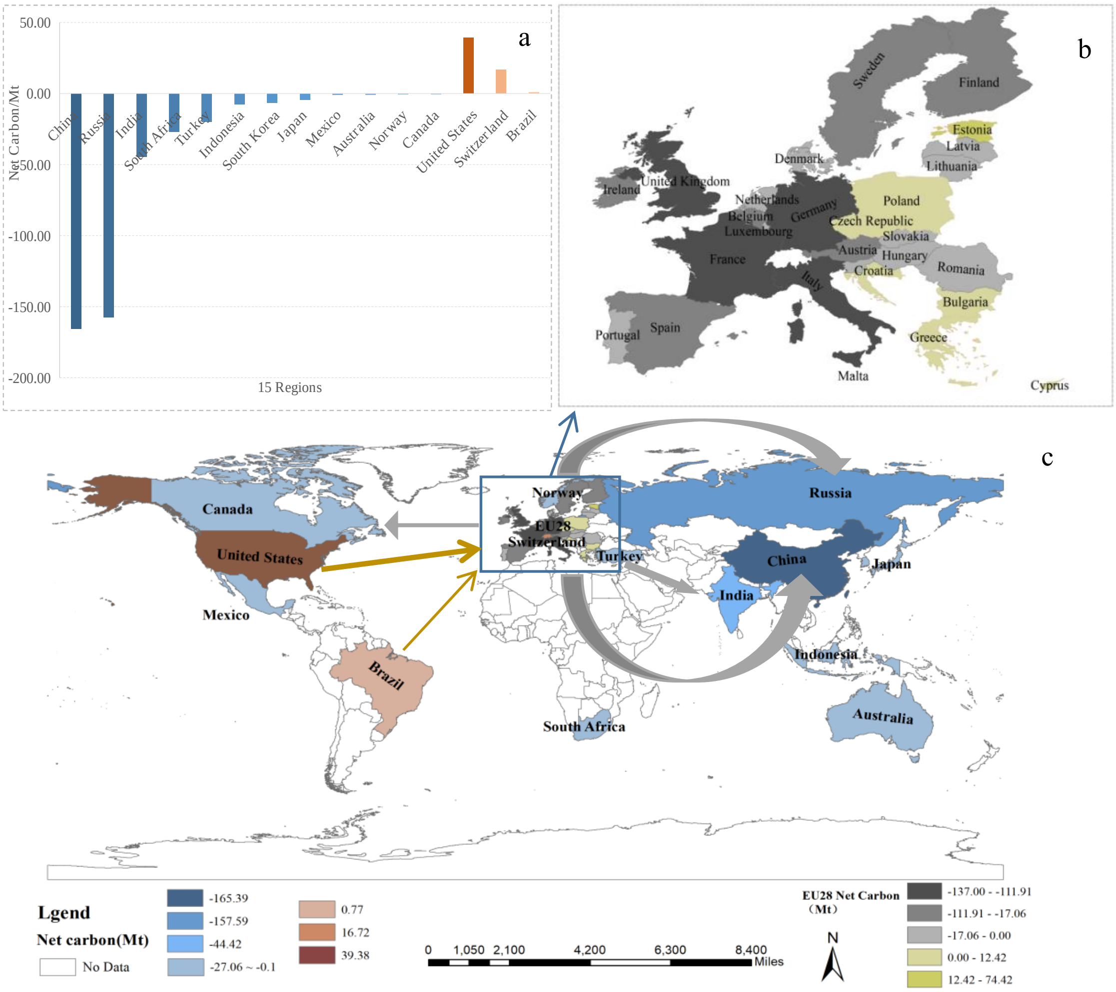

Figure 4 Map of the EU's trade-embodied carbon characteristics in 2022 (a. net transfer of carbon from the EU to other regions; b. map of the distribution of the volume of net carbon transfers from the 28 EU Member States; c. map of the spatial distribution of the EU's net carbon transfer flows from the EU to other regions; negative values represent net transfers of carbon from the EU to other regions, and positive values represent net transfers of carbon from other regions to the EU).

such as Indonesia, South Africa, and Turkey, and small amounts to developed countries such as Japan, South Korea, Australia, and Canada. At the same time, there are also a small number of developed countries or regions that have transferred carbon to the EU on a net basis, mainly the United States (39.38Mt), and Switzerland (16.72Mt). Looking within the EU, except for six countries, such as Estonia, Poland, and the Czech Republic, which have positive net carbon transfers, all other countries, such as Germany, France, Italy, and the UK, have net transfers of embodied carbon to other countries or regions. There is a net transfer of embodied carbon, with the EU in the center, to the majority of the rest of the globe.By transferring carbon to other regions in international trade, the EU reduces the pressure to reduce carbon emissions locally.

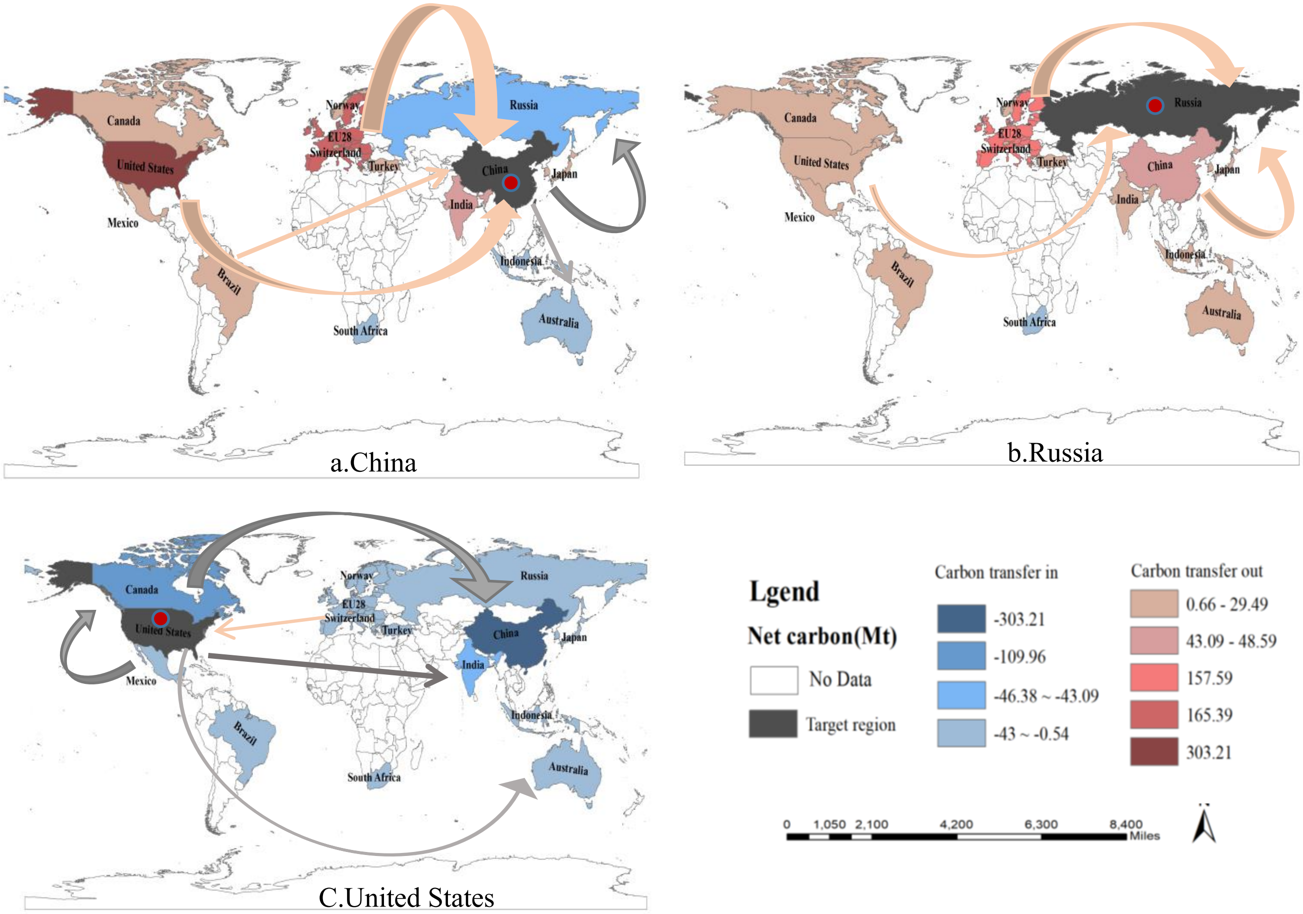

Figure 5 Map of trade-embodied carbon characteristics of three typical countries in 2022 (a. Spatial distribution of China's net carbon transfer flows to other regions; b. Spatial distribution of Russia's net carbon transfer flows to other regions; c. Spatial distribution of the United States' net carbon transfer flows to other regions; negative values represent the typical country's net transfer of carbon to other regions, and positive values represent the other regions' net transfer of carbon to the typical country).

China's net carbon transfer in 2022 is 869.58Mt (Fig. 5.a), of which the U.S. and the EU transfer the most trade-embodied carbon to China, with 303.21Mt and 165.39Mt, respectively, and some other developed countries, such as Japan, Canada, and Norway, also transfer part of their trade-embodied carbon to China. At the same time, China also transferred part of its trade-embodied carbon to other regions, such as Russia (43.09Mt) and

South Africa (12.02Mt). China, as the country exporting the largest international market share, not only benefits from international trade, but is also forced to transfer more trade-embodied carbon. The net carbon transfer from Russia in 2022 is 396.57Mt (Fig. 5.b), of which the EU and China transfer the most trade-embodied carbon to Russia, with 157.59Mt and 43.09Mt, respectively, and of the 16 regions analyzed, all but South Africa, all other regions have net transfer of trade carbon to Russia. Russia, as the world's largest mineral and energy resource reserves, is the largest exporter of oil and gas, causing it to take on carbon inputs from other countries. The net carbon transfer from the US in 2022 is -885.02Mt (Figure 5.c), of which the US transfers more trade-embodied carbon to China, Canada, and India, at 303.21Mt, 109.96Mt, and 46.38Mt, except for Switzerland, the U.S. transferred trade embodied carbon to all other countries or regions. The global overall trade-embodied carbon shows a shift from developed countries to developing countries, with the EU and the U.S. accounting for a larger share of trade-embodied carbon, and resource-based countries such as China and Russia bearing the pressure of trade-embodied carbon inputs from developed countries, and there is a carbon inequality phenomenon.

4.3 Analysis of Carbon Compensation Accounting in Typical Regions

Based on the analysis in 4.1 and 4.2, developed countries represented by the US and EU transfer trade-embodied carbon to developing/transition countries represented by Russia and China, and some developing countries are under pressure to transfer carbon from other regions and do not receive the corresponding economic benefits. Therefore, this study constructs a carbon compensation accounting model (3.3), which uses the average CER settlement price of the European Climate Exchange for monetary valuation, to calculate the amount of carbon offsets in 2022 for the European Union, the United States, China, and Russia (Table 2).

Table 2 Accounting for carbon offsets in the EU, US, China and Russia

Note: - represents victims of absolute carbon inequality in bilateral trade, + represents beneficiaries of absolute

		CII	2022			CII	2022
China	EU28	−	-10084.89	Russia	EU28	−	-8385.81
	United States	○	-10212.94		United States	−	-1256.66
	Japan	−	-3125.06		Japan	○	-433.54
	Canada	○	-555.81		China	○	-850.50
	South Korea	−	-1546.71		Canada	−	-124.59
	Brazil	−	-361.41		South Korea	○	-298.16
	India	○	-1122.04		Brazil	○	-113.79
	Mexico	○	-128.44		India	○	-145.03
	Russia	○	850.50		Mexico	○	-57.86
	Australia	○	-698.53		Australia	−	-77.14
	Switzerland	−	-329.79		Switzerland	−	-191.70
	Turkey	○	-96.04		Turkey	○	-453.21
	Norway	−	-114.56		Norway	−	-93.73
	Indonesia	+	279.64		Indonesia	○	-29.31
	South Africa	+	658.03		South Africa	+	40.50
United States	EU28	○	72.51	EU28	United States	○	-72.51
	Japan	○	531.90		Japan	+	489.09
	China	○	10212.94		China	+	10084.89
	Canada	○	3915.77		Canada	+	360.26
	South Korea	+	739.80		South Korea	+	796.50
	Brazil	+	573.94		Brazil	○	342.51
	India	○	1152.90		India	○	1455.30
	Mexico	+	2526.43		Mexico	+	335.19
	Russia	+	1256.66		Russia	+	8385.81
	Australia	+	236.83		Australia	+	169.71
	Switzerland	−	-102.99		Switzerland	○	-645.69
	Turkey	+	552.34		Turkey	○	765.26
	Norway	+	73.29		Norway	+	224.49
	Indonesia	○	364.50		Indonesia	+	447.43
	South Africa	+	743.27		South Africa	+	1387.03

carbon inequality in bilateral trade, and ○ represents relative carbon equality in bilateral trade. Positive values represent the need to pay carbon offsets to other regions and negative values represent the need to receive carbon offsets from other regions, in M.EUR(Million Euro).

Each country or region is compensated by other countries or regions when it is victim of absolute carbon inequality or relative carbon equality in bilateral trade, and needs to compensate other countries or regions when it is beneficiary of absolute carbon inequality or relative equality in bilateral trade. Russia in quadrant I is only a beneficiary of absolute carbon inequality in its trade with South Africa, so it needs to receive trade carbon offsets from 14 countries or regions other than South Africa, of which the European Union needs to compensate the most, accounting for 8,385.81 M.EUR in 2022 at the average carbon price. China in Quadrant II is beneficiary of absolute carbon inequality with Indonesia and South Africa, and victim of absolute carbon inequality or relative equality with all other regions. The countries that need to receive the most trade carbon offsets are the European Union and the United States, which are 10084.89 M.EUR and 10212.94 M.EUR, respectively, based on the average carbon price in 2022, and they also need to pay trade carbon offsets to Russia, Indonesia and South Africa. South Africa. The U.S. in Quadrant III is victim of absolute carbon inequality only in its bilateral trade with Switzerland, so it needs to pay trade carbon offsets to 14 countries or regions other than Switzerland, with the largest amount of trade carbon offsets paid to China. The EU in Quadrant IV is in a very favorable position in terms of absolute or relative carbon inequality in its bilateral trade with all other regions, so it is required to pay trade carbon offsets to 13 countries or regions other than the US and Switzerland, with the highest trade carbon offsets being paid to China and Russia. The amount of compensation to China and Russia is much larger than the amount of external compensation, and these two countries are resource-based countries with rich energy endowment, which bear a large amount of trade-embodied carbon in global trade. The United States and the European Union, on the other hand, have an external compensation amount that is much larger than their compensated amount. These two regions have developed economies, high per capita GDP, and high levels of consumption, and they import a large number of high-emission, low-value-added products from other countries or regions to satisfy their local consumption needs through trade, which imports carbon to other regions through global trade. Meanwhile, the average CER settlement price of the European Climate Exchange in 2022 was 81 EUR/tCO2 equivalent in 2022, and the carbon price in 2022 has increased significantly, mainly due to the influence of the global climate policy as well as the adjustment of the energy structure. The cost of carbon emission will continue to be high, and the carbon market transaction has been developed vigorously. The carbon offset amount calculated according to the carbon price not only depends on the change of carbon transfer volume, but also affected by the change of carbon marginal abatement cost. The amount of carbon offset between regions not only has the difference between regions, but also exists the change in time. Carbon offsetting can compensate for the environmental losses and economic costs of regions with carbon inequality, thus promoting synergistic cooperation in global carbon emission reduction and global equity and development.

5 Conclusions

Based on the multi-region input-output model and the latest data of EXIOBASE, this paper tracks the transfer of carbon emissions and value-added caused by global trade, and constructs a model for measuring carbon inequality among international trade, bilateral trade carbon inequality index and an accounting model for carbon compensation. We focuses on analyzing the existence of carbon inequality and the characteristics of carbon embodied by trade in different countries or regions in international trade. Finally, the amount of carbon compensation is calculated for different countries or regions, so as to provide suggestions and theoretical support for global carbon emission reduction cooperation. The main conclusions are as follows:

(1) There are significant regional differences in carbon inequality in international trade. Carbon inequality exists in international trade in both 1995and 2022. Among them, developing countries such as China, Russia and South Africa have carbon inequality and are at a disadvantage in international trade since they not only pay the burden of carbon emissions

in trade but also fail to reap the associated economic gains. On the other hand, developed countries such as the European Union and the United States are in a favorable position in international trade, not only importing carbon to other countries or regions through trade, but also obtaining economic benefits.

(2) The amount and flow of trade-embodied carbon are not consistent between developing and developed countries. In terms of the share of trade-embodied carbon in total emissions, developed countries such as the European Union have a value of about 50 per cent, while developing countries such as China have a value of less than 20 per cent. In terms of trade-embodied carbon characteristics, the overall global trade-embodied carbon shows a shift from developed countries to developing countries, and the consumer demand of developed countries is an important reason for the increase in trade-embodied carbon exports from China, Russia and other countries. Resource-based countries such as China and Russia are under pressure from the trade-embodied carbon inputs of developed countries. So China and Russia are not the only parties responsible for their carbon emissions, especially consumers in developed countries should also bear the corresponding responsibility for the increase in carbon emissions in developing countries.

(3) There are spatial and temporal differences in the amount of unfair carbon compensation between regions. Carbon compensation depend not only on changes in carbon transfers, but are also affected by changes in the marginal abatement costs of carbon. And countries such as China and Russia, due to their resource endowment and industrial structure, have contributed significantly to global trade's carbon emissions without receiving any compensation the related financial advantages. Carbon emission reduction is not the responsibility of a single country, but requires multi-party cooperation. Therefore, the United States and the European Union and other regions need to provide carbon compensation to net carbon importing

regions, and provide financial support to developing countries for carbon emission reduction infrastructure construction and technology upgrading and transformation, so as to promote the global carbon emission reduction process.

References

Amaral, L.P., N. Martins and J.B. Gouveia, A review of emergy theory, its application and latest developments. Renewable and Sustainable Energy Reviews, 2016. 54: p. 882-888.

Arowolo, A.O., et al., Assessing changes in the value of ecosystem services in response to land-use/land-cover dynamics in Nigeria. Sci Total Environ, 2018. 636: p. 597-609.

Bjelle, E.L., et al., Adding country resolution to EXIOBASE: impacts on land use embodied in trade. J Econ Struct, 2020. 9(1): p. 14.

Brizga, J., K. Feng and K. Hubacek, Household carbon footprints in the Baltic States: A global multi-regional input–output analysis from 1995 to 2011. Applied Energy, 2017. 189: p. 780-788.

Bruckner, B., et al., Ecologically unequal exchanges driven by EU consumption. Nature sustainability, 2023. 6(5): p. 587-598.

Darwili, A. and E. Schröder, On the Interpretation and Measurement of Technology-Adjusted Emissions Embodied in Trade. Environmental and Resource Economics, 2022. 84: p. 1-34.

Dorninger, C., et al., Global patterns of ecologically unequal exchange: Implications for sustainability in the 21st century. Ecological economics, 2021. 179: p. 106824.

Fan, J., et al., Embedded carbon footprint of Chinese urban households: structure and changes. Journal of Cleaner Production, 2012. 33: p. 50-59.

Franzen, A. and S. Mader, Consumption-based versus production-based accounting of CO2 emissions: Is there evidence for carbon leakage? Environmental Science & Policy, 2018. 84: p. 34-40.

Galik, C.S. and R.B. Jackson, Risks to forest carbon offset projects in a changing climate. Forest ecology and management, 2009. 257(11): p. 2209-2216.

Golgeci, I., D. Makhmadshoev and M. Demirbag, Global value chains and the environmental sustainability of emerging market firms: A systematic review of literature and research agenda. International Business Review, 2021. 30(5): p. 101857.

Groot, L., Carbon Lorenz curves. Resource and Energy Economics, 2010. 32(1): p. 45-64.

Harris, S., Weinzettel, J., Bigano, A., Kallm ¨ ´en, A., 2020. Low carbon cities in 2050? GHG
emissions of European cities using production-based and consumption-based emission accounting

Hertwich E .Carbon fueling complex global value chains tripled in the period 1995-2012[J].Energy Economics, 86[2023-09-03].DOI:10.31235/osf.io/zb3rh.

Hickel, J., et al., Imperialist appropriation in the world economy: Drain from the global South through unequal exchange, 1990–2015. Global environmental change, 2022. 73: p. 102467.

Huang, R. and L. Tian, CO2 emissions inequality through the lens of developing countries. Applied Energy, 2021. 281: p. 116043.

Huo, J., et al., Drivers of fluctuating embodied carbon emissions in international services trade. One earth (Cambridge, Mass.), 2021. 4(9): p. 1322-1332.

Jakob M , Marschinski R .Interpreting trade-related CO2 emission transfers[J].Nature Climate Change, 2012, 3(1):19-23.DOI:10.1038/nclimate1630.

Jakob, M., H. Ward and J.C. Steckel, Sharing responsibility for trade-related emissions based on economic benefits. Global environmental change, 2021. 66: p. 102207.

Liang, X., et al., Exploring global embodied metal flows in international trade based combination of multi-regional input-output analysis and complex network analysis. Resources policy, 2020. 67: p. 101661.

Liu, G. and F. Zhang, China's carbon inequality of households: Perspectives of the aging society and urban-rural gaps. Resources, conservation and recycling, 2022. 185: p. 106449.

Lovell, H. and D. Liverman, Understanding Carbon Offset Technologies. New political economy, 2010. 15(2): p. 255-273.

Mi, Z., et al., Chinese CO(2) emission flows have reversed since the global financial crisis. Nat Commun, 2017. 8(1): p. 1712.

Mörsdorf, G., A simple fix for carbon leakage? Assessing the environmental effectiveness of the EU carbon border adjustment. Energy Policy, 2022. 161: p. 112596.

Peters, G.P. and E.G. Hertwich, CO2 embodied in international trade with implications for global climate policy. Environ Sci Technol, 2008. 42(5): p. 1401-7.

Peters, G.P., et al., Growth in emission transfers via international trade from 1990 to 2008. Proc Natl Acad Sci U S A, 2011. 108(21): p. 8903-8.

Rama, M., et al., Evaluating the carbon footprint of a Spanish city through environmentally extended input output analysis and comparison with life cycle assessment. Science of The Total Environment, 2021. 762: p. 143133.

Serrano, A., et al., Virtual Water Flows in the EU27: A Consumption-based Approach. Journal of industrial ecology, 2016. 20(3): p. 547-558.

Sinha, A., Inequality of Carbon Intensities Across OECD Countries. Energy Procedia, 2015. 75: p. 2529-2533.

Serrano, A., et al., Virtual Water Flows in the EU27: A Consumption-based Approach. Journal of industrial ecology, 2016. 20(3): p. 547-558.

Stadler, Konstantin, Wood, Richard, Bulavskaya, Tatyana, Södersten, Carl-Johan, Simas, Moana, Schmidt, Sarah, Usubiaga, Arkaitz, Acosta-Fernández, José, Kuenen, Jeroen, Bruckner, Martin, Giljum, Stefan, Lutter, Stephan, Merciai, Stefano, Schmidt, Jannick H, et al.,(2021). EXIOBASE 3 (3.8.2) [Data set].Zenodo. https://doi.org/10.5281/zenodo.5589597

Tomás, M., L.A. López and F. Monsalve, Carbon footprint, municipality size and rurality in Spain: Inequality and carbon taxation. Journal of Cleaner Production, 2020. 266: p. 121798.

Wiedmann, T. and M. Lenzen, Environmental and social footprints of international trade. Nature geoscience, 2018. 11(5): p. 314-321.

Wiedmann, T. and M. Lenzen, Environmental and social footprints of international trade. Nature geoscience, 2018. 11(5): p. 314-321.

Wilting, H.C., et al., Subnational greenhouse gas and land-based biodiversity footprints in the European Union. Journal of Industrial Ecology, 2021. 25(1): p. 79-94.

Wu S , Li S , Lei Y ,et al.Temporal changes in China's production and consumption-based CO2 emissions and the factors contributing to changes[J].Energy Economics, 2020, 89.DOI:10.1016/j.eneco.2020.104770.

Yang, G., et al., Interregional carbon compensation cost forecast and priority index calculation based on the theoretical carbon deficit: China as a case. Sci Total Environ, 2019. 654: p. 786-800.

Yu, B., L. Xu and Z. Yang, Ecological compensation for inundated habitats in hydropower developments based on carbon stock balance. Journal of Cleaner Production, 2016. 114: p. 334-342.

Zhang, et al. Revealing Environmental Inequality Hidden in China's Inter-regional Trade[J].Environmental Science & Technology: ES&T, 2018, 52(13):7171-7181.

Zhao, L., et al., Embodied greenhouse gas emissions in the international agricultural trade. Sustainable production and consumption, 2023. 35: p. 250-259.

Zhao, R., et al., Overview of Ｒegional Carbon Compensation: Mechanism，Pattern and Policy Suggestions [J]. Regional Research and Development, 2015, 34 (5): 5. DOI: 10.3969/j.issn.1003-2363.2015.05.05.022

Zhong, S., T. Goh and B. Su, Patterns and drivers of embodied carbon intensity in international exports: The role of trade and environmental policies. Energy economics, 2022. 114: p. 106313.

Acknowledgements

1. Topic Origin

With the continuous warming of the global climate and the frequent occurrence of various extreme weather events, carbon issues have become the focus of global attention. It also attracted my attention. Through searching for information and browsing the news, discussing with my mother’s friends Professor Tao Song and Professor Zhijie Ding, I inadvertently paid attention to trade-embodied carbon, and I wanted to research the issues related to embodied carbon between international trade.

2. Background

Since 1995, the share of trade-embodied carbon emissions in total global carbon dioxide emissions has remained between 20 and 25 per cent. Although the share of trade-embodied carbon emissions in total global emissions has stabilized since 2008, total global CO2 emissions have been increasing, and total trade-embodied carbon emissions have been increasing. As a key issue of greenhouse gas emission reduction, international trade-embodied carbon is of great significance to global climate governance.

3. Process

Under the guidance of Associate Professor Song, I first used Python to measure the embodied carbon transfer and increased transfer of

international trade from 1995 to 2022 using the EXIOBASE database. Then, in response to the calculation results, we discussed several times how to measure carbon inequality and carbon offset. I put forward my own views through literature reading and data analysis, and asked Associate Professor Song and Professor Ding to provide guidance on economic theory. After many discussions and revisions, this study was finally completed.

4. Appreciations

I would like to express my gratitude for Professor Song and Professor Ding's unpaid support throughout the long and challenging research process. In addition, I would like to give special thanks to doctor candidate Erdan Wang, who taught me hand by hand when I faced technical difficulties in using Python and plotting figures. Only because of their patient guidance, I made this work possible.