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Unfolding carbon inequality across Belt and Road Initiative countries and regions under a global trade network

Zekun Lin [a], Fanxin Meng [a,*], Dongfang Wang [a,*], Danqi Liao [a], Yutong Sun [a], Jiaqi Hou [a], Gengyuan Liu [a,b], Biagio Fernando Giannetti [a,c], Feni Agostinho [a,c], Cecília M.V.B. Almeida [a,c]

[a] *State Key Joint Laboratory of Environment Simulation and Pollution Control, School of Environment, Beijing Normal University, Beijing 100875, China*
[b] *Beijing Engineering Research Center for Watershed Environmental Restoration & Integrated Ecological Regulation, Beijing 100875, China*
[c] *Graduation Program on Production Engineering, Paulista University, Sao Paulo 04026-002, Brazil*

A R T I C L E I N F O

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A B S T R A C T

The Belt and Road Initiative (BRI) has boosted global trade and economic development. Carbon inequality embodied in global trade may occur across BRI countries and regions in the world. How to quantify this inequality is the key to achieving the green development of the Belt and Road. In this study, we constructed a methodological framework to analyze carbon inequality across BRI countries and regions under the global trade network. Results showed that nearly half of BRI countries and regions exported net embodied carbon emissions while obtaining net economic benefits. The most severe bilateral trade carbon inequality existed between China and BRI West Asia, whose bilateral trade carbon inequality index (BCI) reached 2.76. Except for Indonesia, Saudi Arabia, and BRI West Asia, BRI countries and regions were negatively affected by global trade carbon inequality, with China and India suffering the most, whose global trade carbon inequality indices (GCI) were -2.06 and -1.26, respectively. This methodological framework can be applied to analyze the inequality of other kinds of ecological impacts embodied in trade on any scale. Furthermore, this study can provide policy implications for the green development of the Belt and Road.

1. Introduction

The Belt and Road Initiative (BRI) was proposed by China as an effort to support the trade and economic development of the world in 2013. Currently, the BRI has boosted trade and economic growth among participating countries and regions (Hafeez et al., 2019; Qian et al., 2022), which cover more than 60% of the global population and 30% of the global GDP (Huang, 2016). Recently, the BRI prioritizes environmental preservation while fostering economies (Horvat and Gong, 2019; Cheng and Ge, 2020; Yang and Ni, 2022), which is in line with the objectives of Sustainable Development Goals (SDGs) (Huang and Li, 2020; Coenen et al., 2021).

When countries and regions with different production levels and trade structures engage in trade (Feng et al., 2013; Yu et al., 2014; Weitzel and Ma, 2014), a potential unequal exchange of carbon emissions and economic benefits may occur, which is called carbon inequality (Prell and Sun, 2015; Prell and Feng, 2016; Zhang et al., 2018). As BRI countries and regions become increasingly active in the global trade network (Hafeez et al., 2018; Muhammad et al., 2020; Chen et al., 2021), carbon inequality might occur across BRI countries and regions and negatively influence their development. Specifically, some BRI countries and regions may undertake net carbon emissions from other countries and regions while bearing net economic losses, contradicting the SDGs designed for climate change mitigation and inequality reduction and posing a challenge to the green development of the Belt and Road (Tahir et al., 2022). Therefore, it is essential to investigate the carbon inequality across BRI countries and regions under the global trade network to explore the path to achieving the green development of the Belt and Road.

Some researchers have started to analyze carbon inequality across BRI countries and regions. Han et al. (2020) used the Theil index to analyze the differences in per-capita carbon emissions among BRI countries and regions. Wang et al. (2022a) constructed the pollution terms of trade (PTT) index to investigate the unequal exchange of carbon emissions and economic benefits embodied in trade between BRI countries and regions and China. However, these indices have certain

* Corresponding authors.
E-mail address: fanxin.meng@bnu.edu.cn (F. Meng).

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limitations. The Theil index disregards the carbon inequality embodied in bilateral trade, while the PTT index ignores the overall status of a country or region in terms of carbon inequality under the global trade network. In summary, existing studies on carbon inequality across BRI countries and regions lack a systematic methodological framework for analysing carbon inequality under the global trade network.

To fill these gaps, we construct a methodological framework to unravel the carbon inequality across BRI countries and regions. Specifically, we evaluate the inter-regional flow of embodied carbon emissions and value added based on multi-regional input-output (MRIO) model. On this basis, a carbon inequality (CI) index combination is proposed to quantify the carbon inequality across BRI countries and regions under the global trade network.Additionally, we identify the detailed production and consumption sectors embodied in carbon inequality. Moreover, this study provides insights into policy implications for achieving the green development of the Belt and Road.

2. Materials and methods

2.1. Multi-regional input-output (MRIO) model

The MRIO model can systematically analyze the environmental impacts embodied in the inter-regional flow of goods at the regional and sector levels. This model is widely used for exploring the transfer of environmental impacts in trade (Arce et al., 2016; Meng et al., 2019a, 2019b; Liu et al., 2021). The MRIO model includes 'm' regions and 'n' sectors, and its basic equation can be written as follows:

$$X = (I - A)^{-1}\mathrm{F} \tag{1}$$

In Eq. (1), $X = \begin{bmatrix} \mathrm{X}^{11} & \cdots & \mathrm{X}^{1m} \\ \vdots & \ddots & \vdots \\ \mathrm{X}^{m1} & \cdots & \mathrm{X}^{mm} \end{bmatrix}$ is the total output matrix, in which $X^{rs} = \begin{bmatrix} \mathrm{x}^{rs}_{11} & \cdots & \mathrm{x}^{rs}_{1n} \\ \vdots & \ddots & \vdots \\ \mathrm{x}^{rs}_{n1} & \cdots & \mathrm{x}^{rs}_{nn} \end{bmatrix}$ is the output of region 'r' for the final use of region 's'. $A = \begin{bmatrix} \mathrm{A}^{11} & \cdots & \mathrm{A}^{1m} \\ \vdots & \ddots & \vdots \\ \mathrm{A}^{m1} & \cdots & \mathrm{A}^{mm} \end{bmatrix}$ is the direct consumption coefficient matrix, where the submatrix $\mathrm{A}^{rs} = \begin{bmatrix} \mathrm{a}^{rs}_{11} & \cdots & \mathrm{a}^{rs}_{1n} \\ \vdots & \ddots & \vdots \\ \mathrm{a}^{rs}_{n1} & \cdots & \mathrm{a}^{rs}_{nn} \end{bmatrix}$ is the direct consumption coefficient matrix of region 's' versus region 'r'. $(I - A)^{-1}$ is the Leontief inverse matrix. $F = \begin{bmatrix} \mathrm{F}^{11} & \cdots & \mathrm{F}^{1m} \\ \vdots & \ddots & \vdots \\ \mathrm{F}^{m1} & \cdots & \mathrm{F}^{mm} \end{bmatrix}$ is the diagonalized final demand matrix, where submatrix $\mathrm{F}^{rs} = \begin{bmatrix} \mathrm{f}^{rs}_{1} & \cdots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \cdots & \mathrm{f}^{rs}_{n} \end{bmatrix}$ is the diagonalized final demand matrix of region 's' versus region 'r', and f^{rs}_{i} is the final demand of region 's' versus sector 'i' in region 'r'.

The matrix of the flow of embodied carbon emissions among all regions E is expressed as follows:

$$E = \widehat{d}(I - A)^{-1}\mathrm{F} \tag{2}$$

In Eq. (2), $E^{rs} = \widehat{d^r} X^{rs}$ is the carbon emissions in region 'r' driven by the final demand of region 's', $\widehat{d} = \begin{bmatrix} \widehat{d^1} & \cdots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \cdots & \widehat{d^m} \end{bmatrix}$ is the diagonalized carbon intensity matrix, where the submatrix $\widehat{d^r} = \begin{bmatrix} d^r_1 & \cdots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \cdots & d^r_n \end{bmatrix}$ is the diagonalized carbon intensity matrix of region 'r', and d^r_i is the carbon intensity of sector 'i' in region 'r'.

The production-based and consumption-based carbon emissions of region 'r' E^r_p and E^r_c are expressed as follows:

$$E^r_p = \sum_{s=1}^{m} E^{rs} \tag{3}$$

$$E^r_c = \sum_{s=1}^{m} E^{sr} \tag{4}$$

2.2. Carbon inequality (CI) index combination

This study proposed a CI index combination to analyze the carbon inequality across BRI countries and regions from the two dimensions of bilateral trade and global trade. The index combination consists of the bilateral trade carbon inequality index (BCI) and the global trade carbon inequality index (GCI). The former is used for quantifying the carbon inequality in bilateral trade between BRI countries and regions, and the latter is used for quantifying the overall global trade carbon inequality status of each BRI country or region.

According to Eq. (2), the net flow of embodied carbon emissions between region 'r' and region 's' $\overline{E^{rs}}$ is expressed as follows:

$$\overline{E^{rs}} = E^{rs} - E^{sr} \tag{5}$$

The matrix of the net flow of embodied carbon emissions among all regions $\overline{\mathrm{E}}$ is expressed as follows:

$$\overline{\mathrm{E}} = \begin{bmatrix} 0 & \overline{E^{12}} & \cdots & \overline{E^{1(m-1)}} & \overline{E^{1m}} \\ \overline{E^{21}} & 0 & & \overline{E^{2(m-1)}} & \overline{E^{2m}} \\ \vdots & & \ddots & & \vdots \\ \overline{E^{(m-1)1}} & \overline{E^{(m-1)2}} & & 0 & \overline{E^{(m-1)m}} \\ \overline{E^{m1}} & \overline{E^{m2}} & \cdots & \overline{E^{m(m-1)}} & 0 \end{bmatrix} \tag{6}$$

Removing all the negative values in $\overline{\mathrm{E}}$, the following matrix can be written as follows:

$$\overline{EN} = \left(\overline{\mathrm{E}} + |\overline{\mathrm{E}}|\right) / 2 \tag{7}$$

Similarly, the matrix of the net flow of embodied value added among all regions $\overline{\mathrm{V}}$ can be expressed as follows:

$$\overline{\mathrm{V}} = \begin{bmatrix} 0 & \overline{V^{12}} & \cdots & \overline{V^{1(m-1)}} & \overline{V^{1m}} \\ \overline{V^{21}} & 0 & & \overline{V^{2(m-1)}} & \overline{V^{2m}} \\ \vdots & & \ddots & & \vdots \\ \overline{V^{(m-1)1}} & \overline{V^{(m-1)2}} & & 0 & \overline{V^{(m-1)m}} \\ \overline{V^{m1}} & \overline{V^{m2}} & \cdots & \overline{V^{m(m-1)}} & 0 \end{bmatrix} \tag{8}$$

Defining the following function for data normalization, the following equation is obtained:

$$\mathrm{f(b)} = (b - \mathrm{b_{min}})/(\mathrm{b_{max}} - \mathrm{b_{min}})(\mathrm{b} \in B_{m \times m}) \tag{9}$$

The bilateral trade carbon inequality index between the region 'r' and region 's' BCI^{rs} is built as follows by referring to the research by Zhang et al. (2018):

$$BCI^{rs} = \begin{cases} f\left(\dfrac{\overline{EN^{rs}}}{\overline{V^{rs}}}\right), \overline{\mathrm{EN}^{rs}} > 0 \; and \; \overline{\mathrm{V}^{rs}} > 0 \\ f(\overline{EN^{rs}}) + f(|\overline{V^{rs}}|) + 1, \overline{\mathrm{EN}^{rs}} > 0 \; and \; \overline{\mathrm{V}^{rs}} < 0 \end{cases} \tag{10}$$

In Eq. (10), $\overline{EN^{rs}}$ is the net flow of embodied carbon emissions between region 'r' and region 's'. $|\overline{V^{rs}}|$ is the absolute value of the net flow of embodied value added between region 'r' and region 's'.

In the calculation of BCI^{rs}, there are two situations: (i) when $\overline{\mathrm{EN}^{rs}} > 0$, $\overline{\mathrm{V}^{rs}} > 0$, and $0 < BCI^{rs} < 1$, it indicates that region 'r' undertakes net carbon emissions while obtaining net economic benefits from region 's', presenting a relatively fair bilateral trade; (ii) when

$\overline{EN^{rs}} > 0$, $\overline{V^{rs}} < 0$, and $BCI^{rs} > 1$, it implies that region 'r' undertakes net carbon emissions while bearing net economic losses from region 's', suggesting a carbon inequality in trade. Generally, the greater the BCI index is, the more unequal the carbon exchange in bilateral trade is.

The total carbon emissions and value added obtained by region 'r' are defined as E^r and V^r, respectively:

$$E^r = \sum_{s \neq r}^{m} \overline{E^{rs}} \tag{11}$$

$$V^r = \sum_{s \neq r}^{m} \overline{V^{rs}} \tag{12}$$

The global trade carbon inequality index of region 'r', GCI^r, is proposed by referring to the research by Wang et al. (2022b):

$$\mathrm{GCI^r} = \begin{cases} -f(E^r) - f(V^r) - 1, E^r > 0 \; and \; \mathrm{V^r} < 0 \\ -f\left(\frac{E^r}{V^r}\right), E^r > 0 \; and \; \mathrm{V^r} > 0 \\ f\left(\frac{E^r}{V^r}\right), E^r < 0 \; and \; \mathrm{V^r} < 0 \\ f(E^r) + f(V^r) + 1, E^r \langle 0 \; and \; \mathrm{V^r} \rangle 0 \end{cases} \tag{13}$$

In the calculation of GCI^r, there are four situations: (i) when $E^r > 0$, $\mathrm{V^r} < 0$, and $\mathrm{GCI^r} < -1$, it indicates that region 'r' bears net economic losses while undertaking net carbon emissions and suffers the most from global trade carbon inequality; (ii) when $E^r > 0$, $\mathrm{V^r} > 0$, and $-1 < \mathrm{GCI^r} < 0$, it indicates that region 'r' obtains net economic benefits at the expense of undertaking net carbon emissions; (iii) when $E^r < 0$, $\mathrm{V^r} < 0$, and $0 < \mathrm{GCI^r} < 1$, it indicates that region 'r' outsources its carbon emissions and bears net economic losses from other regions; and (iv) when $E^r < 0$, $\mathrm{V^r} > 0$, and $\mathrm{GCI^r} > 1$, region 'r' obtains net economic benefits while outsourcing its carbon emissions, in addition to being a beneficiary from both environmental and economic perspectives.

2.3. Data sources

The global MRIO table and CO_2 emission inventory data were obtained from the Global Trade Analysis Project (GTAP) 10 database, which represented the world economy in 2014 and included 141 countries and regions.

Regarding the classification of BRI countries and regions, the BRI countries and regions covered in this study were those that have signed the cooperation document on jointly building the BRI (The Belt and Road Portal, 2022). Notably, India was included in this study due to its geographical location and vital role in trade with BRI countries and regions, although it has not yet signed the corresponding cooperation documents. Therefore, this study focused on 8 countries (China, South Korea, Indonesia, India, Italy, Russia, Saudi Arabia, and South Africa), while the remaining 94 GTAP BRI countries and regions were integrated into 7 BRI regions: BRI Southeast Asia, BRI South Asia, BRI Europe, BRI Central Asia, BRI West Asia, BRI Africa, and BRI Others. The corresponding map and detailed information for these 7 BRI regions were shown in Fig. 1 and Appendix A. Then, we took the remaining countries and regions as a whole: non-BRI countries and regions.

Regarding the sector classification method, this study classified 65 sectors into 8 categories: Agriculture, Mining & Quarrying, Food, Beverages & Tobacco, Manufacturing, Electricity, Gas & Water Supply, Construction, Transportation, and Service. Detailed information on these 8 sector categories is shown in Appendix B. Additionally, the carbon emissions data provided by this database are distinguished by fuel for each country or region.

3. Results

3.1. Amounts and sectoral structures of carbon emissions and value added

In 2014, the production-based and consumption-based carbon emissions of all BRI countries and regions were 16,954.42 Mt and 15,720.16 Mt, accounting for 65% and 61% of the global total (25,966.23 Mt), respectively. On the other hand, the production-based and consumption-based value added of all BRI countries and regions were 27,371.33 billion dollars and 26,855.85 billion dollars, accounting for 41% and 40% of the global total (66,971.43 billion dollars), respectively.

Fig. 2 indicates the amounts and sectoral structures of production-based and consumption-based carbon emissions and value added. For carbon emissions, China was the largest producer and consumer (7445.92 Mt and 6541.94 Mt), accounting for 44% and 42% of the total for all BRI countries and regions, respectively, followed by India (1762.25 Mt and 1636.19 Mt) and BRI West Asia (1239.42 Mt and 1291.69 Mt). For most BRI countries and regions, the production-based carbon emissions were caused mainly by Manufacturing, Electricity, Gas & Water Supply, and Transportation, accounting for 73–95% (Appendix C). Consumption-based carbon emissions were mainly the result of Manufacturing, Electricity, Gas & Water Supply, Construction, and Service, accounting for 69–89% (Appendix C). Regarding value added, China was also the largest producer and consumer (8103.47 billion dollars and 8138.38 billion dollars), accounting for 30% of the total

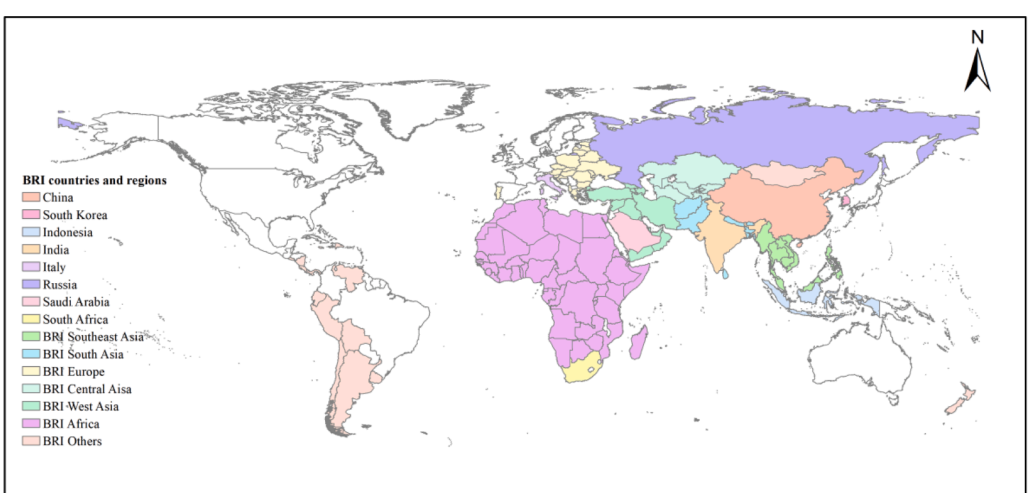

Fig. 1. Geographical scope and classification of BRI countries and regions.

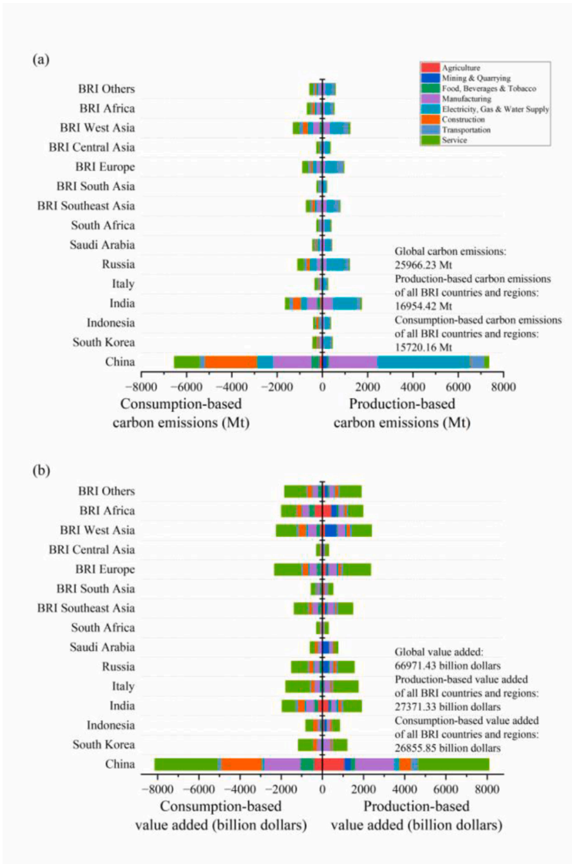

Fig. 2. Production-based and consumption-based carbon emissions (a) and value added (b).

among all BRI countries and regions, followed by BRI Europe (2351.68 billion dollars and 2325.78 billion dollars) and BRI West Asia (2392.83 billion dollars and 2242.23 billion dollars). Service contributed the most in every BRI country or region for production-based value added, accounting for 24–68% (Appendix C). Consumption-based value added was mainly contributed by Manufacturing, Construction, and Service, accounting for 58–89% (Appendix C).

By comparing production-based and consumption-based carbon emissions, the net emissions corresponding to the attributes of BRI countries' and regions can be seen. The net flow includes 2 types: net export and net import, and the former is greater than 0 while the latter is less than 0. More than half of BRI countries and regions were net exporters of embodied carbon emissions, and their production-based carbon emissions were greater than their consumption-based carbon emissions, causing these areas to undertake net carbon emissions from other countries and regions, similar to the results of Han et al. (2018). Among these countries, China was the largest net exporter of embodied carbon emissions, with net exports reaching 903.98 Mt, accounting for 56% of the total for all net exporters (Appendix D). In addition, India (126.06 Mt) and South Africa (139.49 Mt) were also important net exporters of embodied carbon emissions. In contrast, Indonesia, Italy, Saudi Arabia, BRI South Asia, BRI West Asia, and BRI Africa were net importers of embodied carbon emissions, with greater consumption-based carbon emissions than production-based carbon emissions, thus outsourcing their carbon emissions to other countries and regions and benefiting from an environmental perspective. BRI Africa was the largest net importer of embodied carbon emissions, outsourcing 145.82 Mt embodied carbon emissions to outside areas, accounting for 40% of the total for all net importers (Appendix D). Among these sectors, Electricity, Gas & Water Supply was the largest net exporter of embodied carbon emissions for all BRI countries and regions while Transportation's impact was also important (Appendix D). In contrast, Service was usually the largest net importer of embodied carbon emissions (Appendix D). From the value-added aspect, more than half of BRI countries and regions were net exporters of embodied value added, obtained net economic benefits and were beneficiaries from an economic perspective. On the other hand, the largest net importer of embodied value added was India (48.27 billion dollars), followed by China (34.91 billion dollars) and BRI South Asia (34.17 billion dollars) (Appendix D). Regarding the structure of the net imports of embodied value added, Food, Beverages & Tobacco and Construction were the leading net importers (Appendix D).

Fig. 3 classifies BRI countries and regions based on the net flow of embodied carbon emissions and value added. Nearly half of BRI countries and regions are in the first quadrant, indicating that these countries and regions obtained net economic benefits at the expense of undertaking net carbon emissions. In contrast, Italy, South Africa, and BRI Africa are in the third quadrant. These countries and regions outsourced net carbon emissions and bore net economic benefits from other BRI countries and regions. Indonesia, Saudi Arabia, and BRI West Asia are in the fourth quadrant. They obtained net economic benefits while outsourcing net carbon emissions, thus benefiting from both the environmental and economic perspectives. Although Saudi Arabia and BRI West Asia did not outsource much carbon emissions (13.63 Mt and 52.27 Mt, respectively), they obtained the most net economic benefits (167.14 billion dollars and 152.60 billion dollars, respectively). In contrast, China and India bore net economic losses while undertaking net carbon emissions and suffered the most from global trade carbon inequality. China did not bear extensive net economic losses (34.91 billion dollars) but undertook many net carbon emissions (903.98 Mt), even more than 6 times that of South Africa. India did not undertake the most net carbon emissions (126.06 Mt) but bore the most net economic benefits (48.27 billion dollars). This phenomenon preliminarily reflects the carbon inequality across BRI countries and regions.

3.2. Inter-regional net flow of embodied carbon emissions and value added

Overall, BRI countries and regions totally exported embodied carbon emissions to non-BRI countries and regions, consistent with the research results of Hou et al. (2020), Lu et al. (2020), and Fang et al. (2021). The net export of embodied carbon emissions of all BRI countries and regions was 1234.25 Mt, mainly from China (621.01 Mt), India (95.71 Mt), Russia (88.13 Mt), BRI Southeast Asia (105.89 Mt), and BRI Europe (108.12 Mt) (Appendix E). At the same time, BRI countries and regions obtained 515.48 billion dollars net economic benefits (Appendix E).

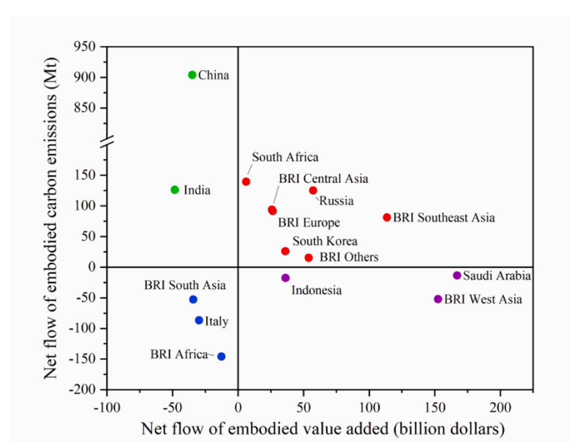

Fig. 3. Classification of BRI countries and regions based on the net flow of embodied carbon emissions and value added.

The main inter-regional net flow of embodied carbon emissions and value added across BRI countries and regions are depicted in Fig. 4(a) and (b). BRI Africa was the largest net importer of embodied carbon emissions among all BRI countries and regions, with a net import of 146.54 Mt from other BRI countries and regions (Appendix E). BRI Africa imported 55.64 Mt and 27.89 Mt net embodied carbon emissions from China and South Africa, respectively, accounting for 38% and 19% of the total, respectively. Moreover, BRI Africa bore 24.42 billion dollars net economic losses from other BRI countries and regions (Appendix E). In addition, Italy, BRI South Asia, and BRI West Asia were also the leading net importers of embodied carbon emissions; they imported 76.95 Mt, 52.22 Mt, and 96.34 Mt net embodied carbon emissions from other BRI countries and regions, respectively (Appendix E). Italy and BRI South Asia bore 40.45 billion dollars and 49.06 billion dollars net economic losses from other BRI countries and regions, while BRI West Asia obtained 102.01 billion dollars net economic benefits from other BRI countries and regions (Appendix E).

China was the largest net exporter of embodied carbon emissions, as was also confirmed in the study of Wang et al. (2022b). China exported 282.97 Mt to other BRI countries and regions (Appendix E). Specifically, China exported net embodied carbon emissions to other BRI countries and regions except for South Africa and BRI Central Asia. Wang et al. (2022a) confirmed that approximately 80% of BRI countries were net importers of embodied carbon emissions in trade with China, similar to our results. China exported net embodied carbon emissions mainly to BRI Southeast Asia (46.02 Mt), BRI West Asia (42.20 Mt), and BRI Africa (55.64 Mt), accounting for 16%, 15% and 20% of the total, respectively. The net export embodied carbon emissions from China were caused mainly by China's Manufacturing and Electricity, Gas & Water Supply, while the main sectors responsible for imported emissions were the Manufacturing, Construction, and Service of BRI countries and regions. Details on the example of China and BRI West Asia can be seen in Appendix F. At the same time, China bore 109.96 billion dollars net economic losses in trade with BRI countries and regions (Appendix E), mainly from South Korea (32.04 billion dollars), Saudi Arabia (27.19 billion dollars), and BRI West Asia (57.90 billion dollars). In addition, South Africa, India, and Russia were also the main net exporters of embodied carbon emissions, exporting 79.14 Mt, 30.35 Mt, and 37.25 Mt net embodied carbon emissions to other BRI countries and regions, respectively. Russia and South Africa obtained 34.74 billion dollars and 2.97 billion dollars net economic benefits from other BRI countries and regions, while India bore 86.79 billion dollars net economic losses from other BRI countries and regions. All these numbers show the unbalanced pattern of the inter-regional flow of embodied carbon emissions and value added, leading to carbon inequality among BRI countries and regions.

3.3. Carbon inequality in bilateral and global trade

Fig. 5(a) displays the BCI indices among BRI countries and regions. Italy was beneficiary in bilateral trade with all other BRI countries and regions, and the BCI index only between Italy and BRI West Asia was higher than 1 (1.09). Indonesia exerted a burden of carbon inequality on many BRI countries and regions. The BCI index between Indonesia and China reached 1.39, and the BCI indices between Indonesia and South Korea (1.09), India (1.23), South Africa (1.02), BRI Southeast Asia (1.13), and BRI Europe (1.02) were all higher than 1. Saudi Arabia imposed severe carbon inequality on many BRI countries and regions. The BCI index between Saudi Arabia and China was 1.67, and the BCI indices between Saudi Arabia and South Korea (1.20), India (1.41), South Africa (1.08), BRI West Asia (1.01), and BRI Others (1.04) were all higher than 1. In addition, BRI South Asia, BRI West Asia, and BRI Africa were also beneficiaries of bilateral trade with several BRI countries and regions. The BCI indices between BRI West Asia and India, and between BRI Africa and India were 1.91 and 1.45, respectively.

China was negatively affected by carbon inequality in bilateral trade with all other BRI countries and regions except South Africa and BRI Central Asia. The most severe carbon inequality existed in bilateral trade between China and BRI West Asia, with a BCI index of 2.76. Take this pairing as a case study, we identify the detailed production and consumption sectors embodied in this carbon inequality. Overall, during trade, China undertook 42.20 Mt net carbon emissions while bearing 57.90 billion dollars net economic losses. Specifically, China's Electricity, Gas & Water Supply undertook 24.77 Mt net carbon emissions from BRI West Asia's Manufacturing, accounting for 59% of the total. However, China obtained only 1.09 billion dollars net economic benefits. Meanwhile, China's Manufacturing and Construction outsourced 2.76 Mt and 2.06 Mt net carbon emissions to BRI West Asia's Mining & Quarrying but bore 38.29 billion dollars and 27.85 billion dollars net economic losses, accounting for 66% and 48% of the total, respectively. More details can be seen in Appendix F. As a result, China was negatively affected both environmentally and economically when trading with BRI West Asia. In addition, severe carbon inequality appeared in the bilateral trade between China and BRI Southeast Asia (2.18). Overall, during trade, China undertook 46.02 Mt net carbon emissions while bearing 20.70 billion dollars net economic losses. Specifically, China's Electricity, Gas & Water Supply undertook 29.58 Mt, 10.86 Mt, and 10.16 Mt net carbon emissions from BRI Southeast Asia's Manufacturing, Construction, and Service. However, China obtained only 0.92 billion dollars, 0.58 billion dollars, and 0.28 billion dollars net economic benefits. Meanwhile, China's Manufacturing outsourced 4.18 Mt and 0.17 Mt net carbon emissions to BRI Southeast Asia's Manufacturing and Service, respectively, but bore 9.56 billion dollars and 6.41 billion dollars net economic losses, respectively. More details can be seen in Appendix F. Additionally, compared to South Korea (1.69), Indonesia (1.39), Saudi Arabia (1.67), and BRI Others (1.56), China was also negatively affected by severe carbon inequality. India was also negatively affected by carbon inequality in bilateral trade with many BRI countries and regions, and the BCI indices with Indonesia (1.23), Saudi Arabia (1.41), BRI Southeast Asia (1.14), BRI West Asia (1.91), and BRI Africa (1.45) were all higher than 1.

Fig. 5(b) indicates the GCI indices of BRI countries and regions, reflecting their overall status in global trade carbon inequality. The results show that the GCI indices of Indonesia, Saudi Arabia, and BRI West Asia were 1.51, 2.13, and 2.02, respectively, indicating that these areas were the primary beneficiaries of inequality associated with the global carbon trade. Taking Saudi Arabia as an example, its Electricity, Gas & Water Supply undertook 91.79 Mt net carbon emissions, whereas its

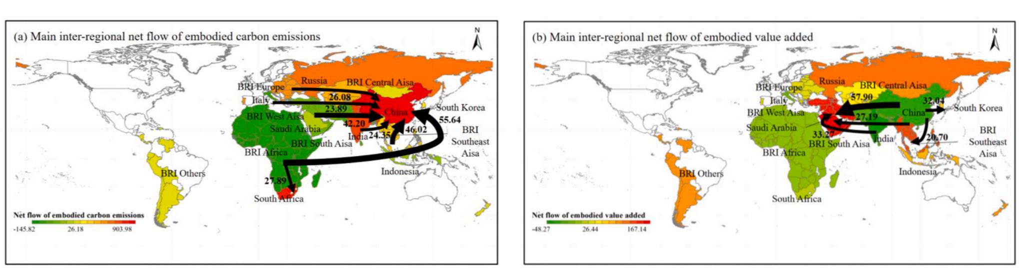

Fig. 4. Main inter-regional net flow of embodied carbon emissions (unit: Mt) and value added (unit: billion dollars) across BRI countries and regions.

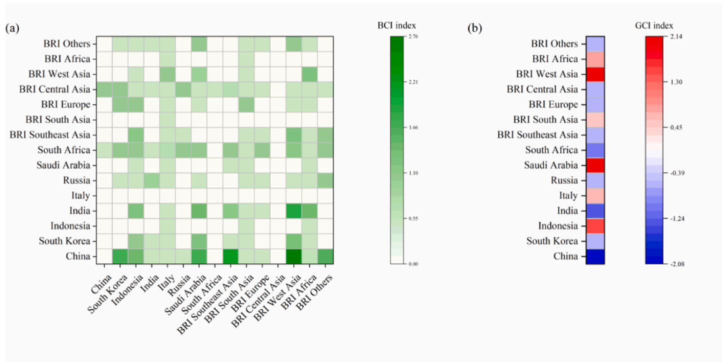

Fig. 5. BCI and GCI indices among BRI countries and regions. (a) Each grid represents the BCI index between the two BRI countries and regions indicated by the horizontal and vertical coordinates. The deeper the color is, the greater the BCI index is. (b) Each grid represents the GCI value of a BRI country or region. The redder the color is, the greater the GCI index is. In contrast, the bluer the color is, the lower the GCI index is.

Construction and Service outsourced 62.74 Mt and 57.00 Mt net carbon emissions, respectively. In general, Saudi Arabia outsourced net carbon emissions. At the same time, although other sectors bore net economic losses, Mining & Quarrying in Saudi Arabia obtained net economic benefits of 332.29 billion dollars; thus, the region obtained a large amount of net economic benefits. Therefore, Saudi Arabia benefited from global trade from economic and environmental perspectives. For BRI West Asia and Indonesia, the details are described in Appendix D.

The GCI index values of most BRI countries and regions are lower than 0, indicating that these areas were negatively affected by global trade carbon inequality. The GCI indices of China and India were −2.06 and −1.26, respectively, suggesting that these areas suffered the most from carbon inequality in global trade. In China, the Manufacturing, Electricity, Gas & Water Supply, and Transportation undertook 457.10 Mt, 3374.44 Mt, and 372.55 Mt net carbon emissions, accounting for 51%, 373%, and 41%, respectively. At the same time, although other sectors obtained net economic benefits, China's Food, Beverage & Tobacco and Construction bore net economic losses of 433.86 billion dollars and 1405.69 billion dollars, respectively, resulting in China's overall net economic losses. Therefore, China bore both additional carbon emissions and economic losses in global trade and suffered the most from global trade carbon inequality. For India, the details are described in Appendix D.

4. Discussion and conclusion

In this study, we constructed a methodological framework to analyze the carbon inequality across BRI countries and regions under the global trade network. Flow analyses of embodied carbon emissions and value added were conducted based on the MRIO model. On this basis, a CI index combination was proposed to quantify the carbon inequality among BRI countries and regions from the two dimensions of bilateral trade and global trade. Moreover, we identified the detailed production and consumption sectors embodied in carbon inequality. This framework can be used to analyze the exchanges of other kinds of ecological impacts (e.g., land use, water consumption, and energy use) and economic benefits in trade on any scale (e.g., China's inter-provincial trade and other country's inter-regional trade).

On the basis of the flow analysis of embodied carbon emissions and value added, we found that nearly half of BRI countries and regions were net exporters of both embodied carbon emissions and value added, meaning that, despite achieving net economic benefits and economic growth, they also undertook net carbon emissions from other countries and regions. At the sectoral level, the Electricity, Gas & Water Supply and Transportation were the main contributors to production-based carbon emissions and net export-embodied carbon emissions. In contrast, the Service contributed the most to production-based value added, adding to the high net exporters of value added. The most severe bilateral trade carbon inequality existed between China and BRI West Asia (BCI=2.76). Except for Indonesia, Saudi Arabia, and BRI West Asia, BRI countries and regions were negatively affected by global trade carbon inequality, with China (GCI=−2.06) and India (GCI=−1.26) suffering the most. The above results indicate that carbon inequality embodied in trade exists among BRI countries and regions and is detrimental to their growth as green economics.

Based on the results, this study provides some policy implications to alleviate carbon inequality and provides methods as well as decision-making guidelines for the green development of the Belt and Road.

First, we suggest changing the trade structures of BRI countries and regions from high-carbon and low-value-added to low-carbon and high-value-added. At the sectoral level, the trade structure being dominated by sectors producing goods with high carbon emissions and low value added (e.g., Electricity, Gas & Water Supply and Transportation) leads to BRI countries and regions undertaking more net carbon emissions while obtaining fewer economic benefits in inter-regional trade, as confirmed by some previous research (Zhang and Zhang, 2018; Kim and Tromp, 2021; Lin et al., 2021). Additionally, the excessive involvement of these sectors may contribute to the unequal exchange of carbon emissions and value added embodied in trade; an example is the trade between China and BRI West Asia. Therefore, BRI countries and regions need to change their trade structures from high-carbon and low-value-added to low-carbon and high-value-added to reduce carbon emissions, obtain more economic benefits, and enhance their status in the global supply chain.

Second, we advise allocating responsibility for reducing carbon emissions between BRI countries and regions from a co-responsibility perspective. Countries and regions (e.g., China and India) that are negatively impacted by carbon inequality would not only be responsible for the net economic losses, but also be forced to shoulder additional costs to reduce carbon emissions. Therefore, we suggest a co-responsibility approach, meaning that consumers' accountability should be considered, and producers and consumers can share the responsibility for carbon emissions. This approach has received some scientific support (Bastianoni et al., 2004; Lenzen et al., 2007; Berzosa et al., 2014; Jakob et al., 2021). Furthermore, those who outsource net carbon emissions are encouraged to reduce the carbon emissions of the undertakers by providing capital, technology, or other services (Hotak et al., 2020).

Third, we recommend introducing a directory of low-carbon goods for BRI countries and regions. A directory of low-carbon goods could help BRI countries and regions identify goods whose production and use processes consume less energy and emit fewer emissions to provide guidance for industrial and trade structure transformation from high-carbon and low-value-added to low-carbon and high-value-added for BRI countries and regions. On the other side, a directory of this kind is useful for encouraging customers to modify their consumption habits and choose to purchase low-carbon goods in order to decrease the demand for high-carbon goods, much like carbon labeling (Vandenbergh et al., 2011; Upham et al., 2011). Thus, a directory of low-carbon goods would be beneficial in allowing BRI countries and regions to reduce their carbon emissions and outsourcing while promoting economic growth during trade, thereby promoting the equal exchange of carbon emissions and economic benefits in trade among BRI countries and regions.

Fourth, we propose establishing a tariff standard on low-carbon goods for trade across BRI countries and regions. The trade of low-carbon goods is beneficial for reducing carbon emissions and outsourcing while promoting economic growth (Frey, 2016; Ahmed et al., 2022), thereby alleviating the unequal exchange of carbon emissions and economic benefits in the trade of BRI countries and regions. To promote the trade of low-carbon goods, a tariff standard, which sets the upper limit of the tariff rate, is needed to limit tariffs on low-carbon-goods trading between BRI countries and regions, as supported by some prior research (Hill, 2016; Janssens et al., 2020; Ding et al., 2022). With low tariffs on low-carbongoods trades, BRI countries and regions would be more willing to produce and trade low-carbon goods, thus further promoting the trade of low-carbon goods and alleviating carbon inequality across BRI countries and regions. Regarding the trade of some low-carbon goods that are conducive to promoting the green transformation of BRI countries and regions, such as renewable energy and clean production equipment, the tariff can be reduced to 0.

This study has two limitations. First, the MRIO table used in this study is from 2014 because it was the most recent data available when we conducted this research. However, since the globalized world is changing rapidly, the data used in this study may be too old to make diagnoses and suggest governmental measures. Second, we integrated 94 GTAP BRI countries and regions into 7 BRI regions, which means that the adverse effects of carbon inequality on some BRI countries and regions may not have been identified. Regarding further research directions, the regional and sector divisions considered herein should be down-scaled to allow more detailed results. Furthermore, exchanges of other kinds of ecological impacts and economic benefits in trade among BRI countries and regions should be investigated.

CRediT authorship contribution statement

Zekun Lin: Conceptualization, Modelling, Investigation, Data curation, Visualization, Writing-original draft. **Fanxin Meng:** Conceptualization, Supervision, Writing-original draft, Funding acquisition. **Dongfang Wang:** Conceptualization, Supervision, Methodology, Writing-Review, Editing. **Danqi Liao:** Modelling, Investigation, Data curation, Writing-original draft. **Yutong Sun:** Methodology, Investigation, Data curation. **Jiaqi Hou:** Methodology, Data curation, Visualization. **Gengyuan Liu:** Writing-Review, Editing, Funding acquisition. **Biagio Fernando Giannetti:** Writing-Review, Editing. **Feni Agostinho:** Writing-Review, Editing. **Cecília M. V. B. Almeida:** Writing-Review, Editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Supplementary materials

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