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Greenhouse gas emissions patterns and insertion in global value chains: a comparative study between Brazil and China (2000–2016)

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Abstract

Purpose – This study aims to analyze and compare the relationship between international trade in global value chains (GVC) and greenhouse gas (GHG) emissions for Brazil and China from 2000 to 2016.

Design/methodology/approach – The input-output method apply to multiregional tables from Eora-26 to decompose the GHG emissions of the Brazilian and Chinese productive structure.

Findings – The data reveals that Chinese production and consumption emissions are associated with power generation and energy-intensive industries, a significant concern among national and international policymakers. For Brazil, the largest territorial emissions captured by the metrics come from services and traditional industry, which reveals room for improving energy efficiency. The analysis sought to emphasize how the productive structure and dynamics of international trade have repercussions on the environmental dimension, to promote arguments that guide the execution of a more sustainable, productive and commercial development strategy and offer inputs to advance discussions on the attribution of climate responsibility.

Research limitations/implications – The metrics did not capture emissions related to land use and deforestation, which are representative of Brazilian emissions.

Originality/value – Comparative analysis of emissions embodied in traditional sectoral trade flows and GVC, on backward and forward sides, for developing countries with the main economic regions of the world.

Keywords International trade, Global value chains, Greenhouse gas emissions

Paper type Research paper

1. Introduction

Climate change, a phenomenon associated with the increase in average earth temperature resulting from the higher concentration of greenhouse gases (GHGs) in the atmosphere (IPCC, 2007), is driving recent studies about international trade effects on the environment. According to the world trade organization (WTO) report (WTO, 2022), as the climate crisis escalates, it will negatively affect the production of goods and services worldwide, especially in more vulnerable areas, thus potentially altering the dynamics of the entire global trading

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JEL Classification — F18, Q51, Q54

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system. Therefore, decarbonizing productive structures in this scenario is crucial to control GHG emissions and achieve sustainable development goals.

The main determinants of emissions associated with international trade are (1) the size of the economy; (2) sectoral composition; (3) global value chains (GVC); (4) transportation; and (5) energy efficiency of production systems (WTO, 2021). According to WTO (2022), GVC are a relevant driver of GHG emissions distribution worldwide because economies that more integrated into GVC promote imports of intermediate inputs, thus increasing the amount of GHG emissions embodied in those imports. Under these circumstances, the accounting of GHG emissions embodied in international trade has been an important measure for understanding the dynamics of pollution transfer by trade flows, supporting the design of consistent climate policies and discussing climate responsibility.

However, consolidating a globalized world poses difficulties to building equitable global solutions. As one observes how pollution level, economic growth and institutional structure relate to one another, one realizes that pollution tends to be concentrated in regions with lower income levels and transform them into "pollution havens." A vast literature has registered this dynamic (Walter, Ugelow, 1979; Cole and Elliott, 2003; Duan, Ji, & Yu, 2021), established historical connections between capitalist accumulation patterns and environmental degradation, and identified a transmission channel in contemporary international trade relations.

In this paper, we conduct an emissions decomposition analysis considering the GHG emissions distribution by global intersectoral production and consumption linkages established by traditional international trade and GVC structure. We used the data from an environmentally extended multi-regional input-output (EE MRIO) Eora-26 model by estimating the GHG emissions embodied in trade flows of Brazil and China with the following economic regions: southern common market (Mercosur), United States, Canada and Mexico (USMCA), European Union (EU), East Asia (EA), and rest of the world (ROW).

In our sample, countries have been selected based on the commercial representativeness of these two large developing economies (Brazil and China), despite their divergent paths. While China's high economic growth rates have shown increased participation of manufacturing industries, thus contributing to the enhancement of that country's international competitiveness, Brazil has reduced its manufacturing sector share and redirected its productive structure toward primary goods and low processing activities as a result of increased global demand, mainly from China (Sturgeon, Gereffi, Guinn, & Zylberberg, 2013).

However, those countries also differ concerning their environmental challenges. A progressive increase in GHG emission rates has followed China's positive economic results, while Brazil has relatively stable emission levels associated with its productive structure. Hence, China faces the challenge of decoupling economic growth from increasing GHG emissions, while Brazil strives to resume a model of industrialization that is compatible with contemporary environmental demands.

In this context, the main questions that drive the discussion here are: what is the structural pattern of both Brazil's and China's GHG emissions? What are the sectors and positions in the GVC with the most significant environmental impact regarding GHG emissions? The analysis assesses the results of emission indicators from 2000 to 2016, a period covering the pre- and post-2008 financial crisis, when global production dynamics were directly impacted. The main contribution of this work is the comparative analysis of emissions embodied in trade flows, on the backward and forward sides, of developing countries with the main economic regions of the world.

The paper is organized as follows. Section 2 presents a brief conceptualization and a literature review of climate change and environmental effects on international trade. Section 3 discusses the methodology for calculating the emission indicators, the sectoral classification and database. Section 4 presents the main results obtained. Finally, the paper closes with concluding remarks and policy implications.

2. Literature review

2.1 Global value chains and greenhouse gas emissions

The enhancement of information and communication technologies (ICT) drove globalization at the end of the 20th century, expanding economic, social and cultural boundaries. Globalization has transformed how goods and services are produced for international trade, promoting the fragmentation of production stages into different companies or economies, defined as GVC. The formation of GVC has changed the traditional view of production for foreign trade, transforming productive structures into highly complex networks (Henderson, Dicken, Hess, Coe, & Yeung, 2002).However, according to the WTO (2022), GVC are seen as a relevant driver for GHG [1] emissions distribution worldwide because the economies that are more integrated into GVC add to their emission profile the amount of GHG emissions embodied in the imports of intermediate inputs and thus contribute to the worsening of the climate crisis.

The estimates of the Intergovernmental Panel on Climate Change (IPCC) report (2014; 2018), when comparing the pre-and post-industrial periods, showed that human activities accounted for an average increase of 0.85 °C in the planet's temperature between 1880 and 2012, causing severe effects and imposing the climate crisis scenario in the following decades. Specialists' are mainly concerned with the scenarios where GHG emission rates keep growing, which estimated an increase of more than 1.5 °C in global temperature between 2030 and 2052. The main effects predicted are the average increase in land and ocean temperatures, with rising levels and acidification, which may cause severe or irreversible damage to biodiversity (IPCC, 2014); and the occurrence of extreme temperatures and increased precipitation in some regions while increasing the probability of prolonged droughts in others, threatening many ecosystems (IPCC, 2018). Most regions subject to impacts are small islands, coastal regions, megacities and mountainous areas, exposing the most vulnerable populations in these localities to unprecedented risks (Albert *et al.*, 2018).

In face of that, decarbonizing GVC is a complex but important challenge to avoid catastrophic events and assuring the future of the international trade system. Two main types of firms trade in GVC: lead firms, which are multinational companies (MNEs) located in developed countries that control and set the operation and pace of the chain in terms of prices, deliveries, and performance; and supplier firms, located in developing countries, which are responsible for producing the goods and services demanded by lead firms (Gereffi & Luo, 2015). This configuration demonstrates that the geographical dispersion of the companies and productive stages is somewhat related to the countries' structural and institutional capacities.

The gains accumulated by the industrialization process in developed countries favored that leading companies came into existence in these regions, to the detriment of discouraging industrial development in emerging economies (Baldwin, 2013). Andreoni and Tregenna (2020) discuss this issue and argue how the high structural heterogeneity and the low level of technical training and experiences that characterized the deindustrialization of middle-income countries – all standard features of Global South countries – have restricted their competitiveness in the international field. Moreover, the type of international insertion they experience reinforces the productive specialization trap these countries find themselves in (Savona & Ciarli, 2019), with concentrated participation in the supply of primary goods and productive activities of lower value added.

In addition, from an environmental perspective, the pollution haven hypothesis addresses the relocation of polluting industries to developing countries due to inequalities in the global economy. The pollution haven hypothesis is that industrial pollution increases in developing countries due to a lack of effective regulation, leading to the development of a 'dirty' production structure (Cole and Elliott, 2003; Duan *et al.*, 2021). At the same time, the participation of polluting industries and processes in developed countries decreases, showing that, through industrial regulatory control and driving structural change toward a sustainable path, "clean" industries and sectors are predominant in developed countries (Savona & Ciarli, 2019).

Under these conditions, the effects of disparate interaction are propagated and stimulated through international trade, acting as a pollution reallocation mechanism according to each country's institutional and economic profile (Cole & Elliott, 2003). Additionally, as trade flows incorporate indirect negative environmental externalities – for example, the GHG emissions embedded into the production and transportation of goods and services abroad – a dynamic of transfer pollution by consumption is established (Arce *et al.*, 2012). Therefore, considering the GVC dynamics, the economies with higher participation in GVC may have a relatively higher share of imported GHG emissions, even when showing lower GHG emissions embedded in their domestic production (Wood *et al.*, 2020).

In this context, studies conducting environmental analyses of international trade have used the input-output method as a valuable technique to map pollution hotspots in the production and trade system. However, the GVC dynamics introduce the need for new methodological tools in this type of analysis due to the international fragmentation of production in different economies. Thus, the GVC framework establishes some metrics to account for and discriminate the origin of the value added in intermediate and final goods trade flows.

Johnson and Noguera (2012) proposed an accounting measure to assess the value added embodied in trade, which Koopman, Wang, and Wei (2014) used to create an input-output approach by identifying the components of value added within gross exports. The main contribution of these models is in properly understanding the new pattern of international trade, showing that analyzing only gross export data can omit information about countries' domestic production capacities (Wang, Wei, & Zhu, 2013). Also, the GVC framework allows one to create measures to shed light on the relationship between international trade and GHG emissions.

Therefore, based on this discussion, the MRIO matrices provide the methodological tool and the availability of data to support the analysis of GHG emissions generated and incorporated in trade relations between countries, which are relevant in the climate crisis scenario.

3. Methodology

The decomposition of value added into trade flows of goods and services usually supports the analysis using GVC indicators, based on Leontief's (1936) fundamentals and structural decomposition analysis methods.

From the beginning, we consider the Leontief's classical production system for an open economy:

$$\mathbf{X} = \mathbf{A}\mathrm{X} + \mathbf{Y} = \mathbf{A}^{D}\mathrm{X} + \mathbf{Y}^{D} + \mathbf{A}^{F}\mathrm{X} + \mathbf{Y}^{F} = \mathbf{A}^{D}\mathrm{X} + \mathbf{Y}^{D} + \mathbf{E}, \tag{1}$$

where the total output $\mathbf{X}$ is the intermediate consumption as a fixed proportion of the output value, expressed by the technical coefficient, $\mathbf{A}$; and final demand variations, $\mathbf{Y}$; considering all the intermediary and final external relations, $\mathbf{E}$ (Miller & Blair, 2009). In this sense, $\mathbf{A}^{D}$ is a domestic technical coefficient, a diagonal block $\mathrm{N}\cdot\mathrm{N}$ matrix of domestic input coefficients (for k countries and m sectors, where $m\cdot k = \mathrm{N}$), given by:

$$\mathbf{A}^{\mathrm{D}} = \begin{bmatrix} \mathbf{A}^{ss} & 0 & \cdots & 0 \\ 0 & \mathbf{A}^{ss} & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & 0 & \mathbf{A}^{ss} \end{bmatrix}$$

Thus, we can define the block matrix of input coefficients that is off the main diagonal as $\mathbf{A}^{\mathrm{F}}$, and is therefore a block matrix of imported input coefficients $\mathrm{N}\cdot\mathrm{N}$, expressed as:

$$\mathbf{A}^{\mathrm{F}} = \mathbf{A} - \mathbf{A}^{\mathrm{D}} = \begin{bmatrix} 0 & \mathbf{A}^{sr} & \cdots & \mathbf{A}^{st} \\ \mathbf{A}^{rs} & 0 & \cdots & \vdots \\ \vdots & \vdots & \ddots & \vdots \\ \mathbf{A}^{ts} & \cdots & \cdots & 0 \end{bmatrix}$$

The subscript s refers to the country of origin, r the trading partner country, and t indicates third countries. So, based on these definitions, the domestic and the global version of the Leontief inverse matrix can be rewritten according to their respective technical coefficient matrices, as follows:

$$\text{Domestic version}: \mathbf{L} = \left(\mathbf{I} - \mathbf{A}^{D}\right)^{-1}, \tag{2}$$

$$\text{Global version}: \mathbf{B} = (\mathbf{I} - \mathbf{A})^{-1}, \tag{3}$$

The division between $\mathbf{A}^{\mathrm{D}}$ and $\mathbf{A}^{\mathrm{F}}$ provides a simultaneous decomposition of production, between intermediate and final goods, and by the location of production and consumption, which is relevant for GVC analysis. Thus, the value added embodied in the countries' production can be defined using the value-added (VA) estimation method by Johnson and Noguera (2012) and Timmer, Los, Stehrer, and De Vries (2013). The expression of this is as follows:

$$\hat{\mathbf{V}}\hat{\mathbf{Y}} + \hat{\mathbf{V}}\mathbf{A}\hat{\mathbf{Y}} + \hat{\mathbf{V}}\mathrm{AA}\hat{\mathbf{Y}} + \ldots = \hat{\mathbf{V}}(\mathbf{I} + \mathbf{A} + \mathrm{AA} + \ldots)\hat{\mathbf{Y}} = \hat{\mathbf{V}}(\mathbf{I} - \mathbf{A})^{-1}\hat{\mathbf{Y}} = \hat{\mathbf{V}}\mathbf{B}\hat{\mathbf{Y}} \tag{4}$$

In this equation, the term $\mathbf{V} = \{v_i^k\} = \left\{v_i^k / x_i^k\right\}$ refers to the VA vector of sector i of country k, divided by the total product x of the same sector; and $\hat{\mathbf{V}}$ is a diagonal matrix of $\mathbf{V}$. The term $\mathbf{B}$ is the global version of Leontief's inverse matrix and $\hat{\mathbf{Y}}$ is a diagonal matrix of global final demand. Each element of the matrix $\hat{\mathbf{V}}\mathbf{B}\hat{\mathbf{Y}}$ represents the VA of a sector in its home country that is directly or indirectly engaged in the production of final goods and services in a given country/sector. The sum of the row and column elements of the matrix is the sector's total VA (direct and indirect) in the country embodied in the final products produced by sector i in country k.

Then, applying Wang *et al.* (2013) VA decomposition on the intermediate and final on $\hat{\mathbf{V}}\mathbf{B}\hat{\mathbf{Y}}$, according to the origin of demand: $\hat{\mathbf{Y}}^{D}$, for final domestic demand; final foreign demand, $\hat{\mathbf{Y}}^{F}$; and $\mathbf{Y}$, global final demand, we obtain the VA decomposition equation:

$$\begin{aligned} \hat{\mathbf{V}}\mathbf{B}\hat{\mathbf{Y}} &= \hat{\mathbf{V}}\mathbf{L}\hat{\mathbf{Y}}^{D} + \hat{\mathbf{V}}\mathbf{L}\hat{\mathbf{Y}}^{F} + \hat{\mathbf{V}}\mathbf{L}\mathbf{A}^{F}\mathbf{B}\hat{\mathbf{Y}}\hat{\mathbf{V}}\mathbf{B}\hat{\mathbf{Y}} \\ &= \hat{\mathbf{V}}\mathbf{L}\hat{\mathbf{Y}}^{D} + \hat{\mathbf{V}}\mathbf{L}\hat{\mathbf{Y}}^{F} + \hat{\mathbf{V}}\mathbf{L}\mathbf{A}^{F}\left(\mathbf{L}\hat{\mathbf{Y}}^{D} + \mathbf{L}\hat{\mathbf{Y}}^{F} + \mathbf{L}\mathbf{A}^{F}\mathrm{X}\right) \\ &= \hat{\mathbf{V}}\mathbf{L}\hat{\mathbf{Y}}^{D} + \hat{\mathbf{V}}\mathbf{L}\hat{\mathbf{Y}}^{F} + \hat{\mathbf{V}}\mathbf{L}\mathbf{A}^{F}\mathbf{L}\hat{\mathbf{Y}}^{D} + \hat{\mathbf{V}}\mathbf{L}\mathbf{A}^{F}\left(\mathbf{B}\hat{\mathbf{Y}} - \mathbf{L}\hat{\mathbf{Y}}^{D}\right) \end{aligned} \tag{5}$$

The trade flow's value added is represented by four N·N square matrices. The first term, $\hat{\mathbf{V}}\mathbf{L}\hat{\mathbf{Y}}^{D}$, indicates the value added embodied exclusively by the domestic matrix for local consumption, that is, a consumption not crossing borders. The second term, $\hat{\mathbf{V}}\mathbf{L}\hat{\mathbf{Y}}^{F}$, indicates the domestic value added embodied in exports of final goods. The third, $\hat{\mathbf{V}}\mathbf{L}\mathbf{A}^{F}\mathbf{L}\hat{\mathbf{Y}}^{D}$, denotes the value added embodied in intermediate inputs in global value chain flows, which cross borders only once. Finally, the term $\hat{\mathbf{V}}\mathbf{L}\mathbf{A}^{\mathrm{F}}(\mathbf{B}\hat{\mathbf{Y}} - \mathbf{L}\hat{\mathbf{Y}}^{\mathrm{D}})$ refers to the value added embodied in intermediate goods through chain participation, crossing the border multiple times (Chen, Akimoto, Sun, Kagatsume, & Wang, 2021). The decomposition shows the value added embodied in intermediate and final goods flows according to global and domestic demand effects.

From this decomposition equation, as in Chen *et al.* (2021), one can adapt equation (5) to obtain the effects of linkages regarding GHG emissions. Such an adaptation aims to observe how the participation of GVC and variations in global and domestic demand can influence the countries' emissions pattern, considering their location of production and consumption. For this, the emissions coefficient is considered:

$$\mathrm{C} = \left\{c_i^s\right\} = \left\{\frac{\boldsymbol{c}_i^s}{\boldsymbol{x}_i^s}\right\} \tag{6}$$

In matrix-related terms, one finds the emissions coefficient **C**, of sector i and country s, in ratio to the total production x, of sector i and country s. Thus, if the diagonal matrix $\widehat{\mathbf{V}}$ is replaced by the diagonal matrix of the emissions coefficient $\widehat{\mathbf{C}}$, one can apply the decomposition method for GHG emissions to obtain:

$$\widehat{\mathbf{C}}\mathbf{B}\widehat{\mathbf{Y}} = \widehat{\mathbf{C}}\mathbf{L}\widehat{\mathbf{Y}^{\mathrm{D}}} + \widehat{\mathbf{C}}\mathbf{L}\widehat{\mathbf{Y}^{\mathrm{F}}} + \widehat{\mathbf{C}}\mathbf{L}\mathbf{A}^{\mathrm{F}}\mathbf{B}\widehat{\mathbf{Y}} + \widehat{\mathbf{C}}\mathbf{L}\mathbf{A}^{\mathrm{F}}\left(\mathbf{B}\widehat{\mathbf{Y}} - \mathbf{L}\widehat{\mathbf{Y}^{\mathrm{D}}}\right) \tag{7}$$

Analogous to equation (5) , one can interpret the four terms of the $\widehat{\mathbf{C}}\mathbf{B}\widehat{\mathbf{Y}}$ decomposition respectively by: (1) emissions embodied in domestically produced and consumed goods; (2) emissions embodied in exported final goods; (3) emissions embodied in the production of intermediate goods crossing borders only once; and (4) emissions embodied in intermediate goods crossing multiple times.

Then, as in Chen *et al.* (2021), the selection and addition of components obtained in the decomposition matrices allow us to analyze the results using three accounting metrics (see Appendix A):

1. Production-based accounting (PBA): shows the emissions distributed through the sale of goods and services – that is, the forward linkages – considering the emissions path of sector i to sector j, from country s to country t. They are classified as production for domestic consumption (PBA_FD), for intermediate goods that are exported but returned to the domestic market (PBA_Fdreturn), for exports of final goods (PBA_EX), and for exports of intermediate goods to GVC (PBA_GVC).

2. Consumption-based accounting (CBA): accounts for emissions embodied in the consumption of goods and services, which refers to the backward linkages. CBA can be divided into emissions embodied in intersectoral purchases of domestic production for domestic consumption (EED_FD), the purchase of imported intermediate goods (EEIM_GVC), and imported final goods (EEM).

3. GVC Accounting: accounts for domestic emissions incorporated into the production of partner countries, i.e., in the production of all exported goods. The metric also quantifies the emissions associated with backward linkages. Still, unlike CBA, it excludes emissions from imported final goods and considers the emissions embodied in exported goods (EED_EX) and goods re-exported and reimported (EEP_GVC).

3.1 Database

The analysis used United Nations Conference on Trade and Development (UNCTAD) Eora-26 [2], a MRIO (Lenzen *et al.*, 2012, 2013). The Eora-26 has been built to study the relationship between production fragmentation and economic development (Casella, Bolwijn, Moran, & Kanemoto, 2019) and concerns climate change issues, identifying the need for accounting pollutant emissions in international trade statistics.

The database has a quadrant called "Satellite Accounts", which considers a set of nonmonetary inputs in each sector's production relations, characterizing it as an MRIO with social and environmental extension. The logic behind this procedure is the following: if a sector buys product A, B or C from others, the base accounts for this transaction having had an energy consumption W and X, exerted a social impact Y and generated pollution Z (Lenzen *et al.*, 2013).

The data composition in the satellite accounts allows the estimation of GHG emissions associated with intersectoral trade flows between countries, registering data for the primary GHG sources applying – carbon dioxide (CO2), methane gas (CH4) and nitrous oxide (N2O). That is precisely why this database has been selected for this analysis. However, emissions data does not capture GHG emissions associated with land use and deforestation, which are considered relevant emissions sources. Thus, this methodological limitation must be acknowledged as our study could be underestimating the level of emissions incorporated into productive activities.

Therefore, the study estimates GHG emissions (Kt CO2 per dollar of production) embodied in the trade relations of Brazil and China with the following economic regions as trade partners:

1. Southern common market (MERCOSUR): Argentina, Bolivia, Chile, Colombia, Ecuador, Paraguay, Peru, Venezuela and Uruguay;
2. USMCA: Canada, Mexico and the United States;
3. EU: Germany, Austria, Belgium, Bulgaria, Croatia, Czech Republic, Denmark, Estonia, Finland, France, Greece, Netherlands, Hungary, Ireland, Italy, Lithuania, Latvia, Luxembourg, Malta, Poland, Portugal, Romania, United Kingdom, Slovakia, Slovenia, Spain and Sweden;
4. EA: China, South Korea, Japan, Mongolia and Taiwan;
5. Bilateral relationship: Brazil and China;
6. ROW: all other countries.

3.2 Sectoral classification

The Eora-26 MRIO offers a high-resolution data classification of 26 sectors for 189 countries and a region aggregated as "rest of the world" (ROW), covering from 1990 to 2018 (Casella *et al.*, 2019). In this analysis, we investigate the results from 2000–2016, which covers the pre and post-2008 financial crisis period. One must highlight that data refer to transactions in intermediate and final goods in current values for each year. Therefore, as we covered the entire period (2000–2016) for a few selected years (2000, 2006, 2010, 2016), the results of the metrics have been presented as a moving average to be consistent with the trend analysis over the entire period.

Also, for practical purposes, we applied the sectoral typology developed by the Industry and Competitiveness Research Group of the Institute of Economics at the Federal University of Rio de Janeiro (GIC/IE-UFRJ), Brazil, to the traditional 26-industries classification of Eora-26. The GIC/IE-UFRJ typology group sectors according to competition patterns, referring to their competitive performance considering supply and demand side factors (Torezani, 2021; Kupfer, 1998). Therefore, in this study, we have arranged the 26 sectors from the Eora-26 database into seven groups (Appendix B): (1) Processed and agricultural commodities (PAC); (2) Industrial commodities (IC); (3) Traditional industry (TI); (4) Innovative industry (II); (5) Energy, electricity and water; (6) Transport and (7) Others.

4. Analysis results

4.1 Origin and destination of greenhouse gas emissions from the global value chain perspective

As presented in the previous section, the terms obtained by the matrix $\widehat{\mathbf{C}}\mathbf{B}\widehat{\mathbf{Y}}$ demonstrate the emissions embodied in trade flows of countries with partner regions, according to variations in global demand. The sum of the lines accounts for the total distribution of emissions through exports, thus observing the role of countries as sellers (forward) of goods and services to foreign trade. In turn, the sum of the columns accounts for the total emissions embodied through the respective partner's consumption of goods and services, which refers to the countries' purchases (backward) from international trade. Therefore, the first results show the origin and destination of embodied emissions for production and consumption.

To analyze the case of Brazil, one should first observe, in Table 1, the Brazilian exports and imports share with the economic regions in gross transactions (US$) in the period.

Table 1 shows that between 2000 and 2006, there was a fall in Mercosur's exports share of 4.1% and in imports share 4.5%, respectively. However, concerning the emissions, Figure 1 below shows that emissions increased in backward and forward transactions with Mercosur in this period. The Brazilian intraregional relations are represented by trade in a more diversified group of goods and services, with a larger share of manufactured and natural resource-based products with more capital intensity and technological content (Bértola & Ocampo, 2012).

In addition, a common attribute of transactions between Mercosur countries is they are exclusively between developing countries. Jimenez and Mercado (2014), when analyzing the interaction between income level and energy intensity in the last 40 years, concluded that the countries with the highest level of income (in general, OECD members) were responsible for a 10% reduction in the world energy intensity, while the countries with the lowest income levels were responsible for an increase of 8%. Thus, as the level of energy intensity for production influences GHG emissions because of dependence on nonrenewable energy sources, the transactions between Brazil and Mercosur and other emerging economies were marked by higher emissions.

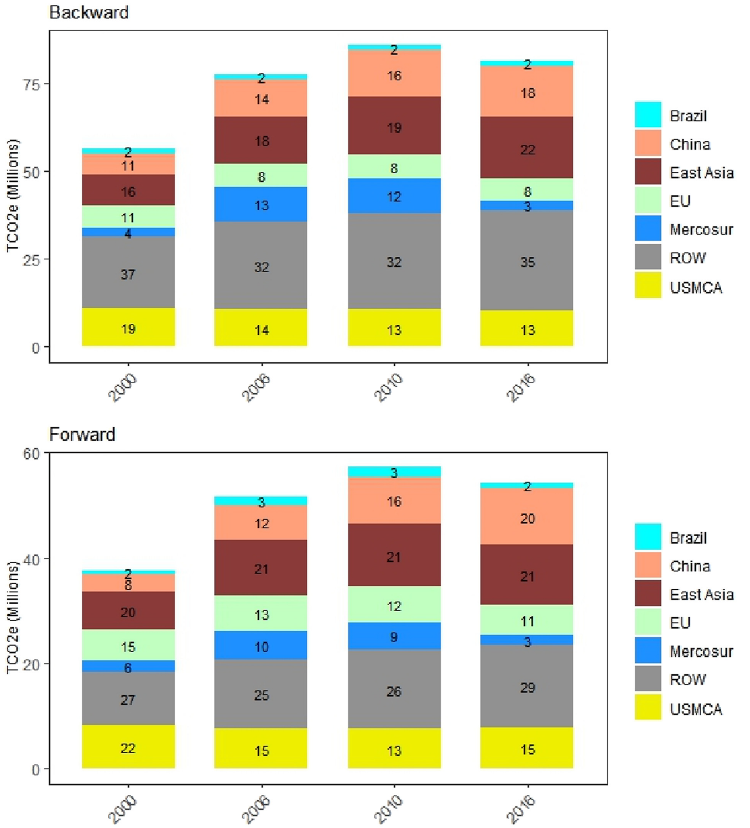
Figure 1 shows the emissions embodied in the Brazilian consumption of goods and services (backward). For the year 2000, the most representative origins of emissions by consumption are the ROW and USMCA countries. At that historical moment, the construction of a Brazilian multilateral trade system with economic groups was in progress (Abreu, 1998), which was observed through the increase in the participation of the other regions in the following years.

From 2000 to 2006, the United States and Europe responded to about 49.4% of Brazilian imports as the country's main trading partners until then (De Oliveira, 2016). However, despite the volume of transactions, the estimates for emissions embodied via backward linkages are less significant when compared, for example, to Mercosur and ROW. That reflects, in part, the tendency of concentration of polluting and emission-intensive processes

Table 1.
Brazilian gross exports and imports by region (in %)

	2000		2006		2008		2010		2016	
	Exp	Imp	Exp	Imp	Exp	Imp	Exp	Imp	Exp	Imp
MERCOSUR	14.1	15.6	10.2	11.1	11.1	9.5	11.3	9.9	10.2	9.6
North America	30.7	25.9	26.8	18.4	27.8	18.3	25.0	18.3	19.8	21.0
Europe	28.1	28.7	22.7	25.2	16.7	25.6	12.6	25.4	16.3	26.2
East Asia	8.2	11.3	10.9	18.0	13.9	20.5	21.6	24.1	24.5	24.4
China	2.0	2.1	6.1	8.6	8.4	11.5	15.3	14.0	19.6	16.8
Total (US$ Billion)	*44.5*	*46.4*	*97.1*	*67.3*	*136.2*	*129.0*	*141.4*	*142.4*	*127.4*	*113.0*

Source(s): Own elaboration with data from Secex



Source(s): Figure by authors

Figure 1. Total Brazilian emissions embodied by backward and forward linkages

in transactions between developing and least-developing countries concerning the emissions reduction in developed countries' transactions.

From 2006 to 2010, the results show a change in the Brazilian foreign trade partners, which was a conditioning factor in the 2008 financial crisis. The fall in consumption of developed countries during the global recession period caused the global productive structure to reconfigure, making space for the growth and strengthening of manufacturing activities in East Asian countries (O'neill, 2011). In 2008, Asia surpassed the other regions and accounted for 27% of Brazilian imports and exports, representing 26.3% of total exports and becoming Brazil's greater trade partner (de Oliveira, 2016). China's role in this changing scenario is central, as shown in Table 1: the share of Chinese goods over Brazilian exports increased from 2% to 19.6% from 2000 to 2016, while the Brazilian demand for Chinese industrially manufactured goods also increased. However, this increase resulted in higher consumption-based emissions, accounting for approximately 16.5% of Brazil's total emissions in 2010. In 2016, the data showed a new pattern of Brazil's international trade in emissions, with more significant shares linked to Asian countries and a decrease in Mercosur, EU and USMCA shares. The Asian industrial development model, led by the expansion of Chinese manufacturing, is characterized by fast industrial upgrading (Lalane, 2022). Still, it has recorded the highest emissions level in Asian exports (Li, Wu, & Li, 2022).

Concerning Brazil's forward emissions, as shown in Figure 1, the emissions level in Brazilian exports has followed the same pattern of backward relations. On average, Brazilian emissions were mainly destined to, respectively, ROW, EA, China, USMCA, UE and Mercosur. The Brazilian emissions embodied in exported goods and services indicate that the transaction volume is relevant for emissions, but the sectoral composition of exports is also relevant. According to data from WITS (2023), Brazil's exports to East Asian countries are concentrated in primary goods, mainly agriculture and mining, while for other regions; the exports' composition is more balanced with intermediate and consumer goods. Zhang, Zhu, & Hewings (2017), when assessing the composition of Brazil's emissions in trade flows, note that the intermediate-good sectors are more emission-intensive than that of primary goods. However, it is noteworthy that these statistics fail to capture emissions from deforestation and land use, which are presently the most significant sources of Brazil's emissions (SEEG, 2021) due to the recent expansion of primary goods sectors.

To analyze the emissions embodied in China's trade flows, Table 2 shows the international trade data regarding gross trade (US$).

Table 2 shows that most of China's import trade shares were with EA, Europe and Central Asia and North America, respectively. However, Figure 2 shows that ROW and Mercosur contributed more significantly to backward emissions between 2000 and 2006. Cui, Peng, and Zhu (2015), in a study of energy embodied in Chinese trade flows from 2000 to 2007, note that most imports of energy-intensive industries – which are associated with higher levels of emissions – were from the Middle East and Africa partners, that here are grouped as ROW. In addition, during that period, China demand for commodities and raw materials from South American countries increased (Bértola & Ocampo, 2012). Figure 2 shows that Mercorsur accounted for 26% of all emissions embodied in China's imports. Still, that share fell drastically to 3% between 2010 and 2016, while China's emissions embodied in its domestic consumption and the imports from EA increased to 18% and 22% in the same period, respectively. Those numbers show that for China, interregional trade with Asian partners is highly emission-intensive and has a growing importance on China's emission pattern.

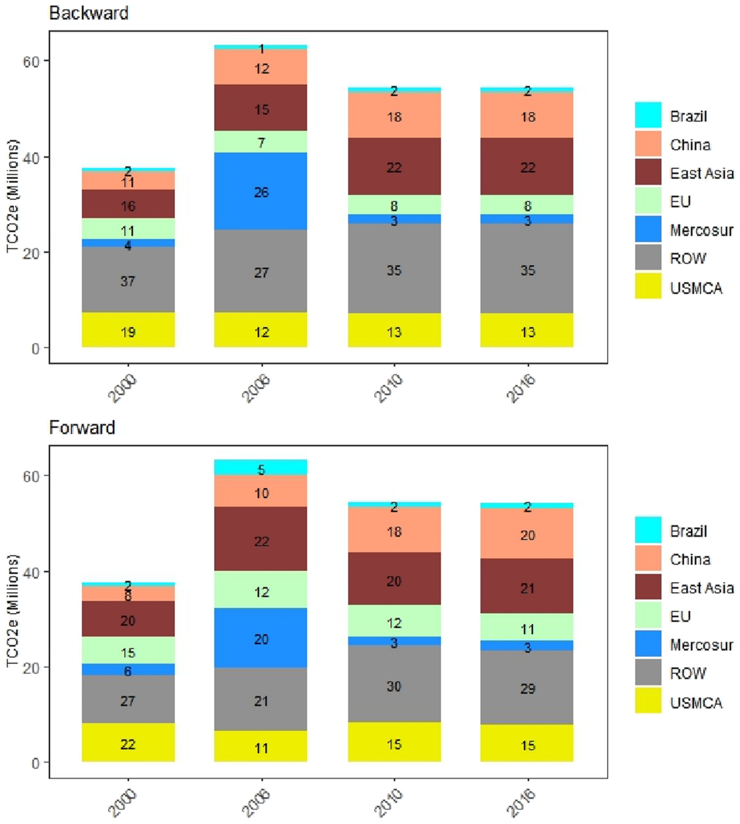
In Figure 2, looking at forward emissions, ROW, EA, North America and Europe have a more significant share as a destination of Chinese emissions. The regional integration of East Asian countries is one of the pillars of Chinese recent economic growth. According to the UNIDO (2018) report, Asia has the highest degree of integration in production chains, being the locus of the global manufacturing industry, in which the largest economies in the region have advanced positions in the production chains and increasing the domestic aggregate value on exports.

However, as Cui *et al.* (2015) discussed, emissions embodied in Chinese exports are also directly associated with energy-intensive sectors but are now generated and distributed by

Table 2.
Chinese gross exports and imports by region (in %)

	2000		2006		2008		2010		2016	
	Exp	Imp	Exp	Imp	Exp	Imp	Exp	Imp	Exp	Imp
East Asia	48.2	48.7	39.5	50.8	36.8	46.6	37.1	47.2	39.1	46.1
Europe and Central Asia	18.7	18.2	23.8	15.1	26.3	15.7	24.3	16.8	20.2	19.1
North America	22.2	11.6	22.7	8.5	19.2	8.3	19.4	8.4	19.7	9.7
Latin America and the Caribbean	2.9	2.4	3.7	4.3	5.0	6.3	5.8	6.5	5.4	6.5
Brazil	0.5	0.7	0.8	1.6	1.3	2.6	1.6	2.7	1.1	2.9
Total (Billion US$)	*230.3*	*183.8*	*875.3*	*635.8*	*1268.0*	*901.3*	*1390.3*	*1139.7*	*1792.6*	*1336.8*

Source(s): Own elaboration with WITS data



Source(s): Figure by authors

Figure 2. Total Chinese emissions embodied by backward and forward linkages

the Chinese production structure. The intensity of Chinese emissions is closely related to the energy matrix composition. Bloch, Rafiq, and Salim (2015) show that three main energy sources have driven the Chinese economic growth process: coal, oil and renewable energy, but with a more significant participation of nonrenewable energy sources on the demand and supply side.

Summing up, reducing the distribution of Chinese emissions through forward linkages depends upon reducing the nonrenewable energy intensity of the manufacturing sector, as well as on migration to renewable energy sources. Moreover, this issue also draws attention to how developed countries are the ones to incorporate the most emissions by consumption, highlighting the role of international trade in transferring the negative environmental externalities to developing countries' borders (Arce *et al.*, 2012).

4.2 Emissions decomposition

The following graphs present the results for the set of emissions indicators obtained from the emissions decomposition equation per year and aggregated by the following sectors: processed agricultural commodities (PAC), industrial commodities (IC), traditional industry (TI), innovative industry (II), energy (E), transport (T) and others.

Concerning the territorial emissions (PBA) from 2000 to 2006, Figure 3 shows that Brazil's emissions significantly increased for intermediary goods to domestic (PBA_FDreturn) and foreign consumption (PBA_GVC). That period was of expansion of transnational companies in the territory, either through direct investment or by fragmentation of production (Schteingart, Santarcángelo, & Porta, 2017). While these new opportunities allowed Brazil to increase its export share of industrial goods, they required increased imports of intermediate inputs and benefits from creating "free trade zones" (Bértola & Ocampo, 2012).

From 2010 and 2016, emissions associated with the trade of intermediate goods decreased, especially concerning the variable PBA_GVC. This fall may be related to the recessionary context imposed by the 2008 financial crisis that caused a fall in economic activity and a drop in global demand, especially from developed countries, thus significantly reducing exports (Gereffi & Luo, 2015). For the sectorial composition of PBA emissions in the period, the emissions generally presented higher percentages for other and traditional industry. In the latter, which refers mainly to the processed food and textile sector, Rustemoglu and Andrés (2016) show that an increase in the energy intensity of nonrenewable sources between 1992 and 2011 followed the growth of Brazilian industry production.

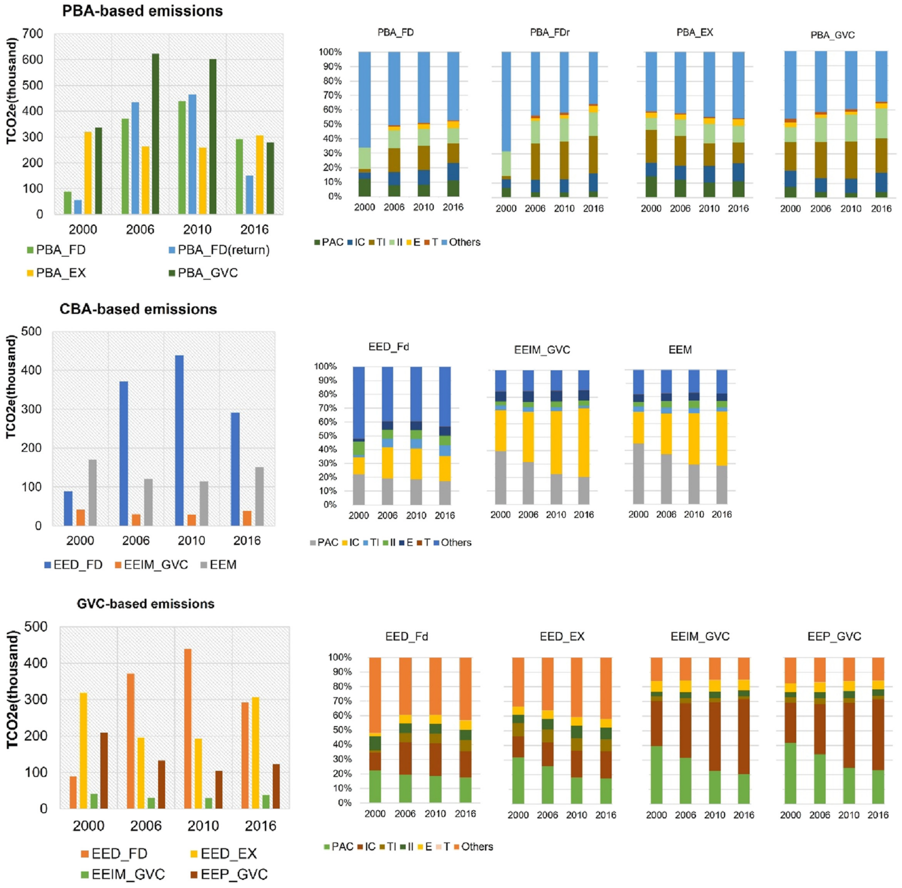


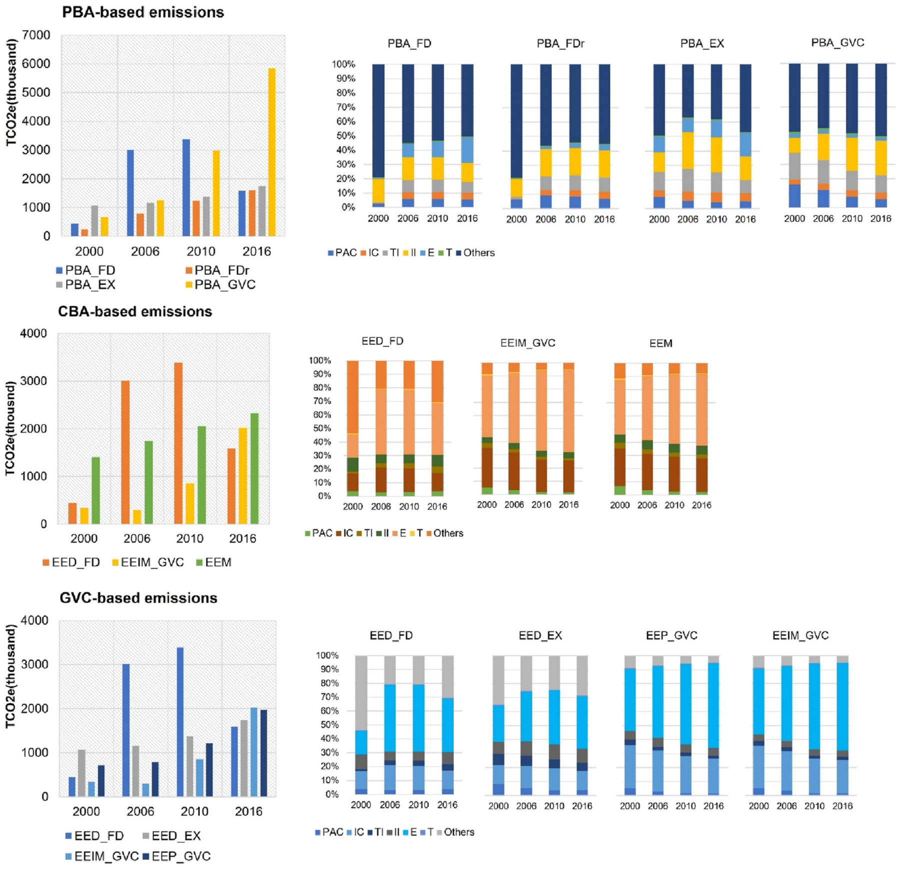
Figure 3.
PBA, CBA e GVC indicators: Brazil

Source(s): Figure by authors

Next, we analyze the Brazilian consumption- and GVC-based emissions. First, we consider the higher emissions embodied by domestic purchases to the domestic market (EED_Fd) from 2000 to 2016, a characteristic of large economies with a complex domestic market. In terms of composition, domestic and foreign demand show different patterns. For CBA-based emissions in domestic metrics, the others sector – which appropriately included the service sectors – was more representative throughout the period. In contrast, the commodities sectors, PAC and IC, presented the highest percentages for foreign demand metrics. For GVC-based emissions, Brazil showed an upward trend in GVC-emissions metrics for industrial commodities.

Such evidence speaks faithfully of the Brazilian productive structure profile, where higher emissions are found for the mainly exporting sectors – including agriculture, mining, fuels and services – (Callegari, Melo, & Carvalho, 2018). However, as discussed by Montoya, Allegretti, Bertussi, and Talamini (2021), the emissions of Brazilian agricultural production are lower than the consumption because Brazilian production was more intensive in renewable energy sources. Then, for this sector – and not counting the emissions for land use – Brazil is in a position where it incorporates more emissions through consumption than production,

Concerning China's case, Figure 4 shows the results of the considered indicators by sector and year. The PBA indicators demonstrate a progressive path in emissions from 2000 to 2010,



Source(s): Figure by authors

Figure 4.
PBA, CBA e GVC indicators: China

with a greater increase in emissions related to GVC. Following the 2008 financial crisis, Li *et al.* (2022) pointed out that between 2009 and 2011, China recovered from the increasing emissions trajectory, which was more pronounced for the intermediate transactions driven by the transition to complex GVC, as observed in 2016. So, the evidence suggests that even with China's transition from traditional trade flows to GVC activities, emissions embodied in production are significant and on an increasing trend.

The composition of China's production-based emissions showed the highest percentages of emissions embodied in others and Industrial sets, which is also consistent with that country's manufacturing profile. Therefore, it is crucial to consider that Chinese territorial emissions are associated with producing final and intermediate manufactured goods to supply domestic and foreign demand. Meng, Peters, Wang, and Li (2018) show that the increase in production-based emissions in China after entering the WTO is non-negligible, highlighting some problematic aspects of assigning responsibility for territorial emissions induced by multiple trading partners (Zhang Zhang, & Zhu, 2020).

Concerning the CBA and GVC indicators, the emissions embodied in final import goods consumed on the domestic market (EEM) and in intermediate goods (EEIM_GVC) showed a progressive increase from 2000 to 2016, on average, while imports for the domestic market (EED_FD) fell. In this sense, foreign transactions recovered, with an increase in GVC, pointing to changes in the production capacity and the structure of Chinese imports, which is probably associated with the industrial and trade policies introduced over the period (Yong, 2020). Finally, the energy, other and industrial commodities sectors showed the highest percentages in Chinese consumption-based emissions for domestic and foreign purchases.

Furthermore, the literature has observed China's shift towards the intermediate goods trade model, which has led to integration into complex production networks. From an economic point of view, this shift demonstrates the positive effects of China's industrial upgrading, which has advanced to the productive stages of higher added value (Marcato, Dweck, & Montanha, 2022). On the other hand, from an environmental perspective, this movement increases CO2 emissions. According to Li *et al.* (2022), this contraposition of economic and environmental results has generated pressures that distance the country from its low-carbon sustainable development goals. Therefore, the best strategy to reverse this situation is to reconcile a reduction in the energy intensity of nonrenewable sources with a decrease in the emissions embodied in exports and to advance to other stages of the production chains.

5. Policy suggestions

The results point to a number of areas where mitigation and adaptation policies can be applied to reduce the impacts of climate change. First, it is noteworthy that climate change is a shared global problem that requires international cooperation to design and implement integrated policies. For this reason, the coordination of the world trade organization with international and regional organizations is essential to support the nationally determined contributions (UN - United Nations, 2015) joint work to promote low-carbon intensity in international trade. As a starting point, emphasis could be placed on the use of financial instruments to support investment in infrastructure and environmental resilience in the countries' most vulnerable to the impacts of climate change, and on the implementation of an effective international system of compensation for the negative environmental externalities of trade, guided by the principle of shared responsibility (Zhu, Shi, Wu, Wu, & Xiong, 2018), as a way to ensure an environmentally and socially just transition at the global level.

In the specific case of Brazil, firstly, since the higher level of GHG emissions is associated with deforestation and land use changes, the continuity of a series of environmental policies to monitor and protect forest areas in the territory is mandatory, such as the action plan for the prevention and control of illegal deforestation in the Amazon (PPCDAm) (Coelho-Junior *et al.*, 2022). Second, despite the availability of renewable energy, industrial and service sector activities are significant sources of GHG emissions. In face of that, increasing energy efficiency through the use of low-carbon intensive technologies is paramount, which can be achieved by stimulating innovation, disseminating best practices in the industrial sector and receiving investments in clean energy. Finally, for Brazil's decarbonization and sustainable development, based on the green new deal brazil proposal (Alvarenga Junior, Costa, & Young, 2022), the need for priority policies in five areas is highlighted: infrastructure, cities and urban organization, land use and forests, transition with social equity and institutional capacity. In addition, the big push for sustainability proposal strengthens the dimension of "green efficiency" in the orientation of the structural transformation process (Gramkow, 2019) and proposes the coordination of investments – public, private and international– for the set of climate and socioenvironmental funds in Brazil (ECLAC, 2023).

The main challenge for China is to decouple economic growth from the growth of GHG emissions. The intensity of China's emissions is closely linked to the composition of its energy matrix, which has been heavily reliant on nonrenewable sources such as coal and fossil fuels. At the 75th United Nations General Assembly in 2020, the country announced that it would reach peak carbon emissions in 2030 and neutrality in 2060, indicating that it has tried diversifying its energy matrix (Zandonai, 2015; Lo, 2014). Indeed, China has become a major investor in renewable energy sources and achieved important milestones in photovoltaics (Yao & Cai, 2019), but this is far from sustaining the demands of its production structure.

In this sense, it is essential that China's set of industrial policies emphasizes the replacement of carbon-intensive technologies with low-carbon ones, especially in the electricity, metals and nonmetallic minerals industries used by intermediate sectors (Li *et al.*, 2022). This is because, as China has moved from simple to complex value chains, the high-emission intensity of these sectors implies a high propagation of emissions along production chains and partners. Therefore, as China's trade growth depends on its participation in GVC, the design of carbon emission reduction targets should logically aim to reduce emissions based on production and consumption, with a focus on improving energy efficiency in emission intensive sectors.

6. Conclusion

The main purpose of this paper was to discuss the relationship between the international trade in GVC of Brazil and China and their respective patterns of GHG emissions, demonstrating how participation in those chains can affect the emissions embodied into production and consumption. This type of analysis is vital because it allows us to have a broader view of the multiple factors influencing the production structure of countries and their respective roles in reducing environmental impacts propagated through international trade relations.

In the context of climate change, we discuss how GVC can drive increased emissions in intermediate trade flows and how these effects are not evenly distributed across countries, highlighting the need for mitigation policies to protect the most vulnerable regions. Additionally, the historical perspective at the events unveils the importance of discussing climate responsibility due to the distortions of an economic system that tends to concentrate industrial pollution in less favored regions, in economic and institutional terms, forming the so-called "pollution havens."

Based on the Eora-26 data, we analyzed the results obtained by the structural decomposition of GHG emissions in commercial flows of final and intermediate goods from Brazil and China, with the world's leading economic regions, from 2000 to 2016. First, for Brazil, the data showed that the trade flows (backward and forward linkages) with Mercosur and ROW until 2006, generated higher GHG emissions than with other economic regions. From 2006 to 2010, Brazil's trade pattern changed, with EA's share in trade volume and GHG emissions increasing. The results corroborated the pollution heavens hypothesis, according to which transactions between developing countries were more pollution-intensive than with the developed countries.

Second, we found that, for Brazil, emissions were more intensive in the production of intermediate goods for GVC before the financial crisis. However, until 2016, the emissions decreased for all indicators. The composition of production-based emissions represented others and traditional industry activities more. At the same time, Brazil's CBA and GVC-based revealed higher emissions embodied by domestic purchases to the domestic market (EED_Fd) from 2000 to 2016, a characteristic of large economies. In the composition, for domestic, the others – which included the service sectors appropriately – were more significant for all periods. In contrast, the commodities sectors, PAC and IC, presented the highest percentages for foreign demand.

In the case of China, we observed that concerning backward linkages, China's embodied emissions from Mercosur and ROW are higher. For forward linkages, the regional transactions and ROW countries were the main destinations of Chinese emissions. In production-based emissions, they were associated with greater participation from others and industrial set activities. Concerning consumption and GVC emissions, emissions incorporated by purchasing final goods reduced, as a consequence of a lower dependence on imports, accompanied by greater participation of incorporation in intermediate flows. Also, the energy, others and industrial commodities sectors showed the highest percentages in Chinese consumption-based emissions for domestic and foreign purchases.

Finally, it is worth noting that our analysis provides a panoramic view of how the composition of emissions evolved for both countries, discriminating the total emissions according to the origin of demand and variations. This type of representation helps understanding the profile of both countries' international insertion in the chains and their respective emission patterns, adding to the discussion on how responsibility for the climate crisis should be accounted for. This analysis provides evidence for future research on more detailed analysis of transactions by country or bilateral trade, which can be enhanced by using more granular input-output data, including, for example, the Exiobase database (Stadler *et al.*, 2018), to investigate other variables and build scenarios for policymaking in the climate change context.

Notes

1. GHGs are classified as a combination of gases in the atmosphere that cause global temperature rise (or enhance the effects of carbon dioxide) and are therefore quantified by the carbon equivalent (CO2e) metric. The main gases mapped are carbon dioxide (CO2), nitrous oxide (N2O), methane gas (CH4) and others in the hydrocarbon group (Lashof, Ahuja, 1990).
2. UNCTAD-Eora26 provides data for years 1990–2016 for free license for academic users.

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Appendix

The supplementary material for this article can be found online.

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