Regional Disparities in Carbon Emissions Embodied in China's Exports: A Bipartite Interregional Input-Output Decomposition

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Abstract: *Trade induces spatial redistribution of carbon emissions. Previous attempts to investigate the impact of trade patterns on the spatial distribution of emissions across regions in China failed to consider the special export structure of each region, leading to inaccurate results. To reassess the emissions embodiment in interregional and international exports (EEX) and quantify the underlying determinants of the EEX growth in each region, we applied the structural decomposition analysis (SDA) within a new environmental bipartite inter-regional input-output (BIRIO) framework that distinguishes processing from ordinary production. Results show that EEX growth rates are significant and vary across regions. On the demand side, the change in total ordinary exports and non-local total final demand are the major contributors to the EEX growth before and after the financial crisis, respectively. On the production side, the production technology effect reversed from positive before 2007 to negative after 2007, showing that the production process changed from emission-intensive before 2007 to decreasing emissions after that year. Overall, the processing export effect is more dominant in coastal regions, which even surpasses the ordinary export effect in South Coast from 2007 to 2012. In contrast, non-local effects dominated the EEX change in inland regions, implying their growing participation in both interregional and international production fragmentation. The results from this study shed light on who is responsible for the increased emissions and support some relevant policy recommendations.*

Keywords: *Structural decomposition analysis; Regional emissions embodied in exports; Bipartite inter-regional input-output table; Processing production*

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1. Introduction

Embodied emissions in trade (EET) is central to debates on equitable allocation of carbon responsibilities between producers and consumers (Davis & Caldeira, 2010; Peters et al., 2011; Dietzenbacher et al., 2020). The CO_2 emissions in China increased rapidly after its entrance into the World Trade Organization (WTO); since 2007, China's carbon emissions have ranked first globally. To support global decarbonization, China has set a target to reduce CO_2 emissions relative to economic output by 13.5% by 2025 compared to 2020 level. China usually breaks down its carbon reduction goal into quotas allocated to each region (Yi et al., 2011). Therefore, it is important to determine regional carbon responsibility. Meng et al. (2013) noted that the CO_2 emissions in the Central Region[1] always contributed significantly to national emissions (23.4% in 2002 and 22.3% in 2007), while Northern Municipalities were always responsible for the lowest share (4% in 2002 and 2.9% in 2007).

However, from the perspective of consumption, one region should not be responsible for all its emissions considering the prevalence of trade. With the increasing geographical fragmentation of production, it is quite common that a large part of the emissions generated in one region is to satisfy the demands of other regions inside or outside China. For instance, Meng et al. (2013) note that most carbon-intensive intermediate inputs required for exports production in coastal regions are sourced from the Central Region. Under the consumption responsibility principle, the emissions embodied in these carbon-intensive intermediates should not be considered as Central Region's responsibility, but should instead be attributable to the place where these intermediates are finally consumed. Since trade creates a mechanism through which the emissions shift from consumption regions to production regions, analyzing the emission embodiment in China's regional trade is crucial to assign emission reduction targets to different regions (Weber et al., 2008; Duan & Yan, 2021) and to examine the regional emissions reduction performances. This challenge of allocating emissions responsibility along complex supply chains is not unique to China but is a central issue in global environmental governance, as evidenced by extensive international research on EET (Wiedmann, 2009; Kanemoto et al., 2014).

Carbon emissions embodiment in China's regional trade have received much attention in academia (Pei et al., 2012; Zhang & Tang, 2015; Duan & Yan, 2021). However, these studies ignore that the proportion of processing exports is high in Chinese international trade. Since the processing production assembles imported components for exports, processing production and ordinary production have distinct input coefficient matrix and the CO_2 intensities are much lower for the former than that for the latter.[2] It has been proven that without distinguishing process

[1] The Central Region covers Anhui, Hubei, Hunan, Henan, Jiangxi, and Shanxi provinces.

[2] In China's customs and economic statistics, processing production and ordinary production are formally distinguished based on the trade regime and tax treatment, rather than the precise proportion of imported inputs. Processing production refers to the activity of assembling or manufacturing goods using imported components that are exempt from tariffs and value-added tax, with the final products then being re-exported. While the intermediate input for processing production are dominated by imported components, they can also include domestically sourced materials. Conversely, ordinary production (non-processing production) utilizes intermediate inputs primarily sourced from the domestic market or imported through general trade (subject to normal tariffs), and its output can be sold either domestically or exported. This fundamental difference in operational mode and tax status results in distinct input structures and emission intensities for the two types of production, with processing production typically being less emission intensive.

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exports, the emission embodiment in exports will be overestimated (Dietzenbacher et al., 2012; Li et al., 2024). To our knowledge, the related researches are confined at the national level, and no literature analyzes the emissions embodiment in outflows and exports by distinguishing the processing production at regional level. Results demonstrate that shares of processing exports in total exports vary significantly across regions. For example, according to calculations based on our compiled BIRIO table, this share was only 7% in the Northwest, while it reached more than 50% in the South Coast (see Section 4 for detailed results). This paper aims to reveal the true emissions embodiment in each domestic region's exports both to other domestic regions and to foreign countries (EEX), by compiling a new environmental inter-regional input-output (IRIO) model which clearly distinguishes the processing production from ordinary production, namely, the Bipartite Inter-regional Input-Output table (BIRIO).[3]

Moreover, due to the rapid economic development, the volume of EEX in China changed dramatically over time (Weber et al., 2008). For example, our results show that the EEX increased by 196% from 2002 (1390.32 Mt) to 2007 (4114.45 Mt), and subsequently increased by only 10% from 2007 to 2012 (4508.81Mt). The growth of emissions embodiment from 2002 to 2007 in regional outflows was 23% in Northern Municipalities, while in the Northwest reached over 300%. It is quite interesting to explore why the EEX increased so rapidly before the financial crisis while it grew at a slower pace after the financial crisis. It is also worth investigating how the driving forces of growth in the EEX differ between coastal and inland regions. Answers to these questions are important to establish effective and targeted policy to promote emission reduction and realize balanced development among regions. However, to our knowledge, little attention has been paid to these issues. Therefore, this paper will fill this gap and analyze the driving forces underlying the EEX growth at the regional level based on the structural decomposition procedure.

This study not only addresses a critical issue within China's sustainable development agenda but also contributes to the global discourse on carbon responsibility by providing a nuanced sub-national case. The findings, particularly the regional heterogeneity in driving forces and the role of processing trade, offer valuable insights for other large, geographically diverse economies engaged in global value chains (e.g., India, Brazil) that face similar challenges in allocating emission responsibilities and designing effective climate policies.

This paper can be distinguished from the existing literature from three perspectives.

First, we estimate and decompose changes in regional EEX by applying the BIRIO tables. This special input-output table can generate more accurate and reliable estimates of EEX change and the contribution of its driving factors, through separating processing production from other types of production. The decomposition results allow us to distinguish the processing- export effect from ordinary-production effect, which would help to issue effective policies on processing exports. This methodological refinement addresses a key limitation in both international and Chinese EET studies, which often lump together processing and ordinary trade (Dietzenbacher et al., 2012).

Second, we explicitly explore the differential impacts of various determinants on EEX change

[3] The interregional matrices are full; hence the term interregional IO table (IRIO) is more appropriate than multiregional IO table (MRIO) thus is used in this paper.

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at the regional level. Although many studies have revealed that the Chinese EEX increased before the financial crisis (Su & Thomson, 2016) and decreased after the financial crisis, few of them investigated the heterogeneous effect of different underlying factors at the regional level. Given the heterogeneity across regions, studies at the national level may skip useful information. Our research shows which factors contributed differently to the EEX change not only before and after the financial crisis, but also across regions, which provides a more comprehensive understanding than international SDA studies that focus on the national or broad regional level (Wiebe & Yamano, 2016).

Third, we provide a more nuanced analysis of the driving forces of EEX change, especially the peer effect and structural effect. For instance, the traditional input structure effect is separated into trade structure and sectoral structure, which can provide insightful results on the changes of production technology and trade pattern. Meanwhile, our method further separates the local effect and non-local effect from the technological and structural factors. This separation is necessary to reveal the role of each region in the territorial division of labor. Compared to the existing decompositions (Wang et al., 2024; Yang et al., 2024; Bai et al., 2025), our approach offers a comprehensive breakdown of shifts in production structure, offering insights into China's possible decarbonization routes. This refined decomposition framework advances the structural decomposition methodology itself, offering a template for analyzing sub-national production networks in other large economies.

The remainder of this paper is organized as follows: Section 2 reviews the related literature; Section 3 describes the study methodology (i.e. the estimation of regional EEX and SDA on BIRIO table); Section 4 reports the empirical results and discussion; conclusions and policy recommendations are presented in Section 5.

2. Literature Review

Input-output methodology is extensively employed in emissions embodiment studies of trade flows (EET). There are two approaches to estimate the EET: multi-region input-output (MRIO) model (Liu et al., 2010; Su & Ang, 2011; Weitzel & Ma, 2014; Zhang & Tang, 2015; Yan et al., 2019; Yang et al., 2024) and single-region input-output (SRIO) model (Sánchez-Chóliz & Duarte, 2004; Peters et al., 2007; Ming et al., 2009; Tang et al., 2022). The differences between these two models are the assumptions about the imported intermediate inputs and production technology. The SRIO model adopts the simplifying assumption that imported goods are produced using domestic technological coefficients. In fact, imports into one country may come from different countries with different production technologies, and thus different emission intensities. These differences cannot be accounted for by the SRIO model. The MRIO model can give a more accurate estimation of emissions and take the feedback effects into account (Su & Ang, 2011). Many reviews show that to calculate the EEX at the national level, the MRIO model is the most suitable method (Wiedmann, 2009; Wiedmann et al., 2007). For this reason, many papers apply the MRIO model to analyze China's emissions embodiment in international trade (Zhang & Tang, 2015; Yang et al., 2024). Globally, the development of MRIO databases like WIOD, EXIOBASE, and EORA has facilitated a surge in EET research, highlighting the significant flow of emissions from developing

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to developed nations (Davis & Caldeira, 2010; Peters et al., 2011; Yan et al., 2025). For instance, Ahmad & Wyckoff (2003) showed that the emissions for satisfying the final demands in OECD countries were 5% higher than emissions from production in these countries in 1995. In other words, this reveals that developed countries outsourced emissions to developing countries. Liddle (2018) compared consumption-based carbon emissions with territory-based carbon emissions for 117 countries from 1990 to 2013 and found that consumption-based emissions were higher than territory-based emissions for most countries. Further studies found that most European cities as well as developing countries exhibited an increase in consumption-based accounting emissions (Harris et al., 2020; Meng et al., 2023).

Further, some studies have applied the SDA to quantify the determinants of emission evolution for individual countries, such as the US (Weber, 2009), Australia (Wood & Lenzen, 2009), and China (Xu et al., 2011; Duan & Yan, 2021; Bai et al., 2025); studies also included countries with an MRIO model (Duan & Yan, 2020; Yang et al., 2024; Bai et al., 2025). Overall, these studies show that a rapid-growing export is the major determinant of CO_2 emissions growth in China (Tang et al., 2022; Bai et al., 2025). International SDA studies consistently identify economic scale (e.g., final demand or exports) as a primary driver of emission growth, while technological changes and shifts in production structure play varying roles across countries and time periods (Hoekstra & van der Bergh, 2003; Su & Ang, 2012, 2023).

The mentioned research focuses on the emission embodiment in international trade, without considering the regional disparity. Nevertheless, for big countries with significant regional diversity, such as China, the trade effect on the environment is different across regions. Feng et al. (2013) show that the trade impact on the environment is more severe for less developed regions than developed regions: about four-fifths of consumption-based emissions in China's developed regions are attributed to interregional imports from less developed regions. Hence, it is significant to investigate the trade-related environmental effects and analyze underlying drivers of carbon emissions growth at regional level. Several studies filled this gap. For instance, Feng et al. (2013) quantified the emission embodied in interregional and global trade by using a global MRIO model. Guo et al. (2012) also estimated the CO_2 emissions embodiment from the perspective of geography and sectors, by using the MRIO model. The results show that the majority of emission embodiment in international trade is generated in Eastern China. Zhang & Tang (2015) analyzed the EET changes at regional level, by applying the logarithm mean Divisia index approach. Tian et al. (2020) employed the multiplicative SDA to MRIO model and found that the increasing emission intensity in central and western regions is mainly due to the changing inter-regional trade. Results imply that coastal regions have shifted more emission-intensive production to inland regions. Yang et al. (2024) also showed that Guangdong outsources most of its emissions to less developed regions. This pattern of carbon leakage within a country mirrors findings in international trade studies (Dietzenbacher & Mukhopadhyay, 2007; Kanemoto et al., 2014; Dietzenbacher & Yan, 2024), underscoring the globality of this issue across different spatial scales.

However, a critical yet underexplored feature in this context is the significant role of processing trade in China's international commerce. It is important to observe that processing production and ordinary production have distinct input coefficient matrices, with intermediate

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inputs for the latter coming from domestic supply while those for the former are mostly imported. The traditional input-output model assumes the same input coefficient matrix for both normal and processing production, which thus biases research conclusions. For instance, related studies show that the exports' impact on economic growth would be exaggerated when processing trade and normal trade are not distinguished; besides, environmental losses from international trade would also be overestimated (Yan et al., 2019). While the treatment of processing trade is a particular concern in China-focused studies, the broader issue of accounting for heterogeneous production within sectors (e.g., export- vs. domestic-oriented) is relevant for many trade-dependent economies, though it is less frequently addressed in global MRIO analyses due to data constraints.

Meanwhile, changes in EEX at regional level in China received limited attention in the literature. We are only aware of research by Zhang & Tang (2015), which disentangle the changes in EET at regional level by applying the logarithm mean Divisia index (LMDI) approach, and Yang et al. (2024), which focuses on Guangdong Province. Nevertheless, LMDI cannot take the indirect effects on emissions into account. This paper aims to fill both gaps by studying the general state of Chinese regions' EEX and the driving forces of EEX growth for all regions in China, by using a new environment Bipartite Interregional Input-Output model (BIRIO). By integrating the regional disparity analysis with a nuanced treatment of processing trade and a comprehensive SDA framework, this study bridges a gap between the broad-brush strokes of international EET literature, and the detailed, context-specific analysis required for effective national and sub-national climate policy.

3. Methodology

This study develops a new Environmental Input-Output (EIO) model to calculate emissions embodiment in exports. The core innovation of the EIO model lies in its integration of carbon emission accounts with a BIRIO table that explicitly distinguishes between processing for export and ordinary production. While the BIRIO table (Duan et al., 2014) provides the foundational economic structure, our EIO model extends it by incorporating environmental satellite data and formalizing the calculus for tracing emissions embodied in trade flows. This integration is crucial for accurately attributing emissions to different production types and trade partners, which is the primary contribution of our methodological framework.

We elaborate the methods to calculate the emission embodiment in exports, using this new EIO model in this section. This model is built upon the BIRIO table constructed by Duan et al. (2014). Our dataset covers m=8 regions and n=17 industries. For each of the 17 industries, two production types are distinguished: processing production (indicated by superscript P); and ordinary production (O). This classification, fundamental to the BIRIO framework, adheres to the official Chinese statistical and customs definitions. The key discriminator is not a specific threshold of imported input share, but the legal and tax status of the production activity. Processing production operates under a special customs regime where imported intermediates are bonded (duty-free) and the output must be exported. This allows for a clear delineation in the IO table, even when both production types utilize some domestic intermediates, as their economic and environmental footprints are governed by different rules and patterns.

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3.1. From the BIRIO Table to the EIO Model to Calculate EEX

The standard BIRIO table captures the interregional flows of intermediate and final goods, disaggregated by processing and ordinary production. Our environmental extension involves linking this economic framework with data on CO_2 emissions. Specifically, we define region- and production-type-specific CO_2 emission coefficient vectors, which measure emissions per unit of economic output. By applying these coefficients to the output vectors derived from the BIRIO system, we transform the purely economic model into an EIO model capable of quantifying the carbon footprint associated with production and trade.

Next, we explain the calculation process of EEX. Firstly, the ordinary SRIO model (Miller & Blair, 2009) can be expressed as $\mathbf{x}=\mathbf{A}\mathbf{x}+\mathbf{f}$, where $\mathbf{x}$ denotes the n×1 output vector, $\mathbf{A}(\mathbf{A}=\mathbf{Z}\hat{\boldsymbol{x}}^{-1})$ denotes the n×n input coefficients matrix whose entries $a_{ij}=z_{ij}/x_j$ indicate the amount of good i required by producing one unit of good j, and $\mathbf{f}$ denotes the n×1 final demand vector.

In the two-region bipartite IO table, we denote $\bar{\mathbf{x}}$ as the output vector (4n×1), $\bar{\mathbf{A}}$ as the 4n×4n input matrix, and $\bar{\mathbf{f}}$ as 4n×1 vector. From table A1 it follows that

$$\bar{\mathbf{x}}=\begin{pmatrix}\mathbf{x}_r^P\\ \mathbf{x}_r^O\\ \mathbf{x}_s^P\\ \mathbf{x}_s^O\end{pmatrix},\ \bar{\mathbf{A}}=\begin{bmatrix}0 & 0 & 0 & 0\\ \mathbf{A}_{rr}^{OP} & \mathbf{A}_{rr}^{OO} & \mathbf{A}_{rs}^{OP} & \mathbf{A}_{rs}^{OO}\\ 0 & 0 & 0 & 0\\ \mathbf{A}_{sr}^{OP} & \mathbf{A}_{sr}^{OO} & \mathbf{A}_{ss}^{OP} & \mathbf{A}_{ss}^{OO}\end{bmatrix}\text{ and }\bar{\mathbf{f}}=\begin{pmatrix}\mathbf{f}_r^P\\ \mathbf{f}_r^O\\ \mathbf{f}_s^P\\ \mathbf{f}_s^O\end{pmatrix}=\begin{pmatrix}\mathbf{ex}_r^P\\ \mathbf{f}_{rr}^O+\mathbf{f}_{rs}^O+\mathbf{ex}_r^O\\ \mathbf{ex}_s^P\\ \mathbf{f}_{sr}^O+\mathbf{f}_{ss}^O+\mathbf{ex}_s^O\end{pmatrix},$$

where the output vector (2n×1) in region r includes the processing production output $\mathbf{x}_r^P$ and ordinary production output $\mathbf{x}_r^O$. The final demand vector (2n×1) in region r includes the demand for processing production ($\mathbf{f}_r^P$) and demand for ordinary production ($\mathbf{f}_r^O$). The final demand for processing products in region r ($\mathbf{f}_r^P$) is the export vector of processing production ($\mathbf{ex}_r^P$), and the final demand for ordinary products in region r ($\mathbf{f}_r^O$) consists of the final demand at home ($\mathbf{f}_{rr}^O$), final demand from region s ($\mathbf{f}_{rs}^O$) and exports ($\mathbf{ex}_r^O$). The input coefficient matrix $\mathrm{A}_{rs}^{BC}=Z_{rs}^{BC}(\hat{x}_s)^{-1}(B,C=P,O)$, $\mathrm{a}_{rsij}^{BC}=z_{rsij}^{BC}/x_{sj}^{C}$ gives the inputs of good i from class B and region r needed for producing one unit of good j in class C and region s.

Then the bipartite interregional IO model can be expressed as:

$$\begin{pmatrix}\mathbf{x}_r^P\\ \mathbf{x}_r^O\\ \mathbf{x}_s^P\\ \mathbf{x}_s^O\end{pmatrix}=\begin{bmatrix}0 & 0 & 0 & 0\\ \mathbf{A}_{rr}^{OP} & \mathbf{A}_{rr}^{OO} & \mathbf{A}_{rs}^{OP} & \mathbf{A}_{rs}^{OO}\\ 0 & 0 & 0 & 0\\ \mathbf{A}_{sr}^{OP} & \mathbf{A}_{sr}^{OO} & \mathbf{A}_{ss}^{OP} & \mathbf{A}_{ss}^{OO}\end{bmatrix}\begin{pmatrix}\mathbf{x}_r^P\\ \mathbf{x}_r^O\\ \mathbf{x}_s^P\\ \mathbf{x}_s^O\end{pmatrix}+\begin{pmatrix}\mathbf{ex}_r^P\\ \mathbf{f}_{rr}^O+\mathbf{f}_{rs}^O+\mathbf{ex}_r^O\\ \mathbf{ex}_s^P\\ \mathbf{f}_{sr}^O+\mathbf{f}_{ss}^O+\mathbf{ex}_s^O\end{pmatrix}. \tag{1}$$

Solving $\mathbf{x}=\mathbf{A}\mathbf{x}+\mathbf{f}$, we obtain $\mathbf{x}=(\mathbf{I}-\mathbf{A})^{-1}\mathbf{f}=\mathbf{L}\mathbf{f}$, where $\mathbf{L}=(\mathbf{I}-\mathbf{A})^{-1}$ indicates the Leontief inverse. In the bipartite two-region IO model, the Leontief inverse is:

$$\bar{\mathbf{L}}=\begin{bmatrix}\mathbf{I} & 0 & 0 & 0\\ \mathbf{L}_{rr}^{OP} & \mathbf{L}_{rr}^{OO} & \mathbf{L}_{rs}^{OP} & \mathbf{L}_{rs}^{OO}\\ 0 & 0 & \mathbf{I} & 0\\ \mathbf{L}_{sr}^{OP} & \mathbf{L}_{sr}^{OO} & \mathbf{L}_{ss}^{OP} & \mathbf{L}_{ss}^{OO}\end{bmatrix}=[\mathbf{I}-\bar{\mathbf{A}}]^{-1}=\begin{bmatrix}\mathbf{I} & 0 & 0 & 0\\ -\mathbf{A}_{rr}^{OP} & \mathbf{I}-\mathbf{A}_{rr}^{OO} & -\mathbf{A}_{rs}^{OP} & -\mathbf{A}_{rs}^{OO}\\ 0 & 0 & \mathbf{I} & 0\\ -\mathbf{A}_{sr}^{OP} & -\mathbf{A}_{sr}^{OO} & -\mathbf{A}_{ss}^{OP} & \mathbf{I}-\mathbf{A}_{ss}^{OO}\end{bmatrix}^{-1}$$

Therefore, the solution of the bipartite two-region IO model is given by,

$$\begin{pmatrix}\mathbf{x}_r^P\\ \mathbf{x}_r^O\\ \mathbf{x}_s^P\\ \mathbf{x}_s^O\end{pmatrix}=\begin{bmatrix}\mathbf{I} & 0 & 0 & 0\\ \mathbf{L}_{rr}^{OP} & \mathbf{L}_{rr}^{OO} & \mathbf{L}_{rs}^{OP} & \mathbf{L}_{rs}^{OO}\\ 0 & 0 & \mathbf{I} & 0\\ \mathbf{L}_{sr}^{OP} & \mathbf{L}_{sr}^{OO} & \mathbf{L}_{ss}^{OP} & \mathbf{L}_{ss}^{OO}\end{bmatrix}\begin{pmatrix}\mathbf{ex}_r^P\\ \mathbf{f}_{rr}^O+\mathbf{f}_{rs}^O+\mathbf{ex}_r^O\\ \mathbf{ex}_s^P\\ \mathbf{f}_{sr}^O+\mathbf{f}_{ss}^O+\mathbf{ex}_s^O\end{pmatrix} \tag{2}$$

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Secondly, to transition from the economic BIRIO model to our environmental EIO model, we multiply the region- and production-type-specific CO_2 emission coefficient vector (**e**) with the output vector of the emissions generated in each region,

$$\begin{pmatrix} E_r^P \\ E_r^O \\ E_s^P \\ E_s^O \end{pmatrix} = \begin{pmatrix} \mathbf{e}_r^{P'}\mathbf{x}_r^P \\ \mathbf{e}_r^{O'}\mathbf{x}_r^O \\ \mathbf{e}_s^{P'}\mathbf{x}_s^P \\ \mathbf{e}_s^{O'}\mathbf{x}_s^O \end{pmatrix} = \begin{bmatrix} \mathbf{e}_r^{P'} & 0 & 0 & 0 \\ \mathbf{e}_r^{O'}\mathbf{L}_{rr}^{OP} & \mathbf{e}_r^{O'}\mathbf{L}_{rr}^{OO} & \mathbf{e}_r^{O'}\mathbf{L}_{rs}^{OP} & \mathbf{e}_r^{O'}\mathbf{L}_{rs}^{OO} \\ 0 & 0 & \mathbf{e}_s^{P'} & 0 \\ \mathbf{e}_s^{O'}\mathbf{L}_{sr}^{OP} & \mathbf{e}_s^{O'}\mathbf{L}_{sr}^{OO} & \mathbf{e}_s^{O'}\mathbf{L}_{ss}^{OP} & \mathbf{e}_s^{O'}\mathbf{L}_{ss}^{OO} \end{bmatrix} \begin{pmatrix} \mathbf{ex}_r^P \\ \mathbf{f}_{rr}^O + \mathbf{f}_{rs}^O + \mathbf{ex}_r^O \\ \mathbf{ex}_s^P \\ \mathbf{f}_{sr}^O + \mathbf{f}_{ss}^O + \mathbf{ex}_s^O \end{pmatrix}, \tag{3}$$

where $\mathbf{e}_r^P(\mathbf{e}_r^O)$ is the emission coefficient for processing (ordinary) production in region *r*; its entries $e_{rj}^P(e_{rj}^O)$ represent the emissions generated by producing one unit output of sector *j*'s processing (ordinary) production in region *r*. As a result, $E_r^P(E_r^O)$ gives the emissions emitted in region *r* for the processing (ordinary) production.

In this study, we define the EEX of region *r* as the emissions that are generated in region *r* but consumed by other domestic regions or foreign countries. According to equation (3), region *r*'s EEX can be obtained as:

$$\mathrm{EEX}_r = \mathbf{e}_r^{P'}\mathbf{ex}_r^P + \mathbf{e}_r^{O'}\mathbf{L}_{rr}^{OP}\mathbf{ex}_r^P + \mathbf{e}_r^{O'}\mathbf{L}_{rr}^{OO}(\mathbf{f}_{rs}^O + \mathbf{ex}_r^O) \tag{4-a}$$

$$+\mathbf{e}_r^{O'}\mathbf{L}_{rs}^{OP}\mathbf{ex}_s^P + \mathbf{e}_r^{O'}\mathbf{L}_{rs}^{OO}(\mathbf{f}_{ss}^O + \mathbf{ex}_s^O). \tag{4-b}$$

According to equation (4), the EXX includes two parts: (4-a) expresses the emissions embodied in region *r*'s final products which are further exported to other domestic regions ($\mathbf{f}_{rs}^O$) or foreign countries ($\mathbf{ex}_r$); (4-b) quantifies the emissions embodied in region *r*'s intermediate inputs that are further processed as final goods by other domestic regions to satisfy the final demand of other domestic regions ($\mathbf{f}_{sk}^O$) or foreign countries ($\mathbf{ex}_s$).

Extending to *m* regions, the EEX is given by,

$$\mathrm{EEX}_r = \mathbf{e}_r^{P'}\mathbf{ex}_r^P + \mathbf{e}_r^{O'}\mathbf{L}_{rr}^{OP}\mathbf{ex}_r^P + \mathbf{e}_r^{O'}\mathbf{L}_{rr}^{OO}(\textstyle\sum_{s\neq r}^m \mathbf{f}_{rs}^O + \mathbf{ex}_r^O) \tag{5-a}$$

$$+\textstyle\sum_{s\neq r}^m(\mathbf{e}_r^{O'}\mathbf{L}_{rs}^{OP}\mathbf{ex}_s^P + \mathbf{e}_r^{O'}\mathbf{L}_{rs}^{OO}(\textstyle\sum_{k\neq r}^m \mathbf{f}_{sk}^O + \mathbf{ex}_s^O)) \tag{5-b}$$

3.2. The Decomposition of EEX

To quantify the effects of factors driving EEX growth, we need to rewrite the expression of EEX in equation (5) by introducing some new variables. Firstly, we use **T** to indicate the production technology. We define $\mathbf{T}_r^P = \sum_{s=1}^m \mathbf{A}_{sr}^{OP}$ and $\mathbf{T}_r^O = \sum_{s=1}^m \mathbf{A}_{sr}^{OO}$, which respectively gives the total intermediate inputs from each sector consumed by region *r* per unit of processing and ordinary production, and thus represents the production technology in region *r*.

Then, we introduce $\mathbf{S}_{sr}^P$ with $s_{srij}^{OP} = a_{srij}^{OP}/t_{rij}^P$, and $\mathbf{S}_{sr}^O$ with $s_{srij}^{OO} = a_{srij}^{OO}/t_{rij}^O$, which respectively give the proportion of intermediate inputs sourced from region *s* (by sector) in the total sectoral inputs needed per unit of processing and ordinary production in region *r*, and therefore represents region *r*'s intermediate inputs trade structure. Thus, $\mathbf{A}_{sr}^{OP} = \mathbf{S}_{sr}^P \circ \mathbf{T}_r^P$ and $\mathbf{A}_{sr}^{OO} = \mathbf{S}_{sr}^O \circ \mathbf{T}_r^O$, where $\circ$ is the element-wise multiplication, known as the Hadamard product.

Analogous to the rewriting of input matrix **A**, we also rewrite the expression of final demand **f** as well as exports **ex**. We define final demand **f** as the Hadamard product of the total quantity of final demand **Q** ($\mathbf{q}_r = \sum_{s=1}^m \mathbf{f}_{sr}^O$) and the final demand trade structure **D** ($d_{srij}^O = f_{srij}^O/q_{rj}^O$). Thus, $\mathbf{f}_{sr}^O = \mathbf{d}_{sr}^O \circ \mathbf{q}_r^O$.

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We define export $\mathbf{ex}$ as the Hadamard product of export level ($\mathbf{x}^P$ for processing production, with $\mathbf{x}^P=\sum_{s=1}^{m} ex_s^P$; $\mathbf{x}^O$ for ordinary production, with $\mathbf{x}^O=\sum_{s=1}^{m} ex_s^O$) and the export structure ($\mathbf{c}^P$ for processing production, with entries $c_{ri}^P=ex_{ri}^P/x_i^P$; $\mathbf{c}^O$ for processing production, with entries $c_{ri}^O=ex_{ri}^O/x_i^O$). Thus, $\mathbf{ex}_r^P=\mathbf{c}_r^P\circ\mathbf{x}^P$ and $\mathbf{ex}_r^O=\mathbf{c}_r^O\circ\mathbf{x}^O$.

With these additional definitions, EEX in equation 5 is determined by 12 factors. For each factor ($\mathbf{U}$), we define a domestic factor as $\mathbf{U}^{(r)}$ and an abroad factor as $\mathbf{U}^{(-r)}$, then EEX_r can be decomposed into 16 matrices and vectors[4]:

$$EEX_r=g^r(\mathbf{e}^{P(r)}, \mathbf{e}^{O(r)}, \mathbf{S}^{P(r)}, \mathbf{S}^{P(-r)}, \mathbf{T}^{P(r)}, \mathbf{T}^{P(-r)}, \mathbf{S}^{O(r)}, \mathbf{S}^{O(-r)}, \mathbf{T}^{O(r)}, \mathbf{T}^{O(-r)}, \mathbf{D}^{(-r)}, \mathbf{Q}^{(-r)}, \mathbf{c}^P, \mathbf{c}^O, \mathbf{x}^P, \mathbf{x}^O) \quad (6)$$

To examine the relative changes in values, the multiplicative SDA is applied to decompose the driving forces of EEX growth. To illustrate how this method works, suppose B=CD, then the growth of B from year (0) to year (1) can be estimated as follows:

$$\Delta B=\frac{B^1}{B^0}=\frac{C^1D^1}{C^0D^0}$$

$$=\frac{C^1D^0}{C^0D^0}\times\frac{C^1D^1}{C^1D^0} \quad (7)$$

$$=\frac{C^1D^1}{C^0D^1}\times\frac{C^0D^1}{C^0D^0} \quad (8)$$

Equations (7) and (8) are the so-called two-polar decompositions. The first polar form (7) is estimated by changing the first variable from the base year to the comparative year, followed by changing the second variable, and so forth. Equation (8), the second polar form, is calculated by changing the first variable from the comparative year to the base year, followed by the second factor, and so forth (Dietzenbacher & Los, 1998). Though it is obvious that the sequence of changes is not limited to these two ways, Dietzenbacher & Los (1998) demonstrated that the average of all decomposition ways can be proxied by taking the average of the two-polar decomposition forms. That is, the effect of changes in factor C and factor D are calculated, respectively, as:

$$\text{(effect of factor } \Delta C)=\sqrt{\frac{C^1D^0}{C^0D^0}\times\frac{C^1D^1}{C^0D^1}}$$

$$\text{(effect of factor } \Delta D)=\sqrt{\frac{C^1D^1}{C^1D^0}\times\frac{C^0D^1}{C^0D^0}}$$

Applying the two-polar decomposition method, the growth in EEX is decomposed into 16 factors, as shown in Table1.[5]

By multiplying the related factors, we obtain the effects of processing (ordinary) exports:

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[4] According to equation (5), EEX are mainly affected by the local emission intensity and non-local final demands, and the non-local emission intensity effects ($\Delta\mathbf{e}^{P(-r)}$ and $\Delta\mathbf{e}^{O(-r)}$) and local final demands ($\Delta\mathbf{D}^{(r)}$ and $\Delta\mathbf{Q}^{(r)}$) on EEX are zeros. Therefore, these factors are not included in Table 1.

[5] The SDA decomposition expressions for equation 6 are essentially the extension of equation (7) and (8).

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TABLE 1. Factor Decomposition of EEX

Factors	Description
$\Delta\mathbf{e}^{P(r)}$	Emission intensities for processing production in the local region
$\Delta\mathbf{e}^{O(r)}$	Emission intensities for ordinary production in the local region
$\Delta\mathbf{S}^{P(r)}$	Intermediate input-trade structure for processing production in the local region
$\Delta\mathbf{S}^{P(-r)}$	Intermediate input-trade structure for processing production in non-local regions
$\Delta\mathbf{T}^{P(r)}$	Production technology of processing goods in the local region
$\Delta\mathbf{T}^{P(-r)}$	Production technology of processing goods in non-local regions
$\Delta\mathbf{S}^{O(r)}$	Intermediate input-trade structure for ordinary production in the local regions
$\Delta\mathbf{S}^{O(-r)}$	Intermediate input-trade structure for ordinary production in non-local regions
$\Delta\mathbf{T}^{O(r)}$	Ordinary production technology in the local region
$\Delta\mathbf{T}^{O(-r)}$	Ordinary production technology in non-local regions
$\Delta\mathbf{D}^{(-r)}$	Distribution effect of non-local final demands
$\Delta\mathbf{Q}^{(-r)}$	Total final demands in non-local regions
$\Delta\mathbf{c}^{P}$	Distribution effect of exports of processing goods
$\Delta\mathbf{c}^{O}$	Distribution effect of exports of ordinary goods
$\Delta\mathbf{x}^{P}$	Total processing exports
$\Delta\mathbf{x}^{O}$	Total ordinary exports

$$\begin{aligned} E_P &= E(\mathbf{e}^{P(r)})\times E(\mathbf{S}^{P(r)})\times E(\mathbf{S}^{P(-r)})\times E(\mathbf{T}^{P(r)})\times E(\mathbf{T}^{P(-r)})\times E(\mathbf{c}^{P})\times E(\mathbf{x}^{P}) \\ E_O &= E(\mathbf{e}^{O(r)})\times E(\mathbf{S}^{O(r)})\times E(\mathbf{S}^{O(-r)})\times E(\mathbf{T}^{O(r)})\times E(\mathbf{T}^{O(-r)})\times E(\mathbf{c}^{O})\times E(\mathbf{x}^{O}) \end{aligned} \tag{9}$$

Similarly, the aggregate effect of the local and non-local production effect can be calculated as the multiplication product of the components related to the local factors and non-local factors:

$$\begin{aligned} E_{local} &= E(\mathbf{S}^{P(r)})\times E(\mathbf{S}^{O(r)})\times E(\mathbf{T}^{P(r)})\times E(\mathbf{T}^{O(r)}) \\ E_{non\text{-}local} &= E(\mathbf{S}^{P(-r)})\times E(\mathbf{S}^{O(-r)})\times E(\mathbf{T}^{P(-r)})\times E(\mathbf{T}^{O(-r)}). \end{aligned} \tag{10}$$

3.3. Data

To study the EEX and the driving factors, we use the BIRIO tables compiled by Duan et al. (2014). Based on the bipartite table at the national level and Chinese IRIO table, BIRIO tables separate the production of normal products and processing products in IRIO tables. In the end, the BIRIO tables cover eight regions and each region with 17 industries.

Here we use the data on CO_2 emissions by production types in each region-industry pair from Yan et al. (2019). They first obtained the emissions by region and industry type according to the estimation procedure in Peters et al. (2006) and Guan et al. (2012), and necessary parameter values from Liu et al. (2015) and Shan et al. (2018). Then the intermediate inputs supplied by energy-related sectors were used to proportionally distribute the emissions of each industry into the two production types.

4. Results and Discussions

4.1. Overall Results: Regional CO_2 Emissions and EEX

We start with the total CO_2 emissions and growth rates for each region. It is worth stating

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at this point that this study only focuses on the CO_2 emissions from production, while excluding the emissions by households. Figure 1 and Table 2 illustrate the results. It is obvious that CO_2 emissions are very uneven among regions. Like the results in Meng et al. (2013), we see that Central Region's CO_2 emissions are the highest, accounting for more than 22% of national emissions each year. This is because the Central Region is the second largest economy and has easy access to the domestic market. Besides, North Coast (the fourth largest economy) surpasses East Coast (the first largest economy) as the second largest emitter, because North Coast's products are concentrated in primary and heavy manufacturing industries with higher emission intensity. Meanwhile, the Northern Municipalities show the lowest CO_2 emissions (7.6% of that in Central Regions in 2012)due to Northern Municipalities' small economic scale and high dependence on interregional imports.

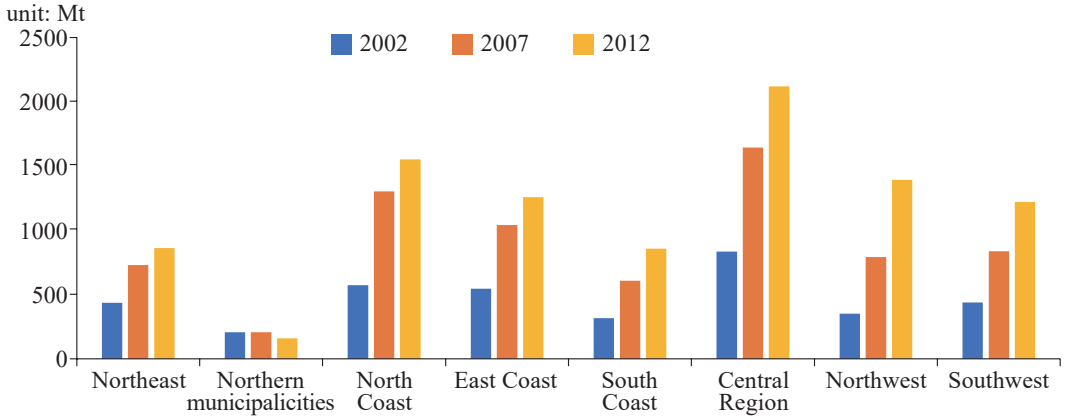

Fig. 1. Regional Total Emissions from Production

The national CO_2 emissions in China rapidly increased by 93.1% from 3707.41Mt in 2002 to 7158.11 Mt in 2007, and by 31.6% from 2007 to 2012 (9417.1Mt in 2012). However, the emission growth is uneven across different regions. All regions except Northern Municipalities experienced significant CO_2 emission growth. Among them, the CO_2 emissions in Northwest and Southwest increased the most from 2002 to 2012 by 296% and 178%, respectively, followed by North Coast (170%), South Coast (169%), and Central Region (153.8%).

TABLE 2. Regional Total Emissions from Production (unit: Mt) and Growth Rate

		Northeast	Northern Municipalities	North Coast	East Coast	South Coast	Central Region	Northwest	Southwest	Total
Emissions	2002	436.28	208.46	574.25	545.15	317.97	834.34	351.32	439.65	3707.41
	2007	730.75	207.19	1301.49	1040.37	608.17	1642.03	791.43	836.68	7158.11
	2012	862.8	161.0	1550.3	1257.8	856.1	2117.6	1391.6	1219.9	9417.14
Growth rate	2002-2007	67.5%	-0.6%	126.6%	90.8%	91.3%	96.8%	125.3%	90.3%	93.1%
	2007-2012	18.1%	-22.3%	19.1%	20.9%	40.8%	29.0%	75.8%	45.8%	31.6%
	2002-2012	97.8%	-22.8%	170.0%	130.7%	169.3%	153.8%	296.1%	177.5%	154.0%

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Table 3 shows the regional EEX (obtained from equation 5) and their shares in total regional emissions in 2002 and 2007 for each region. This table shows a significant difference in EEX among regions and a similar pattern with that of total regional CO_2 emissions. More specifically, the EEX in Central Region is the highest, followed by Northwest and North Coast. Meanwhile, the Northern Municipalities had the lowest EEX in 2012.

Regional EEX increased rapidly from 2002 to 2007; the total EEX in eight regions nearly tripled during that period. The national average share of EEX in total emissions also grew rapidly from 37.5% in 2002 to 57.5% in 2007. The increasing share indicates a larger increase in EEX than that in total emissions over the same period. A similar pattern was found at the global level (Peters et al., 2011; Xu et al., 2014). This shows that geographical fragmentation of productive activities has become more significant not only across countries but also across China's regions, which experienced a huge EEX growth compared with that of coastal areas. For example, as shown in the fourth row in Table 3, EEX in Northwest increased the most by 304%, while those for Northern Municipalities only increased by 23%. This indicated that inland areas' growing involvement in the domestic as well as the international production fragmentations over time, even at a higher speed than the coastal regions.

In contrast, after the financial crisis, the EEX growth rates decreased significantly compared to the levels from 2002 to 2007. The EEX growth rate in Northern Municipalities, Northeast and North Coast even became negative from 2007 to 2012. Furthermore, the EEX growth rates from 2007 to 2012 in all regions were smaller than regional emission growth rates. As a result, the EEX share in total regional emissions in all regions decreased from 2007 to 2012. We will explore further the driving forces of the EEX growth over time and in different regions.

TABLE 3. Regional EEX (unit: Mt) and Shares of EEX in Total Emissions

		Northeast	Northern Municipalities	North Coast	East Coast	South Coast	Central Region	Northwest	Southwest
EEX	2002	130.96	118.10	253.57	202.25	141.93	274.31	128.89	140.31
	2007	407.61	145.59	775.96	590.17	371.90	879.41	520.78	423.03
	2012	368.00	94.88	727.54	670.43	400.17	1011.92	803.17	432.70
EEX GR	2002-2007	211.25%	23.29%	206.01%	191.81%	162.04%	220.58%	304.04%	201.49%
	2007-2012	-9.72%	-34.84%	-6.24%	13.60%	7.60%	15.07%	54.23%	2.29%
	2002-2012	181.00%	-19.66%	186.92%	231.49%	181.95%	268.90%	523.14%	208.39%
EEX share	2002	30.02%	56.65%	44.16%	37.10%	44.64%	32.88%	36.69%	31.91%
	2007	55.78%	70.27%	59.62%	56.73%	61.15%	53.56%	65.80%	50.56%
	2012	42.65%	58.92%	46.93%	53.30%	46.74%	47.79%	57.71%	35.47%

Overall, EEX is a substantial part of regional emissions (Figure 2). The EEX share in total emissions was above 30% for all regions in 2002, and even above 50% in 2007. Moreover, the EEX shares in Northern Municipalities and Northwest were typically larger than those of coastal

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areas, which seems to imply that the responsibility of Northern Municipalities and Northwest is distorted more than that of coastal regions by regional emission data from a production perspective. This supports our viewpoint that a large part of emissions in each region is generated to satisfy other regions' final demand, and therefore this part of emissions is not the producer region's responsibility under the consumption responsibility principle. Therefore, when allocating emissions reduction targets among regions, these parts of emissions should be treated accordingly. However, it is still necessary to note that these regions also import products, and thus, emissions from other regions and countries should be considered when calculating consumption-based emissions. Nevertheless, it is not the focus of this study.

As for the EEX composition of different regions, the results reveal three main features. First, the majority of EEX in East Coast (except in 2012) and South Coast are due to the emissions embodied in international exports, while the majority of EEX in other regions are due to emissions embodied in interregional flow. As front-runners of China's reform and opening-up since 1978, the East Coast and South Coast regions have developed high levels of economic openness and integration into global trade. This is reflected in the predominance of emissions embodied in international exports within their EEX. For instance, the share in East region is around 14% higher than that of emissions embodied in interregional outflow in 2007. Conversely, in inland regions, which participate in interregional trade, emissions embodied in interregional outflow account for around 40% of total regional emissions, while those in exports account for only 10%. This pattern reveals the core-periphery structure within the domestic value chain: coastal areas, deeply integrated into the global value chain through processing trade, have their emissions primarily driven by international final demand, whereas inland regions, embedded more in the domestic value chain through supplying energy-intensive intermediate goods, see their emission growth mainly pulled by investment and consumption demands from other domestic regions. While the underlying mechanism is analogous to the pollution-haven effect observed in international studies, where developed countries outsource emissions to developing nations, it manifests within China as interregional industrial transfer and deepening division of labor. Second, as for different export types, emissions embodied in processing exports are prominent in three coastal regions and Northern Municipalities, but not in other regions. The highest share of emissions due to processing exports was found in South Coast and East Coast in 2007, with 9.3% and 7.9%, respectively. Third, over time, the relative size of emissions embodied in three trade types in each region presents different paths. Although the share of emissions caused by three trade types in each region increased from 2002 to 2007, it decreased from 2007 to 2012 for most regions. Differently, from 2007 to 2012, only the share of emissions embodied in interregional exchange increased for Northern Municipalities (from 38.1% to 41.6%), for East Coast (from 21.7% to 27.8%), and for Central Region (from 35.8% to 36.6%).

Besides emissions contribution of distinct trade types to regional emissions, this paper also examines the contribution of different trade types to gross regional products (GRP). As shown in Figure 3, the shares of three trade types in GRP are highest for three coastal regions and Northern Municipalities. In contrast, the degree of economic openness is much lower in central and western regions, so their shares of emissions attributed to exports in regional emissions are less

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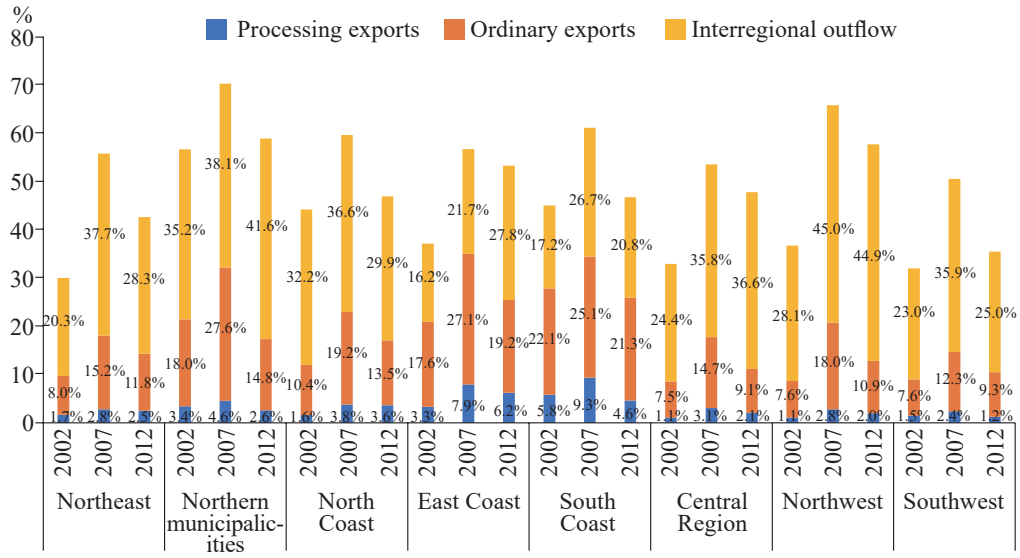

Fig.2. The Proportion of Regional CO_2 Emissions Attributable to Distinct Trade Types within Total Regional Emissions

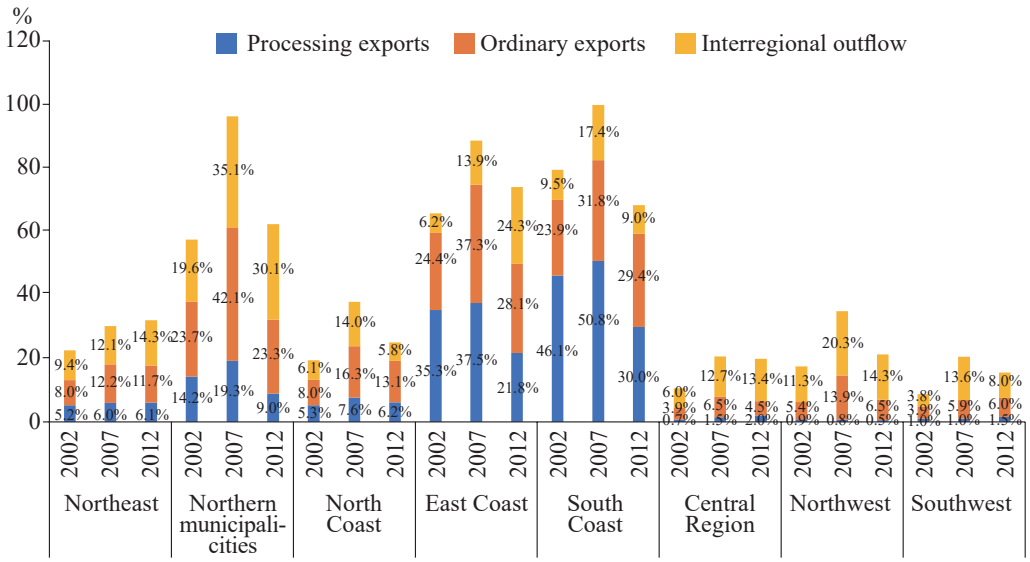

Fig. 3. Share of Different Trade Types in Gross Regional Products (GRP)

significant. One interesting finding is that more than 30% of GRP in East and South Coast comes from processing exports in all years, and even reached 50.8% in the South Coast in 2007. Recall that less than 10% emissions are due to processing exports in these regions, which indicates that processing exports involve cleaner production processes (Dietzenbacher et al., 2012; Duan & Yan, 2021).

Considering the dramatic rise and significant disparity in EEX growth across regions, it is necessary to analyze the factors driving EEX growth. The main questions that need to be addressed are: a) what are the main contributors to EEX growth?; b) how do interregional and international trade changes contribute to this growth?; and c) how the effects of trade changes differ across regions? We further analyze the SDA results in the next sub-section.

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4.2. SDA Results

By using the equations (5) and (6), the changes in regional EEXs are finally decomposed into 16 components as listed in Table 1[6]. The percentage changes in EEX caused by the change in each of the 16 components are shown in Table 4 and Table 5. The last row represents the total percentage changes in each region's EEX.

Take the Northeast region as an example. If all other components had remained unchanged, and only its total ordinary exports ($\Delta\mathbf{e}^{O}$) would have changed as they have from 2002 to 2007, the EEX would have increased by 36.13%. The relationship between the factor effect and the total changes in EEX can be expressed as:

$$\Delta EEX+1=(\Delta\mathbf{e}^{P}+1)\times(\Delta\mathbf{e}^{O}+1)\times(\Delta\mathbf{S}^{P(r)}+1)\times\cdots\times(\Delta\mathbf{c}^{O}+1)\times(\Delta\mathbf{x}^{O}+1)$$

In the example of Northeast, we have $3.11=(1-0.007)\times(1-0.31)\times(1-0.0022)\times\cdots\times(1+0.36)=1\times0.69\times1\times\cdots\times1.36$.

TABLE 4. SDA Results EEX (2002-2007)

Region	Northeast	North Municipalities	North Coast	East Coast	South Coast	Central Region	Northwest	Southwest	Average
$\Delta\mathbf{e}^{P}$	-0.70%	-1.39%	-0.14%	-1.19%	0.23%	-0.46%	-0.22%	-0.22%	-0.51%
$\Delta\mathbf{e}^{O}$	-31.23%	-73.06%	-41.08%	-23.54%	-8.89%	-30.96%	-25.78%	-25.41%	-32.49%
$\Delta\mathbf{S}^{P(r)}$	-0.22%	-0.43%	-0.10%	-0.56%	-0.57%	-0.02%	-0.02%	-0.05%	-0.25%
$\Delta\mathbf{S}^{P(-r)}$	0.01%	-0.34%	0.08%	0.03%	0.03%	0.33%	0.43%	-0.11%	0.06%
$\Delta\mathbf{T}^{P(r)}$	0.81%	2.01%	1.78%	4.74%	6.51%	-0.22%	-0.05%	-0.49%	1.89%
$\Delta\mathbf{T}^{P(-r)}$	-1.88%	-2.45%	-2.07%	-4.22%	-6.56%	-0.01%	-0.48%	-0.32%	-2.25%
$\Delta\mathbf{S}^{O(r)}$	2.89%	15.28%	-8.01%	0.01%	2.25%	-1.84%	3.40%	-1.56%	1.55%
$\Delta\mathbf{S}^{O(-r)}$	23.15%	16.48%	10.17%	0.99%	7.80%	23.58%	47.64%	3.78%	16.70%
$\Delta\mathbf{T}^{O(r)}$	15.62%	18.27%	79.77%	27.95%	15.83%	27.75%	13.83%	26.31%	28.17%
$\Delta\mathbf{T}^{O(-r)}$	21.53%	17.58%	22.44%	9.24%	6.80%	27.54%	21.70%	24.41%	18.91%
$\Delta\mathbf{D}^{(-r)}$	26.49%	11.80%	8.49%	11.06%	5.87%	13.17%	21.45%	24.52%	15.36%
$\Delta\mathbf{Q}^{(-r)}$	43.76%	37.66%	40.66%	29.18%	27.82%	44.56%	41.75%	51.08%	39.56%
$\Delta\mathbf{c}^{P}$	-0.66%	-0.81%	0.45%	3.42%	-2.90%	0.76%	-0.16%	-1.07%	-0.12%
$\Delta\mathbf{x}^{P}$	4.43%	5.23%	3.98%	9.61%	10.38%	3.62%	2.74%	3.95%	5.49%
$\Delta\mathbf{c}^{O}$	0.99%	8.05%	6.19%	-0.87%	-7.34%	0.54%	10.78%	-2.57%	1.97%
$\Delta\mathbf{x}^{O}$	36.13%	45.01%	38.23%	70.04%	58.19%	37.35%	32.05%	35.18%	44.02%
ΔEEX	211.25%	23.29%	206.01%	191.81%	162.04%	220.58%	304.04%	201.49%	190.06%
Processing	1.68%	1.64%	3.94%	11.78%	6.34%	4.00%	2.22%	1.62%	4.15%
Ordinary	68.32%	-21.18%	92.91%	81.95%	82.09%	88.43%	129.60%	57.71%	72.48%
Local	19.66%	38.49%	68.15%	33.29%	25.43%	25.10%	17.62%	23.66%	31.43%
Non-local	46.87%	33.14%	32.21%	5.70%	7.61%	58.11%	79.59%	28.55%	36.47%

[6] Temporal comparisons typically use deflated IO tables in constant price. However, deflation of IO tables requires all kinds of price indices which are not available. Since the BIIO tables are compiled on many assumptions, deflating the BIIO tables with estimated values potentially adds more noise to the data and leads to inaccurate results. Therefore, in this paper we use GDP deflator to deflate the emission intensity and final demand variables, and we will solve the deflation of BIIO tables in future research. However, the relative effects of each factor across regions are not expected to change dramatically when the constant price is applied.

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TABLE 5. SDA Results EEX (2007-2012)

Region	Northeast	North Municipalities	North Coast	East Coast	South Coast	Central Region	Northwest	Southwest	Average
$\Delta\mathbf{e}^{P}$	0.64%	-0.12%	0.27%	0.40%	0.68%	0.06%	0.00%	0.36%	0.28%
$\Delta\mathbf{e}^{O}$	-10.65%	-65.64%	-13.26%	-16.39%	-6.86%	-23.19%	-1.82%	-16.38%	-19.27%
$\Delta\mathbf{S}^{P(r)}$	-0.15%	0.36%	0.15%	-0.17%	0.36%	-0.11%	-0.01%	-0.09%	0.04%
$\Delta\mathbf{S}^{P(-r)}$	-0.16%	0.15%	-0.40%	-0.16%	-0.46%	0.06%	0.06%	-0.18%	-0.14%
$\Delta\mathbf{T}^{P(r)}$	0.52%	-0.61%	1.00%	3.86%	-4.01%	-0.28%	-0.11%	-0.21%	0.02%
$\Delta\mathbf{T}^{P(-r)}$	-1.98%	-2.53%	-3.10%	-8.23%	-3.80%	-2.23%	-1.73%	-2.03%	-3.20%
$\Delta\mathbf{S}^{O(r)}$	2.77%	-3.62%	21.25%	5.65%	10.20%	-0.89%	-7.06%	0.94%	3.65%
$\Delta\mathbf{S}^{O(-r)}$	-12.28%	60.36%	-23.60%	-4.64%	-8.57%	8.28%	25.46%	-6.32%	4.84%
$\Delta\mathbf{T}^{O(r)}$	-13.72%	-7.87%	-16.45%	-8.60%	-7.20%	-6.62%	-1.00%	-6.04%	-8.44%
$\Delta\mathbf{T}^{O(-r)}$	-5.98%	-6.76%	-1.87%	-1.83%	-2.33%	-3.17%	-5.24%	-3.31%	-3.81%
$\Delta\mathbf{D}^{(-r)}$	-17.45%	-0.93%	-6.07%	11.38%	-7.46%	2.35%	-5.42%	-13.99%	-4.70%
$\Delta\mathbf{Q}^{(-r)}$	47.84%	45.95%	46.49%	32.97%	29.88%	48.69%	52.60%	50.84%	44.41%
$\Delta\mathbf{c}^{P}$	1.49%	0.12%	1.11%	-0.80%	-0.47%	0.63%	0.13%	0.23%	0.31%
$\Delta\mathbf{x}^{P}$	-0.07%	-0.38%	0.06%	-0.58%	-0.16%	0.08%	0.08%	0.16%	-0.10%
$\Delta\mathbf{c}^{O}$	7.42%	-6.50%	-3.05%	-0.21%	0.04%	-0.84%	-3.95%	6.82%	-0.03%
$\Delta\mathbf{x}^{O}$	5.12%	8.91%	7.71%	8.12%	14.00%	4.18%	5.27%	4.60%	7.24%
ΔEEX	-9.72%	-34.84%	-6.24%	13.60%	7.60%	15.07%	54.23%	2.29%	5.25%
Processing	0.27%	-3.01%	-0.96%	-5.94%	-7.71%	-1.80%	-1.59%	-1.78%	-2.81%
Ordinary	-26.22%	-53.53%	-31.20%	-18.45%	-3.00%	-23.01%	8.59%	-19.74%	-20.82%
Local	-11.01%	-11.43%	2.47%	0.12%	-1.47%	-7.81%	-8.10%	-5.44%	-5.33%
Non-local	-19.28%	45.96%	-27.64%	-14.22%	-14.49%	2.58%	16.90%	-11.43%	-2.70%

4.2.1 Overall decomposition results

We firstly give an overview of the decomposition results. The last column in Table 4 and Table 5 shows the simple average contribution of each factor to the growth of EEX over eight regions, where regions are weighted equally. The change in non-local total final demands contributes most to the growth of EEX followed by the effect of total ordinary exports ($\Delta\mathbf{Q}^{(-r)}$ and $\Delta\mathbf{x}^{O}$). More specifically, if only non-local total final demands changed as they did, the EEX would have on average increased by 39.56% in 2007 and 44.41% in 2012. If only the total ordinary exports changed as they did, the EEX would have increased by 44.02% in 2007 and 7.24% in 2012. On the contrary, the changes in emission intensities have significantly reduced the EEX. However, their net effects still promoted the EEX, indicating that the increased emissions due to the growth in final demands outweigh the reduced emissions from emission intensity effect. The shift in driving factors before and after the global financial crisis profoundly reflects the combined impact of internal changes in China's economic drivers and external shocks. Prior to 2007, China, acting as the world's factory, saw its emission growth primarily driven by external demand (the ordinary export effect) and extensive production technologies during rapid industrialization (the positive production technology effect). After 2007, however, the contraction in external demand (particularly in processing trade) coupled with robust energy-saving and emission-reduction policies vigorously

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implemented during the 11th (2006-2010) and 12th (2011-2015) Five-Year Plan periods jointly led to a slowdown in emission growth. The reversal of the production technology effect from positive to negative signifies that China's economic growth model began transitioning from scale expansion to quality enhancement, with its production technology path starting to decouple from carbon emissions.

Moreover, the changes in ordinary production technology ($\Delta\mathbf{T}^{O(r)}$ and $\Delta\mathbf{T}^{O(-r)}$) also caused substantial EEX growth (28% and 19%, respectively) before the financial crisis. One reason is that intermediate inputs increased, and value added decreased per yuan of ordinary output in 2007, compared to that in 2002. This holds for 14 out of 17 sectors (exceptions are Agriculture, Chemical products, and Electronic products). The increasing reliance on intermediate inputs means more production per unit output, hence more emissions are generated. Another possible explanation is that the proportion of emission-intensive products in regional intermediate inputs is increasing. Meanwhile, both trade structural effect of intermediate inputs for ordinary production and distribution effect of non-local regional final demands ($\Delta\mathbf{S}^{O(-r)}$ and $\Delta\mathbf{D}^{(-r)}$) contribute 16% increase in EEX. This represents an increasing interregional production fragmentation and consumption, so consumers demand more goods from other regions. In contrast, after the financial crisis, $\Delta\mathbf{T}^{O(r)}$, $\Delta\mathbf{T}^{O(-r)}$ and $\Delta\mathbf{D}^{(-r)}$ became the three main forces that drove down the EEX, causing it to decrease by 8.44%, 3.81% and 4.70%, respectively. The trade structural effect of intermediate inputs for ordinary production in both local and non-local regions ($\Delta\mathbf{S}^{O(r)}$ and $\Delta\mathbf{S}^{O(-r)}$) contributed 3.65% and 4.84% increase in EEX, respectively, from 2007 to 2012. Next, we will analyze the different effects of each component on each region's EEX growth in detail.

4.2.2 The decomposition results for specific regions

Overall, at regional level, the changes in exports, changes in non-local total final demands, and changes in emission intensities are still the main contributors to the EEX change for almost all regions. However, the extents of their effects are quite different across regions.

(1) Total exports and non-local final demand

The total ordinary exports effect ($\Delta\mathbf{x}^{O}$) is the first factor that caused EEX to rise in three regions (East Coast, South Coast and Northern Municipalities) from 2002 to 2007. When comparing across regions, East Coast and South Coast, as important trade areas in China, have the biggest $\Delta\mathbf{x}^{O}$ effect, with 70.04% and 58.19%, respectively. Moreover, the $\Delta\mathbf{x}^{O}$ effects of Northern Municipalities and North Coast, which are around the national average (44.02%), are also important. The high $\Delta\mathbf{x}^{O}$ effects of two coastal regions and Northern Municipalities imply their increasing degree of economic openness and rising participation in international trade. The high contribution of changes in total exports to the EEX growth for all regions is closely related to the increase in exports in each region, as the exports in all regions increased by more than 100% from 2002 to 2007. Another large contributor to the EEX growth is the changes in non-local total final demands ($\Delta\mathbf{Q}^{(-r)}$). The top $\Delta\mathbf{Q}^{(-r)}$ effects are observed in three inland regions, which are Southwest, Central Region, and Northeast. In contrast, the $\Delta\mathbf{Q}^{(-r)}$ effects of Northern Municipalities, East Coast, and South Coast are smaller. This implies that central and inland regions became more important and increasingly involved in domestic division of labor. The importance of this non-local final demand effect in inland regions stems from the interplay of two forces: on one hand,

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it originates from the extension of domestic industrial chains inland, guided by national regional coordination strategies, such as the Western Development and Rise of Central China initiatives; on the other hand, it reflects a form of carbon leakage, where energy-intensive industries relocated to inland areas as environmental regulations tightened in coastal regions. Consequently, while inland regions have benefited from industrial transfer and economic development, they have also shouldered an increased inflow of embodied carbon emissions.

The changes in non-local total final demands ($\Delta\mathbf{Q}^{(-r)}$) became the top driving forces of EEX change in all regions from 2007 to 2012, except for Northern Municipalities. The largest $\Delta\mathbf{Q}^{(-r)}$ is found in Northwest, followed by Southwest and Northeast. During this period, the $\Delta\mathbf{x}^{O}$ effects became smaller than 10% for all regions, except for South Coast with 14%.

(2) Emission coefficients

The emission intensities of ordinary production effect at home ($\Delta\mathbf{e}^{O}$) is the major factor that reduced all regions' EEX from 2002 to 2007. Northern Municipalities have the largest $\Delta\mathbf{e}^{O}$ effect, which would have reduced the EEX by 73.06% if other factors would remain constant. A possible reason may be that Northern Municipalities has much stricter environmental legislation and enforcement than other regions, being at the economic and political center. Taking the polluting emission sulfur dioxide (SO_2) as an example, the levy standard for pollutant discharging fee is the highest in Beijing (10 yuan per kilogram), which is about eight times the national minimum levy (1.2 yuan per pollutant equivalent or 1.26 yuan per kilogram, adopted by most provinces in China, such as Fujian Province in South Coast region) in 2015. As a result, the emission-cutting effect is the highest in Northern Municipalities. Besides, the $\Delta\mathbf{e}^{O}$ effect of North Coast, 41.08%, is also relatively large among regions. Northeast and Central Region's $\Delta\mathbf{e}^{(r)}$ effects are close to the national level (32%). However, that of South Coast is small, only 8.89%. These results are quite consistent with the changes in regional emission intensity, which shows that the total emission intensity in Northern Municipalities has the sharpest decline over time (Table 6). Table 6 also shows that the regional differences of emissions per unit output are expanding over time. Regions with bigger emission intensity, such as Northwest, experienced smaller decline in emission intensity, while Northern Municipalities and East Coast, as regions with smaller emission intensity, had a higher decreasing rate of emission intensity. From 2007 to 2012, $\Delta\mathbf{e}^{O}$ effect was still the largest contributor that drove down the EEX in four regions: Northern Municipalities, Central Region, East Coast, and Southwest.

TABLE 6. Regional Total Emission Intensity Change (unit: t/10000 yuan)

		Northeast	Northern Municipalities	North Coast	East Coast	South Coast	Central Region	Northwest	Southwest
Emission /Output	2002	1.56	1.24	1.43	0.75	0.59	1.50	2.05	1.50
	2007	1.12	0.45	1.01	0.53	0.46	1.17	1.70	1.17
	2012	0.60	0.14	0.65	0.33	0.36	0.70	1.27	0.75
Change rate	2002-2007	-27.93%	-63.49%	-29.30%	-28.90%	-21.84%	-22.41%	-17.29%	-22.02%
	2007-2012	-46.31%	-68.10%	-36.11%	-38.37%	-22.86%	-40.19%	-25.02%	-35.89%

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(3) Commodity structure of intermediate inputs

Production technology effects on ordinary trade both inside ($\Delta\mathbf{T}^{O(r)}$) and outside regions ($\Delta\mathbf{T}^{O(-r)}$) also contributed to EEX increase from 2002 to 2007. The highest $\Delta\mathbf{T}^{O(r)}$ effect is observed in the North Coast region, contributing 80% of its EEX growth. Despite its coastal location, North Coast exhibits an economic structure specialized in primary sector production, such as agriculture, and heavy manufacturing (e.g., steel industry) which rely on emission-intensive intermediates and add less value. With the production specialization promoted by the domestic production fragmentation, the proportion of emission-intensive products in intermediate inputs for North Coast's production is increasing. Therefore, the $\Delta\mathbf{T}^{O(r)}$ effect becomes the major contributor to EEX growth in North Coast. Besides, $\Delta\mathbf{T}^{O(r)}$ effect is around the national average (28.17%) in East Coast, Central Region and Southwest. In contrast, South Coast, Northeast, and Northwest have a small $\Delta\mathbf{T}^{O(r)}$ effect, indicating smaller ordinary production technology changes in these three regions.

As for the incidence of $\Delta\mathbf{T}^{O(-r)}$, Central Region shows the highest effect (27.54%), followed by Southwest (24.41%), North Coast (22.4%), and Northwest (21.70%). As per its definition, $\mathbf{T}^{O(-r)}=\sum_{r=1}^{m}\mathbf{A}_{rs}^{OO}$, the change of ordinary production technology in non-local regions (region s) will impact the intermediate inputs from the local region (i.e., the $\mathbf{Z}_{rs}^{NN}$ matrix), thus affecting the local EEX in the region r. The large $\Delta\mathbf{T}^{O(-r)}$ effect for the Central Region shows that the proportion of input inflow to other regions is large. Therefore, when the total demand of intermediate inputs grow in other regions, more inputs are imported from Central Region, thus increasing region's EEX.

On the other hand, both $\Delta\mathbf{T}^{O(r)}$ and $\Delta\mathbf{T}^{O(-r)}$ effect drove down EEX in all regions from 2007 to 2012. This indicates that the production process became less emission-intensive after the financial crisis. The basic data reveals that the share of the top three emission intensive inputs (Electricity, gas, and water supply, Metal products, and Non-metallic mineral products) in total intermediate inputs were 17.39%, 23.10% and 17.98% in 2002, 2007, and 2012, respectively. This reflects an emission-intensive production method from 2002 to 2007, which became cleaner from 2007 to 2012. The reversal of the production technology effect around the financial crisis can be attributed to the synergistic interplay between policy intervention and technological advancement. After 2007, the Chinese government incorporated reducing energy consumption per unit of GDP as a binding target in its Five-Year Plans, supplemented by stringent environmental enforcement and subsidy policies. These measures compelled enterprises to pursue technological upgrades and enhance energy efficiency. Concurrently, the global diffusion of clean technologies and the strengthening of domestic independent innovation capabilities drove the transition towards a cleaner intermediate input structure.

(4) Intermediate input trade structure

Regarding the intermediate input trade structure for ordinary local production ($\Delta\mathbf{S}^{O(r)}$), a surprising finding is that its effects on regional EEX are quite different across regions. From 2002 to 2007, it increased in Northern Municipalities, Northwest, Northeast, and South Coast's EEX, but decreased the EEX of North Coast, Central Region and Southwest. The intermediate input trade structure indicates the market share of different regions in the specific region's sector-wise intermediate inputs. Accordingly, a positive (or negative) value for the trade structural effect of

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intermediate inputs for local ordinary production shows that the proportion of emission-intensive products from the local region was increasing (or decreasing). A possible explanation for the highest positive $\Delta\mathbf{S}^{O(r)}$ effect in Northern Municipalities is that importing emission-intensive goods from western regions became less profitable than producing locally, due to the increase in resource prices in inland areas after China launched its Western Development Strategy in 2000 (Liu et al., 2014). From 2007 to 2012, the increasing $\Delta\mathbf{S}^{O(r)}$ effect was enhanced in coastal regions, which increased EEX in North Coast the most (21.25%), followed by South Coast (10.20%) and East Coast (5.65%).

Changes in trade structure of intermediate inputs for non-local ordinary production ($\Delta\mathbf{S}^{O(-r)}$) promoted the EEX for all regions from 2002 to 2007. This implies an increasing domestic production fragmentation in which production has become more dependent on intermediate inputs supplied by other regions. Except for Southwest, the inland regions always had a much larger $\Delta\mathbf{S}^{O(-r)}$ effect than the coast regions. For example, the Northwest shows the largest $\Delta\mathbf{S}^{O(-r)}$ effect (47.64%), followed by the Central Region (23.58%) and Northeast (23.15%). In contrast, the $\Delta\mathbf{S}^{O(-r)}$ effects were insignificant for three coastal regions (i.e., less than 1% for East Coast). This indicates the share of intermediate inputs from inland regions for other regions' ordinary production is growing, which reflects again the increasing domestic production fragmentation. A similar pattern is found for the period from 2007 to 2012, during which the $\Delta\mathbf{S}^{O(-r)}$ effect significantly boosted the EEX in Northwest and Central Regions, while drove down the EXX in three coastal regions.

(5) Distribution effect of non-local final demand

The distribution effect of non-local regional final demands ($\Delta\mathbf{D}^{(-r)}$) from 2002 to 2007 shows a very similar pattern to that of intermediate inputs' trade structure in non-local regions ($\Delta\mathbf{S}^{O(-r)}$): a large positive effect on the EEX growth in inland regions (Northeast, Northwest and Southwest), but a small effect on the EEX growth in Coastal regions. This means that consumers shifted to importing more products from inland regions. From 2007 to 2012, the $\Delta\mathbf{D}^{(-r)}$ effect decreased the EEX for all regions except East Coast and Central Region. Due to the global financial crisis, the interdependence among countries declined, and the interdependence among regions rose accordingly. Data show that the growth rate of interregional outflow decreased from above 100% in all regions during the 2000-2007 period to below 100% during the 2007-2012 period, except for the East Coast. The growth rate of interregional outflow in North Coast and South Coast even became negative. This reveals that consumers switched to local produced final products, instead of final products produced by other regions.

(6) Processing export effect vs. ordinary export effect

The rows named *Processing* and *Ordinary* in Tables 5 and 6 show the roles of processing exports and ordinary production in driving EEX evolution (calculated using Eq. (9)). On average, the processing export effect contributed to around 4% EEX change, while the ordinary export effect leads to 72% EEX change from 2002 to 2007. Except for the total processing exports effect $\Delta\mathbf{x}^{P}$, which lead to 6.7% EEX growth, the other factors related to processing trade (emission intensities $\Delta\mathbf{e}^{P}$, intermediate products' trade structure, $\Delta\mathbf{S}^{P}$, production technology, $\Delta\mathbf{T}^{P}$ and export structure, $\Delta\mathbf{c}^{P}$) only enact comparatively small effects on regional EEX growth. This is due to the characteristics of processing trade: most intermediate inputs are imported and thus, the emissions

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from processing production are significantly smaller than those from ordinary trade. As a result, the factors related to processing trade have little impact on EEX. Since export processing zones are concentrated on South and East Coast, $\Delta \mathbf{x}^{P}$ effect in South Coast (10.38%) and East Coast (9.61%) are much more significant than those in other regions (around 5%). The $\Delta \mathbf{S}^{P(r)}$ effect decreases the EEX in all regions by around 0.25%, indicating that the share of emission-intensive products from domestic regions for processing production is decreasing. The $\Delta \mathbf{S}^{P(-r)}$, $\Delta \mathbf{T}^{P(r)}$ and $\Delta \mathbf{T}^{P(-r)}$ are quite different across regions. One interesting finding is that the $\Delta \mathbf{S}^{P(-r)}$ and $\Delta \mathbf{T}^{P(-r)}$ effects are higher in Central region and Northwest, which reflects that inland regions also play an increasing role in processing production fragmentation. This finding challenges the conventional perception that processing trade is concentrated solely in coastal areas, revealing a further extension of the global value chain within China's domestic geography. The underlying mechanism lies in the relocation of certain processing and assembly segments to inland regions with lower costs, as land and labor expenses rose in coastal areas, forming a new division of labor characterized by orders received at the coast and processing conducted inland. However, when participating in processing trade, inland regions may still rely on backward energy structures and technological capabilities, resulting in higher carbon intensity for their processing exports compared to coastal areas. This insight provides a basis for differentiated low-carbon trade policies across regions.

From 2007 to 2012, the processing export effect decreased the EEX in all regions, except in Northeast, while the ordinary export effect drove down the EEX in all regions, except in Northwest. During this period, the export processing effect plays a more important role in driving down the EEX than the ordinary export effect on the South Coast and Northwest. For instance, the EEX in South Coast would have decreased by 7.71% if only the processing export-related factors changed, while the ordinary export effect would have only decreased the EEX by 3%.

(7) Local effect vs. non-local effect

We also calculated the contribution of local production and non-local production to changes in EEX (calculated based on Eq. (10)), as shown in the last two rows in Tables 5 and 6. Both local and non-local effects contributed to increasing the EEX in all regions from 2002 to 2007. Among them, the non-local effect is more than twice the local effect in Northwest, Northeast, and Central Region, while the opposite holds for the three coastal regions and Northern Municipalities. This indicates the increasing dependence of the domestic production network on three inland regions from 2002 to 2007. Even though the interdependence among regions declined from 2007 to 2012, the non-local effect still dominated the EEX increase in Northwest and Central Region.

5. Conclusion

With economic development and trade liberalization, China has become the biggest emitter of CO_2 emissions. This paper studies the effect of both interregional and international trade on the total amount and spatial distribution of national those emissions. We extend previous research by analyzing the regional EEX and quantifying the driving forces underlying those changes, separating processing, and ordinary production by region. We enrich the literature by compiling a new environment bipartite interregional input-output (BIRIO) table and applying Structural Decomposition Analysis within this new environment input-output framework. The empirical

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results lead to the following key conclusions:

EEX accounted for a significant share of each region's total emissions (EEX share), implying the production emissions indeed distort the emission responsibilities of each region. Moreover, the EEX share increased rapidly from 2002 to 2007, indicating the increasing production fragmentation and geographical separation between production and consumption. EEX shares in inland regions keep being smaller than those of coastal regions; however, this gap narrowed over time since inland regions are increasingly participating in international and domestic fragmentation.

The decomposition result shows that changes in total ordinary exports and non-local final demands are the main contributors to EEX growth before and after the financial crisis. While change in emission coefficients is the major force that reduces the EEX in most regions, the trade structural change of intermediate inputs for non-local ordinary production ($\Delta\mathbf{S}^{O(-r)}$) became the top factor that drove down the EEX in North and South Coast. The ordinary production technology effects ($\Delta\mathbf{T}^{O(r)}$ and $\Delta\mathbf{T}^{O(-r)}$) reversed from positive pre-2007 to negative post-2007, showing the production process changed from emission-intensive to cleaner. Moreover, the different performance of trade structural effect of intermediate inputs for non-local ordinary production ($\Delta\mathbf{S}^{O(-r)}$) across regions indicates the expanding integration of inland areas into national value chains. However, the different signs of the distribution effect of non-local final demands ($\Delta\mathbf{D}^{(-r)}$) reveals that consumers' preferences shifted from non-local produced goods to local produced products. Overall, due to their foreign exports-oriented economic strategy, the processing export effect is more dominant in coastal regions, which even surpass the ordinary export effect in South Coast from 2007 to 2012. In contrast, non-local effects dominated the EEX change in inland regions, implying their growing participation in both interregional and international production fragmentation.

Based on the in-depth analysis of the underlying mechanisms, the policy implications of this study are now articulated with greater clarity and specificity. Policy design must fully account for regional heterogeneity, variations in trade patterns, and the dynamic evolution of driving factors, moving beyond a simplistic one-size-fits-all approach. Based on empirical findings and mechanistic analysis, this study proposes the following policy recommendations:

(1) Implement Differentiated Carbon Accounting and Assessment Policies Based on Regional Division of Labor

For coastal regions, carbon accounting should fully reflect their role as gateways to the global value chain. It is recommended that, based on existing production-side accounting, pilot programs incorporate carbon embodied in exports (especially ordinary exports) as a reference indicator in regional carbon budget assessments. This would incentivize these regions to leverage green procurement and technical standards to transmit emission reduction pressures upstream to inland suppliers, thereby promoting decarbonization throughout the entire export value chain.

For inland regions, there is a need to guard against becoming domestic pollution havens during industrial transfer. When accounting for their carbon responsibility, priority should be given to assessing the net outflow of embodied carbon induced by non-local final demand, and corresponding ecological compensation mechanisms should be established. Central government funding for energy-saving and emission-reduction projects should be tilted towards inland regions, supporting them in developing clean industries from a higher starting point and avoiding the

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pollute first, clean up later development path witnessed in some coastal areas.

(2) Construct a Precision Emission Reduction System Aligned with Trade Structure Transformation

Targeting processing trade, its advantage of low emission intensity should be maintained and strengthened. For coastal regions, the focus should be on managing via negative lists, strictly restricting high-carbon projects within export processing zones, and encouraging firms to utilize cleaner imported intermediates. For newly established processing trade in inland regions, higher environmental access thresholds should be set, ensuring the adoption of industry-leading energy efficiency technologies.

About ordinary trade, efforts should be made towards high-quality, lower emission transformation. Leveraging the window of opportunity where the driving force of the ordinary export effect weakened post-financial crisis, policies such as adjusting export tax rebates (e.g., lowering rebate rates for products with high carbon content or levying carbon taxes on exports) can guide the upgrading of the export structure towards lower-carbon products and services.

(3) Drive Comprehensive Production-Side Decarbonization through Technological Innovation and Industrial Structure Upgrading

At the technological level, policy should focus on consolidating and strengthening the driving force of the production technology effect. Coastal regions should leverage their technological and financial advantages to specialize in breakthrough low-carbon technology and process R&D. Inland regions should focus on the application, dissemination, and assimilation of mature energy-saving and environmental protection technologies. The state should establish a cross-regional Technology Transfer and Collaboration Platform to encourage coastal regions to transfer advanced low-carbon technologies to inland regions through technology alliances and jointly built industrial parks.

At the structural level, each region needs to formulate industrial upgrading pathways aligned with their comparative advantages. This is particularly critical for regions with a high concentration of heavy industries, such as the North Coast, where production has historically been emission-intensive. There, policies should accelerate the green and high-end transformation of key sectors like steel and chemicals through stricter access standards and roadmaps for phasing out backward capacity. All regions should actively cultivate high-tech industries and modern services, thereby reducing the carbon intensity of their economic output.

(4) Deepen Regional Coordination and Establish a Nationwide Unified Market for Low-Carbon Factors

Given the significant role of the non-local effect in emission growth, it is essential to break down geographical barriers and promote the cross-regional optimal allocation of emission reduction factors. It is recommended to pioneer a regional carbon market linkage mechanism among key areas like the Beijing-Tianjin-Hebei region, the Yangtze River Delta, and the Guangdong-Hong Kong-Macao Greater Bay Area, allowing a certain percentage of carbon allowances to be traded across regions. This enables regions with the lowest abatement costs to undertake more reduction tasks, achieving cost-effectiveness nationwide.

Concurrently, a cross-provincial compensation fund for embodied carbon transfers should

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be established. Funding could be sourced from specific levies on developed coastal regions and used to support the construction of clean energy infrastructure, foster low-carbon industries, and build capacity in key inland ecological function zones and less developed economic areas. This internalizes the negative externality of embodied carbon flows, promoting interregional fairness and coordinated development.

In summary, by revealing the multi-dimensional drivers of growth in interregional export-embodied carbon emissions in China, this study provides a scientific basis for formulating refined low-carbon governance policies. Future emission reduction policies must transition from singular production- or consumption-based accounting principles towards an integrated governance framework based on value-chain division of labor and regional differentiation, thereby balancing efficiency and equity while advancing sustainable development.

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