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Enormous inter-country inequality of embodied carbon emissions and its driving forces in South America

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ABSTRACT

South America is a crucial developing region under significant pressure to reduce emissions and achieve carbon neutrality. This study fills a vital gap by comprehensively analysing the continent's carbon emissions from both production and consumption perspectives. Utilizing the most up-to-date global Multi-Regional Input-Output (MRIO) models, we examine the emissions embodied in the internal and external trade of nine major South American countries, tracing the emission flows from their origins to final consumers and analyzing the socio-economic drivers behind these patterns. Our analysis reveals that regions bearing heavier burdens of energy-intensive production often face exacerbated economic disparities. Trade-related emissions are embodied in heavy industry and transportation, and the share of emissions attributable to developing countries is continuously climbing. Brazil is the sole net-exporter of emissions, while Colombia has become a significant net importer. Energy intensity offsets the increase in carbon emissions caused by per capita consumption, especially in Brazil. Meanwhile, Colombia experiences an increase in emissions due to its energy structure, whereas a general trend towards decreasing emissions is noted elsewhere. The impact of the industrial chain is mainly domestic and extends forward along the supply chain. Interestingly, the consumption structure reduces emissions in Argentina and Bolivia, but increases them in other countries. Key emission mitigation initiatives include Brazil enhancing its leadership in bioenergy, Chile intensifying the development of green industrial chains for high-emission sectors, and Uruguay advancing its wind energy projects to increase clean energy exports, etc. These measures could facilitate targeted and effective decarbonization while promoting equitable and sustainable economic development across South America.

1. Introduction

The rapid development of the economy is inevitably accompanied by an increase of anthropogenic carbon emissions, which is the main driver of global climate change. With the rapid transition of the global supply chain, the economic focus gradually shifts to emerging regions. In 2022, South America accounted for one-tenth of the GDP in developing countries worldwide (United Nations, 2022). However, the economy and carbon emissions are not decoupled in South America, which has significant potential for emissions as it develops (Wang and Su, 2020). The major countries within South America have signed the Paris Agreement and announced their Intended Nationally Determined Contributions (INDC) based on the production-based accounting principle. For instance, Brazil has pledged to reduce its emissions by 43 % below 2005 levels by 2030 (Bastidas and Mc Isaac, 2019). Argentina pledges not to exceed economy-wide net emissions of 359 Mt by 2030 (Saalfield, 2022), and Chile will reduce greenhouse gas emissions by 30 % below 2007 levels by 2030 (Simsek et al., 2020). Therefore, countries within South America experience enormous pressure due to the dual challenges of low GDP and the high costs associated with necessary carbon mitigation efforts.

South America is deeply integrated into the global industrial chain through international cooperation, trade contributed more than one-fifth of its GDP in 2022 (ECLAC, 2022), particularly in agriculture,

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mining, and energy. Specifically, Brazil and Argentina are major exporters of agricultural products, while Chile and Peru are key players in the mining industry (Bastida et al., 2005). In addition, South America's significance in international trade is amplified by its role as a leading exporter of essential commodities, influencing global markets and supply chains (Jacobs et al., 2014). However, this integration often positions the region at a disadvantage in the global value chain, where it predominantly undertakes energy-intensive production tasks traditionally associated with lower economic returns and more carbon-intensive outputs (Oliveira, 2018). This structural positioning in lower-value segments exacerbates economic disparities between developed and developing regions, and contributes to a cycle of 'carbon lock-in' where the latter (e.g. South America) face escalated challenges in achieving high-quality development while also meeting stringent carbon reduction targets (Seto et al., 2016).

However, international trade significantly reshapes the distribution of emissions among countries (Forslid et al., 2017). The geographic separation of producers and consumers can weaken the effectiveness of reduction policies to some extent due to the carbon leakage under the production-based accounting principle (Shan et al., 2018). This principle allows a country to take on the responsibility of emissions caused by domestic demand associated with exports without considering imports (Grubb et al., 2022). By tracing the emissions at each production stage, the consumption-based accounting principle, which stipulates that a country should be responsible for its emissions resulting from domestic demand and imports but exclude exports, could provide a new perspective on the fairness of emission mitigation responsibilities (Bruckner et al., 2010; Liddle, 2018).

To clarify the division of emissions and clearly formulate suitable decarbonization routes, it is critical to conduct a comprehensive investigation into the production- and consumption-based emissions in South America, as well as their related drivers. This research is organized as follows: Section 2 reviews current studies on embodied emissions and identifies gaps in the existing research. Section 3 provides the framework of an extended multi-regional input–output model, structural decomposition analysis, and the data sources. Section 4 presents the detailed results of the empirical exploration of embodied emissions and their related drivers. Section 5 presents the key findings and relevant policy implications of emission mitigation in South America, and proposes pathways toward equitable decarbonization and sustainable economic development.

2. Literature Review

2.1. Carbon emission embodied in trade

Many scholars have studied the embodied carbon emissions based on the global input–output tables, such as Emerging (Huo et al., 2023), GTAP (Arto et al., 2014), WIOD (Cansino et al., 2016; Zhao et al., 2016a; Zhao et al., 2016b) and Eora (Mangır and Şahin, 2022). Most of them focus on the North-North trade, such as the United States and Japan (Wang and Zhou, 2019), Britain and Germany (Valodka et al., 2020), as well as the South-North trade, such as the China-the United States (Liu et al., 2020; Zhao et al., 2016b), China-Japan (Wu et al., 2016; Zhao et al., 2016a), China-the European Union (Zhang et al., 2023), China-Australia (Jayanthakumaran and Liu, 2016; Tan et al., 2013), India-the United States (Wang et al., 2018), India-Britain (Banerjee, 2020), and the South-South trade, such as China-India (Wang and Yang, 2020), China-Africa (Zhang et al., 2019), China-Pakistan (Kim and Tromp, 2021b). Those studies confirm that most of the emissions transferred from developing countries, particularly China and India, to developed countries, notably the United States, European Union, and Japan, and the scale is continuously climbing. Meanwhile, the volume among developing countries has a rapidly increasing trend (Meng et al., 2023; Meng et al., 2018a; Shao et al., 2016). In addition, the trade in intermediate products become the new star along with the precision of international division (Wu et al., 2020), and lots of them focus on China (Meng et al., 2018b) and India (Wang et al., 2018).

Notably, the studies about South America are far from enough; those researchers agree that Brazil is a net-exporter of emissions embodied in non-energy goods (Machado et al., 2001), which is also the major export in Brazil and linked to the original emitter of basic materials, agriculture and mining industries (Kim and Tromp, 2021b), especially soy, most of which are finally consumed in China and the European Union (Escobar et al., 2020). Meanwhile, the scale of trade-related emissions rapidly climbed in Ecuador from 2000 to 2015, mostly related to the emitter of transportation and industry (Román-Collado et al., 2021). Colombia was a net-importer of emissions in 2015, and half of them focused on environmentally sensitive products, and Chile is the exception due to copper-related exports (Lima and Banacloche, 2017).

2.2. Driving forces in trade-related emissions

The drivers are primarily decomposed into energy structure, energy intensity, industrial structure, consumption structure, consumption scale and population in previous research, with significant differences across factors and periods observed. In detail, the energy structure has an increasing effect in Britain from 1990 to 2007, and a decreasing effect exists in China (Yanmei et al., 2013; Zhang, 2009) and Spain (Cansino et al., 2016). Energy intensity plays an increasing role in Turkey (Akbostancı et al., 2011), Indonesia (Hastuti et al., 2021) and Spain (Cansino et al., 2016), exhibits decreasing effect in South Korea (Kim and Tromp, 2021a), Japan (Li et al., 2022) and China (Guan et al., 2018; Shan et al., 2022). Industrial structure has an increasing influence in India (Zhu et al., 2018) and China (Guan et al., 2008), and shows a decreasing effect in Japan (Li et al., 2022), South Korea (Lim et al., 2009) and China (Mi et al., 2017). Meanwhile, a few studies also estimate the influence of the industrial chain and confirm that the domestic industrial chain decreases the emissions in South Korea; both forward and backward industrial chains exhibit increasing effects (Kim and Tromp, 2021a), and a similar picture could be seen in Germany (Li et al., 2021). Consumption structure increases the export-related emissions in South Korea (Kim and Tromp, 2021a) and Germany (Li et al., 2021). It holds a decreasing effect in China (Mi et al., 2017), India (Wang et al., 2020) and the United States (Feng et al., 2015). Consumption scale has an increasing influence in Indonesia (Hastuti et al., 2021), Germany (Li et al., 2021) and China (Zhao et al., 2016a; Zhu et al., 2012), and shows a decreasing effect in Brazil (Wachsmann et al., 2009). Population growth drives emission increases in Australia (Wood, 2009), India (Zhu et al., 2018) and China (Guan et al., 2018; Mi et al., 2017).

Furthermore, the quantity of studies on South America is not plentiful, and their results demonstrate that economic scale and energy structure increased the emissions in Brazil, Argentina and Colombia during 1990–2006 (Sheinbaum et al., 2011), conversely, energy intensity has been shown to reduce emissions (Peng et al., 2024). Meanwhile, the consumption scale pushed the emissions rise in Brazil from 2000 to 2007, in which industrial structure had a decreasing effect (Ribeiro et al., 2023). Meanwhile, the per capita consumption scale was the major driver of emissions in Ecuador from 1980 to 2010, and the energy structure and industrial structure showed a decreasing effect (Robalino-López and Aniscenko, 2017). In addition, per capita GDP, population scale and industrial structure increase energy demands in Brazil from 1970 to 1996, where energy intensity has a decreasing effect, and the contributor of consumption structure is not obvious (Wachsmann et al., 2009).

2.3. Research gaps

Despite extensive global research on emissions linked to trade, significant gaps exist regarding the specific dynamics of emissions within South American trade. These gaps include (1) a scarcity of detailed studies on intra-regional trade and its global role, (2) a lack of detailed emission breakdowns for both intermediate and final goods, (3) insufficient data tracing emissions from their sources to the final consumers, and (4) outdated research with limited current applicability.

Understanding these dynamics is crucial for assessing South America's impact on global emissions and for shaping effective environmental and trade policies. This study fills these research gaps by implementing a dynamic approach, which is a first in the field. It analyzes the flow of embodied carbon emissions from energy production to final consumption, thereby enhancing the analysis of both intermediate and final goods in South American trade. The study also examines the impact of the industrial chain and explores fundamental drivers like energy structures.

3. Methodology and data

3.1. Methodology

3.1.1. Environmental-extended multi-regional input–output analysis

This study uses the multi-regional input–output (MRIO) model to accurately analysis the emission embodied in intermediate and final products in South America's domestic and international trade. It traces emission flows from original emitters to final consumers through the international industrial chain. Based on the MRIO framework with m countries and n sectors in each, the accounting balance of monetary flow among countries and industries can be expressed as:

$$\sum_{q=1}^{m}\sum_{j=1}^{n} z_{ij}^{pq} + \sum_{q=1}^{m} y_i^{pq} = x_i^p \tag{1}$$

where z_{ij}^{pq} $(i,j = 1,2,\cdots,n,\ p,q = 1,2,\cdots,m)$ indicates the intermediate input from industry i in country p to industry j in country q. y_i^{pq} represents the product i exported from country p to country q. x_i^p refers to the output of industry i in the country p. The direct consumption coefficient can be expressed as $a_{ij}^{pq} = \frac{z_{ij}^{pq}}{x_j^q}$, which represents the inputs from industry i in country p to produce one unit of product by sector j in country q. Therefore, Equation (1) can be formulated as $X = (I-A)^{-1}Y = LY$, where $X = (x_i^p)$, $A = (a_{ij}^{pq})$, $Y = (y_i^{pq})$, $L = (l_{ij}^{pq})$ and its element denotes the total inputs from industry i in country p to produce one unit of product by sector j in country q, including the direct inputs and the indirect inputs through the domestic and international industrial chains. Meanwhile, the direct emission intensity of industry i in country p can be expressed as $f_i^p = \frac{d_i^p}{x_i^p}$, where d_i^p represents the direct carbon emissions emitted by industry i in country p through the consumption of fossil fuels during production activities.

In addition, the embodied emissions in country p can be accounted from production and consumption perspectives, respectively (Zhong et al., 2018). The former can be represented as $E_{Prod}^p = E^{pp} + E_{Exp}^p$, where E^{pp} is the domestic-related emissions and denotes the embodied emissions caused by the final consumption within country p, E_{Exp}^p is the export-related emissions and represents the embodied emissions in export trade of country p. The latter can be represented as $E_{Cons}^p = E^{pp} + E_{Imp}^p$, where E_{Imp}^p is the import-related emissions and denotes the embodied emissions in imported trade of country p.

Notably, the export-related emissions embodied in trade can be divided into final and intermediate goods, respectively (Meng et al., 2018). The former means the exporting country has completed all stages of manufacturing the product and directly exports it to the consuming country for final consumption, the latter denotes the exporting country only participates in part of the manufacturing process, and its exported products require further processing before it is used by the final consumer; if the further processing occurs in the country of final consumer, it is the direct intermediate product; if the further processing occurs in another country except the exporter and importer, it is the indirect intermediate product. Similarly, the domestic- and import-related emissions can be divided into final and intermediate goods as well. Therefore, we have the following:

$$E^{pp} = \sum_r F^p L^{pr} Y^{rp} = \underbrace{F^p L^{pp} Y^{pp}}_{(2a)} + \underbrace{\sum\nolimits_q F^p L^{pq} Y^{qp}}_{(2b)} \tag{2}$$

$$E_{Exp}^p = \sum\nolimits_q E^{pq} = \sum\nolimits_q \sum\nolimits_r F^p L^{pr} Y^{rq} = \sum\nolimits_q \left(\underbrace{F^p L^{pp} Y^{pq}}_{(3a)} + \underbrace{F^p L^{pq} Y^{qq}}_{(3b)} + \underbrace{\sum\nolimits_s F^p L^{ps} Y^{sq}}_{(3c)} \right) \tag{3}$$

$$E_{Imp}^p = \sum\nolimits_q E^{qp} = \sum\nolimits_q \sum\nolimits_r F^q L^{qr} Y^{rp} = \sum\nolimits_q \left(\underbrace{F^q L^{qq} Y^{qp}}_{(4a)} + \underbrace{F^q L^{qp} Y^{pp}}_{(4b)} + \underbrace{\sum\nolimits_s F^q L^{qs} Y^{sp}}_{(4c)} \right) \tag{4}$$

where $F^p = (f_i^p)$, $r (r = 1,2,\cdots,m)$ represents any countries and $s \neq p \neq q$ $(s = 1,2,\cdots,m)$. (2a) and (2b) represent the domestic-related emissions embodied in final and indirect intermediate goods, represents. (3a), (3b), and (3c) represent the export-related emissions embedded in final, direct and indirect intermediate goods, represents. (4a), (4b), and (4c) represent the import-related emissions embedded in final, direct and indirect intermediate goods, represents. For more detailed calculation process please see Fig. S1a (a1-a5) in the supporting information. Meanwhile, the scale of net-exported emissions embodied in trade of country p is expressed as $E_{Net}^p = E_{Exp}^p - E_{Imp}^p$, and this can be used to reflect the inequality of emissions in international trade (Shao et al., 2018). Country p undertakes some emission reduction responsibilities for foreign consumers where $E_{Net}^p > 0$, and country p transfers some emission reduction responsibilities to foreign countries where $E_{Net}^p < 0$. In addition, equation (3) and (4) can be further rewritten as follows:

$$E_{Exp}^p = \sum_q E^{pq} = \sum_q \sum_j \sum_i e_{ij}^{pq} = \sum_q \sum_j \sum_i \sum_r f_i^p l_{ij}^{pr} y_j^{rq} \tag{5}$$

$$E_{Imp}^p = \sum_q E^{qp} = \sum_q \sum_j \sum_i e_{ij}^{qp} = \sum_q \sum_j \sum_i \sum_r f_i^q l_{ij}^{qr} y_j^{rp} \tag{6}$$

where equation (5), (6) demonstrate the link from the original emitters (industry i) in country p to the final producers (industry j) in country r and then to the final consumers in country q, from the final consumers in country p to the final producers (industry j) in country r and then to the original emitters (industry i) in country q, respectively. For more information about the detailed calculation process please see Fig. S1b (b1-b6) in the supporting information.

3.1.2. Structural decomposition analysis

The emission changes can be decomposed into a cumulative sum of each independent factor within a period (Feng et al., 2012), Among these factors, emission intensity is particularly noteworthy and it can be rewritten as follows:

$$
\begin{aligned}
f_i^p &= \frac{d_{\mathrm{i}}^p}{x_{\mathrm{i}}^p} = \frac{d_{\mathrm{c,i}}^p + d_{\mathrm{o,i}}^p + d_{\mathrm{g,i}}^p}{x_{\mathrm{i}}^p} \\
&= \frac{d_{\mathrm{c,i}}^p}{G_{\mathrm{c,i}}^p} \frac{G_{\mathrm{c,i}}^p}{G_{\mathrm{c,i}}^p + G_{o,\mathrm{i}}^p + G_{\mathrm{g,i}}^p} \frac{G_{\mathrm{c,i}}^p + G_{o,\mathrm{i}}^p + G_{\mathrm{g,i}}^p}{x_{\mathrm{i}}^p} \\
&+ \frac{d_{\mathrm{o,i}}^p}{G_{\mathrm{o,i}}^p} \frac{G_{\mathrm{o,i}}^p}{G_{\mathrm{c,i}}^p + G_{o,\mathrm{i}}^p + G_{\mathrm{g,i}}^p} \frac{G_{\mathrm{c,i}}^p + G_{o,\mathrm{i}}^p + G_{\mathrm{g,i}}^p}{x_{\mathrm{i}}^p} \\
&+ \frac{d_{\mathrm{g,i}}^p}{G_{\mathrm{g,i}}^p} \frac{G_{\mathrm{g,i}}^p}{G_{\mathrm{c,i}}^p + G_{o,\mathrm{i}}^p + G_{\mathrm{g,i}}^p} \frac{G_{\mathrm{c,i}}^p + G_{o,\mathrm{i}}^p + G_{\mathrm{g,i}}^p}{x_{\mathrm{i}}^p} \\
&= D_{c,i}^p S_{c,i}^p I_i^p + D_{o,i}^p S_{o,i}^p I_i^p + D_{g,i}^p S_{g,i}^p I_i^p
\end{aligned}
\tag{7}
$$

where $D_{c,i}^p$, $D_{o,i}^p$, $D_{g,i}^p$ represents the emission coefficient of coal, oil, gas in country p sector i, respectively. $S_{c,i}^p$, $S_{o,i}^p$, $S_{g,i}^p$ represents the energy structure of coal, oil, gas in country p sector i, respectively. I_i^p represents the energy intensity in country p sector i. Therefore, the changes of f_i^p can be written as follows:

$$
\begin{aligned}
\Delta f_i^p &= \underbrace{\Delta D_{c,i}^p S_{c,i}^p I_i^p + \Delta D_{o,i}^p S_{o,i}^p I_i^p + \Delta D_{g,i}^p S_{g,i}^p I_i^p}_{(8a)} \\
&+ \underbrace{D_{c,i}^p \Delta S_{c,i}^p I_i^p + D_{o,i}^p \Delta S_{o,i}^p I_i^p + D_{g,i}^p \Delta S_{g,i}^p I_i^p}_{(8b)} \\
&+ \underbrace{D_{c,i}^p S_{c,i}^p \Delta I_i^p + D_{o,i}^p S_{o,i}^p \Delta I_i^p + D_{g,i}^p S_{g,i}^p \Delta I_i^p}_{(8c)}
\end{aligned}
\tag{8}
$$

where Δ represents the changes of elements. Based on previous studies (Wang et al., 2020), A can be further expressed as follows:

$$
A^{**} = A^{pp} + A_{q\neq p}^{pq} + A_{q\neq p}^{qp} + A_{q\neq p}^{qq} + A_{s\neq q\neq p}^{sq}
\tag{9}
$$

where * denotes the set of all countries, A^{pp}, $A_{q\neq p}^{pq}$, $A_{q\neq p}^{qp}$ represents the intraregional industrial chain, interregional forward industrial chain, interregional backward industrial chain of country p, respectively. $A_{q\neq p}^{qq}$ represents the intraregional industrial chain of country q, and $A_{s\neq q\neq p}^{sq}$ represents the interregional industrial chain among countries except country p. Therefore, the change of L^{pr} can be expressed as follows (Xu & Dietzenbacher, 2014):

$$
\begin{aligned}
&\Delta L^{pr} = L_{t1}^{p*} \Delta A^{**} L_{t0}^{*r} \\
&= \underbrace{L_{t1}^{pp} \Delta A^{pp} L_{t0}^{pr}}_{(10a)} + \underbrace{L_{t1}^{pp} \Delta A_{q\neq p}^{pq} L_{t0}^{qr}}_{(10b)} + \underbrace{L_{t1}^{pq} \Delta A_{q\neq p}^{qp} L_{t0}^{pr}}_{(10c)} + \underbrace{L_{t1}^{pq} \Delta A_{q\neq p}^{qq} L_{t0}^{qr}}_{(10d)} + \underbrace{L_{t1}^{ps} \Delta A_{s\neq q\neq p}^{sq} L_{t0}^{qr}}_{(10e)}
\end{aligned}
\tag{10}
$$

where the subscript t1 and t0 represent the terminal and base year, respectively. (10a), (10b), (10c), (10d), and (10e) represent the contribution of each type of industrial chain mentioned on the right-side of equation (9) in sequence. For more detailed information please see Fig. S2 in the supporting information. Meanwhile, the final consumption in country q could be further decomposed as follows:

$$
Y^{rq} = \frac{Y^{rq}}{\sum_r Y^{rq}} \frac{\sum_r Y^{rq}}{V^q} V^q = U^{rq} H^q V^q
\tag{11}
$$

where U^{rq} represents the structure of commodities exported from country r to q. H^q and V^q represent the per capita consumption scale and population in country q, respectively. Therefore, the changes of Y^{rq} can be written as follows:

$$
\Delta Y^{rq} = \underbrace{\Delta U^{rq} H^q V^q}_{(12a)} + \underbrace{U^{rq} \Delta H^q V^q}_{(12b)} + \underbrace{U^{rq} H^q \Delta V^q}_{(12c)}
\tag{12}
$$

where (12a), (12b), (12c) represent the contribution of each element on the right-side of equation (11) in sequence. Therefore, the changes of domestic-, export- and import-related emission of country p can be expressed as follows (Shao et al., 2020):

$$
\begin{aligned}
\Delta E^{pp} &= \Delta \sum\nolimits_r F^p L^{pr} Y^{rp} = \Delta \sum\nolimits_r D^p S^p I^p L^{pr} U^{rp} H^p V^p \\
&= \sum\nolimits_r \left[\left(\Delta D_c^p S_c^p + \Delta D_o^p S_o^p + \Delta D_g^p S_g^p \right) I^p L^{pr} U^{rp} H^p V^p \right] \\
&+ \sum\nolimits_r \left[\left(D_c{}^p \Delta S_c{}^p + D_o{}^p \Delta S_o{}^p + D_g{}^p \Delta S_g{}^p \right) I^p L^{pr} U^{rp} H^p V^p \right] \\
&+ \sum\nolimits_r \left[\left(D_c{}^p S_c{}^p + D_o{}^p S_o{}^p + D_g{}^p S_g{}^p \right) \Delta I^p L^{pr} U^{rp} H^p V^p \right] \\
&+ \sum\nolimits_r \left[\left(D_c{}^p S_c{}^p + D_o{}^p S_o{}^p + D_g{}^p S_g{}^p \right) I^p \left(L_{t1}^{p*} \Delta A^{**} L_{t0}^{*r} \right) U^{rp} H^p V^p \right] \\
&+ \sum\nolimits_r \left[\left(D_c{}^p S_c{}^p + D_o{}^p S_o{}^p + D_g{}^p S_g{}^p \right) I^p L^{pr} \Delta U^{rp} H^p V^p \right] \\
&+ \sum\nolimits_r \left[\left(D_c{}^p S_c{}^p + D_o{}^p S_o{}^p + D_g{}^p S_g{}^p \right) I^p L^{pr} U^{rp} \Delta H^p V^p \right] \\
&+ \sum\nolimits_r \left[\left(D_c{}^p S_c{}^p + D_o{}^p S_o{}^p + D_g{}^p S_g{}^p \right) I^p L^{pr} U^{rp} H^p \Delta V^p \right]
\end{aligned}
\tag{13}
$$

$$
\begin{aligned}
\Delta E_{Exp}^p &= \Delta \sum\nolimits_q E^{pq} = \Delta \sum\nolimits_q \sum\nolimits_r F^p L^{pr} Y^{rq} = \Delta \sum\nolimits_q \sum\nolimits_r \left(D^p S^p I^p L^{pr} U^{rq} H^q V^q \right) \\
&= \sum\nolimits_q \sum\nolimits_r \left[\left(\Delta D_c^p S_c^p + \Delta D_o^p S_o^p + \Delta D_g^p S_g^p \right) I^p L^{pr} U^{rq} H^q V^q \right] \\
&+ \sum\nolimits_q \sum\nolimits_r \left[\left(D_c{}^p \Delta S_c{}^p + D_o{}^p \Delta S_o{}^p + D_g{}^p \Delta S_g{}^p \right) I^p L^{pr} U^{rq} H^q V^q \right] \\
&+ \sum\nolimits_q \sum\nolimits_r \left[\left(D_c{}^p S_c{}^p + D_o{}^p S_o{}^p + D_g{}^p S_g{}^p \right) \Delta I^p L^{pr} U^{rq} H^q V^q \right] \\
&+ \sum\nolimits_q \sum\nolimits_r \left[\left(D_c{}^p S_c{}^p + D_o{}^p S_o{}^p + D_g{}^p S_g{}^p \right) I^p \left(L_{t1}^{p*} \Delta A^{**} L_{t0}^{*r} \right) U^{rq} H^q V^q \right] \\
&+ \sum\nolimits_q \sum\nolimits_r \left[\left(D_c{}^p S_c{}^p + D_o{}^p S_o{}^p + D_g{}^p S_g{}^p \right) I^p L^{pr} \Delta U^{rq} H^q V^q \right] \\
&+ \sum\nolimits_q \sum\nolimits_r \left[\left(D_c{}^p S_c{}^p + D_o{}^p S_o{}^p + D_g{}^p S_g{}^p \right) I^p L^{pr} U^{rq} \Delta H^q V^q \right] \\
&+ \sum\nolimits_q \sum\nolimits_r \left[\left(D_c{}^p S_c{}^p + D_o{}^p S_o{}^p + D_g{}^p S_g{}^p \right) I^p L^{pr} U^{rq} H^q \Delta V^q \right]
\end{aligned}
\tag{14}
$$

$$
\begin{aligned}
\Delta E_{Imp}^p &= \Delta \sum\nolimits_q E^{qp} = \Delta \sum\nolimits_q \sum\nolimits_r F^q L^{qr} Y^{rp} = \Delta \sum\nolimits_q \sum\nolimits_r \left(D^q S^q I^q L^{qr} U^{rp} H^p V^p \right) \\
&= \sum\nolimits_q \sum\nolimits_r \left[\left(\Delta D_c^q S_c^q + \Delta D_o^q S_o^q + \Delta D_g^q S_g^q \right) I^q L^{qr} U^{rp} H^p V^p \right] \\
&+ \sum\nolimits_q \sum\nolimits_r \left[\left(D_c{}^q \Delta S_c{}^q + D_o{}^q \Delta S_o{}^q + D_g{}^q \Delta S_g{}^q \right) I^q L^{qr} U^{rp} H^p V^p \right] \\
&+ \sum\nolimits_q \sum\nolimits_r \left[\left(D_c{}^q S_c{}^q + D_o{}^q S_o{}^q + D_g{}^q S_g{}^q \right) \Delta I^q L^{qr} U^{rp} H^p V^p \right] \\
&+ \sum\nolimits_q \sum\nolimits_r \left[\left(D_c{}^q S_c{}^q + D_o{}^q S_o{}^q + D_g{}^q S_g{}^q \right) I^q \left(L_{t1}^{q*} \Delta A^{**} L_{t0}^{*r} \right) U^{rp} H^p V^p \right] \\
&+ \sum\nolimits_q \sum\nolimits_r \left[\left(D_c{}^q S_c{}^q + D_o{}^q S_o{}^q + D_g{}^q S_g{}^q \right) I^q L^{qr} \Delta U^{rp} H^p V^p \right] \\
&+ \sum\nolimits_q \sum\nolimits_r \left[\left(D_c{}^q S_c{}^q + D_o{}^q S_o{}^q + D_g{}^q S_g{}^q \right) I^q L^{qr} U^{rp} \Delta H^p V^p \right] \\
&+ \sum\nolimits_q \sum\nolimits_r \left[\left(D_c{}^q S_c{}^q + D_o{}^q S_o{}^q + D_g{}^q S_g{}^q \right) I^q L^{qr} U^{rp} H^p \Delta V^p \right]
\end{aligned}
\tag{15}
$$

The contribution of emission coefficient, energy structure, energy intensity, industrial chain, consumption structure, per capita consumption scale and population are each represented sequentially by the elements on the right side of equation (13), (14) and (15), respectively. For more detailed information please see Fig. S3 in the supporting information.

Notably, there are 5040 (7!) equally acceptable decomposition forms in this study, and the contribution of each driver obtained by different forms could be different (Dietzenbacher & Los, 1998; Hoekstra & Van Den Bergh, 2002; Rørmose & Olsen, 2005). To gain the ideal results, we take the arithmetic average of all decomposition forms as the contribution of each driver, as popularly applied in the existing studies (Guan et al., 2009; Liang et al., 2016). For more information about the detailed process, please see Table SC1-SC7 in the supporting information, as well as our previous study (Wang et al., 2020).

3.2. Data sources

To construct an environmental extended input–output model, this study involves two main categories of data sets: the multi-regional input–output tables and the carbon emission inventory. The multi-regional input–output tables is EMERGING (Huo et al., 2022), which is the most widely covered and the latest updates compared with the other sources (e.g., GTAP, Exiobase and WIOD). These tables contain detailed data of consumption and intermediate demands of commodities and services among 134 harmonized industrial sectors in 245 countries/ regions, from 2015 to 2019. Meanwhile, the GDP deflator provided by the World Bank is employed to adjust the original monetary value in the input–output tables at the constant prices from 2015, thereby eliminating the impacts of inflation and achieving comparability of analysis across different years. The fossil fuel-related carbon emission inventory, which measured the emissions directly emitted by production activities, is derived from the International Energy Agency (IEA) and the China Emission Accounts and Datasets (CEADs). Meanwhile, the regional and industrial classifications in the emission inventory are rearranged into the sectoral structure in the input–output tables to retain the integrity of the data, following the International Standard Industrial Classification (ISIC). For more detailed descriptions of the compilation and treatment, please see Table S1 in the supporting information. Two typical relationship types appeared in the matching process: one-to-many and many-to-one. For one-to-many, we use the output in the Emerging Database as a weight to allocate the emissions. For many-to-one, we add all the emissions together. In addition, the population data in each country is obtained from the World Bank, the carbon emission coefficient of fossil energy comes from the statistical bureau of each country and the missing value is replaced by the corresponding data derived from the IEA. All the original data employed in this paper are published and available.

4. Results and discussion

This study thoroughly examines the contributions made by nine major South American countries, which account for 94.2 % of the

Fig. 1. Comparison of emissions from the production and consumption perspective among the nine selected countries in South America during 2015–2019, respectively. The blocks and circles represent the domestic consumption and net-export, respectively. Because of the large numerical difference in emission value, the x-axes are divided into five ranks, identified from largest to smallest in blue, black, green, orange and indigo, respectively.

continent's GDP and 86.9 of its territorial emissions, from 2015 to 2019. The results of the embodied emissions and the factors responsible for them are presented across nine sectors, listed in Table S2 in the supporting information for more detailed classification.

4.1. Fluctuating trends and structure in the embodied emissions landscape

In 2015, South America's consumption-based emissions totaled 909.4 Mt, led primarily by Brazil, Argentina, and Colombia (Fig. 2). By 2019, emissions had decreased to 822.2 Mt, with notable declines in Brazil and Argentina attributed to efficiency gains and structural shifts in sectors such as transportation and heavy industry. This conclusion is similar to previous studies (Anser et al., 2020; Panait et al., 2023). Specifically, Brazil's efforts to modernize its transportation sector, alongside Argentina's technological advancements in heavy industry, have contributed to this downward trend. Conversely, slight emission increases in Chile and Paraguay align with their increased electricity production and industrial activities. The decline in emissions in Colombia and Ecuador during the economically unstable year of 2017 underscores the broader regional dependence of emission trajectories on economic health. These results are consistent with existing studies (Zhang & Tang, 2015), which demonstrate a notable impact of economic downturns on export-related emissions and corroborate the observed temporary reduction during this recession in 2017. In addition, a similar trend was witnessed in production-based emissions, which decreased from 857.9 Mt to 791.3 Mt during 2015–2019. The transportation sector consistently dominated production-based emissions, reflecting its pivotal role in regional commerce and mobility. However, heavy industry in Bolivia overtook other sectors, indicating its industrial focus. Chile's emission profile was distinctly marked by the electricity sector's output, underscoring the country's energy production reliance on carbon-intensive sources.

Export-related emissions initially recorded at 175.6 Mt in 2015 increased by 10.2 Mt by 2019, buoyed by Brazil and Argentina's ramped-up production capacities. The contrasting decrease in Chile and Bolivia's export emissions potentially reflects a strategic pivot towards less carbon-intensive exports or the adoption of cleaner production technologies. A synchronous economic recession in 2017 resulted in a temporary regression in export-related emissions across Brazil, Argentina, and Uruguay, with the transportation and heavy industry sectors experiencing the most significant contraction. Meanwhile, import-related emissions stood at 227.1 Mt in 2015, decreasing by 10.4 Mt by 2019. This decline was most pronounced in Argentina and Brazil, signaling a shift toward more self-sufficient domestic production capabilities, possibly enhanced by investments in sector-specific efficiencies. Conversely, the rise in import emissions in Chile, Paraguay, and Peru may denote a growing dependency on foreign goods, likely spurred by consumer demand and infrastructural development needs. Notably, intermediate products, particularly direct intermediates, have become significant contributors to both export and import emissions, illuminating the deep integration of South America into the global industrial chain and emphasizing the substantial role of sectors such as mining, electricity, and construction in shaping the continent's embodied emissions.

Throughout this period, Brazil was distinguished as South America's sole net exporter of emissions, growing from a net export of 10.0 Mt to 19.1 Mt by 2019, revealing its substantial industrial output, particularly in the transport and heavy industry sectors, which are integral to its trade economy. On the other hand, all other countries are net importers, reflecting the inequity of embodied emissions in international trade. For instance, Colombia exports about 10 Mt of emissions annually, yet imports more than double this amount. This imbalance is common among net importers like Argentina, Uruguay, and Peru, who outsource their production to net exporters such as Brazil, thereby also shifting their carbon reduction responsibilities. This illustrates the need for regional and international agreements to recognise the complexity of trade-related carbon responsibilities and ultimately aim for a more balanced and equitable approach to carbon management.

4.2. Transportation and heavy industry-oriented dynamic pathways of export-related emission

From 2015 to 2019, the main source of export-related emissions in South America was oil, while heavy industry, particularly vehicular equipment (Fig. 2), was the main emitting sector, with Brazil leading the way with 80.7 million tonnes and Chile contributing 17.5 million tonnes. These two countries also has substantial coal-related emissions, which were substantial contributors to their overall export emissions profiles. Other nations in the region shifted towards gas-related emissions, with Argentina and Peru seeing the electricity sector as the primary source, reflecting their national energy structures and priorities.

Transportation emerged as a dominant sector for export-related emissions across Colombia, Ecuador, Bolivia, and Paraguay, contributing 10.1, 5.4, 4.2, and 1.4 Mt, respectively, which underscores the significance of this sector in the regional emission landscape. Argentina's light industry, mainly consisting of vegetable, fruit, and food production, was a notable emitter in 2015 but transitioned towards agriculture by 2019, mirroring the country's agro-oriented economic shift.

The destination of these emissions varied significantly, illustrating the nuanced trade relationships of South America. Due to China's focus on construction, Brazil had China as the primary recipient of its export-related emissions, totaling a staggering 70.2 Mt. The United States and the European Union were other significant destinations, with Colombia and Chile exporting 16.9 and 17.0 Mt, respectively, mainly in transportation sectors. Post-2017, Ecuador and Peru redirected a significant portion of their export emissions from the United States to China, particularly in construction, signifying a deepening of trade ties with developing economies.

In total, 266.7 Mt of South America's export-related emissions were driven by the final demands of foreign households from 2015 to 2019, with a primary share—72.4 %—originating from developed economies, specifically the United States and the European Union. Capital consumption, particularly in China, accounted for a substantial intake of emissions from Brazil (40.4 Mt), Chile (9.0 Mt), Peru (4.5 Mt), and Argentina (3.6 Mt), highlighting the impact of China's rapid industrialization and urbanization on global emission patterns, a finding that aligns with previous studies (Ray & Gallagher, 2016; Shan et al., 2018).

4.3. Household and capital oriented dynamic trajectories shift of import-related emissions

Compared to the exports, South American imports were significantly diverse. Between 2015 and 2019, South American households were responsible for importing 415.6 Mt of emissions, with heavy industry—particularly electronic equipment manufacturing—being the primary sector (Fig. 3). Brazil led the way with 50.7 Mt, followed by Uruguay (6.5 Mt) and Bolivia (5.8 Mt). During this period, the expansion of urbanization and economic development stimulated demand for transport infrastructure, and the transportation sector became predominant in Paraguay (3.2 Mt), Ecuador (4.0 Mt), Colombia (13.7 Mt), and Peru (11.2 Mt). In contrast, Argentina's light industry, notably the food sector, was responsible for 16.0 Mt of emissions. The focus shifted towards the construction sector in Colombia (16.3 Mt) and Peru (10.7 Mt). Simultaneously, capital investments accounted for 209.6 Mt of total emissions. Argentina (16.4 Mt) and Brazil (64.4 Mt) heavily invested in products from the heavy industry, especially boilers and machinery. This aligns with earlier findings that South America has seen substantial industrial growth during this period (Cardoso & Faletto, 2024). However, this also carries significant embodied emissions due to the manufacturing process of such heavy machinery.

Throughout this time frame, China emerged as the major exporter of

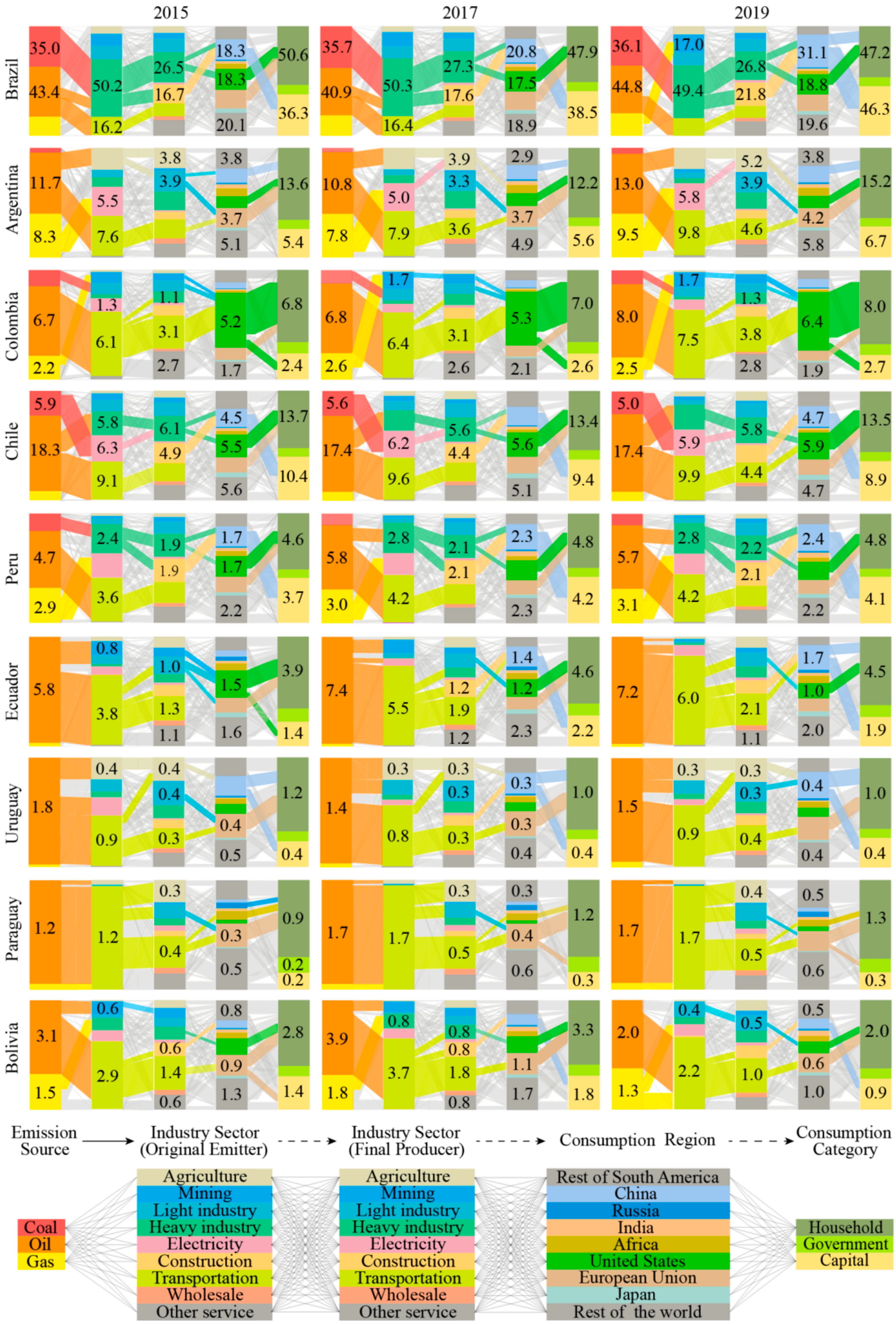

Fig. 2. Sankey diagram of exported emission flows in 2015, 2017 and 2019, the width of the flow represents the scale of emission, and the main path between each layer is marked in color.

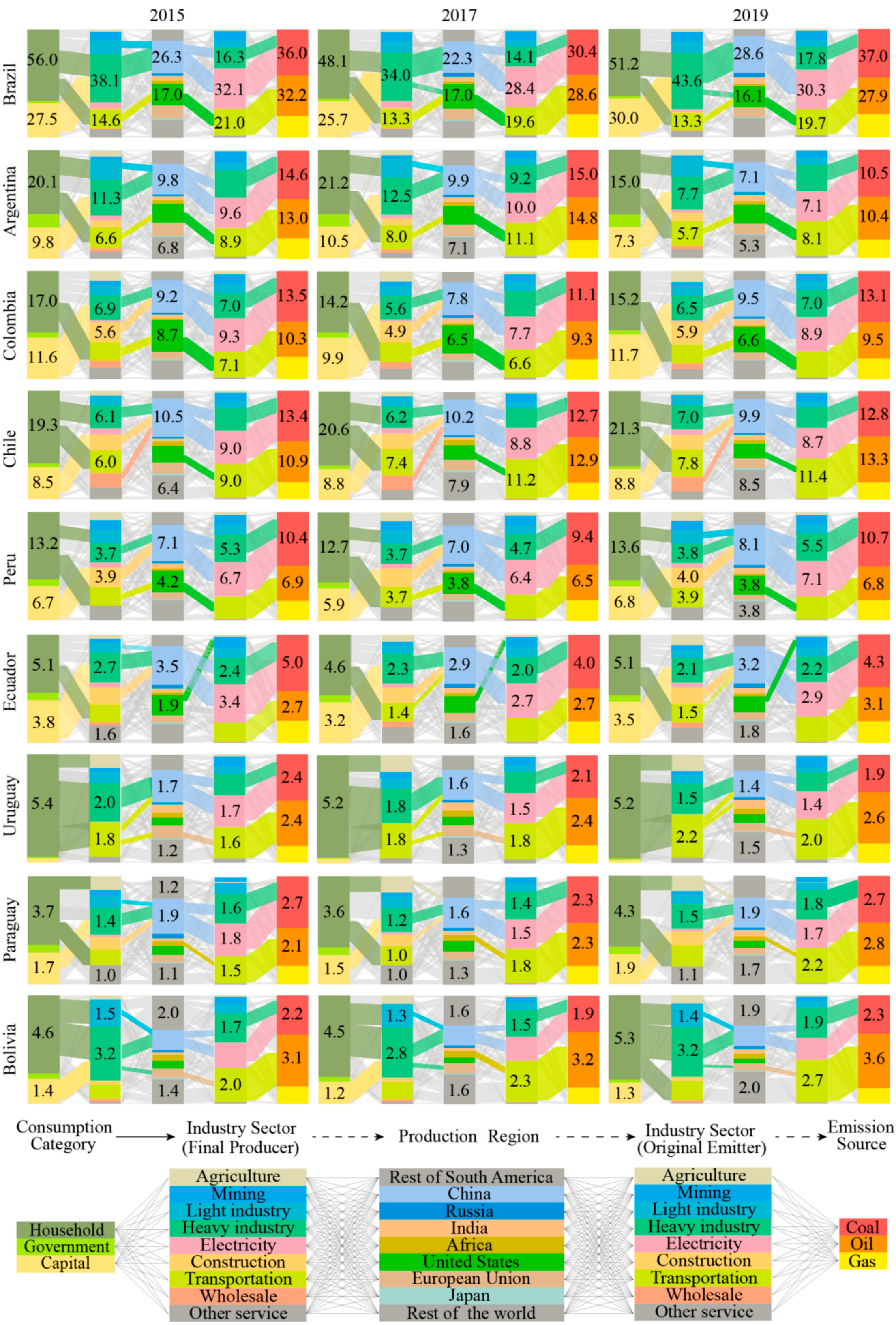

Fig. 3. Sankey diagram of imported emission flows in 2015, 2017 and 2019, the width of the flow represents the scale of emission, and the main path between each layer is marked in color.

emissions to South America, primarily due to its heavy reliance on coal for electricity generation, leading to high emissions in the heavy industry and transportation sectors (Wang et al., 2020). Notably, governmental contributions to emissions were comparatively minor. Additionally, the United States stood as the second-largest source of South America's imported emissions—except for Bolivia and Uruguay, where the European Union took precedence. Furthermore, the emissions from China (206.7 Mt) exceeded the combined contributions of the United States (120.6 Mt) and the European Union (60.5 Mt), with the transportation sector being the major contributor, driven by substantial oil demands. This is due to the growing trade between South America and a wide range of developing countries, represented by China (Michieka et al., 2013), and the lower energy efficiency in China compared to developed countries, as well as China's dependence on coal-oriented energy mix, which contributes significantly to its high export emissions (de Araújo et al., 2020).

4.4. Inequality in the distribution of emission flows among trade partners

From 2015 to 2019, emission flows among South American trade partners reveal a complex pattern. Initially, in 2015, the region recorded an emission outflow of 22.1 Mt, with Brazil contributing the lion's share of 15.6 Mt, followed by Chile at 2.4 Mt, and Argentina at 1.2 Mt. By 2019, this outflow swelled to 29.9 Mt, reflecting the expanding scale of South American trade, with Brazil's emissions decreasing to 13.9 Mt and Chile's to 3.2 Mt (Fig. 4). The European Union, the United States, and Japan were the predominant destinations, with their intake growing from 14.2 Mt to 20.3 Mt, indicative of a trend where developed nations increasingly import emissions from South American countries.

In contrast, the influx of emissions into South America decreased from 71.8 Mt to 59.0 Mt between 2015 and 2019, showcasing a shift towards greater production self-sufficiency, particularly in Brazil, which saw its imports drop from 13.5 Mt in 2015. Meanwhile, Argentina became the major recipient with 17.4 Mt in 2017, and Colombia recorded 15.1 Mt in 2019. China, which began as the primary source of emissions to South America, reduced its contribution from 41.4 Mt to 28.3 Mt, followed by the United States and India, indicates a transition within South America towards bolstering its production capacities, especially within Brazil. This illustrates South America's deep involvement in the international industrial chain.

It is worth noting that South America's international trade flows are about ten times larger than internal trade, which decreased from 8.7 to 7.0 Mt. The primary internal emission path transitioned from Brazil to Argentina, peaking at 3.6 Mt between 2015 and 2017, before shifting focus to Colombia in 2019 with 0.7 Mt. Additional noteworthy paths included emissions from Chile to Bolivia (2.5 Mt) and Peru (2.0 Mt). This internal flow of emissions predominantly moved from countries with larger GDPs to those with smaller GDPs, highlighting the industrial capacity constraints faced by the latter. Nevertheless, the pattern of emissions moving from lower to higher-income countries within South America was less evident, potentially due to a pervasive middle-income trap, suggesting that internal economic disparities influence emission flow patterns differently than external trade dynamics do.

This pattern of emissions embodied in trade within South America not only illustrates the complex dynamics of international trade but also highlights significant emission inequalities among the countries. As wealthier nations like Uruguay and Chile increasingly import emissions through industrial activities, they are also shifting the responsibility of emission mitigation to their trading partners. This redistribution of emissions is reflective of broader global trends, where developed countries outsource carbon intensive production and transfer their related emissions to developing regions. Within South America, this has led to a situation where countries with lesser economic clout, such as Bolivia and Paraguay (Cosbey & Vogt-Schilb, 2023), often deal with the emission consequences of processing raw materials and manufacturing goods primarily destined for export. The result is a carbon emission inequality that mirrors economic disparities, necessitating regional cooperation and policy interventions aimed at achieving a more equitable distribution of responsibilities.

4.5. Energy intensity and consumption patterns drive emission changes

In analyzing the socioeconomic determinants of emissions within South America, it becomes evident that energy intensity, energy structure, and shifts in industrial chains and consumption patterns have played significant roles in shaping the region's carbon footprint from 2015 to 2019.

Energy intensity emerges as the primary driver affecting production-based emissions, notably in Brazil, where a substantial decrease of 40.9 Mt was observed, mainly due to reductions in the electricity sector (26.5 Mt) and heavy industry (10.4 Mt). Additionally, energy intensity in Colombia similarly brought about a significant downward trend in emissions. The observed reductions in energy intensity are largely driven by government policies aimed at enhancing energy efficiency and promoting cleaner energy sources. For example, the "RenovaBio" program has been pivotal in advancing biofuel use in Brazil (Grassi & Pereira, 2019), and Colombia's new Renewable Energy Law (REL), which promotes the adoption and sustainable use of all forms of renewable energy (Villada Duque et al., 2017). However, a reverse trend was noticed in Argentina, with energy intensity increasing, primarily

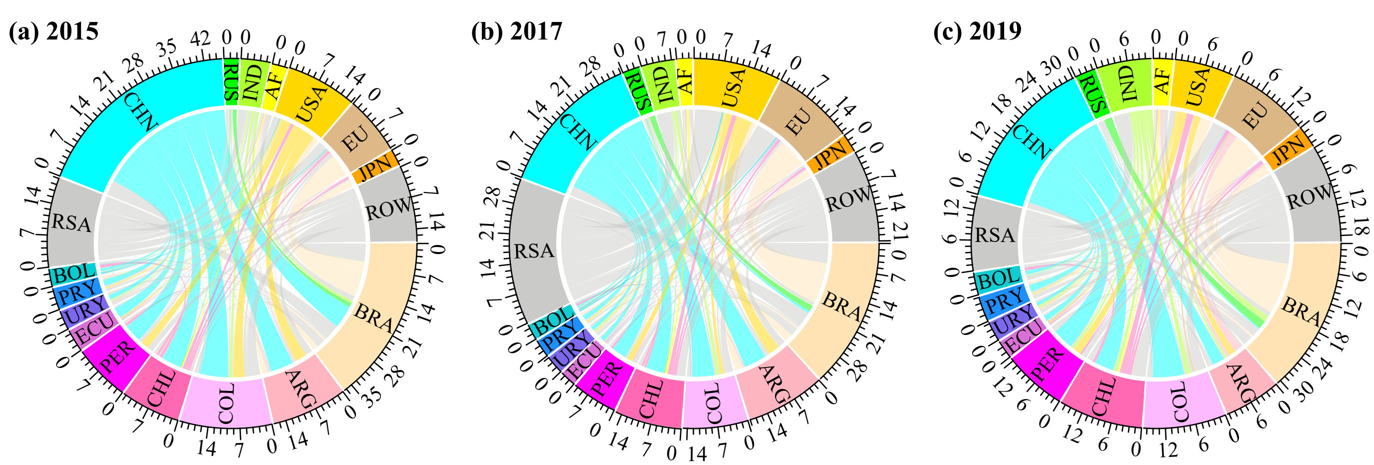

Fig. 4. Flows of emissions embodied in trade between the selected countries and their main partners, which are located inside or outside of South America, for more detailed information please see the Table S3 in the supporting information. The width of the flow indicates the relative emission values, and the unit is million tons. (a), (b) and (c) show the results for three selected years: 2015, 2017 and 2019.

affecting heavy industry and electricity sectors due to their operational inefficiencies. In contrast, energy intensity has decreased in Chile, Ecuador, Peru, and Bolivia due to their advancements in energy saving technology (Camioto et al., 2018).

The energy structure significantly influences production-based emissions across South America. Colombia, for instance, has seen an increase of 10.7 Mt in emissions, primarily from transportation, due to a growing dependence on fuel vehicles. Conversely, Argentina, Brazil, and Chile have reported decreases in emissions due to the shift from oil to natural gas in electricity generation, reflecting a regional trend towards cleaner energy sources (Peng et al., 2024). In Brazil, the transition is further supported by a robust development of renewable energy sources, including bioenergy and wind power (Muhammed & Tekbiyik-Ersoy, 2020). This shift has been greatly aided by governmental incentives and international partnerships, particularly with China (Bae & Velasco, 2011), which have been crucial in facilitating technology transfer and financial investment in renewable sectors. Argentina's 'RenovAr' program has effectively expanded its private renewable power generation capacity, addressing key constraints in the development of renewable energy within the country (Ruggeri & Garrido, 2021).

The role of the industrial chain across South America varies considerably, with domestic industrial chains serving as the primary drivers of domestic-related emissions in all countries. The domestic industrial chain in Brazil, Colombia, Chile, and Paraguay exhibited an initial increase followed by a decrease in emissions. Between 2015 and 2017, emissions in these countries increased by 1.1, 2.9, and 0.6 Mt, respectively. This increase was primarily due to policies on trade protection and import restrictions, which led to a substitution of imported goods with domestic products, coupled with an enhancement in national production capabilities, enabling previously imported materials to be domestically sourced (Oyarzún, 2013). Notably, from 2017 to 2019, it led to a reduction in emissions of 21.6 Mt in Brazil. Additionally, the domestic industrial chain has been a consistent driver of emission reductions in Argentina, Ecuador, Uruguay, and Bolivia, with total reductions amounting to 7.4, 2.6, 0.11, and 0.51 Mt, respectively. This reduction was largely due to a decrease in intermediate inputs consumed by domestic production units, primarily driven by the effects of technological advancements (Raihan, 2023). For more detailed information, please see Fig. S4 in the supporting information.

In the realm of export-related emissions, the forward industrial chain is a major driver in many countries. Specifically, in Chile and Uruguay, it is the primary factor driving emissions reductions, with decreases of 3.9 and 0.14 Mt, respectively. Conversely, in Peru and Ecuador, the forward industrial chain has been the main driver of increased emissions, which rose by 0.3 Mt and 1.1 Mt, respectively. This was due to an expansion in the production capabilities of the exporting countries, improved integration into the global industrial chain and international division, and local government policies that offered tariff incentives to encourage increased exports (Baracat et al., 2015). Finally, due to the minimal contributions of the backward industrial chain, industrial chains of other countries, and industrial chains among countries except the export country, they are not considered here.

On the consumption side, shifts in per capita consumption scale and consumption structure reflect economic fluctuations and changes in demand. The impact of per capita consumption on carbon emissions in Brazil, Colombia, and Peru has shifted from decreasing to increasing, attributed to economic volatility. In contrast, Argentina and Uruguay exhibit opposite trends. Moreover, while the consumption structure varies across South American countries, the population scale significantly contributes to variations in both consumption-based and export-related emissions, highlighting the complex interplay between socioeconomic factors and carbon emissions in South America.

5. Conclusions and policy implications

In this paper, we quantify the carbon emissions in South America from the production and consumption perspectives, using the latest global MRIO tables and emission inventory. We trace the emission flows from original emitters to final consumers and identify their critical driving forces. The results indicate that transportation and heavy industry are the main components of consumption-based emissions, and the primary contributor to trade-related emissions are intermediate products, especially direct intermediate products. Brazil is the only net-exporter, and developing countries are the major partners of trade-related emissions, most of which are embodied in heavy industry and transportation, and are linked to the original emitters themselves. Meanwhile, the main receivers of outflows are developed countries, and this role transfers to developing ones in the inflows; Brazil and Colombia are the primary contributors to outflows and inflows, respectively. In addition, energy intensity completely offsets the increasing influence of the per capita consumption scale in Brazil and holds partial offsetting effects in others. The energy structure continuously increases emissions in Colombia, and the consumption structure overall transfers to hold decreasing influence in Argentina and Bolivia. Furthermore, the effects of the industrial chain in domestic-related emissions are focused on the domestic industrial chain, and this role generally transfers to the domestic and forward industrial chains in export-related emissions.

Based on an exhaustive survey of carbon emissions and their drivers in South America, we propose a set of strategies focusing on technological advances, optimization of the energy mix, sector-specific measures, adjustments to consumption patterns, and a comprehensive overhaul of economic and industrial strategies:

Technological advances have the potential to reduce carbon-intensive products in the production process to promote the reduction of carbon emission intensity, which is the critical driver in decreasing production-based emissions (Fig. 5). Meanwhile, the technical research and development depend on the countries (e.g., Brazil, Argentina, and Peru) with large economic scale considering the long-term and abundant investment. Building on this foundation, a feasible approach is to develop energy- and carbon–neutral technology cooperation with both developed countries (Fig. 4) and emerging economies (Figs. 2 and 3). Simultaneously, smaller countries in South America, such as Paraguay, could seek assistance from the Green Climate Fund to foster the development of low-carbon technologies. Larger countries like Brazil, Argentina, and Peru should implement specific tax incentives and subsidies to encourage industries to invest in green technologies. Further enhancing this strategy, the establishment of a regional technology transfer framework could facilitate the widespread adoption of these technologies across smaller economies.

Meanwhile, another significant measure for reducing emissions is to clean up the energy structure (Fig. 5), which involves increasing the share of renewable energy and reducing reliance on fossil fuels. For example, Brazil should continue its leadership in bioenergy and implement policies to further integrate bioenergy with other renewable energy sources to create a more resilient energy network, while Uruguay should capitalise on its renewable energy strengths by continuing to develop wind energy and increasing the proportion of clean energy exports. Colombia, on the other hand, needs to strengthen its electricity infrastructure and technological innovation further to enhance the stability and reliability of its power supply, thus meeting the demands of its economic and social development. For the South American region, government subsidies and tax incentives for clean energy should be increased, and countries should select appropriate renewable energy development according to their natural advantages.

In addition, transportation emerges as a critical sector for carbon reduction in South America (Fig. 1). South American governments should set strict fuel economy standards and provide financial incentives for consumers to purchase electric vehicles, such as lowering import taxes on electric vehicle parts and offering tax rebates to consumers. Meanwhile, promoting the application of hydrogen in various stages of industrial processes, especially in heavy industry, which is another essential emitter, can accelerates the development of green industry

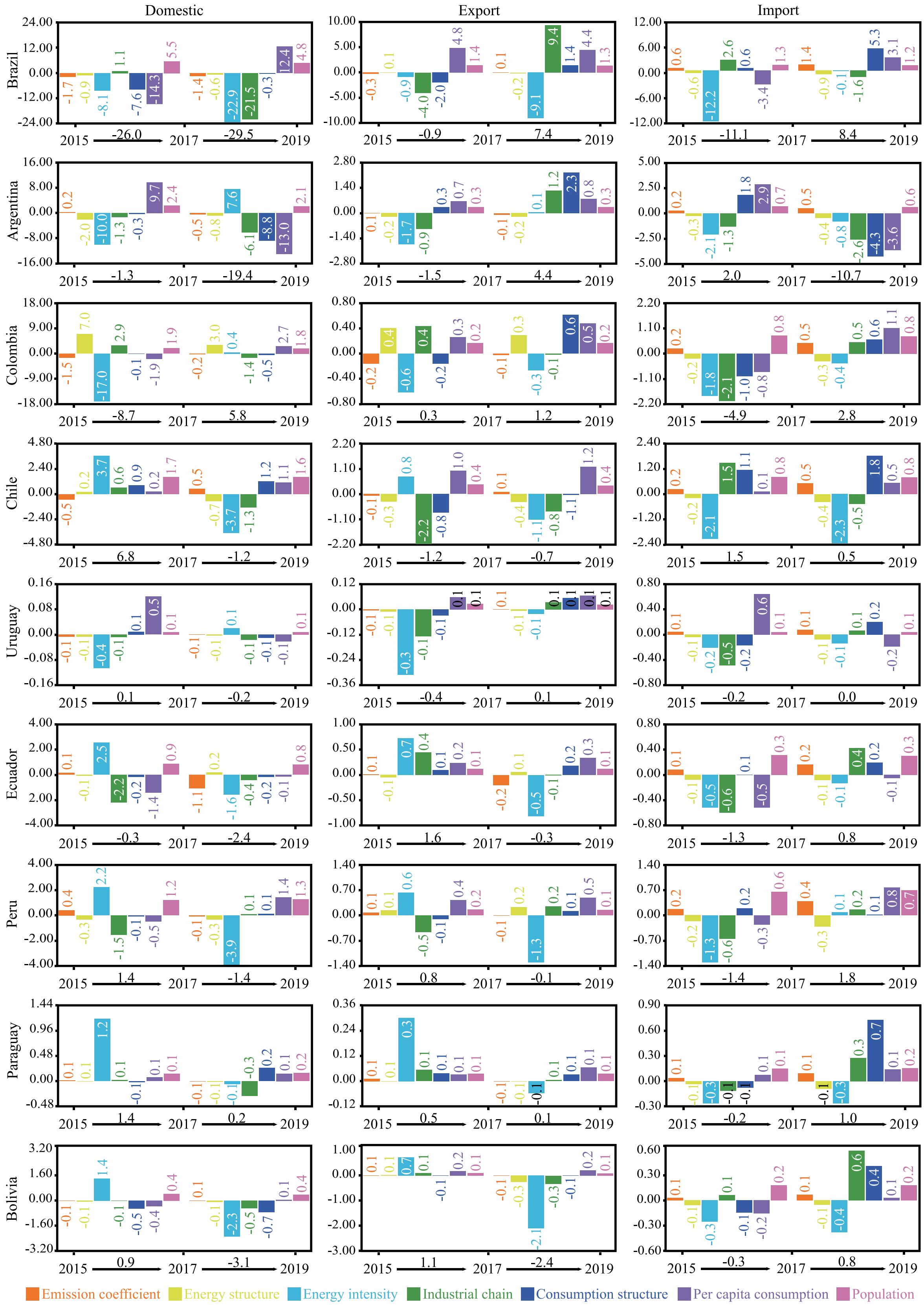

Fig. 5. Contributions of different socioeconomic factors to changes in South America's domestic-, export- and import-related emissions.

chains, especially in Brazil and Chile.

Additionally, the expectation of residents to improve their living conditions may trigger a inelastic demand for urban development in South America, which could promote the rise of emissions to some extent, and a low-carbon consumption structure is an excellent way to offset these negative impacts. Specifically, it would be beneficial for local governments to introduce energy efficiency benchmarks and corresponding grants to stimulate the large-scale production and use of energy-efficient appliances such as air conditioners and washing machines, as well as renewable energy equipment such as solar water heaters and solar lighting, especially in densely populated countries such as Brazil, Colombia and Argentina.

Furthermore, the resource-oriented industry structure induces an extensive economic development model in South America. Therefore, small-scale economies (e.g., Uruguay) should focus on information about leading industries (e.g., agriculture) to exploit their comparative advantages and improve energy efficiency. In contrast, for larger economies like Brazil), enhancing the production capacity of industry (especially high-tech industry) is a reasonable path to improve the added value of products and reverse the dilemma of economic growth, as well as address the long-term net inflow of emissions resulting from the import of manufactured goods in large quantities.

Moreover, further expanding the membership of the Southern Common Market could deepen industrial division among countries; for example, Brazil plans to become the economic and technological centre, and Uruguay has an incentive to become the energy centre. Meanwhile, strengthening the connections of transnational industrial chains and promoting the economic integration among countries in South America can resist external economic shocks and reduce emissions jointly, and moreover, avoiding falling back into poverty while achieving emission reduction targets.

CRediT authorship contribution statement

Zhenyu Wang: Writing – original draft, Methodology, Conceptualization. **Huaxi Peng:** Writing – review & editing, Data curation, Conceptualization. **Jing Meng:** Supervision, Conceptualization. **Heran Zheng:** Methodology. **Jie Li:** Visualization. **Jingwen Huo:** Data curation. **Yuxin Chen:** Validation, Conceptualization. **Quan Wen:** Project administration. **Xiaotian Ma:** Validation. **Dabo Guan:** Funding acquisition, Conceptualization.

Declaration of competing interest

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

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.gloenvcha.2024.102944.

Data availability

Data will be made available on request.

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