Regional inequality and CO₂ emissions-based trade across value chains networks: a multiscalar analysis from Brazilian states

Eduardo Rodrigues Sanguinet

ABSTRACT
This article analyses the interregional linkages and the relative intensity of CO₂ emissions embedded into domestic and global value chains from Brazilian states. An extended environmentally interregional input–output model (EEIIO) was applied to measure the bilateral trade in value-added (TiVA) and the total implicit emissions trade (TTE). The results reveal unbalanced pollution patterns in space. Few manufacturing hubs in core Brazilian states (mainly São Paulo and Rio de Janeiro) are net importers of intensive greenhouse gas (GHG) inputs from peripheries, implying an environmental responsibility driven by networks’ governance and relative position. By recognizing the role that multiscalar integration plays in implicit CO₂ in both production and trade, it is possible to build local strategies to reduce sustainable spatial gaps.

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greenhouse gas (GHG) emissions; implicit GHG; trade in value-added; Brazil; value chains; regional sustainable

INTRODUCTION
There is a gap in the regional science literature in recognizing the spatial variability of carbon footprints at different spatial scales (Batabyal & Folmer, 2020; Chen et al., 2017). The empirical literature has made considerable advances in extending economic models environmentally, mainly input–output (IO) models (Ali et al., 2018; Cruz et al., 2019; Zhang et al., 2019; Zheng et al., 2020). In this light, despite the growing concern of sustainable production networks, applied research lacks the explicit elements of territorial resources in socio-environmental carbon-based accounting, neglecting the identification of those drivers on both supply and demand sides responsible for pollution. The subnational structure is particularly relevant in large economies such as Brazil, which can accommodate spatially defined internal and international production networks (Silveira-Neto & Azzoni, 2012; Aroca et al., 2018; Atienza et al., 2021; Haddad & Araújo, 2021). Carbon-intensive industries are often dispersed geographically, based on location-decision patterns, implying an uneven spatial organization for building
sustainable economic–ecological paths among sectors and regions (Sajid et al., 2019; Visentin & Guilhoto, 2019).

In this regard, this study advances the literature by including spatial and environmental dimensions, measuring the interregional IO linkages and calculating the explicit content of CO$_2$ embedded in value chain networks, applied to the Brazilian case. The contribution is twofold. First, it includes carbon footprints across subnational and foreign networks, revealing the architecture of polluting networks within Brazilian regions. Second, the results provide useful insights for the environmental policies debate. Notably, the paper considers the direct and indirect effects on the supply–demand sides of networks, further shedding light on the role of spatially defined polluting networks inside Brazil.

Empirically, this study measures both backward and forward IO linkages at regional and industry levels and computes trade-offs between the spatial organization of value chains and the CO$_2$ content split between domestic and international scales. The analysis allows an assessment of the interregional dependency of production and an identification of key regional and sectoral drivers in building potential pollution networks (Owen et al., 2018). In the context of value chain networks, this paper adopts the concept of trade in value-added (TiVA), which measures the local value-added embedded in flows to attend to the final demand (Haddad & Araújo, 2021; Los et al., 2016, p. 20; Meng et al., 2017). The greenhouse gas (GHG) emissions considered are related to CO$_2$ content embedded in trade flows on an extended interregional IO structure (Dietzenbacher & Velázquez, 2007; Zheng et al., 2020). The hypothetical extraction method (HEM) is applied to compute both value-added and CO$_2$ implicit content, encompassing domestic and global destinations (Ali, 2015; Ali et al., 2018; Chen et al., 2017; Haddad et al., 2020; Los et al., 2016, p. 201; Zhang et al., 2019).

The results reveal that Brazilian inequalities arise from unbalanced industrial structures, implying uneven environmental responsibilities across interregional flows and the territorial content supplied to global markets (Cruz et al., 2019; Imori, 2015; Fearnside, 2000). This discussion presents valuable insights for policymakers regarding the network pulled and pushed by emissions (Sajid et al., 2019). In particular, it is possible to identify the emissions driven by the supply and demand sides to meet final demand by assessing backward and forward linkages. In addition, structural analysis can identify IO impulses throughout the Brazilian production networks that potentially explain carbon footprints at different geographical scales. Furthermore, by including a spatial dimension in environmental accountability, the results provide a helpful assessment regarding the need to consider IO linkages to design place-based sustainable policies.

The remainder of the paper is structured as follows. The following section presents the related literature. The third section details the method for accounting for TiVA and trade in CO$_2$. The paper then gives the main results and discussion. Finally, the last section presents the main considerations and policy implications of the study.

LITERATURE REVIEW

Despite the growing concern about climate change and international trade, most studies have predominantly focused on associating national integration into global value chains (GVCs) (Allen et al., 2016; Batabyal & Folmer, 2020; Zhang et al., 2019; Zheng et al., 2020). However, for implicit content embedded in trade, such an approach misses the role of subnational configurations of value chains in partially explaining countries’ and regions’ positions in terms of value-added trade and local assets implicitly embedded in production value chain networks (Cao et al., 2019; Pang et al., 2019; Su et al., 2017; Zhang et al., 2019). In this regard, evidence on emission content in trade has been considered an essential analytical tool to understand the main economic drivers – such as industries or stages of the chain of production – acknowledged
as environmentally responsible for a country’s global GHG emissions (Carvalho & Perobelli, 2009; Cruz et al., 2019; Su et al., 2017).

In order to understand the role of subnational geography of polluting networks, it is essential to point out the relationship between production, trade and environmental concerns. First, a composition effect drives the regional specialization in a specific basket of goods associated with competitive advantages (Grether et al., 2009; Krugman, 1991; Wang et al., 2019). In this regard, resource-based regions in international trade are likely to increase pollution (Cao et al., 2019; Copeland & Taylor, 1994). Second, the regional inequalities deal with one particular spatial architecture of networks, in which the supply and demand IO relations can be considered relevant drivers for polluting trade patterns (Cruz et al., 2019; Imori, 2015). Together, those aspects are essential mechanisms for spatial articulation within networks, relevant to economic and environmental governance patterns (Atienza et al., 2021), mainly in large countries, such as Brazil.

The composition effect fundamentally deals with the role of Brazilian regions in both global and domestic production networks. Notably, at the national scale, the country has increased its backward participation in GVCs as providers of low-tech goods and raw materials from agriculture and mining industries (Guilhoto et al., 2015; Hubbard et al., 2017; Lema et al., 2015; Viola & Lima, 2017). Furthermore, the internal organization of a value chain network tends to improve the role of resource-based peripheries to supply raw materials for industrialized areas within borders (Aroca et al., 2018; Azzoni & Haddad, 2018; Perobelli et al., 2019).

On the other hand, regional inequalities matter to promote structural changes for sustainable quality linkages (Zheng et al., 2020). Although the richest Brazilian regions are important demanders of inputs from the subnational peripheries – allowing for local economic development – the transfer of technology and efficiency within IO does not always lead to cleaner production in the backward industries and regions (Mutascu, 2018). Nevertheless, given the structure of domestic value chains in Brazil, trade can considerably affect the polluting role of poorer areas internally. Moreover, given the economic effort involved in mitigating CO₂ emissions, it is essential to assess the link between regional performance and the carbon footprint geographically (Ali, 2015; Sajid et al., 2019; Zhang et al., 2020). In particular, if an industrialized region demands raw materials from a specialized resource region, the IO networks, directly and indirectly, affect the whole value chain network. Meanwhile, the supply–demand economic relations further systemically determine the local content embedded in trade flows, including implicit CO₂ emissions (Chen et al., 2017).

Empirically, environmentally extended input–output (EEIO) models have received considerable attention in assessing GHG in trade (Ali et al., 2018; Zheng et al., 2020). There is analytical potential for integrating the economic, social and environmental interactions as pillars of sustainability (Su et al., 2017) and efficient use of natural resources (Haddad et al., 2020). Thus, purely national-based analyses hide the carbon footprints occurring inside the country, where mitigation policy tools generally take place. Nonetheless, there is a claim for the theoretical inclusion of a spatial dimension. Recent efforts have attempted to include intra-country emissions measures in developed countries (Ali et al., 2018; Chen et al., 2017); however, they have not seen the relevant role of TiVA (Haddad & Araújo, 2021). It is helpful to assess the territorial endowments embodied in TiVA to identify environmental aspects, mainly in large developing countries such as Brazil, with high resource-based, backward linkages towards GVC and persistent inequalities (Cruz et al., 2019).

The implications of value chain networks’ composition are straightforward in formulating environmental and regional policies. For the Brazilian case, however, the subnational inequalities are associated with centralized environmental legislation at the federal (national) level
(Vieira et al., 2018), further comprising economic–ecological sustainability policies in a place-based sense (Daneri et al., 2021). Therefore, there is a claim for evidence of the role of governance rescaling to deal with the environmental responsibility of regions and industries within borders (Setzer, 2017).

**DATA AND METHODOLOGY**

This study relies on the 2011 interregional input–output (IRIO) table estimated by the University of Sao Paulo Regional and Urban Economics Lab (NEREUS) (Haddad et al., 2018). Furthermore, an environmentally extended interregional input–output (EEIIO) matrix was used, with 27 regions \((n = 1, \ldots, 27)\) and 68 industries \((s = 1, \ldots, 68)\). Evidence in the IO suggests that the tables represent the economic structure that tends to be stable over time, as suggested by Timmer et al. (2016), thereby facilitating the assumption that the economic system is not considerably different. The industry-level anthropogenic emissions database is given by the Emissions Database for Global Atmospheric Research (EDGAR) (Huang et al., 2017) available in EORA Multiregional IO tables (Lenzen et al., 2013). For the industrial compatibilization, see Table S1 in the supplemental data online.

Initially, the degree of spatial interdependency was assessed, measuring both the structural backward (BL) and forward (FL) total CO2 linkages, based on the hypothetical extraction method (HEM) (Ali, 2015, p. 20; Ali et al., 2018). As a result, the CO2 industry-level coefficient\(^1\) is given by:

\[
\varphi_s = \frac{P_s}{x_s}
\]

where \(P_s\) is the total emissions; and \(x_s\) is the total output of an industry \(s\). Therefore, \(\varphi\) is the vector representing the direct emissions of each industry in the IRIO model. The total direct and indirect CO2 emissions are measured by multiplying the diagonalized vector \(\hat{\varphi}\) by the Leontief and Ghosh inverse matrices. The demand-side assessment is given by:

\[
\text{Demand:} C^d = \hat{\varphi}(I - A)^{-1}f
\]

\[
\text{Supply:} C^s = v'(I - B)^{-1}\hat{\varphi}
\]

where \(A\) is a technical coefficients matrix equal to \(A = Zx^{-1}\); \(B = \hat{x}^{-1}Z\) represents the output coefficients, with \(Z\) the input requirements needed to produce US$1 of output; \(v'\) is the row vector of regional and industrial value-added; and \(f\) represents the interregional final demand.

First, the CO2 linkages were calculated. Accordingly, the effect of extracting the interregional relations in region 1 is backward in essence, represented by \(BL_1 = [C^d - C^d]\). The superscript \(^*\) represents the Cella HEM extraction from the IRIO (Ali et al., 2018). The same logic is applied to the supply side: \(FL_1 = C^s - C^s\). The normalized indexes are given by:

\[
BL^n_1 = \left[ \frac{i'C^d - i'C^d}{i'C^d} \right] \quad \text{and} \quad FL^n_1 = \left[ \frac{i'C^s - i'C^s}{i'C^s} \right]
\]

where \(i\) is a summation vector of 1s. For analytical purposes, a backward linkage above the unit \((BL^n_1 > 1)\) suggests that an increase of US$1 of final demand \((f)\) will produce an increase in emissions above the average without an extraction. On the other hand, a forward linkage \(> 1\) \((FL^n_1 > 1)\) indicates that an increase of US$1 of value-added will generate emissions in the same way. Both backward and forward linkage indicators above unity indicate a key region for generating emissions (Chang & Lahr, 2016).
The second methodological step measures the relationship between TiVA and CO₂ content in trade, following Haddad et al.’s (2020) strategy. Initially, the bilateral TiVA for each origin-destination pair across domestic and foreign destinations was estimated. For that, the value-added from a given region \( n = 1 \) sent to another region \( n \) is measured. Specifically, it can be viewed as the difference between the total domestic value-added (DVA) of region 1 and the DVA in a counterfactual situation, in which region 1 does not trade with \( n \). This approach was initially proposed for a global perspective by Los et al. (2016) and extended for a multiregional model by Chen et al. (2018) and Haddad et al. (2020). Thereafter, the actual DVA from region 1 is given by:

\[
DVA_{1,n} = v_1(I - A)^{-1}f_i
\]

(4)

where \( v_1 \) is a row matrix of VA coefficients of region 1, and 0s elsewhere like

\[
v_1 = 0 \ 0 \ldots 0\]

In this regard, the counterfactual of DVA is based on the hypothetical extraction (target exclusion) of the intermediate and final demand relations between 1 and \( n \). Indeed, it equals \( DVA_{1,n}^* = v_1(I - A_{1,n}^*)^{-1}f_{1,n}^* \). The amount of TiVA from 1 to \( n \) can be measured as:

\[
TiVA_{1n} = DVA_1 - DVA_{1,n}^*
\]

(5)

As a global multiregional model was not used, it is assumed that international destinations are exogenously defined, as suggested by Haddad et al. (2020), in which the account of TiVA supplied to foreign markets with \( m \) destinations \( \{m = 1, \ldots, m, \text{RoW}\} \) represents how much VA in each region is embedded in GVC.

Finally, the bilateral total implicit emissions trade (TTE) in CO₂ was measured, replacing the coefficient vector \( v \) by \( w \). Therefore, from region 1 to region \( n \) (subnational), the amount of implicit emissions in domestic value chains (EDVC) can be measured as:

\[
EDVC_{1,n} = \varphi_1(I - A)^{-1}f_i - \varphi_1(I - A_{1,n}^*)^{-1}f_{1,n}^*
\]

(6)

Furthermore, the implicit emissions embedded in foreign trade exports – as an indicator of total emissions embedded in GVCs – is given by:

\[
EGVC_{1,m} = \varphi_1(I - A)^{-1}f_i - \varphi_1(I - A)^{-1}f_{i}^*
\]

(7)

The polluting intensity of production value chain networks was measured by the relative ratio of TiVA and both EDVC and the implicit emissions for global value chains (EGVC), following the proposed resource-based index by Haddad et al. (2020). The only measurement change made is that we compute the average index as the ratio between (1) each bilateral TiVA flow and the total TiVA by (2) the ratio of each EDVC or EGVC and the total amount of CO₂ emissions in trade. Furthermore, the average relative emission-based in trade (AET) from region 1 to another subnational region \( (j = 1, \ldots, j) \), and the AET from region 1 to \( m \) \( (m = 1, \ldots, m) \) foreign destination are respectively given by:

\[
AET_{1,n}^{DVC} = \frac{1}{n} \left( \frac{\sum_i TTE_{1,n}}{\sum_i TiVA} \right) \left( \frac{\sum_i TiVA_{1,j}}{\sum_i TiVA} \right)^{-1} \quad \forall \ i, j = \{1, \ldots n\}
\]

(8)

\[
AET_{1,m}^{GVC} = \frac{1}{n} \left( \frac{\sum_i TTE_{1,m}}{\sum_i TiVA} \right) \left( \frac{\sum_i TiVA_{1,m}}{\sum_i TiVA} \right)^{-1} \quad \forall \ i = \{1, \ldots n\}, \ j = \{1, \ldots, m, \text{RoW}\}
\]

(9)
Values > 1 indicate a potentially polluting value chain network; and values < 1 show the opposite.

**Case study overview**

Figure 1 shows Brazil’s core–periphery economic geography pattern and the uneven spatial export orientation. Economic concentration occurs in the hubs of Southeastern states: São Paulo (SP), Rio de Janeiro (RJ), Minas Gerais (MG) and Espírito Santo (ES). The peripheries (mainly Midwest and North) follow an export-based growth model (primarily grains and cattle and mining). Table S2 in the supplemental data online provides details of the Brazilian regional structure.

**EMPIRICS**

The Cella HEM has been extended to assess CO₂ linkages, as shown in Table 1. Table S3 in the supplemental data online shows the results of the industrial linkages. It is noteworthy that Brazil is formed by several small economies with lower backward and forward linkages. The differences between total CO₂ on the supply and demand sides grow according to the hierarchical position of Brazilian states in the domestic value chains’ intermediate flows. The poorer peripheral economies of the North, Northeast and Midwest have similarities in linkages size. An exception is Amazonas (AM) – which has the free import zone – and an essential manufacturing complex in Northern Brazil. Indeed, the Amazonas state is a crucial region, a potential governance driver of transferring CO₂ across networks. The spatial pattern changes when we observe the differences between backward and forward linkages for the Southeastern and Southern states, revealing the network complexity of organizing networks’ domestic architecture. For the industrial content of CO₂ in trade results, see Table S4 in the supplemental data online.

The regional distribution of CO₂ in multiscalar trade is shown in Table 2. Notwithstanding, interregional patterns differ considerably from foreign destinations trade. Except for Sao Paulo, all other states have a heterogeneous profile across domestic networks being potentially CO₂ net importers or exporters. Thereby, four states stand out as net redistributors of CO₂ within the country – mainly São Paulo (SP – Southeastern), Amazonas (AM – Northern), Pernambuco (PE – Northeastern), and Rio de Janeiro (RJ – Southeastern). However, other states stand out as clearly net exporters of emissions for global trade flows, apart from Amazonas and Rio.
Table 1. Backward and forward Cella hypothetical extraction method (HEM) linkages at the regional level.

| Macrozone | State | Total CO₂ (Gg) | Normalized | Total CO₂ (Gg) | Normalized | Role in the interregional system |
|-----------|-------|----------------|------------|----------------|------------|---------------------------------|
| North     | RO    | 595.64         | 0.32       | 835.82         | 0.29       | Self-dependent                  |
|           | AC    | 108.63         | 0.07       | 146.91         | 0.07       | Self-dependent                  |
|           | AM    | 4568.54        | 1.38       | 3380.19        | 1.19       | Key                             |
|           | RR    | 82.93          | 0.05       | 92.21          | 0.04       | Self-dependent                  |
|           | PA    | 2404.92        | 0.96       | 2033.41        | 0.94       | Self-dependent                  |
|           | AP    | 129.98         | 0.07       | 139.81         | 0.05       | Self-dependent                  |
|           | TO    | 486.84         | 0.21       | 412.36         | 0.20       | Self-dependent                  |
| Northeast | MA    | 1175.44        | 0.54       | 966.05         | 0.49       | Self-dependent                  |
|           | PI    | 585.62         | 0.25       | 533.02         | 0.23       | Self-dependent                  |
|           | CE    | 1972.13        | 0.78       | 1678.78        | 0.67       | Self-dependent                  |
|           | RN    | 862.80         | 0.37       | 777.78         | 0.38       | Self-dependent                  |
|           | PB    | 1091.43        | 0.40       | 928.00         | 0.35       | Self-dependent                  |
|           | PE    | 3461.09        | 1.16       | 3013.43        | 1.07       | Key                             |
|           | AL    | 1261.33        | 0.41       | 1141.42        | 0.46       | Self-dependent                  |
|           | SE    | 963.27         | 0.33       | 536.72         | 0.34       | Self-dependent                  |
|           | BA    | 6119.14        | 2.52       | 4484.87        | 2.14       | Key                             |
| Southeast | MG    | 14,252.84      | 5.30       | 10,936.96      | 4.63       | Key                             |
|           | ES    | 2391.86        | 1.12       | 1714.16        | 1.20       | Key                             |
|           | RJ    | 17,683.78      | 5.33       | 7566.93        | 5.36       | Key                             |
|           | SP    | 53,106.29      | 16.02      | 37,496.64      | 14.36      | Key                             |
| South     | PR    | 10,402.84      | 4.39       | 8828.23        | 3.96       | Key                             |
|           | SC    | 5921.89        | 2.39       | 5084.56        | 2.13       | Key                             |
|           | RS    | 8424.95        | 3.54       | 8103.31        | 3.10       | Key                             |
| Midwest   | MS    | 2111.99        | 0.86       | 2018.86        | 0.91       | Self-dependent                  |
|           | MT    | 2404.82        | 1.14       | 2669.94        | 1.12       | Key                             |
|           | GO    | 4509.56        | 1.87       | 4737.63        | 1.78       | Key                             |
|           | DF    | 1761.12        | 1.27       | 1939.82        | 0.80       | Base                            |

Source: Author’s elaboration (2021).

de Janeiro. Interestingly, diversified regions are net emissions’ importers across the domestic value chain network – such as all southern states and southern and Bahia (BA) from the Northeast.

Based on equations (8) and (9), Figure 2a shows each Brazilian state’s average relative emission-based trade for both DVC and GVC. On the sales side (vertical axis), the State of Amazonas (AM) reveals a potential for supplying and transferring local value-added to the rest of the country. Meanwhile, the amount of value-added is further intensified in CO₂. The remaining Northern states present an average index > 1 on DVC trade. Regarding inflows, these states receive more intense polluting TiVA transfers from the Northeastern and Midwestern states. Finally, Figure 2b shows resource peripheries are highly intense in CO₂ emissions to exports. Remarkably, the State of Alagoas (AL) stands out (it is the largest sugar manufacturer and refining exporter in Brazil). Further, Pernambuco (PE) has the highest average relative emission-based trade (AET), indicating that foreign demand induces pollutants in both states. Manufacturing areas also have higher AET, such as Northern Amazonas, Southeastern Sao Paulo, Northeastern Bahia, and Southern Rio Grande do Sul.
### Table 2. Emissions on multiscalar trade (outflows and inflows by origin, Gg CO₂).

| Macrozone | State | Outflows (%) | Inflows (%) | Exports (%) | Imports (%) |
|-----------|-------|--------------|-------------|-------------|-------------|
| North     | RO    | 1674.4 0.6%  | 2336.8 0.8% | 195.2 0.3%  | 171.7 0.3%  |
|           | AC    | 282.1 0.1%  | 606.8 0.2%  | 27.4 0.0%   | 34.2 0.1%   |
|           | AM    | 10,602.0 3.6% | 6460.8 2.2% | 1107.1 1.8% | 2015.7 3.7% |
|           | RR    | 184.5 0.1%  | 395.5 0.1%  | 11.0 0.0%   | 28.0 0.1%   |
|           | PA    | 4340.4 1.5% | 5802.8 2.0% | 2011.6 3.3% | 786.4 1.5%  |
|           | AP    | 253.7 0.1%  | 574.9 0.2%  | 69.3 0.1%   | 43.5 0.1%   |
|           | TO    | 1087.1 0.4% | 1515.4 0.5% | 109.5 0.2%  | 103.0 0.2%  |
| Northeast | MA    | 2251.4 0.8% | 3628.9 1.2% | 563.5 0.9%  | 338.9 0.6%  |
|           | PI    | 1228.3 0.4% | 1806.3 0.6% | 106.1 0.2%  | 151.7 0.3%  |
|           | CE    | 4509.0 1.5% | 5356.9 1.8% | 407.1 0.7%  | 648.0 1.2%  |
|           | RN    | 1786.9 0.6% | 2559.4 0.9% | 151.3 0.2%  | 309.0 0.6%  |
|           | PB    | 2219.7 0.8% | 2688.9 0.9% | 140.3 0.2%  | 268.6 0.5%  |
|           | PE    | 7179.9 2.4% | 6613.9 2.2% | 1145.5 1.9% | 1054.2 2.0% |
|           | AL    | 2367.9 0.8% | 2120.7 0.7% | 1372.0 2.2% | 324.2 0.6%  |
|           | SE    | 1664.2 0.6% | 1838.5 0.6% | 101.3 0.2%  | 268.7 0.5%  |
|           | BA    | 10,425.5 3.5% | 14,964.4 5.1% | 2193.2 3.5% | 2490.7 4.6% |
| Southeast | MG    | 26,034.6 8.8% | 28,807.8 9.8% | 6385.4 10.3% | 4863.8 9.0% |
|           | ES    | 3905.3 1.3% | 6675.1 2.3% | 1635.8 2.6% | 828.1 1.5%  |
|           | RJ    | 29,411.2 10.0% | 28,361.5 9.6% | 4771.9 7.7% | 5676.5 10.5% |
|           | SP    | 105,374.6 35.7% | 79,889.5 27.1% | 23,848.5 38.6% | 21,710.1 40.2% |
| South     | PR    | 21,106.3 7.2% | 25,834.1 8.8% | 4074.2 6.6% | 3358.6 6.2% |
|           | SC    | 12,199.9 4.1% | 14,298.4 4.9% | 2350.1 3.8% | 1937.1 3.6% |
|           | RS    | 18,620.0 6.3% | 20,456.9 6.9% | 3939.8 6.4% | 3578.6 6.6% |
| Midwest   | MS    | 4625.2 1.6% | 4775.3 1.6% | 976.0 1.6% | 518.9 1.0% |
|           | MT    | 5657.9 1.9% | 6075.8 2.1% | 2189.7 3.5% | 665.7 1.2% |
|           | GO    | 10,586.4 3.6% | 10,420.3 3.5% | 1689.9 2.7% | 1183.5 2.2% |
|           | DF    | 5220.8 1.8% | 9933.5 3.4% | 238.9 0.4% | 623.7 1.2% |
| Brazil    |       | 294,799.1 100.0% | 294,799.1 100.0% | 61,811.4 100.0% | 53,980.9 100.0% |

Source: Author’s elaboration (2021).
Figure 2. Multiscalar average relative emission-based trade for domestic and global flows.
DISCUSSION

About 30% of global emissions originate from international trade (Yamano & Guilhoto, 2020). Interregional TiVA is relevant to the total emissions produced within Brazil, in which around 83% of CO₂ emissions embedded in trade are absorbed within the country’s borders. Our assessment identified the leading patterns of CO₂ interdependence across economic geography (Chang & Lahr, 2016). Furthermore, the variety of industrial sectors in the territories implies a prominent heterogeneity in space, building a more complex network of emissions generation and transfer (Atienza et al., 2021). As much as the industries have heterogeneous CO₂ intensity coefficients, the spatial production pattern indicates the polluting role across networks (Zheng et al., 2020). Interestingly, peripheries with relatively lower total emissions in trade are sourced in their territories, while core areas are all key regions in terms of linkages. Pollution governance depends on the Brazilian subnational architecture as forward linkages are stronger than backward linkages, indicating that core states potentially orchestrate polluting exchanges within the country.

The relative accounting between TiVA and the amount of implicit CO₂ in trade provides a clear picture of how states interact concerning pollution. The heterogeneity of productive integration within Brazil suggests the provision of value-added for domestic and global value-added trade flows, imposing barriers to local capacities to sustainable integration in production networks. Our results show that manufacturing can offer higher value-added networks, the most intense CO₂ in the industrial pool. The governance in terms of interregional positions of TiVA and emissions trade flows implies dominance in the core richest areas within Brazil – the main entrance and exit doors for implicit GHG in the whole country. Remote poorer regions have diffuse positions in polluting networks, depending on how they are linked to domestic and global flows – which is strongly guided by the degree of specialization in providing raw materials without processing. Higher linkages were found in more diversified economic core areas, implying the double role of demanding polluting inputs from the hinterland (induced effect) and further transferring across domestic and foreign networks from exports. After that, the hierarchical buyer–supplier relations become a relevant component for identifying spatial environmental responsibility. It can impose several barriers for local capacities to sustainable integration in value chains in large countries like Brazil. The hinterland connectivity to main hubs or gateways regional poles can be addressed (Chen et al., 2017). Finally, when this structural picture is analysed under the lens of environmental accounting, the strength of inequalities becomes a critical analytical tool to guide policymakers to mitigate the pollution intensity in networks.

CONCLUSIONS

This study has identified an uneven spatial pattern in Brazil: a few industrialized hub areas are responsible for most interregional consumption-based trade, mainly due to demand-induced linkages by mostly Brazilian poorer peripheral states.

For the design of regional and environmental policies, these results indicate the need for a broader look beyond the sectorial intensity of emissions, but that incorporates a systemic understanding. The supply–demand impulses propagate through the IO linkages. It is not enough to penalize the highly polluted industries without considering the role of intermediate demand on these sectors. Therefore, it is crucial to promote actions on value-added components, such as tax rates on capital profits aimed at greater environmental justice in affected territories and financial incentives for activities that can induce changes in the logistics distribution of low-carbon goods. This suggestion is intended to discourage investors from allocating capital to input-intensive and potentially emissions-intensive companies. In addition, policy design cannot be spatially blind, where regions dependent on natural resources and a polluting local structure
need to generate mechanisms that allow for changing the composition effect, either through economic diversification or even less polluting technologies.

A limitation of this study is that it includes a limited spatial administrative view, hiding a set of relevant territorial embeddedness. In addition, the EEIO hides the role played by some non-economic actors, revealing a partial picture of networks.

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NOTES

1 For industrial compatibility and emission intensity coefficients, see in the supplemental data online.
2 For bilateral results, see Tables S4 and S5 in the supplemental data online.
3 The emission coefficients of primary activities (agriculture, forest, and mining) are high (see the supplemental data online), but the DVA is relatively small, given the primary character of the industry.

ORCID

Eduardo Rodrigues Sanguineti http://orcid.org/0000-0002-6310-7214

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