Identifying the sources of structural changes of greenhouse emissions in Brazil: an input-output analysis from 2000 to 2020

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Abstract

The present study aims to determine the most relevant effects and sectors contributing to the increase or mitigation of Brazil's GHG emissions between 2000 and 2020. For that, the authors use a Structural Decomposition Analysis (SDA) based on a time series of input-output tables and the country's emissions inventory to build GHG emission vectors and decompose emissions into economic effects. As a result, the study found that in the period analyzed, Brazil's GHG emissions were pushed by an increase in the level of final demand, an increase in the share of emission-intensive final demand categories (such as exports), and an increase in the share of emission-intensive industries. Agriculture, transport, distribution and production of electricity, water and gas, and industrial commodities were the most relevant industries behind the country's emission trajectory in the period. On the other hand, the total increase in GHG emissions – due to level and composition effects – was partially offset by a decrease in the intensity of emissions per unit produced.

Key-words: greenhouse gas emissions; climate change; structural change; input-output analysis

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1. Introduction

Brazil delivers the highest GHG emissions in Latin America. In 2019, the country emitted about 1.5 tCO2e, accounting for 3% of global emissions (Simões & Delivorias, 2022). The country is also one of the largest suppliers of agriculture and livestock commodities worldwide (FAO, 2022). Notably, the emissions of the agriculture sector, including land use and forest change, amount to 73.1% of Brazil's total GHG domestic emissions (SEEG, 2021). As a developing economy, the country should pursue green industrial policies to modernize its production structure and change its international trade pattern. Such a challenge makes new investments in sectoral and structural linkages of the economy a critical element for the global debate about emissions.

Meeting the Paris Agreement's goals requires countries, including Brazil, to identify the primary sources of emissions in their economies and choose paths to take advantage of their main virtues and potential for sustainable development. This paper examines historical data using a structural decomposition analysis (SDA) to identify the main effects that raised or mitigated Brazil's GHG emissions between 2000 and 2020. Our SDA takes advantage of an annual time series of input-output tables (IOT) between 2000 and 2020 (Alves-Passoni & Freitas, 2020) and national greenhouse gas inventories (SEEG, 2021) to identify the leading industries and mechanisms behind the trajectory of Brazil's productive GHG emissions over the last two decades.

The key questions we seek to address are: what are the most polluting industries in the Brazilian economy? What are the main effects inhibiting a decrease in GHG emissions? What are the potential effects to support a decarbonization trajectory? How does the emissions intensity of Brazil's exporting industries compare to the average emissions intensity of the economy? How has this changed over the last two decades?

Our key findings indicate that Brazil's increase in GHG emission increase during this period is attributed chiefly to the inertial rise in the level of final demand, exacerbated by the compositional effect of increased GHG emissions on exports. While reducing emission intensity helped mitigate this increase, much more substantial gains were still needed to curb it fully. Agriculture, energy, transportation, and industrial commodities are the primary industries contributing to the rise in Brazilian emissions despite sporadic signs of improvement in specific periods.

The present study's contributions are threefold. It adds to a broader literature employing SDA and IOT to examine the effects driving emission variations in a specific economy. It adds to the literature on IOT alongside data on energy consumption and pollutant emissions to identify key alternatives for a sustainable development trajectory. It also adds to the more recent literature on national and regional input-output tables aimed at understanding the role of international trade in shaping new emission patterns.

This paper is divided into five additional sections. The second section reviews the existing literature and descriptive statistics to identify historical trends of GHG and other pollutant emissions related to production and trade patterns. The third section introduces the data used in this paper and the SDA method adopted. The fourth section presents the key findings, while the fifth discusses them based on the related literature, to provide insights for policymakers. The sixth section concludes the paper with a summary of its main contributions.

2. Review of historical trends

Since the 1990s, several studies have explored pollution emission trends in Brazil using the input-output framework, particularly delving into the contradictions behind international trade patterns. Young (1998) identified that exports were already more emission-intensive across various pollutants in the 1980s, when export-oriented policies to offset trade deficits further exacerbated that trend. According to Ferraz & Young (1999), Machado et al. (2001), Carvalho & Perobelli (2009), and Gramkow (2011), that trend continued to worsen in export-oriented industries in the subsequent years of liberalizing reforms of the 1990s. However, some other sectors managed to reduce their emission intensities. Even so, the duality of export firms being competitive by waiving environmental standards and the need to comply with environmental standards set by international markets was much debated (Young & Lustosa, 2001; Young & Pereira, 2000).

From the 2000s onward, this debate further expanded, driven by the increased availability and quality of databases and methods, and the emerging trends in trade patterns, production fragmentation, and the pollution havens hypothesis (Cole, 2004; Levinson & Taylor, 2008; Duan, Ji & Yu, 2020).[4] On the one hand, production fragmentation has made it harder to track where pollution is generated and consumed, prompting many studies to examine trends of pollution havens (Kanemoto et al., 2012; Meng et al., 2018a; Wang et al., 2019; Zhong et al., 2022). On the other hand, as a result of production fragmentation, market openness, and deregulation, each stage of the production process could potentially occur in regions showing economic and environmental advantages, thus allowing for a reduction in global emissions (Copeland & Taylor, 2004; Arce González et al., 2012). Additionally, the intensification of South-South trade has also impacted GHG emissions, as highlighted by Meng et al. (2018b).

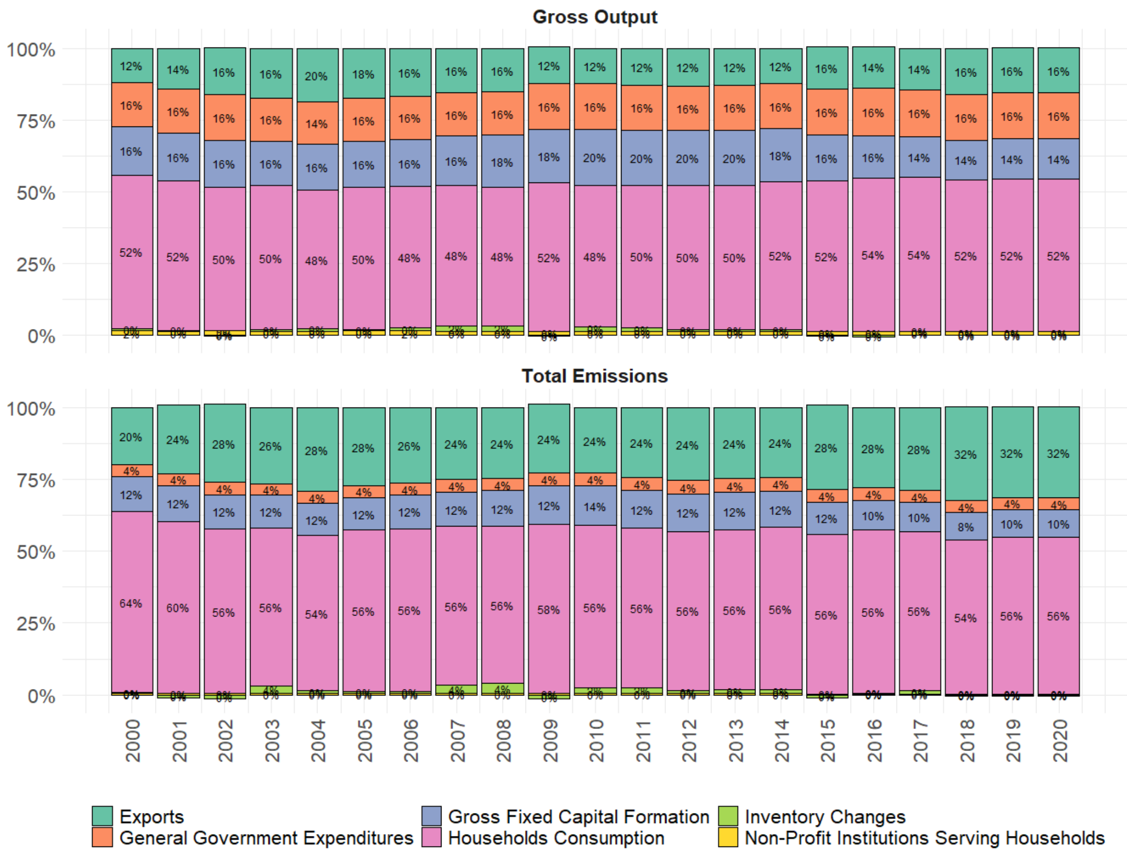
In Brazil in the 2000s, with the rise in economic growth alleviating poverty and encouraging different patterns of consumption, part of the debate also focused on the emissions associated with domestic consumption, especially energy consumption (Perobelli et al., 2015; de Abreu et al., 2021). Nevertheless, historical data show that in Brazil, exports tend to be more carbon and energy-intensive than other components of final demand, raising concerns about the environmental sustainability of the country's current trade pattern and how it has been changing in recent years (Nassif & Castilho, 2020; Castilho et al., 2019). The already high share of commodities in the country's export basket increased (even when discounting the effects of increased commodity prices) as the share of energy-intensive products took off in the last decade (Young, 2016; UNIDO, 2017). From a sustainability standpoint, this seems to be pushing Brazil toward a trade pattern highly specialized in carbon-intensive goods, increasing the country's emissions embodied in trade. Despite pressures to adhere to international environmental standards, such initiatives have not prevented Brazilian exports from becoming increasingly carbon-intensive.

Figure 1 presents the evolution of the gross output and total GHG emissions shares for six final demand categories: households' consumption, gross fixed capital formation, inventory changes, general government expenditures, exports, and non-profit institutions serving households. Although the gross output required to meet "export" demand ranges from 12% to 16% of the total gross output, the total emissions generated due to "exports"

[4] The pollution haven hypothesis holds that stricter environmental regulation procedures in developed countries create a trend for concentrating pollution-intensive activities in developing countries with fewer environmental restrictions.

range from 20% to 32% – which increased significantly after 2014. At the same time, the share of emissions generated to meet the demand for “gross fixed capital formation” and “general government expenditures” remains below the share of gross output driven by these categories throughout the series. The final demand category showing the highest share of emissions and production is “household consumption.” The share of “exports” in total emissions is also higher than in gross output, which can be explained by the high demand of this category for emission-intensive industries such as “agriculture,” “energy, water, gas,” “industrial commodities,” and “transport”.

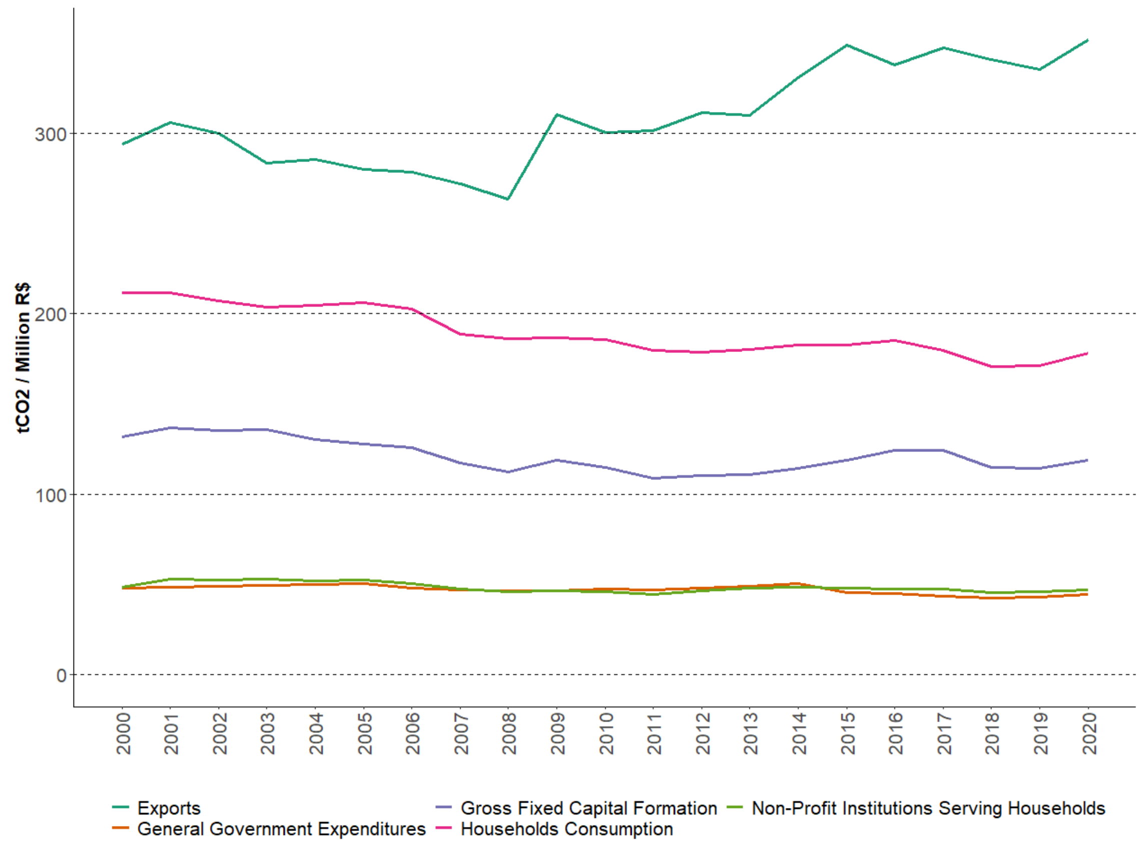
Figure 1. Composition of emissions by final demand component (% of total emission).



Source: own elaboration based on GEE emission vectors (Costa et al., 2023) and input-output tables (Alves-Passoni & Freitas, 2020).
Note: This figure illustrates and compares the share of gross output and GHG emissions generated to meet each component of the final demand (per year in the period from 2000 to 2020). Values may not sum to 100% due to the adjustment variable for Inventory Changes.

Figure 2 shows the emissions intensity (GHG emission for each million R$) to meet each final demand category. Gross output (including intermediate consumption) required for “gross fixed capital formation,” “household consumption,” and particularly for “exports” are more intensive in GHG emissions than the other final demand categories. Furthermore, while the intensity of emissions from the other categories presents a downward trajectory – emphasizing “household consumption” –, the intensity of emissions attributed to “exports” increased considerably after 2008.

Figure 2. The emissions intensity by final demand component (tCO_2 eq. per million R$).



Source: own elaboration based on GEE emission vectors (Costa et al., 2023) and input-output tables (Alves-Passoni & Freitas, 2020).
Note: This figure depicts, for each component of final demand, the intensity of GHG emissions in tons generated per million R$ of gross output (per year in the period from 2000 to 2020).

Indeed, Brazil's trade pattern shifted toward the most carbon-intensive industrial groups, corroborating the country's increasing trade specialization in natural resource-intensive industries (which often have higher energy intensities) in the period under review. Moreover, the Brazilian economic structure has gone in the opposite direction of what would be expected in transitioning to a low-carbon economy, notably from 2010.

Table 1 presents the intensity of emissions by the industrial group between 2000 and 2020.[5] The key sectors showing increases in emissions intensity were "electricity, water and gas", "innovative industry," and "traditional industry." "Processed agricultural commodities" remained roughly the same, while "transport," "agriculture," "industrial commodities," and "other services" decreased emissions intensity.

[5] The groups are based on the perspective of industrial organization. So, each group presents a specific type of industrial pattern of competitiveness, which considers factors like production based on scale, products based on natural resources, labor intensity, and technological progress.

Table 1. Emissions intensity by industrial group (in tCO_2 eq. per million R$)

Industrial Group	2000	2005	2010	2015	2020
Agriculture	2,212	2,161	2,032	1,766	1,851
Industrial Commodities	286	214	231	260	231
Processed Agricultural Commodities	72	65	63	73	72
Traditional Industry	26	25	28	28	29
Innovative Industry	8	6	7	9	7
Electricity, Water, Gas	626	604	616	774	647
Transport, Storage and Mail	628	584	552	602	551
Others Services	2	2	2	3	3

Source: own elaboration based on GEE emission vectors (Costa et al., 2023) and input-output tables (Alves-Passoni & Freitas, 2020).
Note: This table shows the intensity of GHG emissions in tons generated per million R$ of gross output by each industry (per year in the period from 2000 to 2020). Some industries were aggregated for a clearer presentation; check Table B.1 for the list of aggregated industries.

However, while industries such as agriculture, industrial commodities, and transport – which are required to meet export demand – showed a reduction in their GHG emissions intensities, the emission intensity of "export" production worsened in the period, pushed by an increase in the share of these industries – still major GHG emitters despite reducing emission intensities – in "exports". At the same time, the GHG intensity associated with gross output for "household consumption" decreased, which could be a result of such industries – also important to "household consumption" – reducing their GHG intensity. However, it could also be because their relative share in the required production for "household consumption" may have decreased compared to the less emission-intensive industries.

3. Data and SDA Method

To estimate the main effects and identify the industries that contributed to increasing or reducing productive GHG emissions in the last two decades in Brazil, we performed a structural decomposition analysis (SDA) for the period 2000-2020. The SDA disaggregates input-output data into the different components (effects) that could explain the changes in sectorial data (such as emissions and employment) between two or more periods. The SDA starts with the traditional Leontief model, according to Equation (1).

$$E = \hat{e}Ly \qquad (1),$$

In (1), E is the total GHG emissions vector by industry; $\hat{e}$ is the GHG emission intensity diagonalized vector by industry; L is the inverse Leontief matrix (or intersectoral impact matrix), and y is the final demand vector. Following Miller & Blair's (2009) contributions, through appropriate matrix algebra (Annex A), we set up this GHG emission decomposition, as in Equation (2). This equation can be broken down into seven terms that can be interpreted as effects with economic significance.

$\Delta E =$

$\frac{1}{2}(\Delta e L_1 y_1 + \Delta e L_0 y_0) +$ (2.1)

$\frac{1}{2}\left\{e_0\left[L_1\left(\frac{1}{2}[\Delta A^s \otimes (A_0^t + A_1^t)]\right)L_0\right]y_1 + \ e_1\left[L_1\left(\frac{1}{2}[\Delta A^s \otimes (A_0^t + A_1^t)]\right)L_0\right]y_0\right\} +$ (2.2)

$\frac{1}{2}\left\{e_0\left[L_1\left(\frac{1}{2}[(A_0^s + A_1^s) \otimes \Delta A^T]\right)L_0\right]y_1 + \ e_1\left[L_1\left(\frac{1}{2}[(A_0^s + A_1^s) \otimes \Delta A^T]\right)L_0\right]y_0\right\} +$ (2.3)

$\frac{1}{2}(e_0 L_0 + e_1 L_1)\left\{\frac{1}{2}\left[(\Delta Y^s \otimes Y_1^m)(y_1^c)(y_1^l) + (\Delta Y^s \otimes Y_0^m)(y_0^c)(y_0^l)\right]\right\} +$ (2.4)

$\frac{1}{2}(e_0 L_0 + e_1 L_1)\left\{\frac{1}{2}\left[(Y_0^s \otimes \Delta Y^m)(y_1^c)(y_1^l) + (Y_1^s \otimes \Delta Y^m)(y_0^c)(y_0^l)\right]\right\} +$ (2.5)

$\frac{1}{2}(e_0 L_0 + e_1 L_1)\left\{\frac{1}{2}\left[(Y_0^s \otimes Y_0^m)(\Delta y^c)(y_1^l) + (Y_1^s \otimes Y_1^m)(\Delta y^c)(y_0^l)\right]\right\} +$ (2.6)

$\frac{1}{2}(e_0 L_0 + e_1 L_1)\left\{\frac{1}{2}[(Y_0^s \otimes Y_0^m)y_0^c + (Y_1^s \otimes Y_1^m)y_1^c]\Delta y^l\right\}$ (2.7).

It is worth noting that the effects in each term represent an industrial change (whether increase or decrease, or the ΔE) in GHG emissions between two time periods. To present the results, we considered intervals every 5 years and the total period (2000-2020). The specific interpretation of each effect can be described as follows:

(2.1) Emission intensity effect: variations in GHG emissions due to variations in the ratio of tCO_2e per unit of gross output of a given industry;

(2.2) Import of intermediate demand effect: emission variations due to variations in the share of imports of inputs of a given industry;

(2.3) Technological effect: emission variations from shifts in the amount and the share of each input used in the production of a given industry;

(2.4) Final Import effect: emission variations due to replacing national production for imports in the final demand;

(2.5) Sectoral composition effect: emission variations due to shifts in the share of emission-intensive industries in final demand;

(2.6) Final demand composition effect: emission variations due to variations in the share of final demand categories;

(2.7) Level effect: emission variations due to variations in total final demand.

To perform the estimations, we relied on two databases: a time-series of input-output tables (Alves-Passoni & Freitas, 2020), with annual and constant price data for 42 industries; and a time-series of GHG emission vectors (Costa & Alvarenga, 2023), a database built through the translation of the annual emissions inventory (De Azevedo et al., 2018; SEEG, 2021) at the IOT industry level.[6] It is worth noting that for this paper, we focused solely on production-related GHG emissions, meaning those not associated with deforestation and changes in land use, which are the leading causes of greenhouse gas emissions in Brazil. Such a choice stems from our understanding that the dynamic of emissions related to land use has its own intricacies, with annual demand and production being just two of many contributing factors.

In addition to the extensive literature using SDA based on Regional Input-Output Tables to decompose pollutants emissions and energy consumption, among other variables, there is also a significant body of literature employing such a method based on national tables worldwide (Casler & Rose, 1998; Wood, 2009; Yamakawa & Peters, 2011; Brizga et al.,

[6] The GHG emission vectors by industry were built by Costa et al. (2023) – EEIST Project Report – based on the IOT from Alves-Passoni & Freitas (2020) and emission inventories (SEEG, 2021; De Azevedo, 2018). The methodology for building these vectors follows Gramkow (2011).

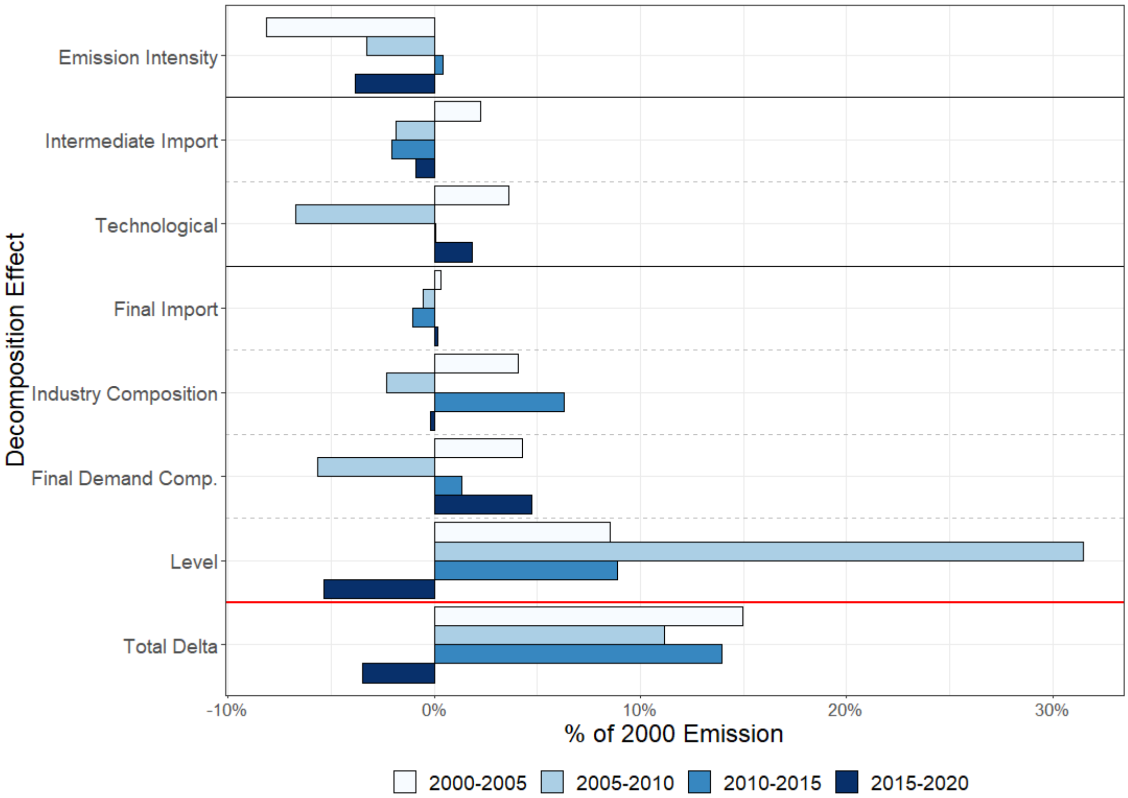
2014; Su et al., 2017; Zhu et al., 2018;) and for Brazil (Wachsmann et al., 2009; Silva & Perobelli, 2012; Lenzen et al., 2013; Perdigão et al., 2017; de Abreu et al., 2021; Naspolini et al., 2020; Sesso et al., 2020; Ribeiro et al., 2023). This method based on the national tables and secondary data on pollutants and energy consumption allows for an understanding of how the final demand components and productive sectors participate in various mechanisms that may be correlated with prominent economic trends in the period. As such, this method also provides valuable insights for policymakers regarding trajectories that positively influence GHG emissions while rejecting negative ones. The SDA method also agrees with the Risk-Opportunity Analysis framework (ROA) as it is a form of system mapping that helps understand system structures and can inform more dynamic modelling efforts focusing on the process of change in the economy (Grubb et al., 2021).

4. Results

Table 1 presents the contribution of each decomposition effect to the changes in GHG emissions every five years as a percentage of the total production-related GHG emissions in 2000. The “final demand level” effect is the most critical determinant for the increase in Brazil’s emissions from 2005 to 2010, especially in periods of higher economic growth. In 2015-2020, under significant economic recession, the 'level' effect reduced total emissions. It is also worth highlighting the positive effects of “final demand composition” and “industry composition of final demand,” a trend not observed in the period 2005-2010, probably due to the increased share of investment (less emission-intensive) vis-à-vis the decreased share of imports (a more emission-intensive category).

The “emissions intensity” effect relieved the total emissions increase in most periods – except 2010-2015. The “technological” and “import of intermediate demand” effects accounted for slightly reduced emissions, but less consistently. Finally, no significant changes were observed in productive GHG emissions due to replacing domestic-produced final demand with imported final demand. Table B.2 (Appendix B) presents the same results with the exact percentages of each component in each subperiod.

Figure 3. Aggregated results of the structural effects of GHG emissions by component

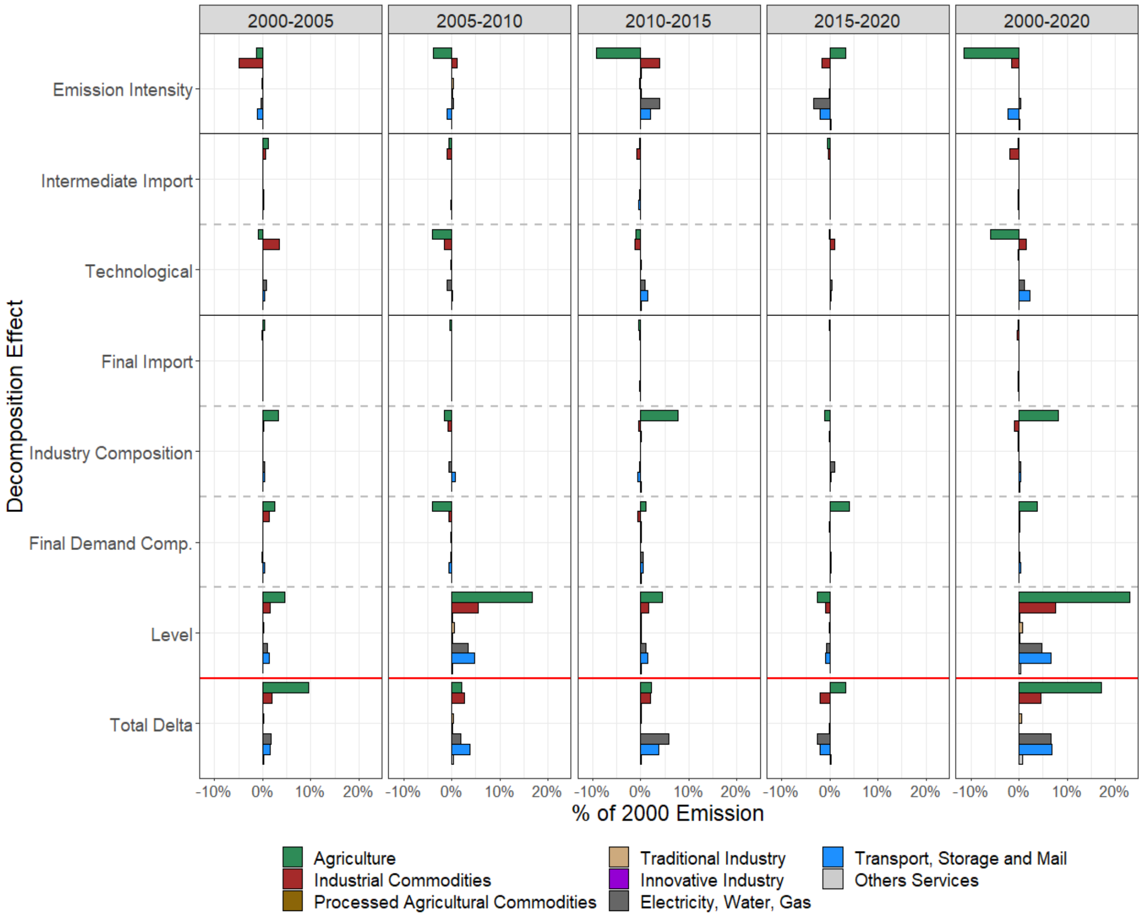


Source: own elaboration based on GEE emission vectors (Costa et al., 2023) and input-output tables (Alves-Passoni & Freitas, 2020).
Note: This figure illustrates the contribution of each effect in the SDA as a percentage of total productive emissions in 2000, the first year of the time series. The colors represent each 5-year subperiod within the 2000-2020 interval. Bars to the left of the 0% axis indicate that the effect during that subperiod helped mitigate emissions, while bars to the right of the 0% axis indicate that the effect during that subperiod increased emissions. It is worth highlighting that in 2000 emissions were equivalent to 851 MtCO2e. Therefore, a 1% effect in any period corresponds to an increase of 8.5 MtCO2e.

Figure ***4*** shows the evolution of GHG emissions through SDA in Brazilian industries. The most striking results refer to the long-run effects (2000-2020) of structural changes in agriculture. This sector partially reduced emissions through intensity and technology effects but contributed to the total GHG emission even more (i) by increasing its share compared to other industries (industry composition effect); (ii) by increasing the share of final demand categories highly dependent on agriculture (exports, for instance); and (iii) due to the level effect.

Nevertheless, emissions increased for all industries, especially “agriculture,” “electricity, waste, water and gas,” “transport, mail and storage,” and “industrial commodities” – more specifically the “oil and gas extraction”, “cement”, and “steel manufacturing” industrial commodities. However, in most cases, emissions grew mainly because of the “final demand level” effect, which more than offsets the reduction obtained from other effects. Table B.3 (Appendix B) presents the results for the entire period (2000-2020) with the exact percentages of each component and industry.

Figure 4. Structural decomposition effects for Brazilian economy (% of 2000 emissions).



Source: own elaboration based on GEE emission vectors (Costa et al., 2023) and input-output tables (Alves-Passoni & Freitas, 2020).

Note: This figure shows how each industry contributed through each SDA effect as a percentage of total productive emissions in 2000, the series's first year. The bars' colors refer to the eight industries, while the vertical panels correspond to the estimates for each subperiod. The last panel provides data for the entire period between 2000 and 2020, while bars below the red line represent the total emission changes in each period. The sums of the effects in a period equal the total variations for that same period. One must highlight that in 2000, emissions were equivalent to 851 MtCO2e. Therefore, a 1% effect in any period means an increase of 8.5 MtCO2e.

If the "final demand level" offsets any reduction in emissions that may have occurred through other means in most periods, the "final demand composition" and "industry composition" further deepened the increase in GHG emissions in the period. "Agriculture," "transport", and "electricity, waste, water, and gas" showed an increase in emissions through those three effects, meaning that: (i) these emissions-intensive industries increased their shares compared to other industries (the industry composition effect); (ii) final demand categories with more outstanding shares of these industries also increased their shares across the different demand categories (the final demand composition effect); and (iii) such industries remained relevant to the point that an increased level of final demand implies an increased level of GHG emissions from these industries (the level effect). It is also worth noting that the "industrial commodities" industry contributed to the increase in GHG emissions via the "level of final demand" effect, mainly in the 2005-2010 period.

The “final import” and “intermediate demand import” effects seem nonsignificant for most individual industries but can be important in understanding GHG emissions from trading patterns. “Agriculture” and manufacturing, mainly “industrial commodities,” have a slight negative import effect on GHG emissions; replacing domestic products from these industries with imported ones, whether to meet intermediate demand or final demand, can reduce national GHG emissions. However, regarding public policy to reduce global emissions, this mechanism should only receive attention if the imported product is less carbon-intensive than the domestically produced one. Nevertheless, such a decrease is (almost) neutralized by the shift to exports in final demand – as shown by the “final demand composition” effect.

The “emission intensity” effect is the most favorable to reduce GHG emissions based on the SDA as shown in Figure 4. Despite the fluctuations in the period, “agriculture,” “industrial commodities,” and “transport” managed to reduce total emissions by decreasing the intensity of their GHG emissions per R$ of output. Public policies are the most strategic instruments to offset emissions that consistently increase with final demand and production growth. In contrast, industrial commodities such as “cement” and “oil and gas extraction,” along with “electricity, water, and gas,” raised emissions due to the increased intensity effect. While for the cement industry, deterioration occurred between 2010 and 2020, for oil and gas extraction it took place between 2005 and 2015. “Electricity, water and gas” declined considerably from the mid-2010s onwards due to an increased share of dirty energies, such as in the use of fossil fuel plants. It is worth mentioning that the marginal falls in “organic and inorganic chemicals,” “iron ore extraction,” “petroleum refining,” and “steel production” resulted in an overall decrease in the intensity of industrial commodities. However, many of these sectors remained significant emitters, both directly and indirectly.

Finally, it is important to highlight the dual contribution through the “technological” effect: on the one hand, “agriculture” has considerably reduced GHG emissions due to the “technological” effect; however, other emission-intensive industries, such as “transport,” “industrial commodities,” and “electricity, sewage, water and gas” increased emissions through their technical coefficients.

5. Discussion and policy recommendations

Based on the results of the SDA, we found the “level” effect to be the primary factor contributing to the increase in emissions during the period. This finding is not news for Brazil or other developing countries, as other authors found similar results referring to the level effect (or population growth effect) using SDA, either for the last two decades or earlier periods (Wachsmann et al., 2009; Silva & Perobelli, 2012; Lenzen et al., 2013; Perdigão et al., 2017; Sesso et al., 2020). Naspolini et al. (2020) found the level effect prominent even in decomposition for water use. However, from a policymaker's perspective, such a result does not point to an obvious path for sustainable development once economic growth is also a desirable objective.

Therefore, if the level effect has been the primary driver of increased emissions in Brazil since 2000 or even before, the solution to offset the rise in emissions requires alternative mechanisms. Based on descriptive statistics, the SDA findings, and the existing literature, three alternative pathways stand out: (i) the “composition of final demand” effect, which highlights international trade, Brazilian exports, and the role of sustainable investment; (ii) the “emission intensity” effect, mainly through the adoption of best practices and investments to enhance intra-industrial processes; and (iii) the “industrial composition of final demand" effect in cases which specific industries should be recognized as losers in a green development trajectory.

5.1. Final demand categories

Based on both the descriptive statistics and the SDA, one can grasp the role of final demand components and their associated industries in Brazilian emissions. First, exports accounted for almost a third of domestic emissions in recent years, with the production required to generate those exports representing about 16% of total gross output. At the same time, the "final demand composition" effect was positive primarily due to an increase in agriculture emissions. Although exports give growing contributions to GHG emissions, their role is not new, as already described by Young (1998), Machado et al. (2001), Carvalho & Perobelli (2009), Lenzen et al. (2013) and Liu et al. (2019). However, for many emission-intensive exported goods, such as agricultural and industrial commodities, eliminating GHG emissions is likely to increase the cost of production – at least in the short term –, potentially compromising the competitiveness of Brazilian industries.

For Brazilian producers in these sectors to reduce emissions without losing competitiveness, facing the right conditions in global markets is essential. That is, if Brazil is responsible for producing and exporting GHG emissions, importing countries must also be held accountable in the context of productive fragmentation and pollution havens, as already highlighted by Meng et al. (2018a), Zhong et al. (2022) and Arce González et al. (2012). Consequently, Brazil must have a strong interest in negotiating with other major producer and consumer countries in these sectors to agree on standards (Candau & Dienesch, 2017; Cherniwchan et al., 2017), on the adoption of less carbon-intensive technology (Barrows & Oliver, 2021), and on other viable measures to ensure low emission producers are rewarded and not penalized by global markets.

The SDA conducted in this paper allowed us to identify the effects on Brazilian emissions in the last two decades stemming from the substitution of domestic production with imported goods (intermediate and final imports). The most significant result was the fall in emissions deriving from the "industrial commodities" link by substituting domestic intermediate demand with imported demand. Despite no similar analysis was to be found in the reviewed literature, it is conceivable that countries undergoing a sudden process of industrialization (or deindustrialization) in a scenario of growing production fragmentation could have experienced similar effects. Nevertheless, expecting a consistent strategy to reduce emissions by replacing domestic-made products with imported ones, whether for final or intermediate consumption, does not seem appropriate unless production relocates to countries with lower emission coefficients – which does not seem to be the case (Meng et al., 2018a; Arce González et al., 2012). Nonetheless, these effects have low potential to reduce net emissions in the Brazilian context.

In addition to exports, two other crucial components of final demand are household consumption and gross fixed capital formation. Concerning policies to mitigate GHG emissions, it is challenging to envision a feasible scenario that targets the household consumption patterns for emission reduction. In this case, the preferable approach involves a secondary effect stemming from reducing emission intensities in industries demanded in the household consumption basket.

Despite experiencing a decline in its share of final demand in recent years, investment can also be perceived as a central element. Although this category of final demand is relatively emission-intensive due to the high materialization of demanded products, it would be desirable for appropriately directed investment to trigger a virtuous cycle. In other developing countries, such as China and India, effects resulting from increased investment in contexts of significant economic growth appear to have acted as drivers for emissions growth (Liu et al., 2019; Sesso et al., 2020). In this paper, we have identified that the share and the carbon intensity of gross capital formation have decreased in Brazil – which could be better, as adequate investment can enable structural changes toward a sustainable trajectory. So, despite investments requiring some GHG emissions in the short term, one needs to incentivize green investments to enable productive industries to reduce their emission intensities over time.

5.2. Emission intensity and intraindustry changes

Based on the descriptive statistics and the SDA results, the most polluting industries are found to be reducing the intensity of their GHG emissions. Lenzen et al. (2013) demonstrate that, from 1995 onward, the intensity effect is a leading GHG emission mitigator in Brazil – a trend that has become even more apparent after 2000 (Silva & Perobelli, 2012; Perdigão et al., 2017; Liu, 2019; Sesso et al., 2020). Similarly, Ribeiro et al. (2023), Perdigão et al. (2017), and Silva & Perobelli (2012) also point to reductions in intensity in agriculture, despite this sector remaining the primary contributor to emissions – like other industrial commodities that also showed significant results in specific subperiods.

At the same time, our results for the intensity effect in the "electricity, waste, water, and gas" sector go against the trend observed in recent decades. Especially in the 2013-2015 water crisis (Nobre et al., 2016; Hunt et al., 2018), this industry has significantly raised its GHG emission intensity by increasingly relying on thermoelectric power plants. Based on a recent observation, this finding has few precedents in the literature, but it is nevertheless concerning considering Brazil's advantages for green energy generation. Perdigão et al. (2017) unveils the contrast between the electricity and transportation sectors in Brazil compared to those in China, Russia, and India: while Brazil historically displays low intensity in electricity generation through hydropower, those countries often rely on thermopower plants – and even more in the last decades. Conversely, the transportation sector in Brazil historically depends on road transport and, therefore, fossil fuels – and biofuels more recently –, showcasing a trend contrary to that of other BRIC nations.

Although such results reinforce the idea that several industries benefit from increasingly cleaner production processes, more significant gains must be made to reduce emission intensities to compensate for the stationary level effect of final demand. Given the potential for generating green energy in Brazil (Lima et al., 2020; Hunt et al., 2018; da Silva et al., 2016), the country should be able to gradually reduce the emission intensity in energy-dependent industries instead of relying on fossil fuels and on thermoelectric plants in periods of water crises, as observed in the last decade. Consequently, policymakers should also pay special attention to the transport sector providing it with adequate infrastructure and investments and promoting environmentally sustainable transportation.

If agriculture has undergone significant reductions in GHG emission intensity recently (excluding deforestation), much more can be done to turn this sector into an ally in fighting climate change. Predatory processes, such as extensive livestock farming associated with deforestation and high methane emissions and plantations with high consumption of pollutant-rich fertilizers, must adapt to more restrictive standards involving GHG emissions (SEEG, 2022). Concerning methane emissions, in addition to enteric fermentation in livestock, mitigation through waste management is also paramount, as methane emission from solid and liquid waste represents a high share of GHG emissions from the aggregated "energy, waste, water, and gas" industry (SEEG, 2022).

As for "industrial commodities," even more ambitious reductions in GHG emission intensity can be envisioned. Sectors like cement, steel, and biofuel manufacturing must imperatively contribute to achieving GHG emission reductions.[7] Conversely, industries such as oil and gas extraction and refining should gradually cede their prominence. This is because not only are they carbon-intensive themselves, but they also supply inputs that exacerbate the carbon intensity of other industries.

In this regard, it is crucial to understand that promoting structural change toward a sustainable future requires acknowledging that new industries are emerging, traditional industries must change, and others may face decline. In most cases, the incentives for transitioning to sustainable and green processes encompass intra-industrial structural transformations and require economic and institutional measures, along with green investments in low GHG emission production technologies. Some industries are nevertheless inherently incompatible with a long-term sustainable trajectory.

6. Conclusion

In this paper, we developed a descriptive and structural decomposition analysis of Brazil's GHG emissions trajectory to identify the leading mechanisms and industries behind the increase and partial reduction in the country's total emissions. Agriculture, transport, energy, and industrial commodities remained the protagonists in the almost inertial increase in total emissions despite some gains observed in the emission intensity of those sectors in specific periods of the last two decades.

Additionally, our SDA underscores that factors such as the level and composition of final demand effects have been the primary drivers of the recent upswing in total emissions despite the emission intensity effect partially mitigating this escalation. On the one hand, there are noteworthy implications concerning the composition of final demand, particularly considering the heightened contribution of exports to productive GHG emissions and competitive positioning in international markets. On the other hand, the inertial impact of the level of final demand must persist as long as there is a desire for economic growth – even in an optimistic scenario where growth can simultaneously alleviate inequalities and generate green jobs towards a sustainable development trajectory. Therefore, we recognize that the intensity effect of GHG emissions plays an increasing role counterbalancing those inertial effects and preventing rises in total emissions.

Policymakers must consider the role played by technological factors, changes in trade patterns, and final demand growth and composition. The current trade patterns of the Brazilian economy rely on energy-intensive products like soybeans and meat, which impact (directly and indirectly) the emissions pattern through the production process and deforestation. One option for transitioning to a low-carbon economy is mission-oriented industrial policies that change current trade patterns and shift production away from GHG

[7] The platform "Nossa Descarbonização" estimates several decarbonization goals for industrial sectors and other areas, along with measures and pathways for decarbonization. Available in: https://nossadescarbonizacao.org/

emission-intensive products (such as livestock, mineral extraction, and non-renewable energy). Concentrating policy incentives to implement increasingly less carbon-intensive production processes can improve the competitiveness of export-oriented sectors, with desirable economic development goals and positive climate change effects.

Three paths are crucial for informing policymakers. First, one must consider the synergies involving the effects of the composition of final demand, the composition of industries in final demand, and intra-industrial improvements. A path towards a low-carbon economy also requires providing economic incentives and appropriate conditions (energy efficiency loans, carbon pricing, energy efficiency labels, low carbon technologies) for sectors with a more significant green potential (such as transport, energy, livestock breeding, cement, iron and steel, and chemicals). Such a path entails not only the identification of strategic industries but also the optimization of intra-industrial processes, along with the judicious steering of final demand for exports and gross fixed capital formation. Brazil has not consciously adopted this path on a large scale in recent years, as shown by the SDA.

Second, economic incentives must favor, as far as possible, sectors or technologies with more significant potential to support a green economy – not only the existing green industries but also new ones and the bioeconomy.

Third, it is essential to secure significant gains by reducing GHG emission intensity. In recent years, sectors such as agriculture, transport, and industrial commodities managed to offset part of the increase in emissions through this mechanism. Still, they were far from offsetting the scale effect of final demand. Significant reductions in GHG emissions intensity are much more complex and costly in some cases, such as in steel manufacturing and extractive industries. However, sectors such as agriculture, transport, and electricity generation account for most of Brazil's emissions.

Increased efforts are needed to ensure emission intensities reduce sufficiently fast on the side of technology development and regulations to promote green growth and development. Inducing technological change in the private sector toward a low-carbon economy will require governments to employ varied instruments and policies, including market-based programs, regulatory measures, voluntary agreements, targeted development, and infrastructure support measures. Adopting a set of measures appropriate to national, regional, and local conditions is paramount.

7. References

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8. *Appendix A*

In this appendix we demonstrate through matrix algebra how to set up the Structural Decomposition Analysis equation based on the traditional Leontief model. The starting point is the Leontief model in which productive sectors' GHG emissions are estimated.

$$E = \hat{e}Ly \quad (A.1).$$

That is, total sectoral GHG emissions vector (E) is the result of the product between the diagonalized emissions intensity vector (ê), the intersectoral impact matrix (L), and the final demand vector by industry. Considering one can calculate the difference in the level of industrial emissions between a period $t = 0$ and $t = 0$, Equations A.2 and A.3 are as follows.

$$\Delta E = \Delta\hat{e}L_1y_1 + \hat{e}_0\Delta Ly_1 + \hat{e}_0L_0\Delta y \quad (A.2)$$
$$\Delta E = \Delta\hat{e}L_0y_0 + \hat{e}_1\Delta Ly_0 + \hat{e}_1L_1\Delta y \quad (A.3).$$

Note that the subscript in each vector or matrix represents the period t, while $\Delta x = x_{1-}x_0$. Decomposing changes in sectoral emissions (ΔE) can be performed in several ways, but we adopted the polar forms, following Dietzenbacher & Los (1998). So, ΔE can also be decomposed into the average between A.2 and A.3.

$$\Delta E = \frac{1}{2}(\Delta\hat{e}L_1y_1 + \Delta\hat{e}L_0y_0) + \frac{1}{2}(\hat{e}_0\Delta Ly_1 + \hat{e}_1\Delta Ly_0) + \frac{1}{2}(\hat{e}_0L_0\Delta y + \hat{e}_1L_1\Delta y) \quad (A.4).$$

In Equation A.4, changes in GHG emissions by industry are decomposed into three terms: emissions due changes in the emission intensity ($\Delta\hat{e}$), emissions due to changes in the matrix of intersectoral impacts (ΔL), and emissions due to changes in the final demand vector (Δy). The first term refers to the effect of the emission intensity per industry on total emissions. As the first term already has an important economic meaning for the purpose of this paper, the other two can be adapted to represent effects with better interpretation.

Intersectoral impact matrix: following Rose & Casler (1996), we propose an additive decomposition of the variation term for ΔL. First, we start from $L = (I - A)^{-1}$, with A representing the matrix of domestic technical coefficients. So, we can define $A = A^s \otimes$

A^t, with the Hadamard product between the total technical coefficients A^t (domestic and imported inputs) and the share of domestic inputs in the total technical coefficients A^s. Thus, ΔA can be decomposed as Equation A.5.

$$\Delta A = \frac{1}{2}[\Delta A^s \otimes A_1^t + \Delta A^s \otimes A_0^t] + \frac{1}{2}[A_0^s \otimes \Delta A^t + A_1^s \otimes \Delta A^t] (A.5).$$

That is, changes in domestic technical coefficients (ΔA) depend on changes in the total technical coefficients ΔA^t (domestic and imported inputs) plus changes in the share of domestic inputs in each industry (ΔA^s). While changes associated with ΔA^t can be understood as a technological effect, those related to ΔA^s represent an intermediate imports effect – as those in the share of domestic inputs are directly associated with changes in the share of imported inputs.

Final demand vector: we can explicitly define the final demand vector as $y = (Y^s \otimes Y^m)y^c y^l$. Y^s is the matrix of share of final demand that is met domestically (equal to 1 when a category of final demand by an industry is entirely met domestically); Y^m is the share of each industry in the final demand of each final demand category; y^c is the share vector of each final demand category in total final demand; and y^l is a scalar representing the level of final demand. Following both Rose and Casler (1996) and Dietzenbacher & Los (1998), changes in final demand can be decomposed as Equation A.6.

$$\begin{aligned}\Delta y = \frac{1}{2}[(\Delta Y^s \otimes Y_0^m)y_0^c y_0^l + (Y_1^s \otimes \Delta Y^m)y_0^c y_0^l + (Y_1^s \otimes Y_1^m)\Delta y^c y_0^l \\ + (Y_1^s \otimes Y_1^m)y_1^c \Delta y^l\,] \\ + \frac{1}{2}[(\Delta Y^s \otimes Y_1^m)y_1^c y_1^l + (Y_0^s \otimes \Delta Y^m)y_1^c y_1^l + (Y_0^s \otimes Y_0^m)\Delta y^c y_1^l \\ + (Y_0^s \otimes Y_0^m)y_0^c \Delta y^l] \quad (A.6).\end{aligned}$$

Changes related to ΔY^s are due to those in the share of domestic (or imported) products in final demand; changes related to ΔY^m are due to those in the mix of industries in a given final demand category; changes related to the vector Δy^c are due to those in the share of each category of final demand in the total final demand; changes associated with scalar Δy^l are due to those in the total level of domestic final demand.

Therefore, the GHG emission by industry as in Equation A.1 can be redefined as follows:

$$E = \hat{e}\,(I - A^s \otimes A^t)^{-1}\,[(Y^s \otimes Y^m)y^c y^l] \quad (A.7).$$

ΔE can also be decomposed using Equations A.4, A.5, and A.6 as proposed in Equation 2 of the section 3 of this paper.

9. *Appeendix B*

Table B.1. Relationship between industries at the level 42 and 8.

42 Industry Level	8 Industry Level
Agriculture, forestry, livestock and fisheries	Agriculture
Extraction of oil and gas, including support activities	Industrial Commodities
Extraction of iron ore, including processing and agglomeration	Industrial Commodities
Other mining and quarrying	Industrial Commodities
Food and drinks	Traditional Industry
Manufacture of tobacco products	Processed Agricultural Commodities
Manufacture of textiles	Traditional Industry
Manufacture of wearing apparel and accessories	Traditional Industry
Manufacture of footwear and leather goods	Traditional Industry
Manufacture of wood products	Processed Agricultural Commodities
Manufacture of pulp, paper and paper products	Processed Agricultural Commodities
Printing and reproduction of recordings	Traditional Industry
Oil refining and coking plants	Industrial Commodities
Manufacture of biofuels	Industrial Commodities
Manufacture of other organic and inorganic chemicals, resins and elastomers	Industrial Commodities
Pharmaceutical products	Innovative Industry
Perfumery hygiene and cleaning	Traditional Industry
Manufacture of pesticides, disinfectants, paints and various chemicals	Traditional Industry
Rubber & Plastics	Traditional Industry
Cement and other non-metallic mineral products	Industrial Commodities
Manufacture of steel and its derivatives	Industrial Commodities
Metallurgy of nonferrous metals	Industrial Commodities
Metal products - exclusive machinery and equipment	Industrial Commodities
Furniture and products of various industries & Machinery and equipment	Innovative Industry
Household appliances and electronic material	Innovative Industry
Automobiles trucks and buses	Innovative Industry
Parts and accessories for motor vehicles	Innovative Industry
Other transportation equipment	Innovative Industry
Electricity generation and distribution gas water sewage and urban cleaning	Electricity, Water, Waste and Gas
Construction	Other Services
Trade	Other Services
Transporting warehousing and mail	Transport, Storage and Mail
Accommodation and food services	Other Services
Information services	Other Services
Financial intermediation insurance and supplementary pension and related	Other Services
Real estate activities and rentals	Other Services
Business and family services and maintenance services	Other Services
Public administration, defense and social security	Other Services
Public education	Other Services
Private education	Other Services
Public health	Other Services
Private health	Other Services

Note: This table converts industries at level 42 to industries at level 8. In this paper, estimates have been calculated using level 42; however, for enhanced visualization and understanding of the outcomes, we opted to display the aggregation into 8 industries.

Table B.2. Structural decomposition effects by subperiods (% of 2000 emissions).

Period	Total Delta	Level	Final Demand Comp.	Industry Composition	Final Import	Technological	Intermediate Import	Emission Intensity
2000-2005	15.0%	8.5%	4.3%	4.1%	0.3%	3.6%	2.2%	-8.1%
2005-2010	11.2%	31.5%	-5.6%	-2.3%	-0.5%	-6.7%	-1.8%	-3.3%
2010-2015	13.9%	8.9%	1.3%	6.3%	-1.0%	0.1%	-2.1%	0.4%
2015-2020	-3.5%	-5.4%	4.7%	-0.2%	0.2%	1.8%	-0.9%	-3.8%
2000-2020	36.6%	43.5%	4.7%	7.9%	-1.1%	-1.1%	-2.5%	-14.8%

Source: own elaboration based on GEE emission vectors (Costa et al., 2023) and input-output tables (Alves-Passoni & Freitas, 2020).
Note: This table illustrates the contribution of each effect in the SDA as a percentage of total productive emissions in 2000, the time series' first year. The values in this table and in Figure 3 are precisely the same. Emissions in 2000 were equivalent to 851 MtCO2e; therefore, a 1% effect in any period means an increase of 8.5 MtCO2e.

Table B.3. Structural decomposition effects by industries (% of 2000 emissions).

Industry	Emission Intensity	Intermediate Import	Technological	Final Import	Industry Composition	Final Demand Comp.	Level	Total Delta
Agriculture	-11.4%	-0.2%	-5.9%	-0.3%	8.2%	3.7%	23.1%	17.1%
Industrial Commodities	-1.6%	-1.8%	1.6%	-0.3%	-1.0%	0.2%	7.5%	4.5%
Processed Agricultural Commod.	-0.1%	0.0%	-0.1%	0.0%	-0.1%	0.1%	0.2%	0.1%
Traditional Industry	0.1%	-0.1%	0.0%	0.0%	-0.1%	0.0%	0.7%	0.6%
Innovative Industry	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.2%	0.1%
Electricity, Water, Gas	0.4%	-0.1%	1.1%	-0.1%	0.4%	0.3%	4.8%	6.7%
Transport, Storage and Mail	-2.3%	-0.3%	2.2%	-0.3%	0.5%	0.4%	6.7%	6.9%
Other Services	0.1%	0.0%	0.0%	0.0%	0.2%	0.0%	0.3%	0.7%

Source: own elaboration based on GEE emission vectors (Costa et al., 2023) and input-output tables (Alves-Passoni & Freitas, 2020).
Note: This table illustrates the contribution of each effect in the SDA as a percentage of total productive emissions in 2000, the time series' first year. The values in this table and in Figure 4 are precisely the same. Emissions in 2000 were equivalent to 851 MtCO2e; therefore, a 1% effect in any period means an increase of 8.5 MtCO2e.