An input-output analysis of CO_2 emissions from a regional income perspective: an application to the Brazilian economy[1]

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Fernando Salgueiro Perobelli[2]
Geoffrey J D Hewings[3]
Eduardo Amaral Haddad[4]
Edson Paulo Domingues[5]
Guilherme Perobelli Salgueiro[6]

Abstract

While the imbalances in Brazilian regional dependencies in terms of production and income have been documented, little research has been directed to the impact on emissions; are there similar imbalances? To address this problem, a multiregional economic network model exploring different dimensions - spatial (nation, region) and sectoral (different industries) to better understand the pressures that variations in income exert on CO_2 emissions. This will be accomplished by modifying an inter-regional input-output matrix for the 27 states of the Federation with 68 productive sectors for a base year in 2019. The goal is to identify the "key" agents responsible for CO_2 emission and, given the nature of the interregional interdependence, the concepts of embodied emissions will more fully reveal the drivers of emissions. The results of our paper reinforce the tradeoff between income growth and emissions, the heterogeneity of the results both in sectorial and spatial terms and the necessity to customize the mitigation policies in a country with a spatial production structure with high degree of specialization like Brazil.

Key-words: CO_2 emissions; inter-regional input-output; Brazilian economy

1. Introduction

Using data from SEEG, the climate observatory, Brazil emitted 2.3 billion gross tons of greenhouse gases in 2022, representing an 8% drop compared to the previous year, when 2.5 billion tons were emitted. However, it is a high level of pollution. Deforestation is the main source of greenhouse gas emissions in Brazil; in 2022, the destruction of forests resulted in the emission of 1.12 billion gross tons of carbon dioxide, corresponding to 48% of Brazilian emissions. In the same year, 2022, the amount of greenhouse gases from

[1] The authors acknowledge the financial support from the Leman Center for Brazilian Studies at UIUC - USA
[2] Full Professor in the Department of Economics at Federal University of Juiz de Fora, CNPq researcher.
[3] Emeritus Professor and Emeritus Director at Regional Economics Applications Laboratory at the University of Illinois – Urbana-Champaign – USA.
[4] Full Professor in the Department of Economics at University of São Paulo, CNPq researcher.
[5] Full Professor in the Department of Economics at Federal University of Minas Gerais, CNPq researcher.
[6] PhD candidate in CEDEPLAR – UFMG.

agriculture grew to 617.2 million tons, an increase of 3.2% compared to 2021 and accounting 27% of the country's total.

The primary objective of this paper is to explore the spatial, sectoral and institutional drivers of the primary sources of emissions. This will entail a detailed analysis of the structure of production, the structure of trade and the structure of income formation and expenditures. This paper contributes to the literature implementing an analysis for a middle-income country, observing the impacts from the supply side, building a typology of sectors and regions and conducting a systemic analysis. Section 2 provides the context for the discussion and the interactions between production, trade and consumption in an explicit spatial setting. Section 3 introduces the data and methodology, which enables us to determine the key regions and sectors in terms of emissions. Section 4 presents the results at different spatial aggregation levels and sectorial results. Section 5 summarizes the main conclusions

2. The Context

Issues relating to sustainable growth have been studied extensively in the literature in their most diverse aspects, such as pressures on the use of water and energy and emissions generated from production processes, household consumption and international trade. These three aspects are strongly linked through the circular flow of income. For example, household consumption plays two roles in terms of environmental impacts. The first one is the direct impact from their common activities like the waste generation and the fuel used in their automobiles. The second is an indirect impact due to the composition of their consumption basket. Thus, from one side, these movements induce more production and income and from another side produce negative externalities.

Since the primary source of emissions may be traced to production, any measures to address mitigation require a careful analysis of the links between economic performance, energy consumption and CO_2 emissions. However, there is rarely a simple path between production and emissions, complicated by increasingly fragmented production chains that have resulted in economies becoming more dependent on transportation systems – a further and an increasing source of CO_2 emissions. Hence, the contribution of the diverse productive sectors to CO_2 emission will need to be established, considering the technological structure of the economy, the interrelations among sectors, and the sectoral capacity of generating value-added (especially income to employees). The nature and structure of the production interdependence, income and consumption will be important factors in determining the economic dynamics of a region. Hence, on the production side, it is important to understand both the emissions arising from each sector and those inherent to the production chain. Finally, it is also important to understand the pressures that variations in income exert on CO_2 emissions, one of the major objective of this paper.

As the Sixth Assessment Report (AR6) from the Intergovernmental Panel on Climate Change (IPCC, 2023) affirms, there are several options for reducing industrial emissions that differ by type of industry. Many industries are affected climate change, especially extreme events. Reducing emissions from industry will imply a coordinated action across value chains to promote all mitigation options, including demand management, energy efficiency, the circular flows of materials, as well as abatement and transformational changes in production processes. Actions to reduce emissions in the industrial sector can change the location of GHG-intensive industries and the organization of value chains, with distributive effects on the employment and economic structure.

Due to the economic efforts that emission mitigates needs, it is necessary to analyze the relation between economic performance, energy consumption and CO_2 emissions. Thus, the role played by each productive sector in terms of CO_2 emissions need to be measured, considering factors like the technological structure of the economy, the degree of interdependence among sectors and sectorial contribution to value added.

Following Alcántara and Padilha (2006), the paper will analyze the most important drivers from a production perspective responsible for CO_2 emissions and apply it to Brazilian economy for the year 2019. To achieve this goal, use will be made of an input-output approach from the supply side to capture the impact of income generation upon CO_2 emissions.

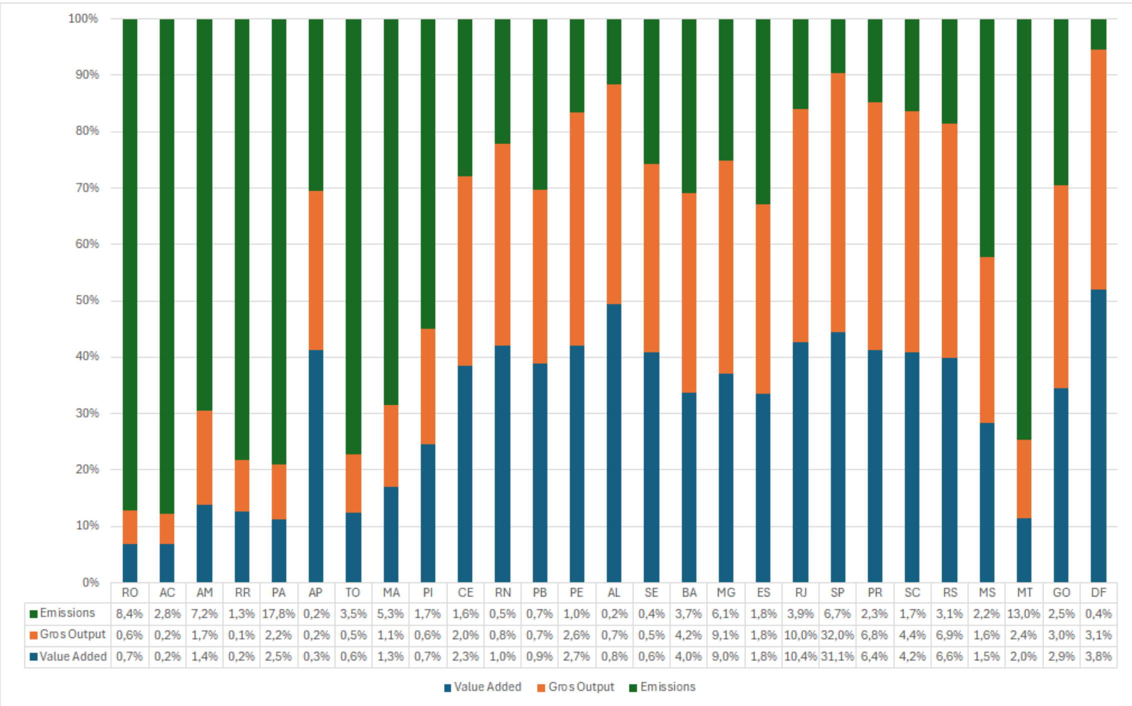
The use of input-output analysis has been growing in the field of environmental assessment. From the household perspective we can highlight the studies such as those from Lenzen, *et al.*, (2006), Peters and Hertwich (2006), Zhu *et al.*, (2014), Perobelli, *et al.* (2015), Wang *et al.* (2015), Zhang *et al.*, (2017), Zhou and Gu (2020). Several analyses use multi-regional modeling such as Lenzen, *et al.*, (2004), Liang, *et al.* (2007), Andrew, *et al.* (2009), Wiedmann (2009), Wiedmann, *et al.* (2010), Su and a-Ang (2014), Zhang, *et al.* (2015), Bachmann, *et al.* (2015), Ning, *et al.* (2019), Su, *et al.* (2021), de Araujo, *et al.* (2020). Finally, there are papers that estimate the impacts of international trade and interregional trade, such as Machado, *et al.* (2001), Wiebe, *et al.* (2012), Wiebe, *et al.* (2012b), Vale, *et al.* (2018), Haddad *et al*. (2024). In the next section, the available data will be presented together with the methodology that will be used.

3. Data and Methodology

3.1 Data

Two sets of data are used. First, an interregional input-output matrix for the 27 states of the Brazilian Federation will be accessed; this model features 68 productive sectors for a base year in 2019. The emissions in the Brazilian economy are obtained from Greenhouse Gas Emissions and Removals Estimation System dataset (SEEG). The NEREUS group in São Paulo provided a consistent bridge that enabled the emissions data to be linked with the interregional input-output matrix (Haddad, *et al* 2024).

Figure 1 – Value Added, Gross Output and Emissions: regional distribution (%)



	RO	AC	AM	RR	PA	AP	TO	MA	PI	CE	RN	PB	PE	AL	SE	BA	MG	ES	RJ	SP	PR	SC	RS	MS	MT	GO	DF
Emissions	8,4%	2,8%	7,2%	1,3%	17,8%	0,2%	3,5%	5,3%	1,7%	1,6%	0,5%	0,7%	1,0%	0,2%	0,4%	3,7%	6,1%	1,8%	3,9%	6,7%	2,3%	1,7%	3,1%	2,2%	13,0%	2,5%	0,4%
Gros Output	0,6%	0,2%	1,7%	0,1%	2,2%	0,2%	0,5%	1,1%	0,6%	2,0%	0,8%	0,7%	2,6%	0,7%	0,5%	4,2%	9,1%	1,8%	10,0%	32,0%	6,8%	4,4%	6,9%	1,6%	2,4%	3,0%	3,1%
Value Added	0,7%	0,2%	1,4%	0,2%	2,5%	0,3%	0,6%	1,3%	0,7%	2,3%	1,0%	0,9%	2,7%	0,8%	0,6%	4,0%	9,0%	1,8%	10,4%	31,1%	6,4%	4,2%	6,6%	1,5%	2,0%	2,9%	3,8%

Source: Own elaboration based on IIOA

Figure 1 presents a synthesis of the dataset; value added, gross output and total emissions for each Brazilian state are shown[7]. Note the differences in terms of the economic contribution and of CO_2 emissions. For example, the contribution of the state of Para for the Brazilian value added is 2.5% and in terms of CO_2 emissions is 17.8%. On the other

[7] To implement the fixed effect model, we use per capita income data for agriculture, trade, extractive, industry and service sector and emissions per capita by each Brazilian state from 2002 – 2018.

hand, São Paulo state is responsible for 31.1% of the Brazilian value added nug only 6.7% of the CO_2 emissions.

2.2 Methodology[8]

To capture the effects of embodied emissions from the supply side, an input-output model that relates sectoral gross production to the primary inputs is used. In other words, the total input of a specific sector is equal to the sum of interindustry supplies from other sectors (including the sector itself) and supply of factors of production (value added). Algebraically, for an economy divided into *r* regions and *i* sectors the following elements are defined:

$\boldsymbol{Z}$ – matrix of intermediate consumption. The elements $\boldsymbol{z_{ij}^{rn}}$ are the interindustry sales by sector *i* located at the region *r* (intermediate sales) to sector *j* locates at the region *n*. In the case of this paper $i = 1 \ldots 68; j = 1 \ldots 68, r = 1 \ldots 27\ and\ n = 1 \ldots 27$

$\boldsymbol{x}$ – vector of gross production

$\boldsymbol{y}$ – vector of final demand.

$\boldsymbol{v}$ – vector of value added.

$\boldsymbol{A}$ – matrix of technical coefficients. The elements are represented by $a_{ij}^{rb} = \frac{z_{ij}^{rn}}{x_j^r}$

$\boldsymbol{I}$ – identity matrix

$\boldsymbol{A'}$ - transpose matrix of technical coefficients

$\boldsymbol{B}$ – Leontief inverse

$\boldsymbol{s}$ – vector of value-added coefficients by region. These show the relationship between the value-added of sector *i* (v_i^r) and the production of sector *i* on each region *r*; that is: ${v_i^r}/{x_i^r}$ – a vector of the ratio between value added and gross production

$\boldsymbol{g}$ – vector of the relative share of sectorial emissions – emissions from sector *i* on region *r* divided by the total emissions

$\boldsymbol{\hat{g}}$ – diagonal vector

$\boldsymbol{\hat{s}}$ - diagonal vector

u – unit vector

The interregional input-output model is represented by:

[8] The methodology presented is based on the inter-regional input-output model, but a similar formulation applies to the national input-output model (see Alcântara and Padilha, 2006 and Bon, 1998)

$$x = \hat{x}A'u + v \tag{1}$$

Dividing both sides of (1) by $\hat{x}^{-1}$, we obtain:

$$u = A'u + s \tag{2}$$

Therefore, we can write:

$$u = (I - A')^{-1}s \tag{3}$$

From equation (3), it is possible to distribute any variable related to production among sectors. The case of emissions is presented next.

Let **c** be a vector of sectoral direct CO_2 emissions for each region. Premultiplying both sides of expression (3) by this vector, we obtain:

$$c = \hat{c}(I - A')^{-1}s \tag{4}$$

Considering g' = $(g_1^r \cdots g_n^r)$ be a vector of the distribution of total emissions among the n productive sectors and r regions, so that $\sum_{i=1}^{n}\sum_{1=1}^{r} g_i^r = 1$. Thus, vector **c** can be expressed as follows:

$$c = Cg \tag{5}$$

C is a scalar that shows the total level of CO_2 emissions in the country.

Thus,

$$c = c\hat{g}(I - A')^{-1}s \tag{6}$$

and premultiplying both sides of (6) by *u'*, we obtain:

$$C = C\hat{g}(I - A')^{-1}s \tag{7}$$

From (7) we can implement a simulation exercise. Consider a proportional increase of the size α in the value-added. *Ceteris paribus*, it would lead to an increase in total emissions, namely:

$$\Delta C = C\hat{g}(I - A')^{-1}s\alpha \tag{8}$$

Dividing both sides of this expression by total emissions **C**, we obtain:

$$C^{-1}\Delta C = g'(I - A')^{-1}s\alpha \tag{9}$$

The diagonalization of *s* in (9) leads to the vector:

$$\varepsilon' = g'(I - A')^{-1}\hat{s}\alpha \tag{10}$$

whose characteristic element ε_i^r shows the proportional change in (direct and indirect) sectoral total emissions in each region *r* in relation to a proportional change in income. These can be interpreted as elasticities. Notice that, in fact, the proportional increase of the size α, in income is equivalent to the ratio ${\Delta v_i^r}/{v_i^r}$ for each sector *i* in each region *r*. Thus, vector ε' can be expressed as follows:

$$\varepsilon_i = \frac{\Delta C/C}{\Delta v_i/v_i} = \frac{\Delta C}{\Delta v_i}\frac{C}{v_i} \tag{11}$$

The elements of the vector obtained in (10) shows the proportional change in total emissions per region when there is a percentage increase in the value-added of each of the sectors in each region. In other words, the income elasticity of total emissions, which we consider as a measure of sectoral impact. For a more accurate interpretation of this result, we diagonalize vector *g'* and assume α = 1%:

$$E^v = \hat{g}(I - A')^{-1}\hat{s} \tag{12}$$

The characteristic element of matrix E^v, E_{ij}^v, shows the percentage increase in the emissions of sector *i* (with respect to total emissions) in response to a 1% increase in the value-added generated in sector *j*, and it can be interpreted as an elasticity. The sum of the elements of the sector *j* column $\sum_i^n E_{ij}^v$, expresses the percentage of variation in CO_2 emissions experienced by the economy in response to a 1% growth in value added experienced by sector *j* (total impact) in each region.

The sum by rows of this matrix, $\sum_j^n E_{ij}^v$, shows the sectoral distribution of emissions and is an indicator of the impact that a global economic increase of 1% would have on the emissions of each sector (direct impact). In this approach, for the productive structure, the higher or lower capacity of generating value-added of the diverse sectors and regions, and the direct emission intensity are decisive elements for determining the environmental impact of each sector.

4. Results

In this section, the national typology, the regional results (e.g., typology and spatial aspects) and the fixed effects results are presented.

4.1 National Results

Table 1 presents a sectorial typology to show the role played by each sector in terms of its relevance for CO_2 emissions. The direct and total impacts are presented in terms of quartiles. The sectors localized in the third and fourth quartiles in both distributions are those that have the major impact (both direct and total). The results for these sectors are above the average for the two kinds of impact; as a result, one can classify the sectors as "key" in terms of CO_2 emission.

Table 1. Sectoral classification according to direct and total impact - 2018

		Direct Impact			
		4th. Quartile	**3rd. Quartile**	**2nd. Quartile**	**1st Quartile**
Total Impact	**4th Quartile**	1, 2, 3, 5, 10, 19, 21, 26, 27, 38, 42, 43 Total = 0,6073 Direct = 0,8037		55	53, 59
	3rd. Quartile	17, 41, 44	4, 25, 39, 52, 58, 60, 61	22, 29, 57	24, 37, 46
	2nd. Quartile		7, 8, 40, 47, 68	16, 20, 31, 32, 34, 50, 63	18, 48, 51, 67
	1st. Quartile		9, 11, 13, 62, 66	45, 64, 65	12,14,15, 23, 30, 35, 36, 49 Total = 0,0017 Direct = 0,0001

Source: Own elaboration based on IIOA

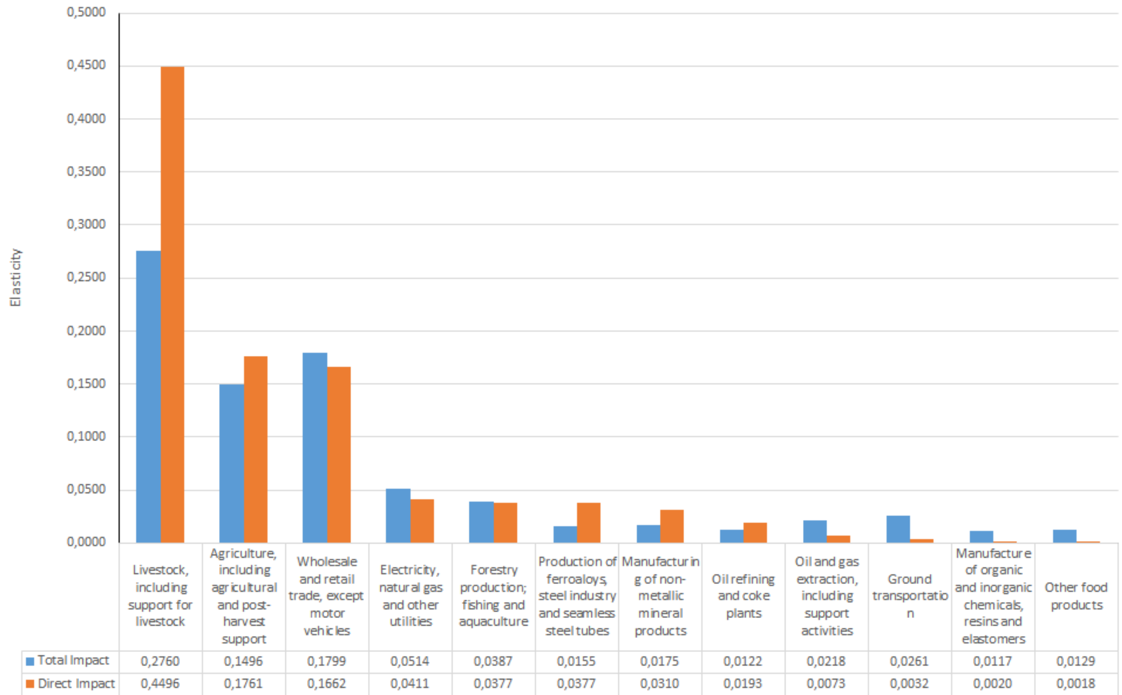
From 68[9] sectors, twelve are in the fourth quartile. An 1% increase in the economy's income means a change of 0.8037% in total direct emissions in this set of twelve key sectors. On the other hand, a 1% increase in the value-added in these sectors implies a 0.6073% total increase in emissions of the economy. It is possible to highlight the importance of these results due to the mitigation policies, in the sense that mitigation policies, from an emissions perspective, could be more effective in these sectors than in others.

Expanding the analysis to sectors located in the third quartile, for 2019, twenty-two sectors out of a total of sixty-eight are in the quadrant formed by the third and fourth

[9] Appendix A presents the list of sectors.

quartiles. Hence, in terms of mitigation policies, these new sectors would be the second option when trying to focus more on the most effective mitigation policies. However, it is important to emphasize that the elasticity of these sectors is small. For 2019, the direct effect is 0.0162% and the total is 0.0406%, strengthening the degree of concentration in terms of CO_2 emissions in the Brazilian productive chain. Furthermore, a comparison between the costs, in terms of the value-added, of the reduction emissions between sectors located at the first quartile and the fourth quartile will be greater in the case of the first quartile.

Figure 2 - Impact of the “key” sectors in CO2 emission – 2018



Source: Own elaboration based on IIOA

Figure 2 shows the elasticity of the emission of the sectors classified as “key” (see Table 1) in response to a 1% increase in value-added. Note that Livestock, including livestock support activities (S2), is the sector that presents the highest total elasticity. In this case, a 1% increase in the value-added of sector (S2) induces a 0.2760% increase in total CO_2 emissions. On the other hand, an increase in the income of the economy implies 0.4496% direct increase in CO_2 emissions in sector (S2), that represents around 45% of total increase in emissions. The second highest sector in terms of direct impact is Agriculture[10], including agricultural support and post-harvest activities (S1). The results

[10] In the econometric model, agriculture is split into exports and non-exports sectors to capture the different impact upon emissions.

show that a 1% increase in income of the economy implies a 0.1761% direct increase in total CO_2 emissions. From the perspective of the total emissions, the second most important sector is Wholesale and retail trade, except motor vehicles (S42). Observing those three sectors for S2 and S1, the direct impact is higher than the total impact, implying a different mitigation policy for these sectors when compared to sectors that present a higher total impact.

4.2 Regional Results

Table 2 present the results for *direct impacts* – that measure the percentage increase in the emissions of the economy that occurs in each region in response to a 1% increase in value-added by all regions and *total impacts* – that measure the percentage increase in the emissions generated by the whole productive system in response to a 1% increase in value-added by the corresponding region.

Table 2 - Total and direct impact on CO_2 emissions by Brazilian states: 2019

Regions	Total Impact	Direct Impact	Most relevant impact
Rondônia	0,0637	0,0924	Direct Impact
Acre	0,0178	0,0288	Direct Impact
Amazonas	0,0563	0,0784	Direct Impact
Roraima	0,0095	0,0139	Direct Impact
Pará	0,1298	0,1937	Direct Impact
Amapá	0,0016	0,0021	Direct Impact
Tocantins	0,0217	0,0356	Direct Impact
Maranhão	0,0396	0,0565	Direct Impact
Piauí	0,0113	0,0168	Direct Impact
Ceará	0,0135	0,0164	Direct Impact
Rio Grande do Norte	0,0051	0,0052	Direct Impact
Paraíba	0,0049	0,0072	Direct Impact
Pernambuco	0,0114	0,0102	Total Impact
Alagoas	0,0029	0,0019	Total Impact
Sergipe	0,0032	0,0034	Direct Impact
Bahia	0,0305	0,0366	Direct Impact
Minas Gerais	0,0498	0,0568	Direct Impact
Espírito Santo	0,0130	0,0149	Direct Impact
Rio de Janeiro	0,0442	0,0347	Total Impact
São Paulo	0,1077	0,0623	Total Impact
Paraná	0,0245	0,0212	Total Impact
Santa Catarina	0,0153	0,0157	Direct Impact
Rio Grande do Sul	0,0296	0,0298	Direct Impact
Mato Grosso do Sul	0,0149	0,0216	Direct Impact

Mato Grosso	0,0563	0,1159	Direct Impact
Goiás	0,0193	0,0241	Direct Impact
Distrito Federal	0,0063	0,0038	Total Impact

Source: Own elaboration based on IIOA

Pará state presents the highest total and direct impacts; a 1% increase in Para´s value added would lead to a 0.1298% increase in total emission. On the other hand, an 1% increase in the value added in all other regions would cause a direct improvement in Para state global emissions of 0.1937%.

Rondônia, Amazonas and Mato Grosso state also reveal a direct impact greater than the total impact, which means that the emissions in those three regions are more sensitive to the variation of the value-added in the other regions. Furthermore, this result occurs for twenty-one of the Brazilian states.

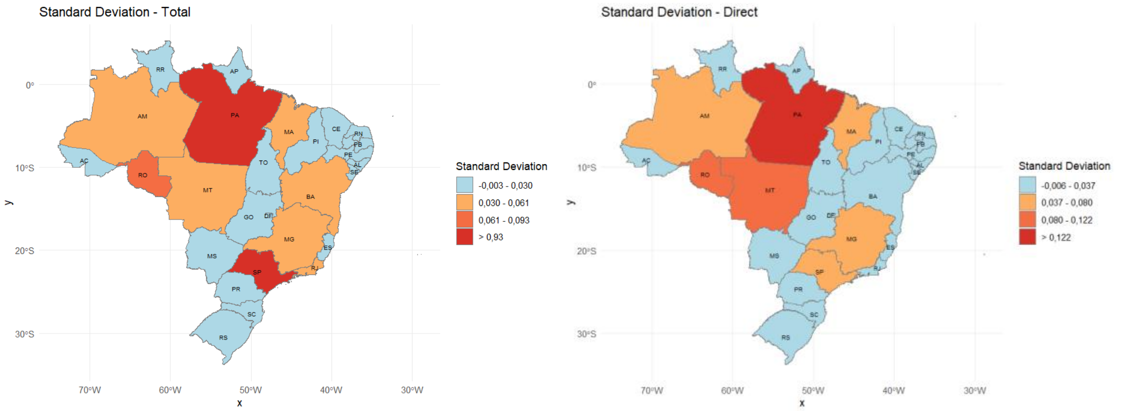
On the other hand, São Paulo state has a direct impact that is smaller than the total impact, which means that the local driver of emissions in São Paulo state is more prominent, generating an increase in the value added in São Paulo that will impact the emissions in the rest of the country. Pernambuco, Alagoas, Rio de Janeiro, Paraná and Distrito Federal also present direct impacts that are smaller than total impact.

Figures 3A and 3B shows the spatial distribution of the total and direct impact in terms of the standard deviation and Figures 4A and 4B shows the spatial autocorrelation[11] (*e.g.* clusters) for the total and direct impact.

When observing Figure 3A, nine states are above one standard deviation, highlighting the results of São Paulo, Paraná and Rondônia. In relation to direct impacts, it appears that seven states are located above one standard deviation, with emphasis on the states of Pará, Rondônia and Mato Grosso. In the specific case of Rondonia, its emission process is both influenced by the variation in value added in other states and by the variation in value added in the region itself.

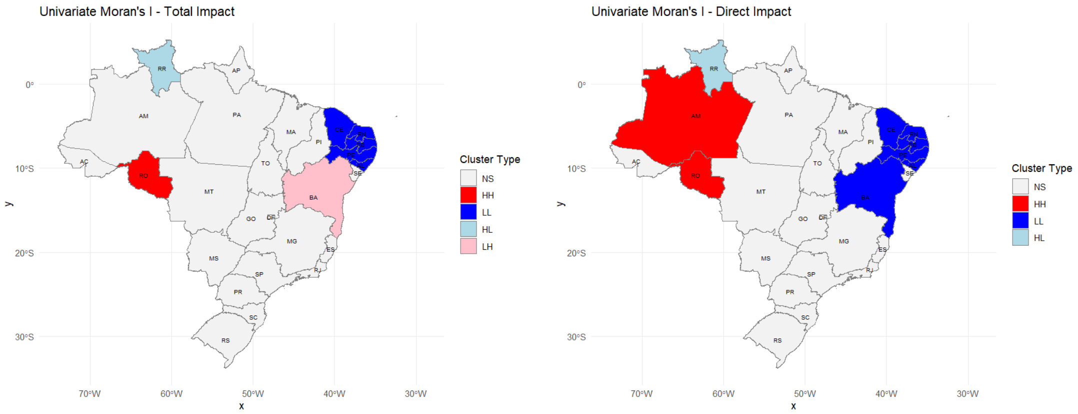
[11] We implement the spatial analysis using a *k*-nearest neighborhood with $k = 4$.

Figure 3 – Total and direct impact: standard deviation



(3A) **(3B)**

Figure 4 - Local univariate Moran: total and direct impact



(4A) **(4B)**

The cluster analysis implemented through the univariate local association indicator (Local Moran's *I*) makes it possible to highlight the neighborhood effect in the result of emissions impacts. For the two types of impacts analyzed, the significant clusters are formed by states that belong to the North and Northeast regions of Brazil. In the case of total impacts, the states of Rondonia and Roraima were the most prominent and in the case of direct impacts, the states of Amazonas, Rondonia and Roraima stood out. This assessment is relevant, given the productive characteristics of this region, which will be analyzed in the sectoral results section. Furthermore, the results show that one of the most important regions in terms of agriculture production and forest preservation has its impacted emissions both for the intra-regional and inter-regional variation of the value-added.

Table 3 presents a regional typology to show the role played by each Brazilian state in terms of its relevance for CO_2 emissions. The direct and total impact were classified in terms of quartiles. The regions localized in the fourth quartile in both distributions are those that have the major impact (both direct and total). The results for these regions are above average for the two types of impact. From these perspectives, it is possible to classify the regions as “key” in terms of CO_2 emission.

Table 3. Regional classification according to direct and total impact

		Direct Impact			
		4th. Quartile	**3rd. Quartile**	**2nd. Quartile**	**1st Quartile**
Total Impact	**4th Quartile**	RO; AM; PA; MG; SP; MT Total - 0,5033 Direct - 0,6560	RJ	55	53, 59
	3rd Quartile	MA	TO; BA; RS; GO	PR	
	2nd Quartile		AC; MS	PI; CE; ES; SC	PE
	1st Quartile			RR	AP; RN; PB; AL; SE; DF Total = 0,1849 Direct = 0,2173

Source: Own elaboration based on IIOA

It can be observed that six Brazilian states are located at the fourth quartile. An 1% increase in the economy's income implies a variation of 0.6560% in total direct emissions for this set of regions. From the other side, an 1% increase in the value-added in these regions implies a 0.5033% total increase in emissions of the economy. The importance of these results can be highlighted in terms of mitigation policies; In other words, *ceteris paribus*, mitigation policies could be more effective in these regions than in others.

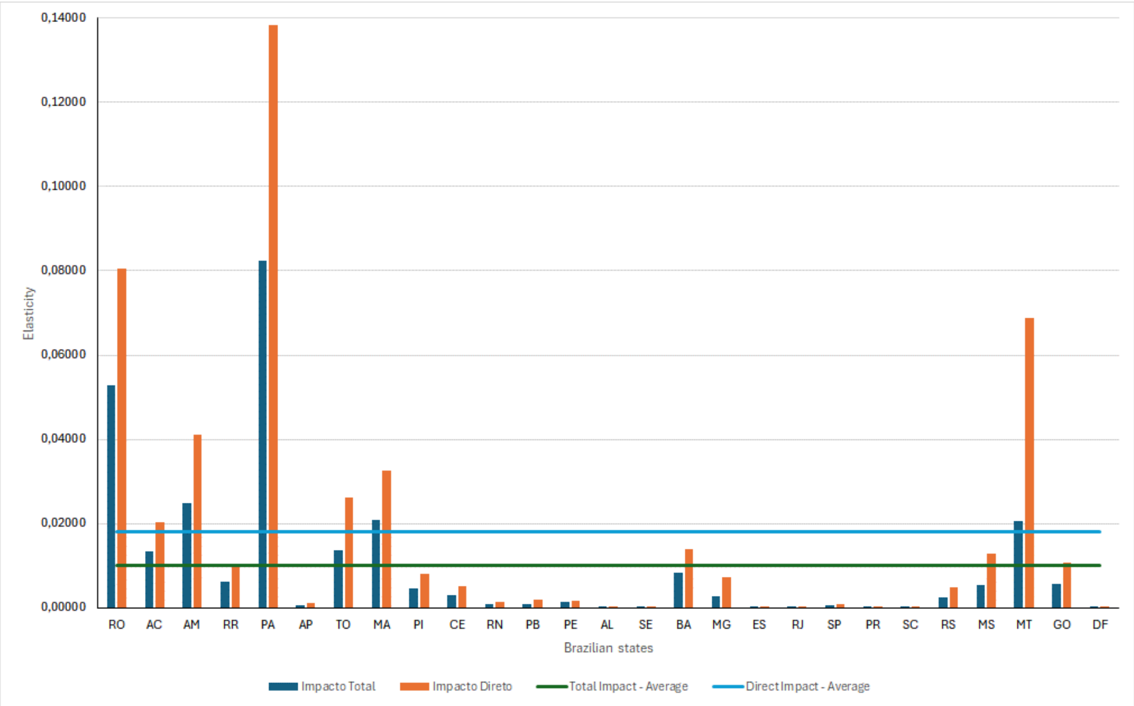
Expanding the analysis to the regions that are located at the third quartile, note that twelve Brazilian states out of 27 are in the quadrant formed by the third and fourth quartile. In terms of mitigation policies, these new regions would be the second option when trying to focus on an enhanced impact from mitigation policies. However, it should be emphasized that the elasticity of these regions is small; for example, the direct is 0.2173%

and the total is 0.1849%, strengthening the degree of concentration in terms of CO_2 emissions in the Brazilian regional productive chain. Furthermore, a comparison between the costs, in terms of the value-added, of the reduction emissions between regions located at the first quartile and the fourth quartile will be greater in the case of the first quartile. An observation must be made, the approach used in this paper is a supply analysis and is important to consider that there is an amount of production of these regions that are made for other regions. Thus, the analysis presented here is complementary to the analysis from demand side from the input-output perspective.

4.3 Sectorial Results by region

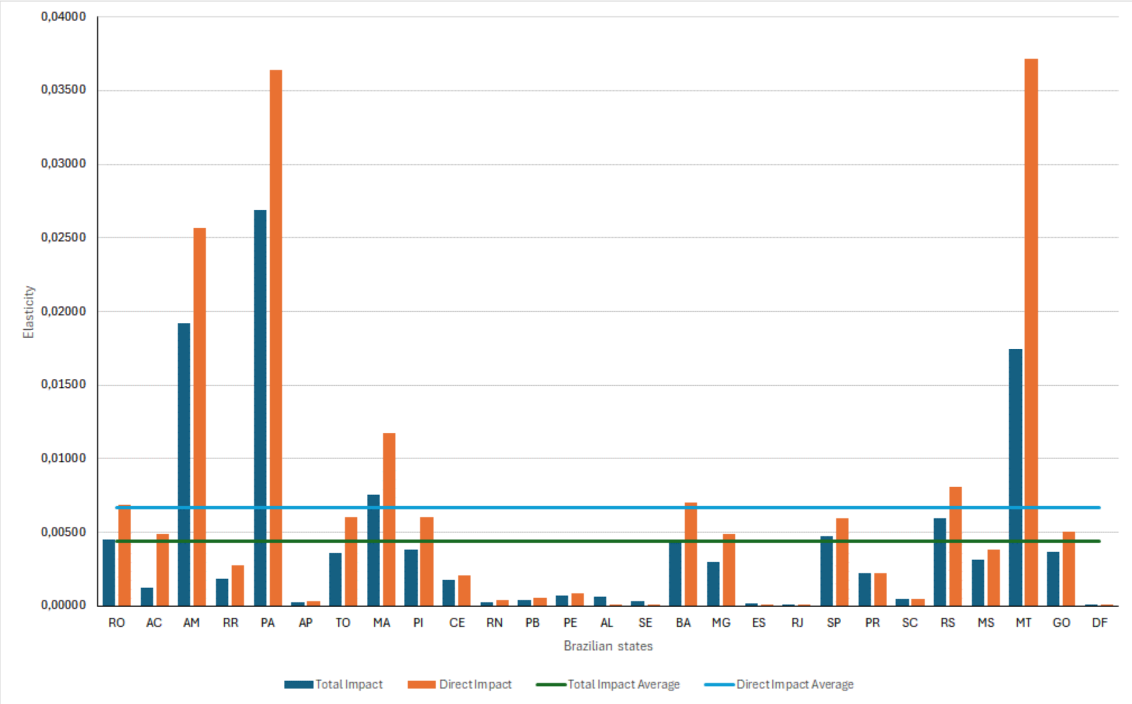
In this section, attention will be directed to the sectorial results by region. Analysis focused on some of the sectors classified as" key" for the Brazilian analysis (see Figure 2). To provide a better comparison between those sectors, two were chosen for the primary sector, one for the industrial sector and one that represents the service and trade sector.

Figure 5. Livestock including support for livestock: Total and Direct impact by Brazilian states



Source: Own elaboration based on IIOA

Figure 6. Agriculture: Total and Direct impact by Brazilian states

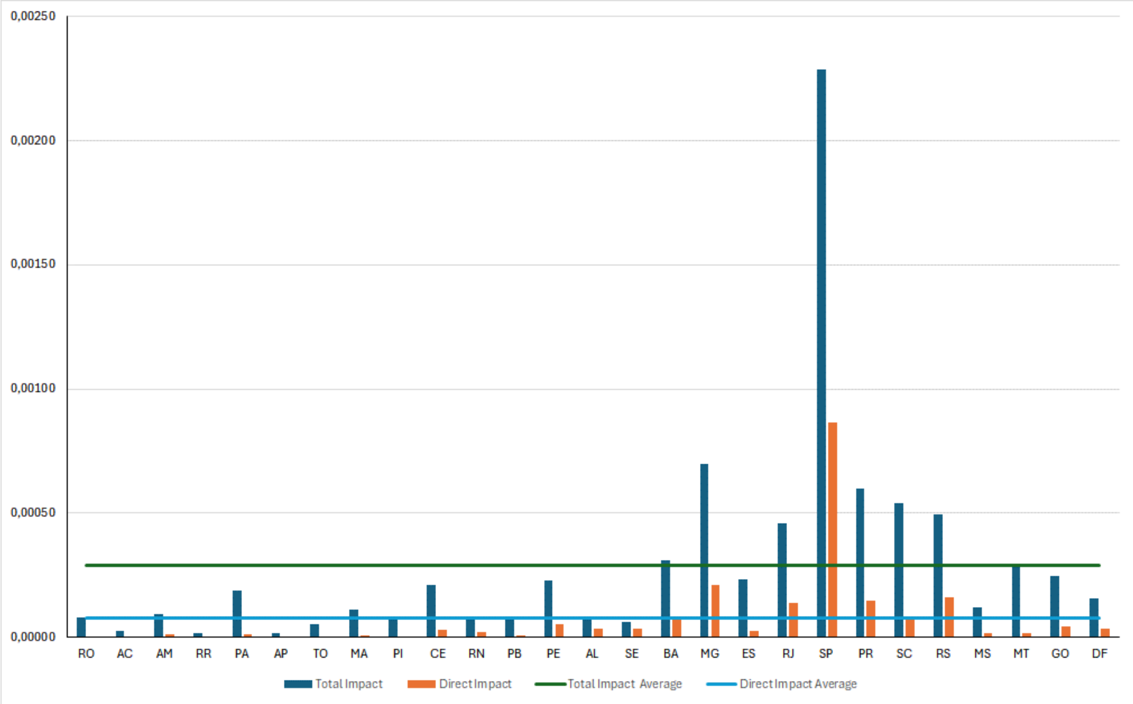


Source: Own elaboration based on IIOA

Observing Figure 5, notice the role played by most of the states located in the North and Center-west regions both in terms of direct impact and total impact. Pará (PA), Rondônia (RO) and Mato Grosso (MT) are the three that present the highest elasticity in terms of direct impact. They are responsible for around 83% of the total elasticity. In a comparison with the agriculture sector (Figure 5) we also notice a considerable difference in the size of the elasticity. While for Livestock, the highest elasticity is around 0.4%, for Agriculture it is around 0.04%, putting more pressure on the emissions of these sectors located at PA, RO and MT since an increase in 1% in the economy´s income implies a considerable variation in direct emissions.

From Figure 6, it can see that for most of the Brazilian states, the direct impact is higher than the total impact, meaning that 1% increase in the value added of those states in agriculture sector would lead to an increase in total emission. This outcome is most evident in the results for Pará (PA) state, Mato Grosso (MT) state and Amazonas (AM) state, that presents a percentage variation of 0.03718%, 0.03639% and 0.02563%, respectively. Furthermore, Rondônia (RO), Maranhão (MA), Bahia (BA) and Rio Grande do Sul (RS) also present an elasticity above the average. The picture for total impact is slightly the same. The novelty is the role played by São Paulo (SP) state that is located above the average.

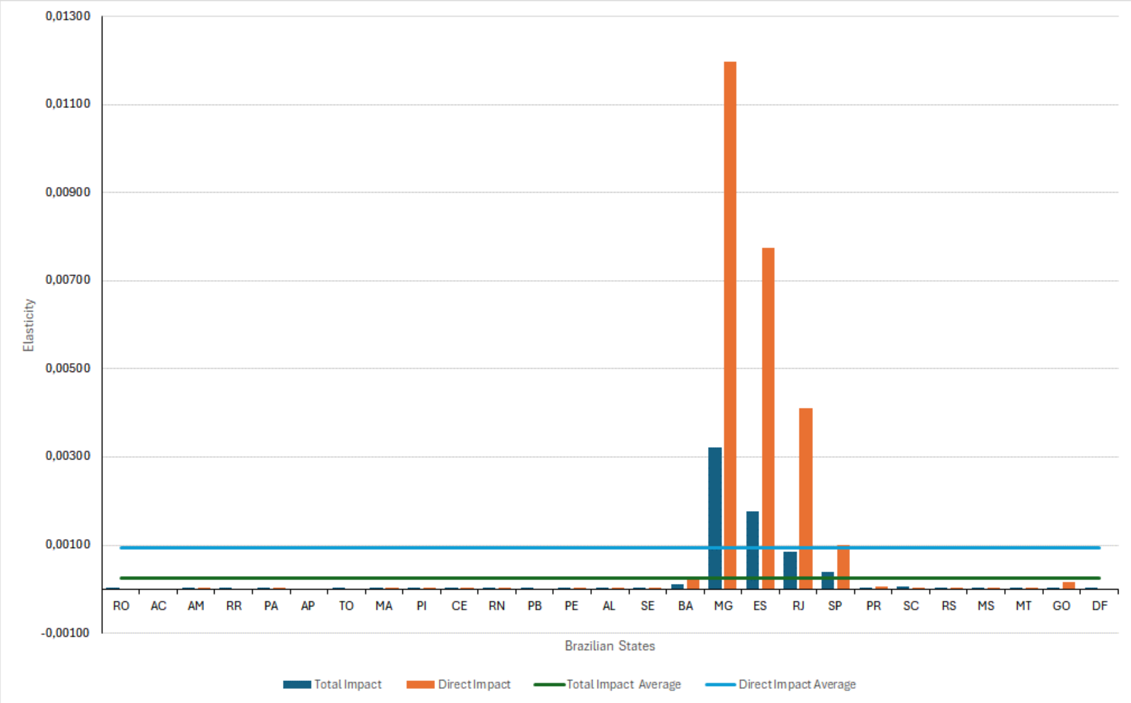
Figure 7. Wholesale and Retail Trade: Total and Direct impact by Brazilian states



Source: Own elaboration based on IIOA

Figure 7 presents the results for the wholesale and retail trade sector. The result is on the opposite side from the previous one both in terms of the impact (direct and total) and in terms of the most important regions. For most of the states, the total impact is higher than the direct one, meaning that a 1% increase in the value-added in this sector in each region implies a total increase in emissions of the economy. Thus, observing the result for São Paulo (SP) state, the increase in the value-added in the rest of the Brazilian economy pressures the emission at the state, that presents an elasticity near to 0,00229. Furthermore, the elasticity is smaller than the ones presented by Agriculture and Livestock.

Figure 8. Production of pig iron/ferroalloys, steel industry and seamless steel tube: Total and Direct impact by Brazilian states



Source: Own elaboration based on IIOA

Figure 8 presents the results for Production of pig iron/ferroalloys, steel industry and seamless steel tube sector. Here, the results are spatially concentrated, and the total impact is higher than the direct for all the states, meaning that a 1% increase in the value added of those states in this sector would lead to an increase in total emissions. Minas Gerais (MG) state presents the highest elasticity (0.01198%), followed by Espirito Santo (SP) and Rio de Janeiro (RJ) state. The hierarchy for the total impact is the same as the direct impact.

4.4 Fixed Effect Model

When carrying out the analysis of emissions in a systemic way on the supply side, that is, evaluating issues related to income, discussion could be raised about potential difficulties in implementing mitigation policies. In the previous sections, it was noted that there is great heterogeneity, both sectoral and spatial, in terms of emissions. To complement this analysis and test the significance of the relationship between income from different sectors and emissions, a fixed effects model was built to capture the correlation between sectoral income and emissions. Due to the importance of some sectors in this context (see section 4.1 and 4.3), the sectoral income data were grouped into large productive sectors:

agriculture, mineral extraction, industry, commerce and services (RAIS, 2024) as covariates to capture the correlation with emissions (SEEG). A panel data[12] with 459 observations, was specified using data from 2002 to 2018 for the 27 units of the Federation. The functional form specified is as follows:[13]

$$Emissions_i^t = \alpha_i + \beta_1 income_{extractive}{}_i^t + \beta_2 income_{industry}{}_i^t + \beta_3 income_{trade}{}_i^i + \beta_4 income_{service}{}_i^i + \beta_5 income_{agriculture\_exports}{}_i^t + \beta_5 income_{agriculture\_nonexports}{}_i^t + \epsilon_i^t$$

where:

$Emissions_i^t$ - is the dependent variable and represents emissions per capita, with *i* varying from 1 to 27 (representing the 27 units of the Federation)

α_i – represents the fixed effects

$\beta_1 income_{extractive}{}_i^t$ – per capita labor income from the mining extractive sector,

$\beta_2 income_{industry}{}_i^t$ – per capita labor income in the industrial sector,

$\beta_3 income_{trade}{}_i^t$ – per capita labor income from the trade sector,

$\beta_4 income_{service}{}_i^t$ – per capita labor income in the services sector,

$\beta_5 income_{agriculture\_exports}{}_i^t$ – per capita labor income of the exporting agricultural sectors,

$\beta_5 income_{agriculture\_nonexports}{}_i^t$ - per capita labor income of the non-exporting agricultural sectors,

ϵ_i^t – error term

[12] We have a balanced panel. The model specification follows the following functional form: $Y_t^i = \alpha_i + X_i^t \beta + \epsilon_i^t$, where α_i is a fixed component that captures the heterogeneity between the units of analysis, which in this model are emissions, and the subscript *i* suggests that the intercepts may be different in each unit; X_i^t – represents the set of explanatory variables; ϵ_i^t – represents the error term.

[13] Income from inter-regional trade (*e.g* inter-regional exports) in agriculture, for example, are not considered since comparable time series are not available.

Table 4 – Fixed Effect Model

Variables	Coefficients
$income_{extractive}$	1.39e-07** [4.99e-08]
$income_{industry}$	2.63e-08*** [7.34e-09]
$income_{trade}$	-3.36e-08 [1.97e-08]
$income_{service}$	-2.30e-08*** [4.42e-09]
$income_{agriculture\_exports}$	6.58e-05** [1.07e-05]
$income_{agriculture\_non\_exports}$	-1.06e08** [3,43e-08]
Number of obs	459
R^2	0.38016
R^2 $ajusted$	0.3336
SQregression	5.83e-09
SQ residual	3.61e-09
F	10.4658

** Significant at 0,01
*** Significant at 0,001

Source: Prepared by the authors

The coefficients presented in Table 4 show that: for income per capita from the extractive, industry and agriculture of export goods sectors, there is a positive relationship with emissions per capita, that is, an increase in income per capita in these sectors leads to an increase in emissions per capita. For trade, services and agriculture of non-export goods sectors there is an inverse relationship, that is, an increase in income per capita in these sectors has a negative impact on emissions per capita.

What do these results reveal about regional growth? In 2024, agriculture exports represented around 49% of the total exports and accounted for 3% of Brazilian GDP (IBGE, 2024). Thus, this contribution cannot be overlooked but comes at a "cost" in terms of the potential emissions from agriculture (see Table 1 and Table 4). Furthermore, this leads us to a discussion of mitigation policy, which in the Brazilian case would lead, in principle, to the existence of a tradeoff between income growth and per capita emissions. Therefore, the analysis on the income side using the fixed effects model strengthens the systemic discussion carried out previously and brings to the discussion, for example, issues related to technological change and energy efficiency as contributors to emission reduction. In terms of policy mitigation actions, a good example is subsidizing the development of alternative energy sources with low emission intensity, to increase the speed of convergence towards economies with low GHG emissions. In other words, it is necessary to achieve energy efficiency through the consumption of clean energy (less intensive in carbon emissions) and, for this, it is necessary to replace fossil fuels. Furthermore, it is necessary to improve the programs of transfer of technologies with low carbon emissions from developed countries to middle income nations, like Brazil. However, Brazil does have some current initiatives that could reduce the impact of agriculture activities upon CO_2 emissions such as RenovaBio (Law 13,576/2017), Agroforestry Systems (Law 12,651/2012) and ABC+ Plan (2020-2030).

5. Final Considerations

This paper contributes to the literature measuring the impacts of emissions from the supply side, building a typology of sectors and regions and implementing a systemic analysis. First, an analysis for the Brazilian economy is implemented to capture the key sectors in terms of emissions. Due to the high degree of spatial heterogeneity of the Brazilian economy the second analysis disaggregates the results for the 27 Brazilian states considering all the 67 sectors available in the dataset. Furthermore, considering the spatial and sectorial heterogeneity from systemic analysis, a fixed effects model is estimated to capture the relationship between a group of income per-capita sectors and per-capita emissions.

The sectorial typology built for the Brazilian economy shows the role played by each sector in terms of its relevance for CO_2 emissions. The sectors are divided into quartiles taking into consideration the direct and total impact that enables us from this perspective build a hierarchy in terms of sectorial mitigation. The analysis for the Brazilian economy pointed out the high degree of heterogeneity among the sectorial elasticities, varying from 0.2760 to 3.94E-06 for total impact and from 0.4496 to 0.0000 for direct impact.

Dividing the elasticities in two measures (*e.g.* total and direct) may contribute to a better design of the potential mitigation policies both in spatial and sectorial terms. The spatially aggregate results help to better understand which are the main driver of the emissions, if local – when the direct impact is higher than the total impact or if it is in the rest of the economy – when the total impact is higher than the direct impact. In that case we observe the case of São Paulo and Pará. For the first region the main driver is local, meaning that an increase in the value added in São Paulo will impact the emissions in the rest of the country and for the second regional the main driver is located at the rest of the country, meaning that the emission at Pará is more sensitive to the variation of the value-added in the other Brazilian states.

The sectorial regional analysis highlights the degree of the heterogeneity among the Brazilian states and the different regional drivers for the emissions. For agriculture and livestock, the main driver is local. On the other hand the whole sale and the retail trade the main driver is the rest of the economy.

An observation must be made, the approach used in this paper is a supply analysis and it is important to consider that there is an amount of production of these sectors that are made for other sectors. Thus, the analysis presented here is complementary to the analysis from the demand side from the input-output perspective. Furthermore, in the econometric approach from the agriculture side inter-regional exports are not considered because of the lack of time series data. The recent improvement in the transportation system in Brazil implies an increase in the internal trade. Thus, considering internal trade could be an issue for the future research agenda. Haddad, *et al* (2024) using a multiregional input-output approach for a Legal Amazon region took inter-regional trade into consideration to measure the impact upon deforestation.

On the other hand, the results in this paper reinforce the tradeoff between income growth and emissions, the heterogeneity of the results both in sectorial and spatial terms and the necessity to customize the mitigation policies in a country with a spatial production structure with high degree of specialization like Brazil.

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Appendix A

List of Sectors

CODE	SECTORS
S1	Agriculture, including agricultural and post-harvest support
S2	Livestock, including support for livestock farming
S3	Forestry Production; fishing and aquaculture
S4	Extraction of mineral coal and non-metallic minerals
S5	Oil and gas extraction, including support activities
S6	Extraction of iron ore, including processing and agglomeration
S7	Extraction of non-ferrous metallic minerals, including processing
S8	Slaughter and meat products, including dairy and fish products
S9	Sugar manufacturing and refining
S10	Other food products
S11	Beverage manufacturing
S12	Manufacturing of tobacco products
S13	Manufacturing of textile products
S14	Production of clothing and accessories
S15	Manufacture of footwear and leather articles
S16	Manufacturing of wooden products
S17	Manufacture of pulp, paper and paper products
S18	Recording printing and playback
S19	Oil refining and coke plants
S20	Biofuel manufacturing
S21	Manufacture of organic and inorganic chemicals, resins and elastomers
S22	Manufacture of pesticides, disinfectants, paints and various chemical products
S23	Manufacture of cleaning, cosmetics/perfumery and personal hygiene products
S24	Manufacture of pharmochemical and pharmaceutical products
S25	Manufacture of rubber and plastic products
S26	Manufacture of products from non-metallic minerals
S27	Production of pig iron/ferroalloys, steel industry and seamless steel tubes
S28	Nonferrous metal metallurgy and metal fishing
S29	Manufacture of metal products, except machinery and equipment
S30	Manufacture of computer equipment, electronic and optical products
S31	Manufacture of electrical machinery and equipment
S32	Manufacture of machines and mechanical equipment
S33	Manufacture of automobiles, trains and buses, except parts
S34	Manufacture of parts and accessories for automotive vehicles
S35	Manufacture of other transport equipment, except automotive vehicles
S36	Manufacture of furniture and products from different sectors
S37	Maintenance, parts and installation of machines and equipment
S38	Electricity, natural gas and other utilities
S39	Water, sewage and waste management
S40	Construction
S41	Sales and repair of motor vehicles and motorcycles
S42	Wholesale and retail trade, except motor vehicles
S43	Ground transportation
S44	Water transportation

S45	Air Transport
S46	Storage, auxiliary transport and mail activities
S47	Accommodation
S48	Food
S49	Print-integrated publishing and editing
S50	Television, radio, cinema and sound and image recording/editing activities
S51	Telecommunications
S52	Development of systems and other information services
S53	Financial intermediation, insurance and supplementary pension
S54	Real estate activities
S55	Legal, accounting, consultancy and company headquarters activities
S56	Architecture, engineering, technical testing/analysis and R&D services
S57	Other professional, scientific and technical activities
S58	Non-real estate rentals and intellectual property asset management
S59	Other administrative activities and complementary services
S60	Surveillance, security and investigation activities
S61	Public administration, defense and social security
S62	Public education
S63	Private education
S64	Public healthcare
S65	Private healthcare
S66	Artistic, creative and performance activities
S67	Membership Organizations and Other Personal Services
S68	Domestic services