Analysis of Socioeconomic Factors and Greenhouse Gas Emissions in the State of São Paulo

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Abstract: Climate change is one of the most pressing global challenges and is closely related to the increase in greenhouse gas emissions resulting from human activities. The State of São Paulo stands out due to its economic relevance and pronounced socioeconomic heterogeneity among municipalities, making it an appropriate case for analyzing the relationship between development and environmental emissions. This study aims to examine the socioeconomic determinants of carbon dioxide equivalent emissions in the State of São Paulo, using the STIRPAT model estimated through fixed effects regressions. The results indicate that the expansion of the vehicle fleet has a positive and statistically significant impact on CO_2eq emissions. Conversely, industrial value added shows a negative coefficient, suggesting productivity gains and a potential decoupling between industrial growth and emissions in certain places. The findings reveal a strong spatial concentration of emissions among a small number of municipalities within the state.

Keywords: Brazil, Climatic change, Carbon dioxide, Emissions, Panel data, STIRPAT.

1. INTRODUCTION

Since the Industrial Revolution, the world has experienced accelerated economic and population growth alongside a significant increase in greenhouse gas (GHG) emissions. Between 1950 and 2020, the world's population more than tripled, while global carbon dioxide (CO_2) emissions grew nearly sevenfold during the same period, demonstrating a direct association among demographic, productive, and environmental dynamics [1].

In the Brazilian context, the historical behavior of GHG emissions reflects a complex process of socioeconomic transformations, territorial expansion, and changes in land use patterns [2]. In recent decades, the country has consolidated its position among the top global emitters. This is particularly evident in sectors such as agriculture and land-use change [1, 3].

However, the State of São Paulo, the most populous and economically relevant in the country, presents a structurally different emissions profile. Marked by high population density and a heavy industrial concentration, São Paulo's emissions are dominated by the energy and transportation sectors, distinguishing it from the national average [2, 4].

This disparity has led the state to formulate its own mitigation strategies. The State Policy on Climate Change (PEMC), established in 2009, represented a milestone by setting a goal to reduce state emissions by 20% by 2020 [5]. Nevertheless, the 10-year review report published in 2022 revealed that the actual reduction was only 2.1% [6].

The difficulty in reaching these climate targets corroborates the critiques by [7], who pointed out that the lack of systemic integration and binding metrics has historically fragmented and limited the effectiveness of the state's climate actions. To address this gap, recent frameworks such as the State Energy Plan 2050 (PEE 2050) and the SP Carbon Neutral 2050 commitment have been introduced to promote the transition to a low-carbon matrix [8].

However, formulating effective policies requires an understanding of how distinct socioeconomic structures influence emissions profiles at the local level. The municipal scale is frequently neglected, yet it is fundamental for understanding how local factors contribute to the aggregated pattern of emissions, enabling more refined analyses that are accurately tailored to territorial realities [9].

While the relationship between economic variables and GHG emissions is widely documented globally, studies exploring this dynamic at the municipal level remain scarce in Brazil [9]. This gap is particularly significant given the pronounced heterogeneity of municipalities in terms of economic structure, population density, and institutional capacity. Observing emissions on a municipal scale is essential to investigate the extent to which local income generation is tied to activities with high environmental impacts [4, 10].

Analyzing GHG emissions against socioeconomic variables requires statistical tools that can simultaneously capture structural differences between territorial units and their transformations over time [11].

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A widely used econometric model, favored for its simplicity, is the pooled OLS. This approach applies to classical linear regression as if all data belonged to a single sample and disregards the panel structure entirely [12].

Although useful as a starting point and for comparative purposes, the pooled model tends to ignore unobservable heterogeneities across units. This oversight can result in biased estimates and limited interpretations when there are significant structural differences among the studied municipalities [12].

The random effects (RE) model emerges as an alternative to the fixed effects model when researchers assume that the specific characteristics of the analyzed units are random and uncorrelated with the regressors [11]. This assumption allows for efficiency gains in the estimation, especially in samples containing many units but few observations per unit [11].

On the other hand, the theoretical framework STIRPAT (Stochastic Impacts by Regression on Population, Affluence and Technology) provides a robust conceptual structure to define the explanatory factors of emissions. This becomes particularly useful when evidencing how regional affluence and population growth directly drive the carbon footprint [13].

Unlike rigid deterministic models, STIRPAT introduces stochasticity, allowing researchers to estimate the relative weight of factors such as population and regional affluence on the carbon footprint through statistical elasticities [13, 14]. Combined with panel data econometric models, this approach effectively captures both spatial heterogeneity and temporal dynamics, overcoming the limitations of static analyses [15, 16].

The primary contribution and novelty of this research lie in bridging this gap by shifting the analytical focus from macro-level national assessments to a granular, municipal-level analysis. While the majority of Brazilian literature focuses on aggregated national emissions, historically driven by deforestation and agriculture, this study isolates the unique urban-industrial dynamics of São Paulo across its 645 municipalities. By applying the STIRPAT model at this regional scale, this study captures extreme structural heterogeneities that are otherwise masked in state or national averages, providing essential empirical evidence to tailor climate actions to specific local realities.

In this context, this study evaluated the relationship between socioeconomic variables and GHG emissions in the municipalities of the State of São Paulo between 2003 and 2020. Econometric panel data models were applied to understand how local development has historically been associated with emission levels over time.

2. MATERIAL AND METHODS

2.1. Database Construction and Variables

To structure the utilized data, a temporal scope from 2003 to 2020 was adopted for the municipalities in the State of São Paulo. The final database, described in Table **1**, integrates data from multiple sources. Economic and population indicators were obtained from the SEADE system (State System of Data Analysis Foundation).

Carbon dioxide equivalent (CO_2eq) emissions data were obtained through the project "Spatial correlation analysis by deep learning of morbidity and mortality rates with indicators associated with climatic and socioeconomic changes (CNPq Process: 444734/2023-6)". Lastly, information on the vehicle fleet was extracted from the National Traffic Department (DENATRAN). The dataset was structured as a balanced panel featuring annual observations per municipality.

To ensure reproducibility, the construction of the variables was established as follows: Industrial PVA

Table 1: Variables used in Econometric Analysis and their Respective Sources

Variable Name	Type	Unit	Source
CO_2eq emissions	Dependent	Tons	CNPq: 444734/2023-6
Industrial PVA	Independent	R$	SEADE
Vehicle fleet	Independent	Number of vehicles	DENATRAN
GDP per capita	Control	R$/Inhabitant	SEADE
Resident population	Control	Inhabitants	SEADE
Demographic density	Control	Inhabitants/Km²	SEADE

Source: Organized by the authors.

(proxy for productive intensity) represents the gross wealth generated exclusively by the industrial sector. The vehicle fleet represents the absolute sum of all registered passenger vehicles per municipality. For the control variables, GDP per capita was operationalized as the ratio between the total municipal GDP and the resident population, while demographic density was calculated by dividing the total resident population by the municipal territorial area.

2.2. Panel Data Econometric Models and Diagnostic Tests

The adopted strategy was based on the empirical application of the STIRPAT model, which allows for the estimation of elasticities between socioeconomic variables and GHG emissions [10]. The stochastic formulation of the model makes it possible to evaluate the relative weight of factors such as population, income, and economic activity on environmental impact. This considers both the variations among municipalities and the changes over time.

The dependent variable was defined as the annual CO_2eq emissions per municipality. The industrial value added and the passenger vehicle fleet were used as the main independent variables, representing proxies for productive intensity and urban growth respectively. Control variables were also included to capture the structural characteristics of the municipalities: GDP per capita, total population, and demographic density.

All quantitative variables were transformed into natural logarithms (ln). This transformation allows the estimated coefficients to be interpreted as elasticities. In other words, they indicate the percentage variation in CO_2eq emissions associated with a percentage variation in the explanatory variables [10].

Furthermore, the log transformation helps to reduce the asymmetrical distributions, improve the linearity of relationships, and mitigate the influence of extreme values, which are all desirable characteristics in regression models. The STIRPAT formula used for this study, with the natural logarithm applied, is presented in Equation 1.

$$\ln\left(CO_{2eq_{it}}\right) = a_i + \beta_1\, ln(IPVA_{it}) + \beta_2\, ln(Fleet_{it}) + \beta_3\, ln(GDP_{it}) + \beta_4\, ln(Pop_{it}) \; + \beta_5\, ln(Dens_{it}) + \varepsilon_{it} \qquad (1)$$

Where:

$\ln\left(CO_{2eq_{it}}\right)$ is the natural log of annual emissions for municipality in year;

a_i is the unobservable municipality-specific fixed effect;

β_n are the estimated elasticities;

$ln(IPVA_{it})$ is the industrial value added (proxy for local productive intensity);

$ln(Fleet_{it})$ is the number of passenger vehicles (proxy for urban mobility and energy use);

$ln(GDP_{it})$ is the GDP per capita (proxy for economic affluence);

$ln(Pop_{it})$ is the total resident population (demographic dimension);

$ln(Dens_{it})$ is the demographic density (proxy for urban pressure and land occupation);

ε_{it} is the stochastic error term.

To ensure the statistical validity of the results and justify the model selection, a sequence of diagnostic tests was performed. First, the F-test for poolability was utilized to evaluate the inclusion of fixed effects. The obtained statistic ($F = 1{,}321.10;\ p < 0.01$), strongly rejected the null hypothesis of absence of individual effects, indicating that municipal heterogeneity is statistically relevant and the Pooled OLS model is inadequate. Subsequently, the choice between fixed and random effects was conducted via the Hausman test.

The result ($\chi^2 \approx 640;\ \mathrm{p} < 0{,}01$) rejected the null hypothesis of no correlation between specific municipal effects and explanatory variables, suggesting that the random effects model would generate inconsistent estimates. Following these diagnostics, the Fixed Effects (FE) model was selected as the primary specification.

To address potential issues of heteroscedasticity and serial autocorrelation, final estimates were reported with robust standard errors clustered at the municipal level. This adjustment ensures greater reliability for the inferential statistics (p-values and t-stats) without altering the estimated coefficients.

All analyses were conducted in Python. The *pandas, numpy, matplotlib*, and *seaborn* libraries were predominantly used for data manipulation and visualization. The econometric models were estimated with the support of the *linearmodels* and *statsmodels* libraries, utilizing the PanelOLS class for the estimation of the panel regression models.

3. RESULTS AND DISCUSSION

Table **2** contains the results of the FE model, which considers specific variations of each municipality as part of the error. The estimated coefficients for the study variables in the fixed effects models reveal contrasting effects on CO_2eq emissions. For example, the industrial PVA presented a coefficient of -0.015 (p <

Table 2: Results of the Fixed Effects (FE) Model

Variable Name	Coefficient	Standard Error	T-Stat	P > |t|
CO_2eq emissions	9.27	3.43	2.70	0.00
Industrial PVA	-0.01	0.00	-2.61	0.01
Vehicle fleet	0.22	0.01	17.58	0.00
Resident population	-0.23	0.61	-0.38	0.70
Demographic density	0.30	0.61	0.50	0.61
GDP per capita	0.14	0.01	12.36	0.00

Source: Organized by the authors.

0.01). This indicates that, holding other variables constant, a 1% increase in industrial activity is associated, on average, with a 0.015% reduction in emissions. This result is statistically significant but of small magnitude.

In contrast, the vehicle fleet was positively associated with emissions, showing a coefficient of 0.217 ($p < 0.01$). This suggests that a 1% growth in the fleet results in an average 0.22% increase in municipal emissions. The diffuse and massive growth pattern of the fleet, especially in peripheral and medium-sized areas in the interior of São Paulo, gives individual transport a structuring weight in local emissions. As highlighted by [15, 17], the elasticity between the fleet and emissions tends to be high in developing countries given the predominance of combustion engine vehicles and the limitations of low-carbon collective mobility. These findings highlight the relevance of both variables as distinct vectors of environmental impact.

Regarding industry, evidence from literature suggests that regions with higher industrial intensity can reduce their emissions over time [9]. This is achieved through process modernization, environmental control policies, and sectoral reallocation. These results also reflect the findings of [18], who emphasized the importance of structural transformations, such as the adoption of renewable energy, to continuously improve long-term environmental quality.

The descriptive analysis reveals a profound structural heterogeneity among the 645 municiities, as evidenced by a Gini Coefficient of 0.712. This high value indicates a severe spatial concentration: while the top 1% of emitting municipalities alone accounts for approximately 22% of the state's total emissions, the top 10% concentrate 63.4% of the total carbon footprint. To visualize this disparity, the Lorenz Curve (Figure **1**) illustrates that most municipalities contribute marginally

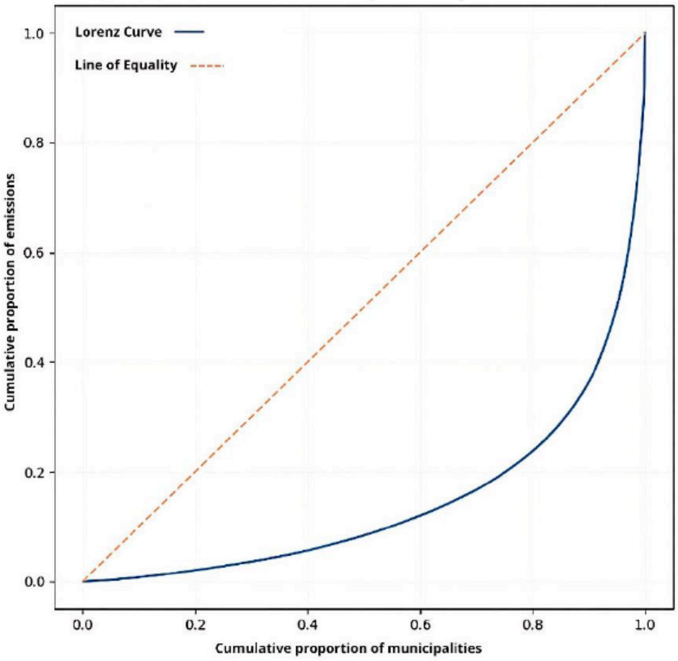

Figure 1: Lorenz curve applied to the studied municipalities to conceptualize their heterogeneities.

Source: Organized by the authors.

to the total emissions, while a small group of industrial and logistical hubs drives the state's environmental impact.

From an engineering and policy perspective, this concentration is a critical finding: it suggests that the "moderate" success of the State Policy on Climate Change (PEMC), which only achieved a 2.1% reduction by 2020, may be due to its diluted focus [8]. Our results imply that mitigation efforts should not be spread uniformly but rather prioritized through targeted engineering interventions in these high-impact clusters.

Spatial analysis reinforces the need to interpret econometric coefficients considering territorial dynamics. Figure **2** shows the logarithmic variation in CO_2 emissions (Figure **2a**), Industrial PVA (Figure **2b**), and the vehicle fleet (Figure **2c**) between 2003 and 2020. Regarding emissions, a more intense concentration of increases is observed in the western and northwestern regions, as well as in consolidated industrial hubs in the interior. However, the growth of industrial PVA is heavily concentrated in the southeast of São Paulo, the coast, and the Ribeira Valley. In these specific regions, emissions often remained stable or even fell, which strongly suggests efficiency gains.

To make this comparison more objective, two scatter plots were created (Figure **3** and Figure **4**) to relate the logarithmic variation of emissions to the variation of industrial PVA and the fleet, respectively. In both cases, the diagonal line represents the point where emissions and activity grew in the exact same proportion. Points below the diagonal indicate a reduction in carbon intensity, meaning emissions grew at a slower pace than the PVA or fleet.

Regarding emissions (Figure **2a**), a more intense concentration of increases is observed in the western and northwestern regions, as well as in consolidated industrial hubs in the interior. However, when comparing this with the variation maps for industrial PVA (Figure **2b**) and the vehicle fleet (Figure **2c**), it is noticeable that these variables do not follow a territorial pattern as cohesive as that observed for emissions.

Figure **3** and Figure **4** indicate that the vehicle fleet has a more direct and cohesive relationship with the increase in emissions, as most municipalities follow a pattern close to the 45° line with less dispersion. In the case of industrial PVA, however, the data reveal greater heterogeneity. Several municipalities significantly expanded their industrial activity without proportional increases in emissions, represented by the

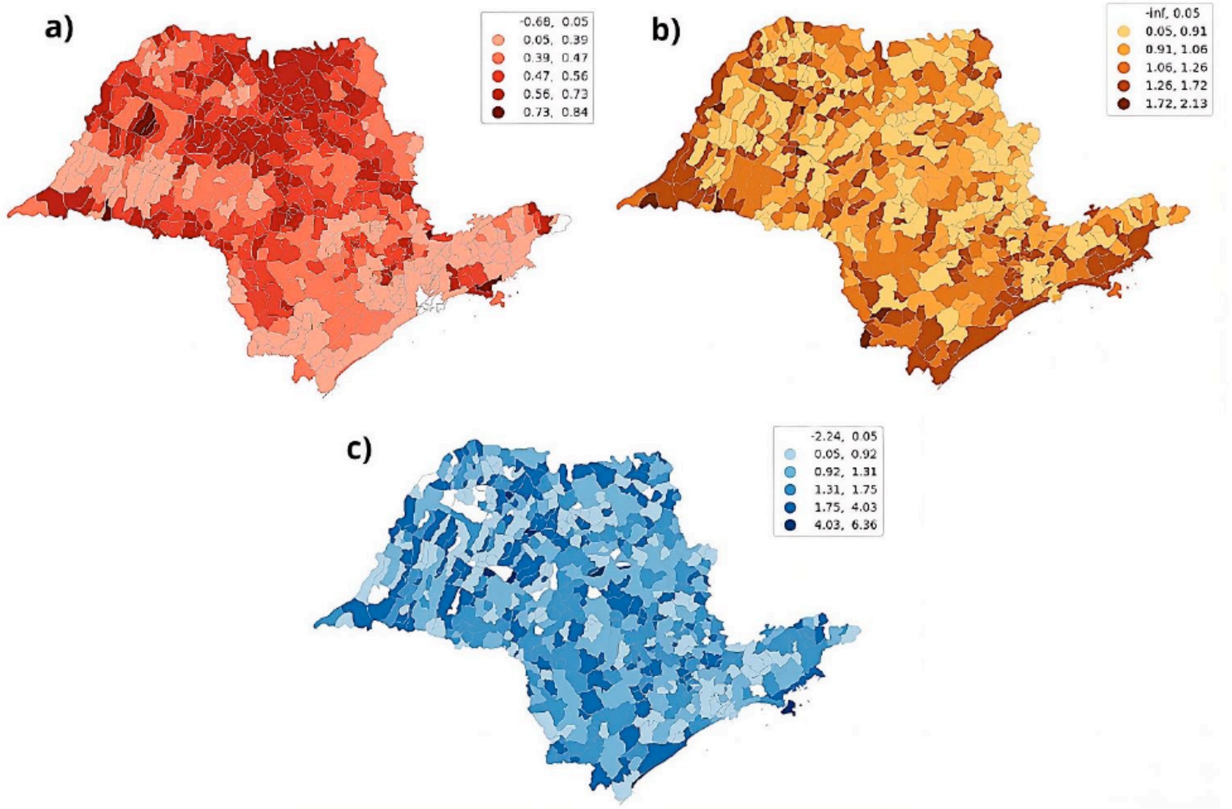

Figure 2: (**a**) Comparative maps of indicator variation in the period on a logarithmic base for CO_2 emission; (**b**) Comparative maps of indicator variation in the period on a logarithmic base for Industrial PVA; (**c**) Comparative maps of indicator variation in the period on a logarithmic base for the vehicle fleet.

Source: Organized by the authors.

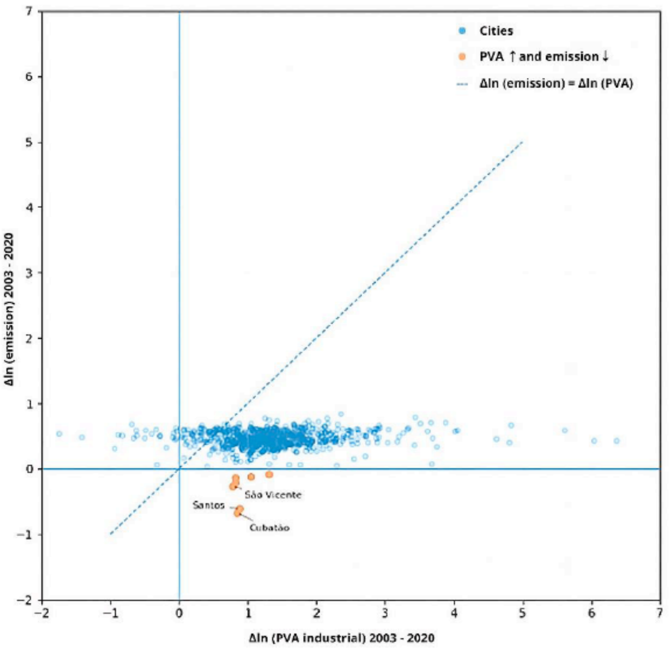

Figure 3: Scatter plot of the delta of emission by the delta of industrial PVA in the period from 2003 to 2020.
Source: Organized by the authors.

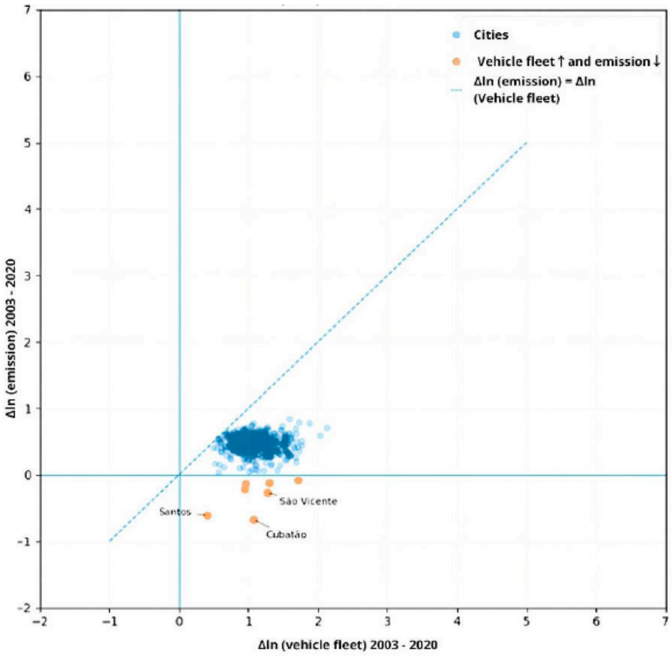

Figure 4: Scatter plot of the delta of emission by the delta of the vehicle fleet in the period from 2003 to 2020.
Source: Organized by the authors.

points scattered further to the right of the 45° line. This aspect is widely discussed by [19] and reaffirmed by [3] as one of the main challenges for the energy transition in urbanized regions.

The growth of industrial PVA is heavily concentrated in the southeast of São Paulo, the coast, and the Ribeira Valley. In these specific regions, emissions often remained stable or even fell, which strongly suggests efficiency gains. The evidence from literature suggests that regions with higher industrial intensity can reduce their emissions over time [9].

This is achieved through process modernization, environmental control policies, and sectoral reallocation. The phenomenon is clearly observed in traditionally industrial municipalities like Cubatão and Santos. These results also reflect the findings of [18], who emphasized the importance of structural transformations.

The phenomenon of "decoupling" between economic development and emissions, carrying significant environmental policy and engineering implications [20]. In Cubatão, for example, this decoupling is widely documented. Historically considered one of the most polluting industrial hubs in Brazil, the municipality underwent a major environmental restructuring process driven by the Environmental Pollution Control Program [21].

From an engineering perspective, this transformation was achieved through the mandatory adoption of "end-of-pipe" technologies and energy efficiency upgrades in industrial plants. The program established rigorous emission control targets, promoted the adoption of clean technologies, and consolidated a robust air quality monitoring system. As a result, Cubatão transformed from one of the most polluted places on the planet into a national benchmark for urban environmental management, achieving reductions of over 90% in emissions of sulfur dioxide, nitrogen oxides, and inhaling particles [21].

About the vehicle fleet, the positive and statistically robust sign reinforces the critical role of the transportation sector in urban emissions. This aspect is widely discussed by [19] and reaffirmed by [3] as one of the main challenges for the energy transition in urbanized regions.

The diffuse and massive growth pattern of the fleet, especially in peripheral and medium-sized areas in the interior of São Paulo, gives individual transport a structuring weight in local emissions.

Cases like Cubatão, Santos, and São Vicente stand out for reducing their CO_2eq emissions between 2003 and 2020, even in the face of expressive growth in industrial activity and the vehicle fleet. The Environmental Pollution Control Program, institutionalized by 15 in 1985, established rigorous emission control targets, promoted the adoption of clean technologies, and consolidated a robust air quality monitoring system [21]. Such an effort consolidated a continuous air quality monitoring system and strict environmental licensing, the positive effects of which are still observed today.

Despite the good performance observed in the variation of emissions, with some municipalities in the Baixada Santista region even showing absolute reductions, the area still accounts for a significant volume of total emissions. For this reason, public policies continue to be implemented to mitigate their climate impacts. A primary example is the set of state guidelines established by Decree No. 55.947/2010, which regulated the State Policy on Climate Change [5].

A recent municipal example is the Santos Climate Action Plan (PACS), launched in 2022, which establishes guidelines for mitigation and adaptation to climate change. The plan sets targets related to urban energy efficiency, the control of atmospheric emissions, and resilient infrastructure [22]. Although its quantitative impacts have yet to be fully measured, the PACS signals the ongoing commitment of large emitting centers to reducing their environmental footprint.

4. CONCLUSION

This study advances the existing literature by shifting the analytical focus from macro-level national assessments to a granular, municipal-level analysis of GHG emissions in the State of São Paulo. By applying the STIRPAT model across 645 municipalities, the primary contribution of this research is demonstrating that state-wide climate policies (such as the PEMC) often fall short because they fail to account for profound local socioeconomic heterogeneities.

Consequently, the main implication of our findings is that transitioning to a low-carbon economy requires territorially customized strategies rather than one-size-fits-all mandates. As our spatial analysis revealed that the top 10% of emitting municipalities concentrate 63.4% of the total carbon footprint, our primary policy recommendation is that state mitigation efforts and financial resources should be prioritized toward targeted engineering interventions in these high-impact clusters.

Furthermore, the significant elasticities found for industrial value added and vehicle fleets indicate that mitigation efforts must be integrated into local urban planning and engineering. Practical applications, such as stringent industrial environmental monitoring (evidenced by Cubatão) and the electrification of urban mobility (as planned in Santos), prove that effective environmental control is inherently dependent on targeted, municipal-level interventions.

CONFLICTS OF INTEREST STATEMENTS

The authors declares that there are no relevant financial or non-financial competing interests to report.

AUTHORS’ CONTRIBUTION

Pedro de Oliveira Masetti: Data curation, Formal analysis, Writing original draft.

Liliane Moreira Nery: Conceptualization, Supervision, Writing review and editing.

Darllan Collins da Cunha e Silva: Supervision, Writing review and editing.

All authors have read and agreed to the published version of the manuscript.

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ETHICAL STATEMENTS

Ethical approval and informed consent were not required for this study as it exclusively utilized secondary, aggregated, and publicly available data.

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