AGE-STRUCTURE AND ENERGY-RELATED EMISSIONS: RECENT DEMOGRAPHIC CHANGES IN BRAZIL

https://doi.org/10.56238/sevened2024.041-021

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ABSTRACT
This study investigates the effects of the rapid aging process in Brazil, specifically in the São Paulo state, on the CO2 emissions from gasoline and residential energy. This geographic region was chosen precisely because it is one of the country's most densely populated regions and the largest in terms of residents. Therefore, the impact related to human activities is more accurately measured within this environment. This investigation employed a balanced panel dataset with 631 municipalities from 2006-2015, with diagnostic tests, the STIRPAT method, and robustness procedures. Results show that the region does not experience an environmentally friendly aging process, contrary to previous studies conducted on developed economies, and that all age groups positively affect emissions intensity. This outcome allows policymakers to understand the situation better and develop specific initiatives to tackle it accordingly, especially concerning the elderly population. Besides, this manuscript contributes to an ever-growing plethora of knowledge regarding the effects of pollutant emissions on adults in developing countries.

Keywords: Pollution. Environmental Impact. Energy. Aging. Brazil.

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INTRODUCTION

The increasing extreme temperatures and weather patterns in every part of the world have alerted scientists, policymakers, and governments to climate change (Yuan et al., 2024). Traditionally, it has been argued that climate change is generally attributed to significant carbon emissions worldwide. Carbon dioxide (CO_2) is the main contributor to greenhouse gas emissions, which trap heat and make the planet warmer (Wang and Li, 2021). Consequently, reducing CO_2 emissions can be crucial to mitigate climate change effects. For this reason, a considerable amount of literature has been published about CO_2 emissions, highlighting several factors that have been linked to increased carbon emissions, such as globalization (Gyamfi et al., 2023; Yang et al., 2021), urbanization (O'Neill et al., 2010), industrial structure (Yu et al., 2018), and population aging (Gyamfi et al., 2023; O'Neill et al., 2010; Yang et al., 2021; Yu et al., 2018).

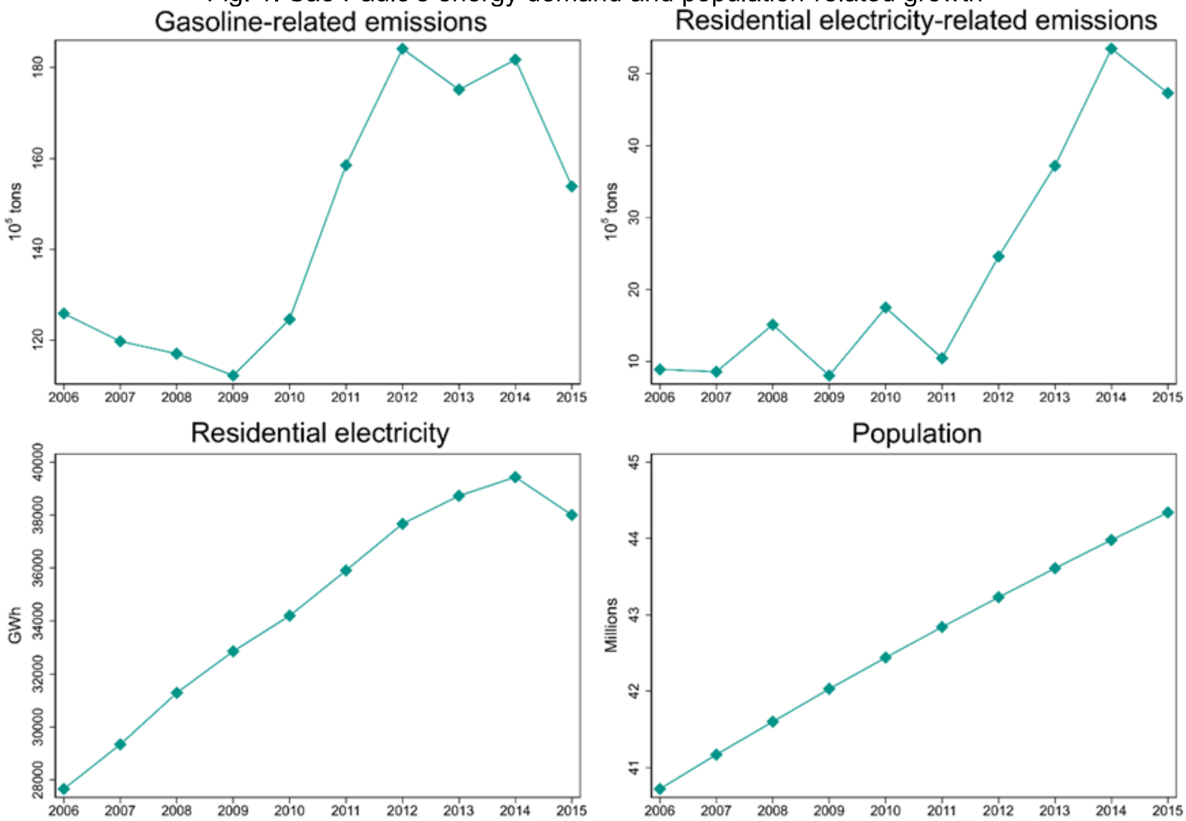
Population aging and climate change are some of the most profound transformations in global society (Li et al., 2024). However, the discussion about these topics has been controversial (Zhou et al., 2023). Previous studies have reported that the increase in population aging results in higher carbon emissions (Wang and Wang, 2021). Conversely, literature has emerged that offers contradictory findings about this issue. In this case, there is a decrease in carbon emissions when population aging increases because older adults spend more time indoors, resulting in reduced physical activity compared to other age demographics (Gyamfi et al., 2023; Yang and Wang, 2021; Wang and Li, 2021). From an economic point of view, so far as population aging increases, financial and productive activities tend to be reduced (Kim et al., 2021; Zhou et al., 2023). In this way, population aging and carbon emissions are two major challenges to the development of a sustainable society, and this theme claims studies that discuss those subjects together (Wang and Wang, 2021).

Thus, this study investigates the relationship between São Paulo’s population age structure and the CO_2 emissions from gasoline and electricity. Brazil has a fast-growing economy and is the largest country in Latin America. The country’s energy-related emissions have been growing considerably as a result of the country’s development. Taking the State of São Paulo, Brazil's most populated and developed region, as an example, we see in Figure 1 that CO_2 from gasoline and residential energy presented high growth levels in recent years. As the population size increases, the demand for direct and indirect energy grows.

Furthermore, the aging process of the Brazilian people is usually ignored by the few environmental-related studies in the region. Developed economies took their time to grow old, meaning their aging process took almost 100 years, while the Brazilian process is rapid (Almeida & Souza, 2019). The Brazilian elderly population is expected to increase from 8.6% in 2010 to 13% in 2020, and the projection is that this number will increase to 20% in 2050 (Campos & Gonçalves, 2018). Therefore, including the age structure in empirical studies is very important for the region. São Paulo, as shown in Figure 2, presents a similar path.

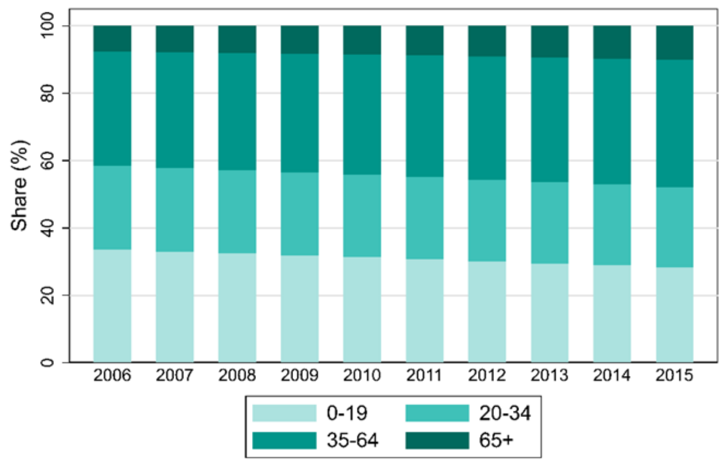
The paper is structured as follows: The next section describes the research method. Second, we report the empirical results and relate some discussions. The final section describes this study's conclusions, implications, and limitations.

Fig. 1. São Paulo’s energy demand and population-related growth



Note: Considering the sample's 631 municipalities, please visit Section 2 for data sources.

Fig. 2. São Paulo's yearly age structure.



Note: Considering the 631 municipalities in the sample, data from DATASUS is needed.

METHOD

We utilize a comprehensive municipal-level dataset encompassing data from 631 out of 645 municipalities within São Paulo, spanning 2006 to 2015. The exclusion of 14 municipalities from our analysis was necessitated by the unavailability or unreliability of data, rendering them unsuitable for inclusion in the present investigation. Notably, the omitted municipalities do not constitute a representative sample of the São Paulo state in terms of geographical distribution or socioeconomic characteristics. Thus, the integrity and validity of our research remain uncompromised by focusing solely on the remaining 631 municipalities as the primary subjects of our study.

We start the analysis with the Stochastic Impacts by Regression on Population, Affluence, and Technology (STIRPAT) (Dietz & Rosa, 1997) model, which is widely used for similar applications, with the advantage of allowing researchers to include or exclude variables according to the relevance for the phenomena studied. There are a few points of attention when applying such a model, and the main one is that the regression must contain all relevant variables to the phenomenon to avoid bias issues. A direct regression containing the variables significant to explain environmental impact can be found in Equation 01.

$$ln\, I = \beta_0 + \beta_1\, ln\, P + \beta_2 ln\, A + \beta_3 ln\, T + e \quad (01)$$

The index I represents the environmental impact, P represents the population, A represents affluence, and T represents technology.

Our model can be expressed as:

$$ln\, \mathbf{Y}_{it} = \beta_0 + \beta_1 \ln \mathbf{A}_{it} + \beta_2 ln\, GDPPC_{it} + \beta_3 ln\, DENS_{it} + \alpha_i + e_{it} \quad (02)$$

Here, Y represents the set of dependent variables, A represents the age-related variables (population), GDPPC represents the real per capita GDP (affluence), DENS represents the population density (which symbolizes the technological level as indicated by Liddle (2014)), i is the geographic region, t represents the time, αi is the regional fixed-effect coefficient, and e is the error term.

The dependent variables analyzed in this study encompass per capita CO2 emissions originating from two primary sources: gasoline combustion (GAS_CO2) and residential electricity consumption (RES_CO2), alongside per capita residential energy demand (RES_MWH). To compute emissions attributable to electricity consumption, we applied conversion factors as detailed in Appendix A. A conversion factor of 69.3 CO2 tons per terajoule (TCO2/TJ) was employed for gasoline-related emissions, as recommended by the Intergovernmental Panel on Climate Change (IPCC) in 2006. Notably, in compliance with Brazilian legislation, ethanol content blended with gasoline was duly accounted for and deducted from the emissions calculations to ensure accuracy and consistency.

Moreover, the delineation of age cohorts within our study encompasses three distinct groups: individuals aged 20 to 34, referred to as young adults; those aged 35 to 64, categorized as middle-aged; and individuals aged 65 and above, denoted as elderly. As advocated by Liddle (2011), this classification is underpinned by the assertion that such a segmentation better captures the nuanced phases of life and corresponding consumption behaviors, thus aligning more closely with current demographics and trends.

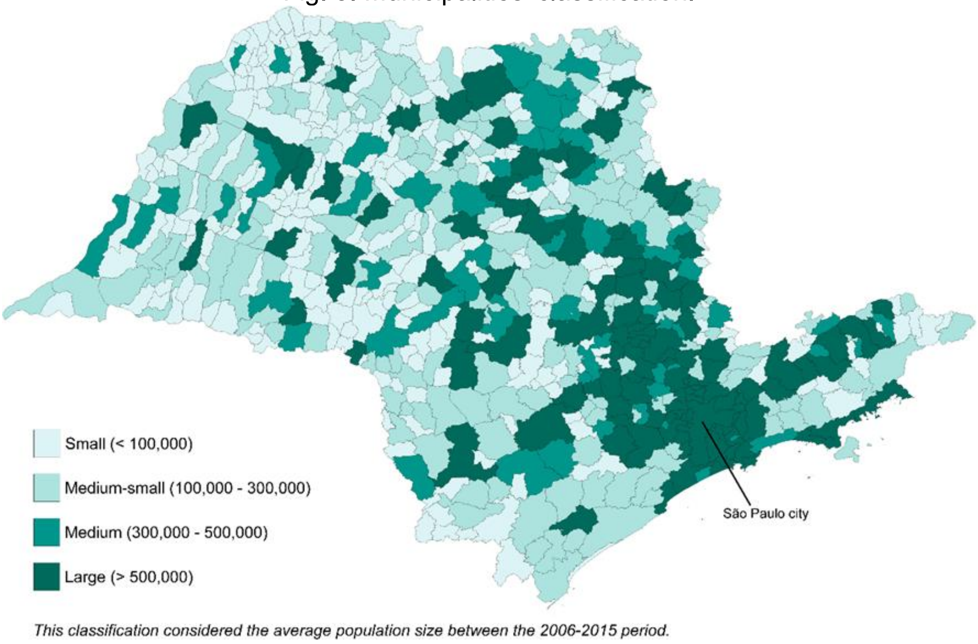
Age-related data is sourced from DATASUS, an extensive database maintained by the Brazilian Ministry of Health, providing comprehensive information on demographic trends and health indicators. Fuel-related data is extracted from the Brazilian National Agency of Petroleum, Natural Gas, and Biofuels (ANP), offering detailed insights into fuel consumption patterns and market dynamics. Additionally, all remaining data pertinent to our study is retrieved from Fundação Sistema Estadual de Análise de Dados Estatísticos (SEADE), a reputable institution specializing in the collection and analysis of statistical data at the state level, ensuring a robust and multifaceted dataset for our study.

The results of the Hausman test strongly support the utilization of fixed-effects estimation in our analysis. Additionally, to address potential issues of heteroskedasticity, autocorrelation, and cross-sectional dependence, we conduct a battery of diagnostic tests. Specifically, we employ the modified Wald test to assess heteroskedasticity, the Wooldridge test to detect autocorrelation, and the Pesaran test to examine cross-sectional dependence. Given the presence of cross-sectional dependence and a dataset characterized by a more significant number of cross-sectional units (N) than periods (T), we implement the Driscoll-

Kraay estimator (Driscoll & Kraay, 1998) to adjust standard errors, thereby ensuring the robustness and consistency of our findings.

Furthermore, to evaluate multicollinearity, we calculate the Variance Inflation Factor (VIF), which consistently remained below the threshold of 10 across all models, indicating no significant multicollinearity issues. Additionally, we estimate the results for three subsamples: small municipalities, small and medium-small municipalities, and medium-sized municipalities. Hence, we avoid possible outliers (e.g., São Paulo city) while still representing most of the region, as shown in Figure 3.

Fig. 3. Municipalities' classification.



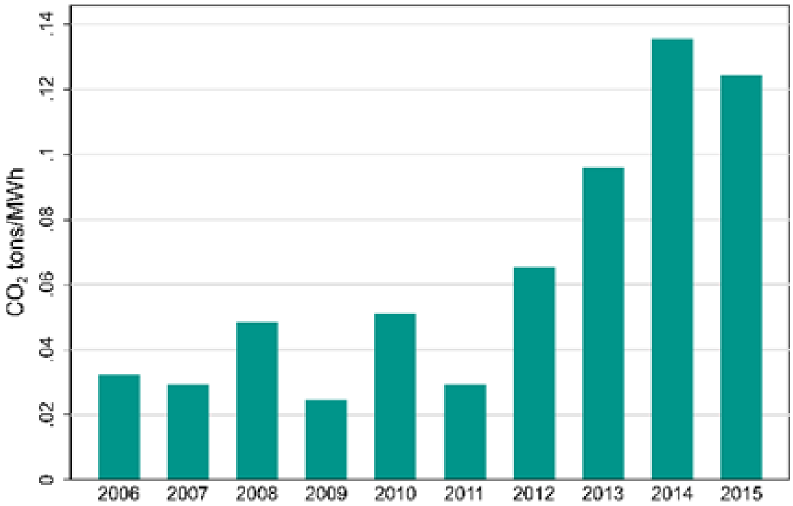
Note: Data from DATASUS.

EMPIRICAL RESULTS

Our analysis reveals a positive relationship between all age cohorts and CO2 emissions from gasoline combustion and residential energy consumption. Notably, the middle-aged population (aged 35-64) significantly influences fuel consumption patterns, with elasticity ranging between 2% and 2.3%. Furthermore, in medium-sized urban centers, young adults emerge as particularly significant contributors to heightened emission levels associated with residential energy usage.

Regarding emissions from electricity, the results are volatile. Although all age groups present positive and significant coefficients, the elasticities are potentially enormous. We argue these results are the product of an ever-changing conversion factor, as depicted in Figure 4. It is possible to verify lower conversion factor values for the earlier years, from 2006 to 2011, since the highest value registered within this period was 0.05 in 2010. On the other hand, from 2012 to 2015, higher conversion factor values are generated, with 2015 surpassing 0.12 and 2014 almost reaching the 0.14 mark.

Fig. 4. Electricity conversion factors.



Note: Data from the Ministry of Science, Technology and Innovation.

In recent years, Brazil has witnessed a decline in its energy contribution from renewable sources, such as hydroelectric power, consequently leading to an adjustment in the conversion factor. This shift implies that even minor electricity demand escalations may yield substantial increases in CO2 emissions. Hence, we introduced residential electricity consumption as an alternative dependent variable to provide a more comprehensive understanding of the observed phenomena, enhancing our capacity to elucidate the underlying dynamics.

Table 1. Main findings

Variables	Dependent: GAS_CO2				Dependent: RES_CO2			
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
	Overall	Small	S-MS	Medium	Overall	Small	S-MS	Medium
p2034	0.923***	0.825**	0.657**	2.098***	2.974***	3.480***	3.138***	0.0976
	(0.349)	(0.343)	(0.331)	(0.344)	(0.399)	(0.491)	(0.462)	(0.669)
p3564	2.186***	2.327***	2.086***	1.861	2.039**	2.799***	2.819***	-5.342
	(0.670)	(0.581)	(0.548)	(2.219)	(0.954)	(0.888)	(0.855)	(3.313)
p65+	1.159***	1.207***	1.260***	1.295	5.886***	5.860***	5.745***	7.802***

	(0.413)	(0.400)	(0.385)	(0.863)	(0.518)	(0.481)	(0.464)	(1.284)
Gdppc	0.0778***	0.0821**	0.0657**	0.167***	-0.0379	-0.0416	-0.0325	0.341***
	(0.0271)	(0.0362)	(0.0280)	(0.0330)	(0.0651)	(0.0831)	(0.0726)	(0.124)
Dens	0.261	0.534***	0.774***	-0.0825	3.277***	3.477***	3.826***	3.344***
	(0.187)	(0.165)	(0.178)	(0.340)	(0.466)	(0.564)	(0.623)	(0.757)
Constant	-16.07***	-17.37***	-16.78***	-17.36***	-45.86***	-49.32***	-48.87***	-19.73**
	(3.363)	(3.112)	(3.038)	(6.161)	(6.001)	(6.196)	(5.988)	(8.773)
Hausman	318.98***	193.66***	342.02***	51.14***	3522.88***	2428.53***	2449.43***	85.45***
Wooldridge	56.7***	41.6***	86.2***	88.7***	665.6***	1964.0***	286.9***	1032.9***
Mod. Wald	24238***	21790***	19531.3***	322.3***	271.7	177.7	219.3	18.8
Pesaran	715.9***	374.8***	423.7***	99.6***	1201.5***	744.7***	829.2***	118.3***
F	58.7***	22.7***	24.2**	51.0***	38.3***	45.3***	46.0***	55.7***
R^2	0.3831	0.3463	0.378	0.5297	0.7546	0.7571	0.7518	0.7823
Observations	6,310	3,940	4,390	610	6,310	3,940	4,390	610
Municipality	631	394	439	61	631	394	439	61
Standard errors in parentheses. *** p<0.01, ** p<0.05, * p<0.1. S-MS: Small and medium-small municipalities. All variables were employed in their natural-log form.								

The findings presented in Table 2 reaffirm a positive correlation between all age cohorts and energy consumption. Notably, the middle-aged demographic continues to substantially influence energy usage patterns. Furthermore, our analysis highlights a pronounced impact attributed to the elderly population, particularly concerning electricity consumption, a trend notably accentuated within small municipalities.

Table 2. Complementary results

Variables	Dependent: RES_MWH			
	(9)	(10)	(11)	(12)
	Overall	Small	S-MS	Medium
p2034	0.327***	0.467***	0.188	1.023***
	(0.121)	(0.0606)	(0.140)	(0.141)
p3564	0.974***	0.828***	0.878***	1.312***
	(0.145)	(0.195)	(0.157)	(0.356)
p65+	0.895***	1.080***	0.991***	0.657***
	(0.0950)	(0.0937)	(0.102)	(0.154)
GDPPC	0.0150**	0.0204***	0.00905**	0.0975***
	(0.00750)	(0.00764)	(0.00415)	(0.0281)
DENS	0.564***	0.602***	0.831***	0.311***
	(0.0666)	(0.109)	(0.104)	(0.0855)
Constant	-9.274***	-9.544***	-9.328***	-11.67***
	(0.773)	(0.795)	(0.715)	(0.819)
Hausman	242.18***	593.22***	359.76***	37.79***
Wooldridge	137.1***	958.8***	261.9***	168.0***
Mod. Wald	160000***	21196***	160000***	4514.21***
Pesaran	344.9***	203.3***	218.4***	38.9***
F	958.4***	1684.5***	487.5***	292.0***
R^2	0.6937	0.8293	0.6811	0.7689
Observations	6,310	3,940	4,390	610
Municipalities	631	394	439	61

Standard errors in parentheses. *** p<0.01, ** p<0.05, * p<0.1. S-MS: Small and medium-small municipalities. All variables were employed in their natural-log form.

These results demand some notes. Compared to studies on developed economies in which young adults are the main contributors to emissions due to their purchase power, the middle-aged adults from our sample are the main contributors to gasoline emissions and electricity consumption. Our results align with those of Cao and Yang (2017) in China and Hasanov and Mikayilov (2017) in Azerbaijan. Cao and Yang (2017) indicated that older residents were more likely to own a car and emit more CO2 from commuting trips, associated with their preferences, lifestyle, and the built environment through land use and transport policies, affecting their residential choices and CO2 emissions.

Brazilians are challenged with low-paying jobs, especially at the beginning of their careers. Yet, middle-aged adults have better earnings and some financial stability that enables investments in cars, traveling, appliances, and big houses. Interestingly, young adults increase gasoline emissions in medium-sized regions. These municipalities represent good job opportunities in the countryside and are fast-growing regions that attract many recent graduates and workers able to relocate. Additionally, the elderly group is significant to electricity demand. Hasanov and Mikayilov (2017) commented that older adults (particularly in Western cultures) spend their days in-house doing energy-intensive activities. This seems to be the case for the growing elderly population in São Paulo.

Other authors also consider factors that would explain changes in gas emissions scenarios related to the aging population. O'Neill et al. (2010) found that aging and urbanization can substantially influence emissions in particular world regions, meaning a long-term decrease, particularly in industrialized country regions, associated with lower labor productivity by an aging population, leading to slower economic growth. On the other hand, if there is a growth in urbanization, it can lead to an increase in emissions, particularly in developing country regions, also mainly through effects on labor supply.

Q. Wang and L. Li (2021) quoted several authors who analyzed the behaviors of older adults and their relationship with pollutant emissions. For example, the tendency to use public transportation reduces gas emissions. However, older people demand more services from energy-intensive industries, such as medical care. These authors concluded that the effects of aging, life expectancy, population density, and per capita GDP on per capita CO2 are nonlinear.

Y. Yu et al. (2017) showed that population aging and changes in industrial structure were the main driving forces of CO2 emissions in China. Still, they indicated that further investigation is needed to determine the deep internal reasons and whether the effect of population aging and industrial structure on emissions will change. Also, suggestions were raised to deal with these issues: Focus on demographic structure and implement the universal two-child policy, resolve the contradiction in industrial structure and promote supply-side structural reform, set targets of CO_2 emission reductions in stages, and establish the relevant regulation system.

In their study, D. Balsalobre-Lorente et al. (2021) offer insights into the challenges of demographic shifts, particularly the aging population and escalating globalization trends across the five largest European nations. They advocate for a recalibration of policy frameworks to promote the diffusion of energy innovations while mitigating natural resource exploitation, aiming to curtail carbon emissions. These recommendations align with the Sustainable Development Goals outlined by the United Nations, underscoring the imperative for coordinated action to achieve environmentally sustainable and socially equitable outcomes.

Consequently, while developed economies are actively transitioning their societal norms toward sustainable living practices, the rapid aging phenomenon observed in Brazil does not, at least presently, appear to precipitate a significant decline in emissions. Notably, even among young adults, who are typically predisposed to embrace sustainable lifestyles, our analysis indicates a positive correlation with emissions, suggesting a complex interplay of factors influencing environmental behaviors in the Brazilian context.

CONCLUSIONS

In summary, this study delves into the contemporary demographic shifts in São Paulo and their consequential environmental impacts. Our principal discovery underscores that all age demographics within the region influence CO_2 emissions. Consequently, despite São Paulo's status as a developed area within Brazil, our analysis reveals a population-environment dynamic distinct from that observed in developed regions, wherein aging populations typically correlate with reduced emissions. This nuanced understanding underscores the importance of contextual factors in shaping environmental behaviors and emphasizes the need for tailored policy interventions to address emissions challenges in diverse socio-demographic contexts.

Considering Brazil’s elderly are growing fast, policymakers should consider the age structure for future policies, especially within the energy context. Integrating all ages into a more sustainable environment is fundamental to developing a future where humans have a more harmonic relationship with the environment. This could be implemented by implementing subsidies for photovoltaic panels for older people, according to the results observed in this research.

In conclusion, future research endeavors must delve deeper into this issue, undertaking more comprehensive investigations. Such studies should leverage larger datasets and explore the applicability of diverse econometric methodologies to elucidate further the complexities underlying the relationship between demographic shifts and environmental outcomes. By expanding the scope of inquiry and employing diverse analytical tools, researchers can gain deeper insights into the multifaceted dynamics at play, facilitating more informed decision-making and policy formulation to effectively address environmental challenges.

DECLARATION OF COMPETING INTEREST

The authors declare that they have no conflict of interest.

ACKNOWLEDGMENTS

This work was supported by the FAPESP Foundation (Process nº 2019/19905-0). The first author acknowledges the financial support from the Brazilian National Council for Scientific and Technological Development (CNPq, 140263/2020-9).

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