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Spatiotemporal variability of O_3, NO_2 and PM_{10} in São Paulo reveals territorial contrasts under altered emission regimes

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Abstract

The state of São Paulo (SP), a major economic hub in Brazil and Latin America, faces environmental problems related to air pollution, which poses a significant challenge for its policymakers. The study aimed to evaluate a time series (2018–2024) of the concentration of ozone (O3), nitrogen dioxide (NO2), and particulate matter (PM10) in industrialized regions of SP, which also have sugarcane farming, in order to contribute to efforts to mitigate the concentration of these pollutants. To this end, a methodology based on linear mixed models, incorporating an AR(1) structure and using robust standard errors, was applied to data on PM_{10}, NO_2, O_3, temperature, relative humidity, wind speed, solar radiation, precipitation, and fire hotspots obtained from ten locations across the state. The results indicated that time had a slight effect on pollutant concentrations, with increasing trends for PM_{10} and NO_2, while O_3 did not show significant temporal variation. The lockdown period contributed to a reduction in NO_2 and PM_{10} concentrations due to decreased vehicle emissions; however, it did not alter O_3 concentrations, demonstrating that controlling this pollutant involves factors related to the dynamics of its formation and consumption. Furthermore, burning, common in sugarcane-growing areas, had a strong influence on PM_{10} concentrations. The results highlight the importance of considering local and regional factors in air pollution mitigation policies, as significant spatial variability in pollutant concentrations was observed across the study area.

Introduction

Population and economic growth are often associated with the expansion of industrial and agricultural activities, driving the development of production and consumption systems and contributing to income generation. However, this process also directly affects land use, as the expansion of transportation infrastructure and urban settlements alter landscapes and fragments forest cover. In addition to increasing the demand for natural resources, these changes also generate environmental pressures, including the emission of air pollutants (Silveira et al., 2021; Souza et al., 2024).

The state of São Paulo, Brazil, exemplifies the environmental consequences of land-use changes. It is the most industrialized state in the country and has intense agricultural activity, particularly in sugarcane cultivation. São Paulo stands as the most developed state in Brazil and is the nation's principal hub of wealth, boasting an economy that surpasses those of several Latin American countries (Seade, 2025). However, this high level of economic activity is also associated with substantial air pollutant emissions. The state has the largest vehicle fleet in the country, which, together with industrial activities and burning of agricultural areas, is responsible for the increased concentration of air pollutants, such as particulate matter (PM), nitrogen oxides(NOx), sulfur dioxide (SO_2), volatile organic compounds (VOCs), and ozone (O_3) (Simone et al. 2021; CETESB, 2025). The increase in anthropogenic activities and the resulting rise in air pollution has been the main factors contributing to poor air quality in the state, with implications for the environment and public health (Bulbovas et al., 2020; Chiquetto et al., 2019; Corá et al., 2020; Rahaman et al., 2021; Silveira et al., 2021; Souza et al., 2024,).

The World Health Organization (WHO) identifies air pollution as the leading cause of disease and premature death worldwide (Bainy et al., 2021; Simone et al., 2021; WHO, 2018). Air pollutants can exacerbate respiratory and cardiovascular diseases, lead to preterm birth, and cause low birth weight (Bainy et al.,2021; Ge et al., 2023; Ji et al., 2019; Li et al., 2019).

Air pollution has well-documented negative effects on vegetation, ranging from biochemical responses to impacts at the individual level (Bulbovas et al., 2014; Gill & Tuteja, 2010;). These effects can lead to agricultural losses, as cultivated plants produce fewer fruits and lower-quality grains (Bulbovas et al., 2014; Silva & Bulbovas, 2022). In addition, air pollution affects forests and urban green areas by reducing the presence of more susceptible species, thereby altering the composition and structure of plant communities and the surrounding landscape (Gottardini et al., 2014; Gottardini et al., 2017).

All these negative effects of air pollution on human health and vegetation have a strong influence on the economy, as they increase morbidity among the economically active population, increase healthcare expenditures, and elevate agricultural production costs (Rezende, 2021; Simone et al., 2021).

Updated guidelines from the World Health Organization establish air quality guidelines to reduce the concentration levels of major air pollutants and protect public health (WHO, 2021). These guidelines also influence the environmental quality of forests and agricultural crops. In Brazil, the most recent legislation, which establishes limit values for air pollution, was based on WHO guidelines and introduced stricter limits for the concentration of major pollutants. It also established a timeline for a gradual reduction in the concentration of these pollutants (CONAMA, 2024), requiring governments and managers across Brazil to make efforts to achieve the air quality targets set by the legislation.

Monitoring changes in air pollutant levels over time helps determine whether actions to reduce air pollution are improving air quality and supporting the achievement of government and regulatory targets. Such analyses also enable the identification of regional particularities that should be considered in decision-making and inform strategies to reduce air pollution, supporting the development of studies, public policies, and mitigation measures, particularly in highly industrialized and developed regions of Brazil, such as the state of São Paulo.

Thus, the objective of this study was to evaluate time series data (2018–2024) of ozone, nitrogen dioxide, and particulate matter concentrations in different heavily industrialized regions of the state of São Paulo, which also include agricultural activities, particularly sugarcane cultivation. The selected period enables the assessment of temporal trends in pollutant concentrations and the evaluation of the impact of the COVID-19 lockdown on overall pollution patterns.

The study's findings support the development of public policies aimed at achieving national air quality targets and reducing the disease burden associated with air pollution exposure. Evidence shows that countries adopting evidence-based policies have achieved significant improvements in air quality (WHO, 2025). Given the scale of Metropolitan Region of São Paulo (MRSP), these findings also have broader implications for environmental quality and climate change mitigation.

Materials and methods

Study Area

São Paulo is Brazil's most industrialized state and a major economic hub. Its capital has the highest volume of motor vehicle traffic in the country and in Latin America, making it a major source of urban air pollution. Approximately 90% of the state's pollutant gas emissions result from the combustion of vehicle fuels.

To ensure effective environmental management, the territory of the state of São Paulo is divided into Water Resource Management Units (UGRHIs; Law No. 16,337; São Paulo, 2016). These units are classified according to their economic focus into industrialized, industrializing, agricultural, and conservation areas. This study was conducted in three UGRHIs classified as industrialized, but which also contain agricultural areas, particularly sugarcane plantations. Within these UGRHIs, cities or city districts were selected to collect meteorological data, pollutant concentration data, and data on wildfires, totaling 10 study sites (Fig. 1):

- The city of São Paulo is the state capital and has a high concentration of residents and motor vehicle traffic. It has meteorological and air quality monitoring stations in various regions, each with distinct traffic patterns. Four regions were selected for the study: Ibirapuera Park, with wide avenues, heavy automobile traffic, and a large green area due to the major municipal park that shapes the region's landscape; Interlagos, situated in the southern part of the city, near a vegetation preservation area; Dom Pedro II Park, located in the city center with heavy vehicle traffic; and Pinheiros, near a major thoroughfare with heavy automobile traffic.
- The city of Guarulhos borders the city of São Paulo and, together with it, forms the MRSP. It was chosen for the study because it is served by two highways with heavy traffic of large vehicles transporting goods produced by industry and agriculture. It also houses one of the largest airports in Latin America, through which much of the industrial and agribusiness production is exported.
- The city of São Bernardo do Campo, like Guarulhos, also borders the city of São Paulo and is part of the MRSP. It was selected due to its strategic location along two major highways that provide access to Brazil's largest port, supporting the flow of industrial and agricultural goods.
- The cities of Jundiaí, Piracicaba, Sorocaba, and Tatuí have smaller populations compared to São Paulo and are also located farther from the MRSP. However, industry plays a major role in their economies. Piracicaba stands out due to its significant sugar and ethanol industry, with extensive sugarcane cultivation and sugar and ethanol production plants.

Data Extraction and Imputation

The data used in this study refer to the period from 2018 to 2024 and was obtained from various official sources and public databases. The values for particulate matter (PM_{10}), nitrogen dioxide (NO_2), ozone (O_3), mean air temperature (TC), relative humidity (RH), and wind speed (WS) were extracted from

CETESB's automatic air quality monitoring stations, located in various cities and regions of São Paulo, and made available on the QUALAR platform.

Data for the variables solar radiation (RAD) and precipitation (PREP) were obtained from the TerraClimate database, accessed via Google Earth Engine (GEE), which also provided additional climate variables used as predictors in the missing data imputation algorithms.

Data on fire hotspots (FIRE_HOTSPOT) were extracted from the National Institute for Space Research (INPE) Fire Data Bank (BDQueimadas), specifically from the NPP-375D product, which provides fire detections from the VIIRS sensor at a resolution of 375 meters.

Missing values in CETESB temperature and relative humidity (33% and 34%, respectively) were imputed using machine learning models trained on observed data and TerraClimate-derived covariates (daily temperature, precipitation, and solar radiation). For temperature, Linear Regression was selected based on its superior performance ($R^2 = 0.90$, RMSE = 0.71) under 10-fold cross-validation. For relative humidity, Gradient Boosting achieved $R^2 = 0.71$ with RMSE = 3.55.

Other variables with lower proportions of missing data (PM_{10}: 26%, NO_2: 14%, wind speed: 21%) were imputed using Gradient Boosting models, with satisfactory predictive performance ($R^2 \geq 0.80$). The resulting dataset, with complete time series for all variables, was used in subsequent analyses.

Models and Fittings

The analysis of temporal trends and pandemic effects on air pollutants was performed using Linear Mixed Models (LME), fitted by Restricted Maximum Likelihood (REML) in R (nlme package). Each model included a random intercept for monitoring station and fixed effects for meteorological and environmental variables derived from TerraClimate (air temperature [TC], relative humidity [RH], wind speed [WS], solar radiation [RAD], and precipitation [PREP]), as well as for the number of fire hotspots obtained from INPE (NPP-375D product).

We also included terms for temporal trend (time) and lockdown intervention, representing the linear change in concentrations from 2018 to 2024 and the level change associated with the onset of the COVID-19 pandemic, respectively. The post-pandemic time term was tested but excluded because of collinearity with time and the absence of a significant post-intervention trend.

Temporal autocorrelation [AR(1)] and heterogeneous variance [varIdent] structures across monitoring stations were compared using Likelihood Ratio Tests (LRTs). For the pollutants O_3, NO_2, and PM_{10}, the joint inclusion of the AR(1) and varIdent structures resulted in a significant improvement in the fit ($p < 0.001$), indicating both serial dependence among consecutive monthly observations and heterogeneity of variance among monitoring stations.

The presence of residual heteroscedasticity was assessed through graphical inspection and specific tests. To ensure robust inference, coefficient estimates were evaluated using CR2-type robust standard

errors clustered by monitoring station (clubSandwich package). The variance inflation factors (VIF) remained below 3 in all models, confirming the absence of significant multicollinearity among the covariates.

Results

Robust modeling and inferences

For each pollutant (O_3, NO_2, and PM_{10}), Linear Mixed Models (LME) were fitted using the Restricted Maximum Likelihood (REML) method, with a random intercept for monitoring station. The residual structures of temporal autocorrelation (AR(1)) and heterogeneous variance across stations (varIdent) were tested and retained whenever they significantly improved the model fit (likelihood ratio test, $p < 0.001$).

After model fitting, residual diagnostics indicated no remaining heteroscedasticity, suggesting that the model adequately captured the variance structure. Nevertheless, to ensure greater robustness in the inferences, especially given the temporal structure of the data and the possibility of residual correlation within the series, robust standard errors of the CR2 type were used, clustered by air quality monitoring station (AQS).

Ozone (O_3)

The model with an AR(1) structure and heterogeneous variances across study sites (varIdent) showed a significant improvement in model fit compared to the model without temporal correlation (LRT, $p < 0.001$; $\Phi = 0.54$). The time variable was not significant ($p = 0.387$), nor was the immediate effect of the lockdown ($p = 0.193$), indicating the absence of a linear trend or abrupt change in O_3 concentrations.

Based on models with CR2 robust errors, positive associations were observed between O_3 and air temperature (TC; $p = 0.012$), wind speed (WS; $p = 0.003$), and solar radiation (RAD; $p < 0.001$), as well as a negative association with relative humidity (RH; $p = 0.003$). The remaining variables did not show statistical significance after applying robust standard errors (Table 1). The model presented a marginal R^2 of 0.53 and a conditional R^2 of 0.81.

The random intercepts indicate residual variations in pollutant concentrations among the monitoring stations in the different cities and regions studied, even after controlling for meteorological and temporal factors. Cities with the highest positive intercepts for O_3 were São Paulo, in the Ibirapuera region, and São Bernardo do Campo. This pattern indicates that these locations tend to record higher concentrations of O_3 than predicted by the model, even when accounting for meteorological and temporal conditions.

This may be associated with combinations of heavy traffic, urban green areas (emitting biogenic precursors), and urban structures that favor the secondary formation of the pollutant (Fig. 2 and Fig. 3). On the other hand, the Pinheiros region and the city of Sorocaba showed negative intercepts, suggesting

that in these locations the observed concentrations were lower than expected, which may reflect a lower precursor load or more efficient dispersion processes (Fig. 2 and Fig. 3).

Table 1
Estimated coefficients for the O_3 mixed model with an AR(1) structure and heterogeneous variances across air quality monitoring stations (AQS). The coefficients represent the average effect of each covariate on O_3 concentrations. Robust standard errors(CR2) were used for inference.

Term	Estimate (β)	Robust SE	p-value	Significance
Intercept	6.03	9.82	0.556	—
time	−0.025	0.028	0.387	—
intervention	1.72	1.22	0.193	—
NO_2	0.046	0.039	0.287	—
Temperature (TC)	**0.985**	0.292	**0.012**	*
Relative humidity (RH)	**−0.337**	0.077	**0.003**	**
Wind speed (WS)	**6.224**	1.292	**0.003**	**
Precipitation	−0.0023	0.0025	0.389	—
Fire hotspots	0.0032	0.049	0.952	—
Solar radiation (RAD)	**0.148**	0.0166	**< 0.001**	***

Nitrogen Dioxide (NO_2)

The model with an AR(1) structure and heterogeneous variances across air quality monitoring stations (varIdent) showed a significant improvement in model fit compared with the model without temporal correlation (LRT, $p < 0.001$; $\Phi = 0.56$). Models with CR2 robust standard errors indicated a significant positive temporal trend in NO_2 concentrations ($\beta = 0.00936$; $p = 0.009$), as well as an abrupt reduction associated with the onset of the lockdown intervention ($\beta = -4.007$; $p = 0.002$).

NO_2 concentrations were negatively associated with air temperature (TC; $p = 0.0289$), relative humidity (RH; $p = 0.004$), wind speed (WS; $p = 0.049$), and solar radiation (RAD; $p < 0.001$). The remaining environmental variables were not statistically significant after applying CR2 robust standard errors (Table 2). The model showed good overall fit (marginal $R^2 = 0.319$; conditional $R^2 = 0.836$).

Regarding random effects, the largest positive values were observed in the Interlagos and Pinheiros districts of São Paulo, as well as in Jundiaí, indicating that these locations tend to exhibit NO_2 concentrations higher than those predicted by the model. This pattern is consistent with areas characterized by intense traffic and potential industrial influence. In contrast, Piracicaba, Sorocaba, and Tatuí showed significantly negative intercepts, particularly Tatuí, suggesting lower-than-expected NO_2

concentrations, which may reflect lower vehicle density or more efficient local dispersion processes (Fig. 4 and Fig. 5).

Table 2
Estimated coefficients for the mixed NO_2 model with an AR(1) structure and heterogeneous variances among air quality monitoring stations (AQS). The coefficients represent the average effect of each covariate on NO_2 concentrations. Robust standard errors (CR2) were used for inference.

Term	Estimate (β)	Robust SE	p-value	Significance
Intercept	**83.98**	**12.92**	**< 0.001**	***
time	**0.0936**	**0.025**	**0.0093**	**
intervention	**−4.007**	**0.785**	**0.002**	**
O_3	0.0132	0.047	0.789	—
Temperature (TC)	**−0.397**	**0.14**	**0.0289**	*
Relative humidity (RH)	**−0.385**	**0.086**	**0.0044**	**
Wind speed (WS)	**−6.557**	**2.347**	**0.0495**	*
Precipitation	−0.00345	0.00271	0.243	—
Fire hotspots	0.0953	0.0959	0.386	—
Solar radiation (RAD)	**−0.0608**	**0.00748**	**< 0.001**	***

Particulate matter (PM_{10})

The model with an AR(1) structure and heterogeneous variances across air quality monitoring stations (varIdent) showed a significant improvement in model fit compared with the model without temporal autocorrelation (LRT, $p < 0.001$; $\Phi = 0.41$). Models with CR2 robust standard errors indicated a positive temporal trend in PM_{10} concentrations ($p = 0.032$), as well as a significant reduction associated with the onset of the lockdown intervention ($p < 0.001$).

PM_{10} concentrations were positively associated with O_3 ($p < 0.001$) and fire hotspots ($p = 0.0013$) and negatively associated with relative humidity (RH; $p < 0.001$), wind speed (WS; $p = 0.007$), precipitation (PREP; $p = 0.005$), and solar radiation (RAD; $p < 0.001$). Air temperature (TC) did not show a significant effect after applying CR2 robust standard errors ($p = 0.222$) (Table 3). The model showed good overall fit (marginal $R^2 = 0.550$; conditional $R^2 = 0.779$).

The Interlagos region and the cities of Jundiaí and Piracicaba showed the largest positive random intercepts, indicating higher-than-expected PM10 concentrations. Piracicaba, in particular, is associated with agricultural activities and wildfire hotspots, which may explain this pattern. In contrast, Sorocaba

showed negative intercepts, indicating lower-than-expected concentrations, which may reflect lower industrial activity or more efficient local dispersion processes (Fig. 6 and Fig. 7).

Table 3
Estimated coefficients for the mixed model of $PM_{10}$with an AR(1) structure and heterogeneous variances among air quality monitoring stations (AQS). The coefficients represent the average effect of each covariate on PM_{10} concentrations. Robust standard errors (CR2) were used for inference.

Term	Estimate (β)	Robust SE	p-value	Significance
Intercept	**105.36**	**7.02**	**< 0.001**	***
time	**0.046**	**0.0164**	**0.032**	*
intervention	**−2.904**	**0.447**	**< 0.001**	***
O_3	**0.242**	**0.0237**	**< 0.001**	***
Temperature (TC)	−0.206	0.153	0.222	—
Relative humidity (RH)	**−0.699**	**0.077**	**< 0.001**	***
Wind speed (WS)	**−7.505**	**1.735**	**0.0067**	**
Precipitation	**−0.0134**	**0.00307**	**0.0047**	**
Fire hotspots	**0.343**	**0.0484**	**0.0013**	**
Solar radiation (RAD)	**−0.100**	0.012	**< 0.001**	***

Discussion

The concentrations of O_3, NO_2, and PM_{10} observed from 2018 to 2024 across the ten evaluated locations reflect the combined influence of local sources, urban characteristics, and meteorological conditions. Temporal trends indicated a slight but statistically significant increase in PM_{10} and NO_2 concentrations over the study period, while O_3 levels remained relatively stable. These results suggest that, although there is no evidence of a marked deterioration in air quality, subtle changes in pollutant dynamics may be occurring over time.

The intervention associated with the start of the lockdown in March 2020 resulted primarily in temporary reductions in PM_{10} and NO_2, consistent with the sharp drop in urban mobility. Overall, NO_2 was the pollutant that decreased the most during the lockdown period (23–37%), followed by PM_{10} (14–20%), $PM_{2.5}$ (7–16%), and CO (7–11%) (Liu et al., 2021).

In the context of the Metropolitan Region of São Paulo, previous studies have reported drastic reductions in NO (up to 77.3%), NO_2 (up to 54.3%), and CO (up to 64.8%) concentrations in urban areas during the partial lockdown, compared to the monthly averages from the five years prior to the pandemic (Nakada & Urban, 2020). This sharp decline is consistent with the dominant role of road traffic as a source of

primary pollutants, accounting for approximately 68% of NOx emissions and 98% of CO emissions (Nakada & Urban, 2020).

On a global scale, intra- and inter-city movement restrictions have been identified as the most effective measures for reducing primary pollutants such as NO_2 (Berman & Ebisu, 2020; Schneider et al., 2022; Sharma et al., 2020; Sicard et al., 2020), suggesting that policies targeting vehicle emissions can effectively improve air quality. In contrast, no consistent reductions in O_3 concentrations were observed across different locations during the restriction period (Nakada & Urban, 2020). Similar patterns have been reported in cities such as Nice, Rome, Turin, Valencia, and Wuhan (Sicard et al., 2020), as well as in several cities in India (Rahaman et al., 2021; Sharma et al., 2020).

Furthermore, consistent with the literature, some cities heavily influenced by traffic showed increases of approximately 30% in O_3 concentrations during the lockdown (Nakada & Urban, 2020; Sicard et al., 2020), in line with global analyses reporting a positive association between restriction measures and O_3 levels (Liu et al., 2021).

This increase can be explained by atmospheric chemistry: the sharp reduction in NO decreases O_3 consumption, leading to higher concentrations (Bainy et al., 2021; Guerra et al., 2004; Sharma et al., 2020; Sicard et al., 2020). Additionally, vehicle emissions modeling in the RMSP indicates that the lockdown increased the NMHC/NOx ratio near central São Paulo, favoring the formation of tropospheric O_3 (Ibarra-Espinosa et al., 2022). These findings highlight that O_3 formation responds to changes in emission patterns and that controlling tropospheric ozone is inherently complex, requiring consideration of local formation and removal processes (Rushton & Tate, 2025).

Moreover, both in São Paulo and in other international contexts, reductions in pollutant concentrations during the lockdown were short-lived. As activities resumed, concentration quickly returned to or exceeded pre-pandemic levels, resulting in no sustained changes in the time series (Amritha et al., 2025; Kumari & Toshniwal, 2020).

Meteorological variables played a central role in explaining the daily variability of pollutants, consistent with previous studies (Bainy et al., 2021; Sharma et al., 2020). O_3 formation increased under conditions of higher temperature, solar radiation, and wind speed, and decreased on more humid days, as expected in urban environments where photochemical processes depend on radiation availability and atmospheric dispersion. For PM_{10} and NO_2, humidity and wind tended to reduce concentrations, reflecting wet and dry deposition processes as well as atmospheric dispersion.

The dynamics of particulate matter proved to be more complex. Studies suggest that the impact of the lockdown on PM may be nonlinear, reflecting a balance between reduced traffic and a relative increase in stationary and residential emission sources, especially during colder months (Becchetti et al., 2025). In Italy, for example, the increase in domestic heating during the lockdown offset the reduction in traffic, leading to an unexpected rise in PM concentrations (Becchetti et al., 2025). On a global scale, the

reduction in PM was more modest than that of NO_2, partly because PM is influenced by natural, secondary, and regional sources, in addition to vehicle emissions (Schneider et al., 2022).

The inclusion of satellite-detected fire data was particularly relevant for explaining PM_{10} variability, especially in Piracicaba, where extensive sugarcane plantations and frequent fire events are observed, despite legislation prohibiting the burning of cultivated areas (São Paulo, 2002). Biomass burning contributes substantially to particulate matter loads in the atmosphere, particularly during dry periods that favor its spread. These emission sources, common in parts of South and Central America, behave differently from vehicle emissions subject to lockdown restrictions (Amritha et al., 2025). In addition to emitting large amounts of particulate matter, biomass burning also releases ozone precursor gases (Bainy et al., 2021; Nakada & Urban, 2020).

Although annual averages describe the absolute magnitude of pollution in each city, the random effects estimated by the models provide a complementary interpretation: they indicate whether the observed concentrations are higher or lower than expected after controlling for meteorological and seasonal factors. This type of heterogeneity is consistent with international findings, which show distinct responses to the lockdown across regions, with more pronounced effects in more industrialized, more populous countries with a higher number of confirmed COVID-19 cases (Berman & Ebisu, 2020; Chen et al., 2020; Liu et al., 2021; Zhang et al., 2021).

In the case of ozone, locations such as Ibirapuera, São Bernardo do Campo, Interlagos, and Parque Dom Pedro II exhibited positive intercepts, indicating higher-than-expected O_3 concentrations even after controlling for meteorological conditions. This may reflect specific emission patterns, stronger traffic influence, urban configuration, or other factors not included in the model.

The pattern observed in Ibirapuera is consistent with previous studies identifying this region as one of the areas with the highest frequency of elevated O_3 concentrations, particularly during summer, when high solar radiation and temperature favor photochemical ozone formation in environments characterized by intense traffic and the presence of large green areas that may emit biogenic precursors (Bulbovas et al., 2010; Esposito et al., 2009; Souza et al., 2009).

In contrast, Pinheiros and Tatuí showed negative intercepts for O_3, indicating lower-than-expected concentrations. This does not necessarily imply low absolute levels, but rather that, given the meteorological conditions, higher concentrations would be expected. In Tatuí, for example, the climate favors ozone formation, and peri-urban areas may include emissions of biogenic volatile organic compounds. The negative intercept suggests that, even under conditions favorable to O_3 formation, observed concentrations remained lower than expected based on the model.

A similar pattern was observed for PM_{10}. Piracicaba exhibits high average concentrations and a positive intercept, indicating an additional contribution beyond that explained by meteorology, seasonality, and regional wildfires, which is consistent with the influence of wildfires and agricultural practices. Sorocaba, in turn, shows a negative intercept for PM_{10}, suggesting that it tends to record lower values than

predicted by the models, possibly due to lower emissions from urban and industrial sources. This spatial heterogeneity reinforces the need for differentiated regional approaches to mitigate emissions, tailored to specific local contexts (Amritha et al., 2025; Liu et al., 2021; Zhang et al., 2021).

Overall, the results show that air quality at the ten sites assessed is governed by a combination of meteorological factors, local sources, regional wildfires, and photochemical reactions. The effects of the lockdown were significant but temporary and did not alter the long-term trends of the time series (Amritha et al., 2025; Kumari & Toshniwal, 2020). However, provided insights into local atmospheric dynamics, which can aid in the management and governance of air pollution in the cities included in the study. Furthermore, research conducted during the pandemic showed that temporary reductions in pollution can have a measurable impact on health outcomes, reinforcing the role of chronic exposure to air pollution as a determinant of mortality and hospitalizations (Giani et al., 2020; Liu et al., 2021;).

Random intercepts highlight locations where control policies may be prioritized. Areas with consistently higher-than-expected concentrations—such as Ibirapuera and São Bernardo do Campo for O_3, and Interlagos, Jundiaí, and Piracicaba for PM_{10}—require more intensive actions. In contrast, locations with consistently lower-than-expected concentrations, such as Sorocaba for PM_{10} and some stations with negative intercepts for O_3, may help identify mitigation factors that could be replicated in other regions. By integrating seven years of data, multiple pollutants, meteorological conditions, and satellite-detected wildfires, this study provides a comprehensive overview of recent air quality dynamics in industrialized areas of the state of São Paulo, highlighting the importance of sustained policies, regional coordination, and integrated monitoring to support lasting improvements in environmental and urban health.

Conclusions

This study evaluated time series data (2018–2024) of ozone (O_3), nitrogen dioxide (NO_2), and particulate matter (PM_{10}) concentrations across industrialized regions of the state of São Paulo that also include agricultural activities, particularly sugarcane cultivation.

The results showed a slight increasing trend in PM_{10} and NO_2 concentrations over time, while O_3 remained stable. The COVID-19 lockdown led to short-term reductions in NO_2 and PM_{10}, highlighting the importance of vehicular emissions as key drivers of these pollutants. However, these effects were temporary and did not alter long-term air quality trends. In contrast, O_3 concentrations did not decrease during the lockdown, reinforcing the complexity of its formation and the need for control strategies that consider local photochemical processes. Additionally, biomass burning played a significant role in PM_{10} variability, particularly in agricultural regions, indicating the need for stricter control of fire-related emissions.

Spatial variability in pollutant concentrations revealed strong site-specific patterns, demonstrating that local and regional factors must be considered in air quality management. These findings emphasize that effective mitigation policies require integrated approaches that account for emission sources, meteorological conditions, and regional characteristics.

Overall, the results highlight the complexity of air pollution dynamics in industrial-agricultural regions and underscore the importance of sustained, locally adapted policies to achieve long-term improvements in air quality and public health.

Declarations

Clinical Trial Number

not applicable.

Declarations Section

All authors have read, understood, and have complied as applicable with the statement on “Ethical responsibilities of Authors” as found in the Instructions for Authors.

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Author Contribution

B. B. S.: conceptualization, methodology, investigation, data curation and writing original draft. R. K. N.: data curation, formal analysis and review.R. C. A. C.: formal analysis and review. P. B. H.: conceptualization, methodology, supervision, data curation, review and editing.

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Data Availability

Data availability statementThe values for particulate matter (PM10), nitrogen dioxide (NO2), ozone (O3), mean air temperature (TC), relative humidity (RH), and wind speed (WS) were extracted from CETESB's automatic air quality monitoring stations available on https://www.cetesb.sp.gov.br/cetesb/qualidade_ambiental/ar/qualar Data for the variables solar radiation (RAD) and precipitation (PREP) were obtained from the TerraClimate database, accessed via Google Earth Engine (GEE). The dataset is in the public domain, licensed under the Creative Commons Public Domain (CC0) license. Abatzoglou, J.T., S.Z. Dobrowski, S.A. Parks, K.C. Hegewisch, 2018, Terraclimate, a high-resolution global dataset of monthly climate and climatic water balance from 1958-2015, Scientific Data 5:170191, doi:10.1038/sdata.2017.191Data on fire hotspots was obtained from TerraBrasilis, licence CC 4.0 (https://terrabrasilis.dpi.inpe.br/queimadas/bdqueimadas/) Adding research funding statementsCAPES – Coordination for the Improvement of Higher Education Personnel (Funding – Code 001). The Article Processing Charge (APC) for the publication of this research was funded by the Coordination for the Improvement of Higher Education Personnel (CAPES; ROR identifier: 00x0ma614).CAPES – Coordination for the Improvement of Higher Education Personnel for awarding the Master's Scholarship from the Support Program for Graduate Studies at Private Educational Institutions (PROSUP) to Beatriz Barbosa de Souza.

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Figures

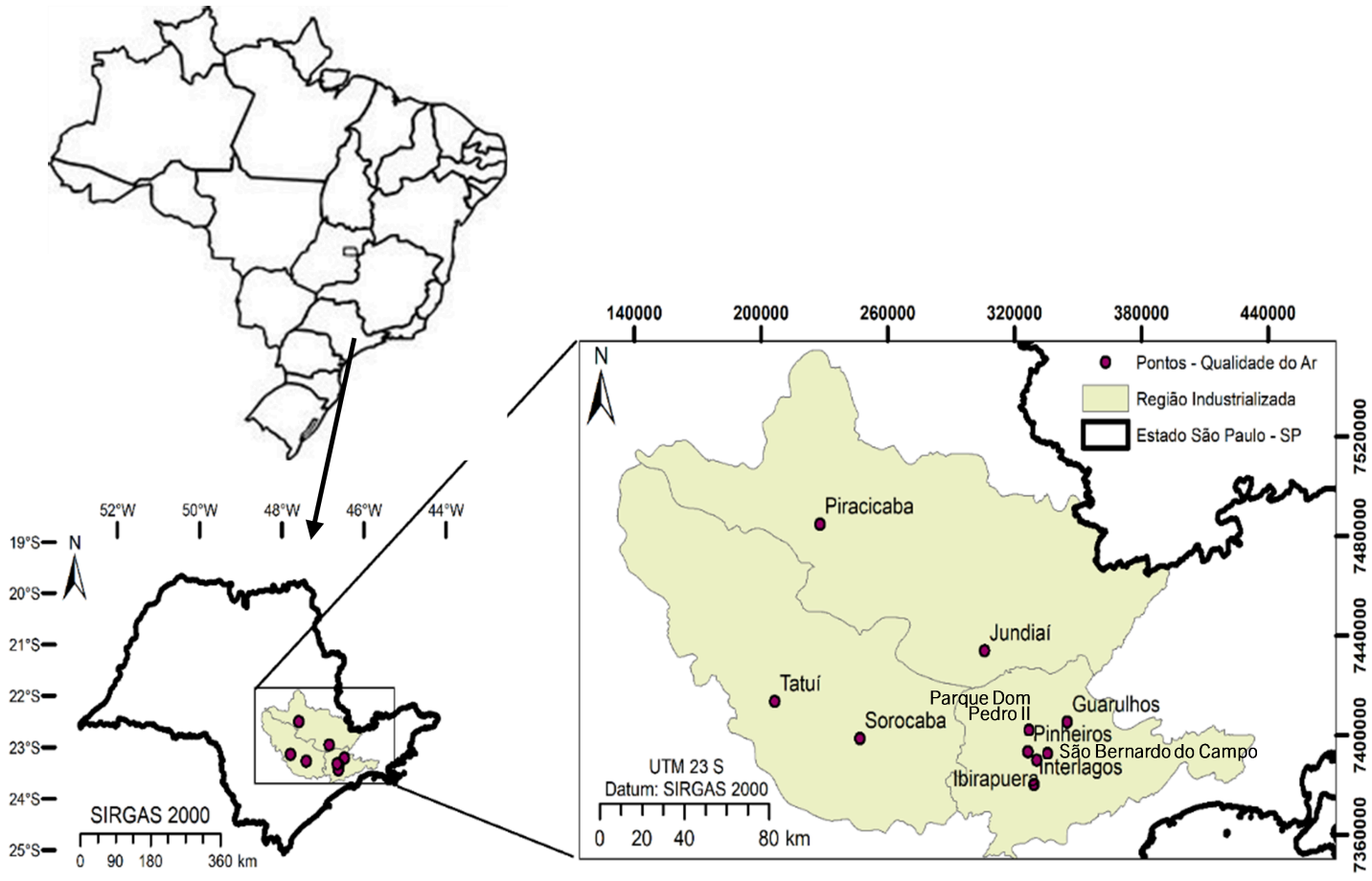


Figure 1

Study sites according to their economic classification and corresponding UGRHI codes.

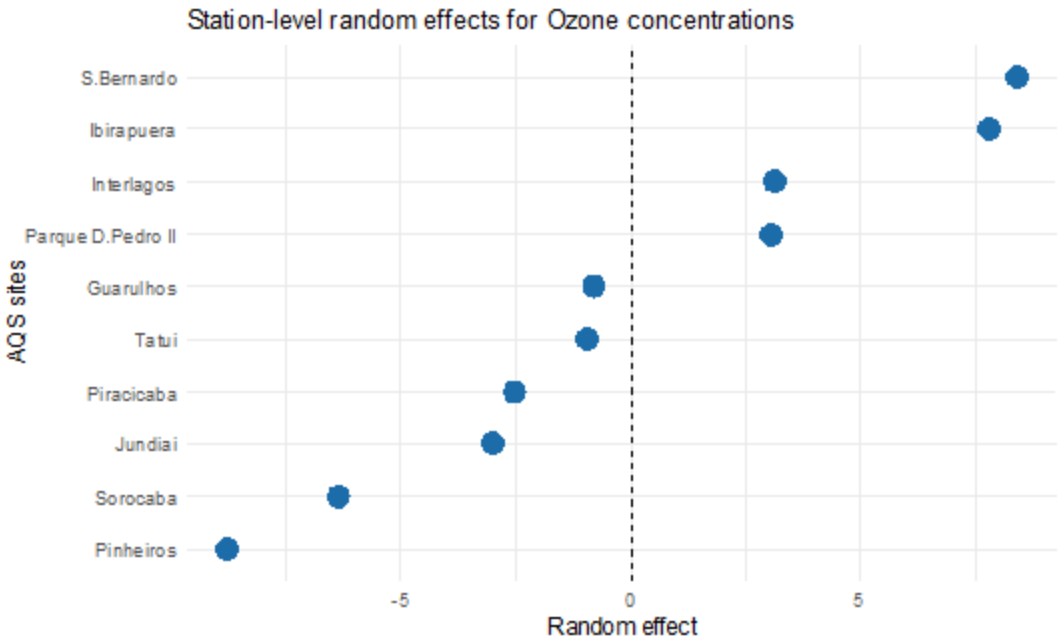


Figure 2

Estimates of random effects by monitoring station obtained using a linear mixed-effects model (LME) for ozone (O_3) concentrations during the period 2018–2024. The dashed vertical line indicates the average effect, highlighting the spatial variability among stations.

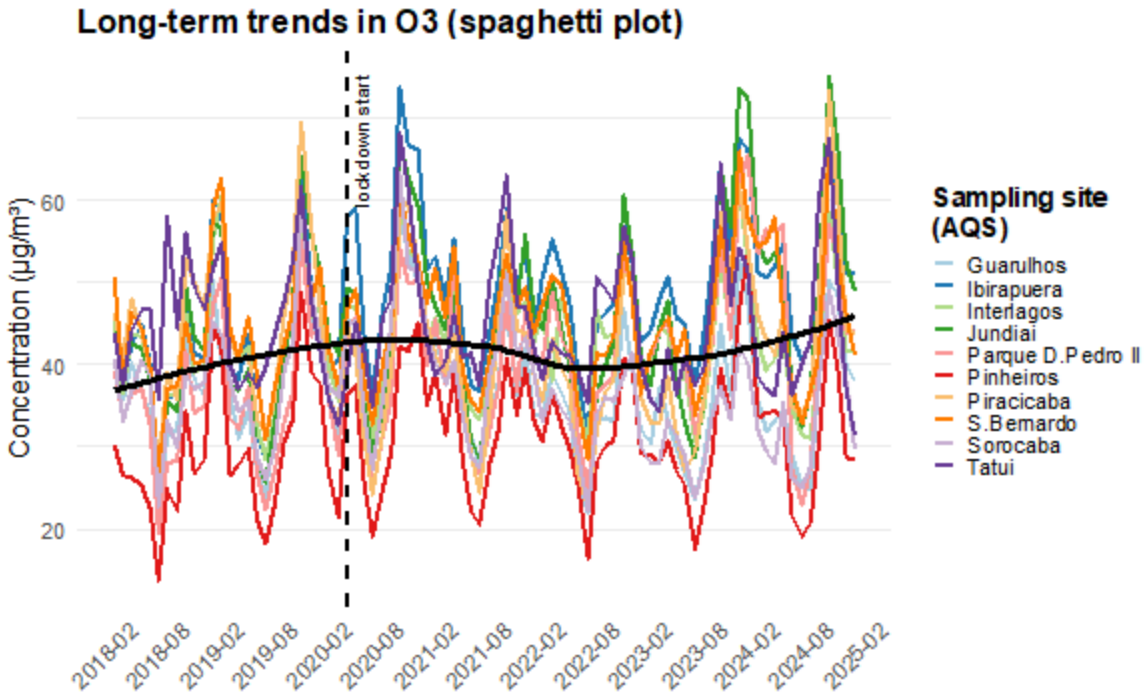


Figure 3

Long-term trends in ozone (O_3) concentrations at the 10 air quality monitoring stations (AQS) between 2018 and 2024. The colored lines represent the daily time series for each AQS (spaghetti plot), while the thick black line shows the smoothed overall trend(LOESS). The dashed vertical line indicates the start of the lockdown period.

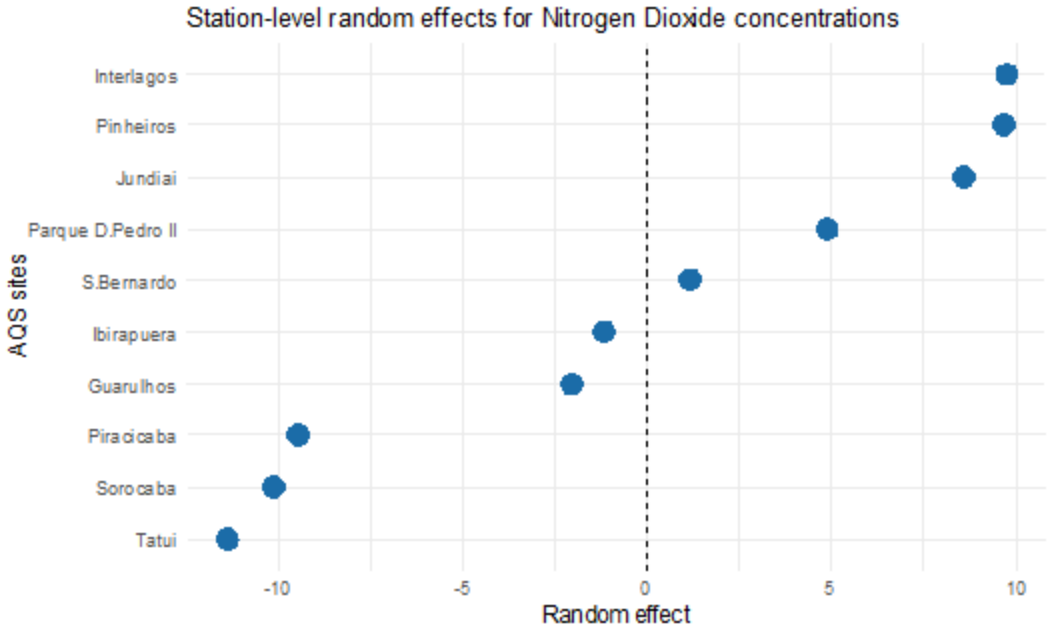


Figure 4

Estimates of random effects by monitoring station obtained using a linear mixed-effects model (LME) for nitrogen dioxide (NO_2) concentrations during the 2018–2024 period. The dashed vertical line indicates the mean effect, highlighting the spatial variability among stations.

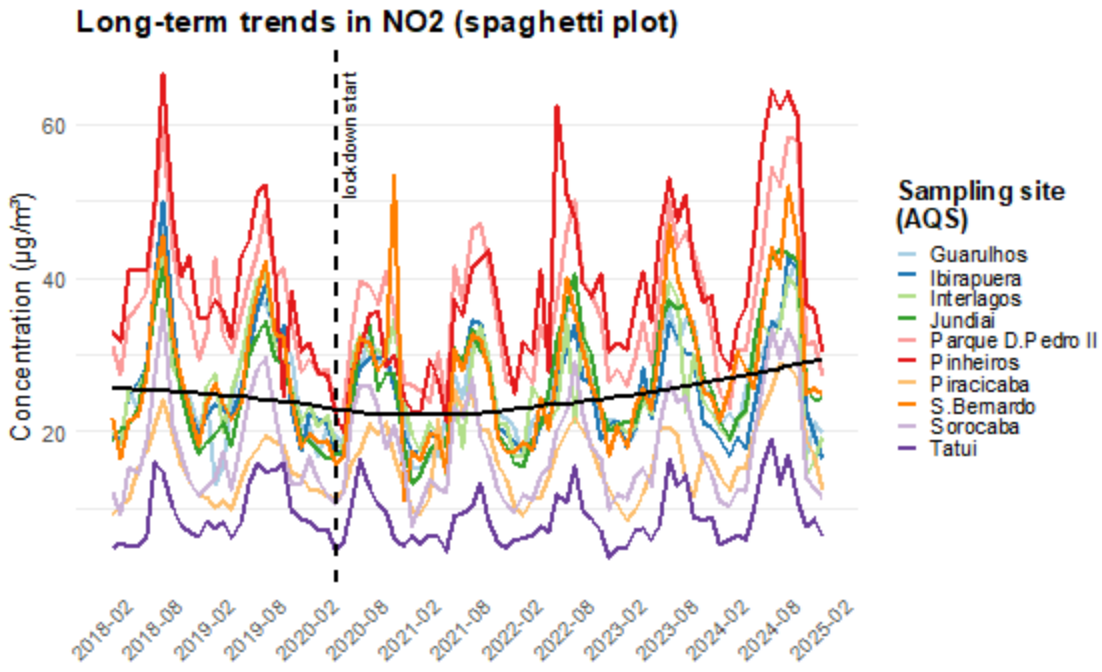


Figure 5

Long-term trends in nitrogen dioxide (NO_2) concentrations at the 10 air quality monitoring stations (AQS) between 2018 and 2024. The colored lines represent the daily time series for each AQS (spaghetti plot), while the thick black line shows the smoothed overall trend (LOESS). The dashed vertical line indicates the start of the lockdown period.

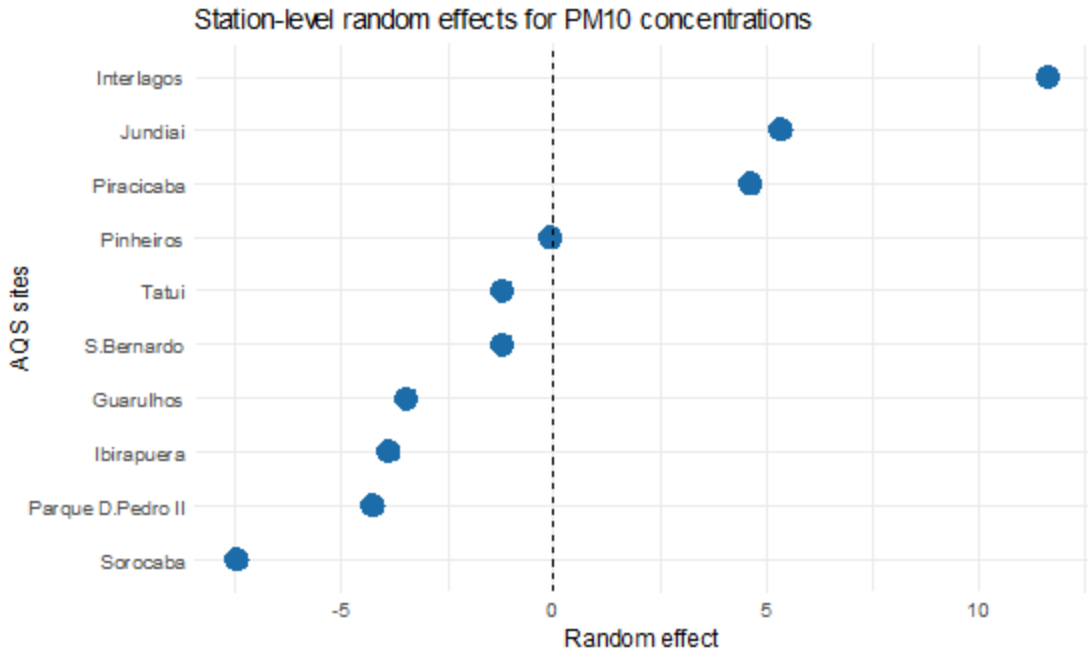


Figure 6

Estimates of random effects by monitoring station obtained using a linear mixed-effects model (LME) for particulate matter (PM10) concentrations during the period 2018–2024. The dashed vertical line indicates the average effect, highlighting the spatial variability among stations.

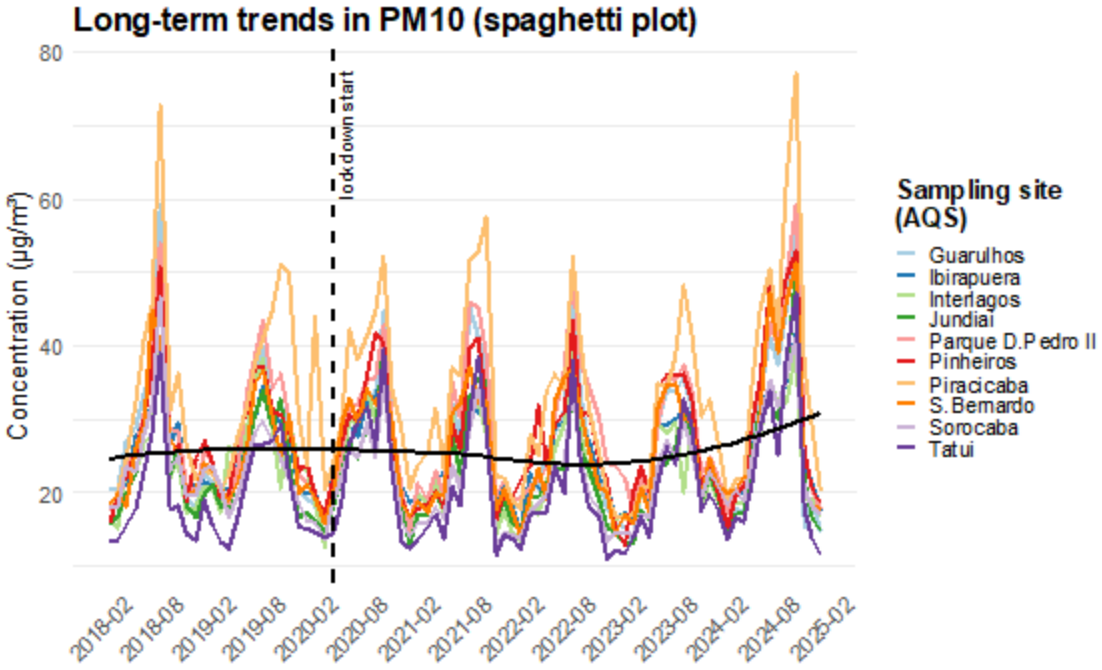


Figure 7

Long-term trends in particulate matter (PM_{10}) concentrations at the 10 air quality monitoring stations (AQS) between 2018 and 2024. The colored lines represent the daily time series for each station (spaghetti plot), while the thick black line shows the smoothed overall trend (LOESS). The vertical dashed line indicates the start of the lockdown period.

Supplementary Files

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