




Prenatal exposure to fine particulate matter $PM_{2.5}$ and small for gestational age: a Bayesian model for area-based data in Milan

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Abstract

Air pollution is a known risk factor for adverse birth outcomes, including Small for Gestational Age (SGA) births. This study examines the association between fine particulate matter ($PM_{2.5}$) exposure and SGA births in Milan, Italy, considering spatial dependencies and socioeconomic factors. We applied a Bayesian hierarchical spatial model with a binomial regression framework to birth data aggregated at a $500\text{ m} \times 500\text{ m}$ grid level. A Conditional Autoregressive (CAR) prior captured spatial correlations. Covariates included maternal age, Deprivation Index, Normalized Difference Vegetation Index (NDVI), surface temperature, and Road Coverage. Parameter estimation was performed using Markov Chain Monte Carlo (MCMC) methods. Among 7635 eligible births in 2016, 8.5% were SGA. A $10\text{ }\mu\text{g}/\text{m}^3$ increase in $PM_{2.5}$ was associated with a 15% increase in SGA odds (OR: 1.153, IQR: 0.853–1.556). The Deprivation Index also showed a strong positive association (OR: 1.075, IQR: 1.028–1.125). NDVI exhibited a weak positive association, potentially reflecting socioeconomic disparities. Maternal age, temperature, and Road Coverage were not significantly associated with SGA. $PM_{2.5}$ exposure and socioeconomic deprivation are linked to higher SGA risk in Milan. The spatial correlation highlights localized risk factors. Targeted policies to reduce air pollution and address social inequalities are needed to improve perinatal outcomes.

Keywords Small for gestational age · Air pollution · Particulate matter · Bayesian spatial modeling · Socioeconomic deprivation · Perinatal health

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1 Background

The first thousand days from conception are a pivotal period for each child's physical and neurological development, laying the foundation for lifelong growth and health. Among neonatal disorders, being born small for gestational age (SGA) is particularly concerning, as it is a major cause of perinatal mortality (Katz et al. 2013). Being born SGA stresses development in the uterus causing short (Ashorn et al. 2023) and long-term impacts in physical and mental development during childhood and adolescence (Ochiai et al. 2008; Shim et al. 2013), and is closely associated with significant health risks in adulthood (Risnes et al. 2011). Given the significant impact of this condition on neonatal outcomes and its long-term effects on children's quality of life, it is crucial to assess the risk factors associated with this condition. Furthermore, the high prevalence of this condition, approximately 10% across Europe (Hocquette et al. 2021), highlights its importance as a public health concern.

During this critical time, air pollution stands out as one of the major threats, with one-fifth of the global neonatal disorder burden attributed to $PM_{2.5}$ (Zhao et al. 2023). Evidence suggests that particulate matter may increase oxidative stress and systemic inflammation (Ghio et al. 2012; Møller et al. 2014), potentially impairing fetal growth (Nobles et al. 2019) through mechanisms such as reducing placental volume, decreasing uterine blood flow, inducing epigenetic changes in placental and fetal tissues, and altering mitochondrial content (Proietti et al. 2013). The impact of $PM_{2.5}$ on abnormal fetal growth is not uniform but varies according to its chemical constituents (Zhong et al. 2025), depending on their specific compositions and concentrations. However, the mechanisms underlying its effects on SGA risk remain unclear. Evidence suggests that higher $PM_{2.5}$ exposure may increase maternal blood pressure and hemoglobin levels during pregnancy, leading to fetal growth restriction and ultimately elevating the risk of SGA (Zhu et al. 2022a).

Evidence suggests a harmful effect of $PM_{2.5}$ on the risk of being born SGA. However, the nature of this pollutant—as a mixture of elements that may differ considerably across studies—and the uncertainty surrounding the mechanisms linking higher maternal exposure to increased SGA risk remain under debate.

For this reason, in this paper, we aim to investigate the association between air pollution and the number of SGA births in the population of Milan, encompassing approximately 1.5 million residents. We adopt a spatial regression model that accounts for geographical correlations between adjacent areas, using a regular grid linked to air pollution estimates from the 'Urban Tool for Air Quality' (UTAQ) (Tunesi et al. 2024).

While previous studies have demonstrated associations between air pollution and low birth weight, (Pedersen et al. 2013; Bell et al. 2007; Liu et al. 2019a; Mitku et al. 2020) usually using individual-level data, few have explicitly modeled the spatial distribution of the number of SGA births. This unconventional approach may strengthen the evidence for an association between $PM_{2.5}$ exposure and the risk of being born SGA. Typically, if data are defined over space, a common statistical approach is to model the spatial distribution of the health outcome using techniques that account for the geographical correlations in the data (Mitku et al. 2020). Standard frequentist methods include geographically weighted regression on individual-level data on

newborns and mothers to integrate spatial information (Song et al. 2020; Tu et al. 2016). This approach underscores the importance of defining neighborhood structures that can vary based on population density to capture local variations in the data.

In this manuscript, instead, we consider the Bayesian approach to the problem, since it automatically provides uncertainty quantification of the regression parameters. The posterior inference is computed through simulation methods easily obtained using probabilistic programming languages. Bayesian models have been widely used to analyze the effects of air pollution on low birth weight newborns and modeling their spatial distribution (Coker et al. 2015; Li et al. 2016). These models often incorporate spatial random effects using a conditional autoregressive (CAR) prior (Besag 1974) to account for spatial correlations between individual observations (Ngwira 2019). In contrast, other studies have worked with aggregated areal data, using logistic regression models to estimate the probability of low birth weight based on area-level air pollution exposure (Harris et al. 2014).

By identifying spatial patterns in the relationship between air pollution and SGA births, this study aims to contribute to a better understanding of environmental determinants of perinatal health. The findings could have implications for urban planning, air quality regulations, and public health interventions aimed at reducing the burden of adverse birth outcomes.

2 Methods

2.1 Population data

Data collected included newborns born in 2016 whose mothers were residents in the municipality of Milan at the time of the child's birth. Birth data were retrieved from the National Birth Attendance Certificate (CEDAP) database, which collects information on the characteristics and outcomes related to pregnancy, delivery, the newborn, and the postpartum period for both mothers and infants. Major risk factors for being born SGA are maternal medical disorders during pregnancy, such as hypertension and diabetes, as well as fetal conditions, including birth defects, that increase the likelihood of SGA (Liu et al. 2019b). For this reason, we chose to apply the following exclusion criteria: stillbirth or death within 30 days of birth; presence of major malformations or hydrops fetalis; twin births; maternal age under 18 years; residency in the municipality of Milan for less than nine months or residence change during pregnancy; maternal history of pre-existing or pregnancy-related chronic conditions (hypertension, eclampsia, pre-eclampsia, diabetes, and gestational diabetes); gestational age under 25 or over 42 weeks; and a history of previous stillbirth. Births with missing data on sex and gestational age were excluded. Furthermore, each neonate's SDS (standard deviation score) was calculated based on the reference values provided by Spada et al. (2024) which establishes SDS as a normalized metric for evaluating birth weight relative to gestational age and sex. Neonates with an absolute SDS greater than 4 were considered outliers or anomalous cases and subsequently excluded from the analysis. This approach ensures a more consistent evaluation of birth weights within typical growth patterns for the given gestational age and sex.

While other researchers typically use a threshold of 3 (World Health Organization, 2006), we opted for a threshold of 4 to adopt a more permissive criterion.

Birth data from CEDAP included infant birth weight, gestational age, and maternal age. The maternal address at the time of delivery was retrieved from the database of assisted persons (NAR) managed by the local health agency (ATS) of Milan and geolocalized using ArcGIS Software Pro Version 3.3.1. The indicator of SGA was determined based on the growth charts provided by Spada et al. (2024).

A newborn is classified as being SGA if the birth weight is below the 10th percentile of the reference weight distribution for newborns of the same sex and gestational age (Spada et al. 2024). Given the spatial nature of this project, to protect privacy, individual-level data were aggregated into areal data at a fixed spatial resolution, i.e., for a total of $515\,500\text{ m} \times 500\text{ m}$ grid cells (see Sect. 2.2 for their definition). For this reason, outcome is defined as the number of births classified as SGA within each areal unit.

3 Exposure data

Air pollution concentration (NO_2 , PM_{10} , and $PM_{2.5}$) was calculated from a dispersion model of air pollutants carried out according to UTAQ (UTAQ) (Tunesi et al. 2024). Modeling was carried out on an annual basis (2015) for the municipality of Milan on a domain of $20 \times 22\text{ km}^2$ divided into 802×879 cells with a size of $25\text{ m} \times 25\text{ m}$, which included the whole city of Milan and 40 neighboring municipalities. However, the original areas are too small to yield meaningful non-zero data, so we have opted to use $500\text{ m} \times 500\text{ m}$ areas instead. This is particularly relevant, as using an overly fine spatial resolution may misrepresent exposure compared to a coarser grid (Harris et al. 2014).

Due to the high correlation of the pollutants we have only included $PM_{2.5}$ in the model (see Figures A1, A2, A3 in Supplementary Material to check the correlations between air pollutants). The spatial distribution of $PM_{2.5}$ in Milan is represented in Fig. 1.

4 Areal-level information

Figure 2 displays the number of SGA births in each areal unit included in the analysis. The $500\text{ m} \times 500\text{ m}$ cells obtained have been filtered based on the following criteria: they must fall within the boundaries of the municipality of Milan, and each cell must have a minimum population of 15 people, at least 5 fertile women, and at least 1 newborn.

Hence, some areas within the municipality of Milan remain uncoloured in Fig. 2, either because there were no newborns in that area in 2015 or because the population and the number of fertile women (women aged 15–49 years (ISTAT. *Natalità* 2022) Figure A4 in Supplementary Material) were insufficient (less than 15 and 5, respectively). They have been removed from the final dataset we have analyzed. For illustrative purposes only, we have included Figure A5 in Supplementary Materials,

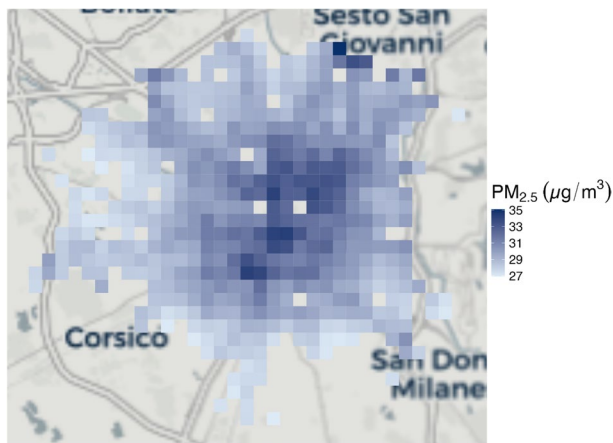


Fig. 1 Average levels of $PM_{2.5}$ concentration in each $500\text{ m} \times 500\text{ m}$ grid cells across the municipality of Milan in 2015

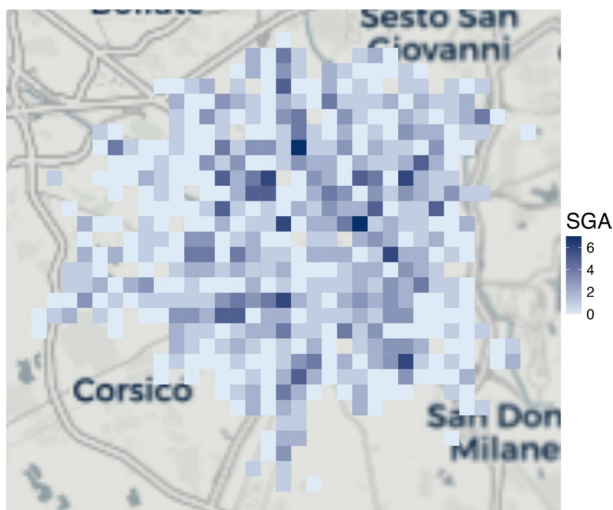


Fig. 2 Number of SGA births in each $500\text{ m} \times 500\text{ m}$ grid cell across the municipality of Milan in 2016

which displays the percentage of SGA births for each grid cell, i.e., the number of SGA births over the total number of births in each cell.

The only individual-level variable considered, maternal age, was aggregated at the areal level by computing its empirical mean within each grid cell (see Figure A6 in Supplementary Material).

To account for socioeconomic status, we consider the Italian deprivation index in 2011 (Rosano et al. 2020). The index included in the dataset, later denoted as Deprivation Index, takes values between 1 (less deprived) and 5 (the most deprived areal unit). Details on its exact definition can be found in Supplementary Material A.1.1.

To account for green areas, we compute the Normalized Difference Vegetation Index (NDVI). This index ranges from -1 to 1 . Values between -1 and 0 indicate water bodies or non-vegetated surfaces, while positive values indicate vegetated areas. Higher NDVI values correspond to denser vegetation. Details on its exact definition from raw data are in Supplementary Material A.1.2.

We also consider the average Temperature and the Road Network density in each grid cell and include them in the dataset; see Supplementary Material A.1.3–A.1.4. To account for temperature differences across various areas of Milan, we use land surface temperature data from the Landsat 8 satellite (Loveland et al. 2016). To adjust for Road Network density, we include an areal variable that quantifies the percentage of each grid square covered by major roads, highways, and extra-urban roads. Further details are provided in Supplementary Material.

Finally, we computed the Moran Index for the variables of the dataset to assess the extent of their spatial association. The full explanation and the resulting table with the Moran Index of each variable can be found in Supplementary Material A.3.

Maps for Deprivation Index, NDVI, Temperature, and Road Network density in the area of interest can be found in Supplementary Materials (Figures A7–A10).

5 The Bayesian model

To evaluate the association between exposure to $PM_{2.5}$ and the number of SGA births, we assume a binomial regression model at the areal level within the territory of Milan. The response in each area of the municipality of Milan included in the dataset is the total number of SGA births in 2016. The logit of the proportion of SGA births in each area is modeled as the linear predictor associated with fixed effects for areal covariates plus an areal random effect accounting for spatial dependency. We assume the Bayesian approach, i.e., the parameters of the regression model are random and account for a priori belief. As mentioned in the Introduction, it automatically provides uncertainty quantification of the regression parameters.

Covariate adjustments were informed by the literature, which identifies maternal age as a risk factor for SGA (Eo 2021; Palatnik et al. 2020; Desplanches et al. 2019). Accordingly, given the nature of our data, we included maternal age in the model, expressed as the mean age within each grid cell. Potential confounders in the relationship between air pollution and SGA include socioeconomic deprivation, availability of green areas (Akaraci et al. 2020), temperature, (Kloog et al. 2018; Ha et al. 2017) and road traffic (Stieb et al. 2016) For this reason we include average maternal age, Deprivation Index, NDVI, surface temperature, and road coverage percentage as continuous covariates in the model. Moreover, assuming a proper prior for the random effects, i. e. the Gaussian CAR prior, typical in the spatial framework (Harris et al. 2014), we are able to assume spatial association for the areal responses, allowing for a more flexible model. Effects are expressed as Odds Ratios (OR) of disease (from the Bayesian estimates) with the corresponding posterior Interquartile Range (IQR) of estimation. In particular, the posterior IQR is defined by two quantiles of the marginal posterior distribution of the associated parameter, and it represents a credible

interval of level 50%. See Supplementary Material A.2.2 for details on the Bayesian approach, the specific model we have fitted to the dataset, and effect specifications.

6 Results

In Milan, 11,063 babies were born in 2016, of whom 7635 remain eligible after applying the exclusion criteria described in Sect. 2.1. Descriptive statistics for the eligible population are presented in Table 1. Among these, 3,890 (50.9%) were male, and 646 (8.5%) were classified as SGA, including 354 males (9.1%) and 292 females (7.8%). The average gestational age was 39 weeks. Table 1 also presents the empirical Mean and the Inter Quartile Range (IQR) of variables aggregated within 500 m × 500 m grid cells.

Across the total area, the mean number of SGA births is 1.26, with an IQR from 0 to 2 across spatial units, and an average of 15 newborns per unit. The average maternal age is 34 years, with an IQR between 32 and 35 years, indicating a relatively narrow distribution. The Deprivation Index shows a mean value of 3.3, indicating an intermediate level of deprivation with a tendency toward moderate disadvantage. Data on pollution levels are summarized in Table 1, showing mean concentrations for 2015 of $PM_{2.5}$ (29.68 $\mu\text{g}/\text{m}^3$), PM_{10} (32.54 $\mu\text{g}/\text{m}^3$), NO_2 (54.81 $\mu\text{g}/\text{m}^3$), and NO_X (77.72 $\mu\text{g}/\text{m}^3$) in the area.

Table 2 summarizes the estimated Posterior Mean (with IQR) of the ORs and the Posterior Probability of a Positive Association for each covariate. $PM_{2.5}$ has an OR for an increment of 10 $\mu\text{g}/\text{m}^3$ of 1.153 (IQR 0.853–1.556), with a posterior probability of being larger than 1 equal to 62%. The Deprivation Index has an OR of 1.075 (IQR 1.028–1.125), with a posterior probability of being greater than 1 equal to 86%. NDVI has an OR for an increase of 0.01 of 1.007 (IQR 1.002–1.010), with

Table 1 Population—and areal-level data for the cohort of newborns born in 2016 in the city of Milan. Air pollution concentrations are from 2015, and the Deprivation Index is from 2011. Areal-level information corresponds to 500 × 500 m grid cells

Population-level information	Values (7635 newborns)
Sex, n (%)	
Male	3,890 (50.9)
Female	3,745 (49.1)
Small for Gestational Age (SGA), n (%)	
Male	354 (9.1)
Female	292 (7.8)
Gestational age (weeks), mean (IQR)	39 (38, 40)
Areal-level information	Mean (IQR)
Number of SGA	1.26 (0, 2)
Number of newborns	15 (5, 22)
Mother’s Age (years)	34 (32, 35)
Deprivation Index	3.3 (2.3, 4.2)
NO_2 Levels $\mu\text{g}/\text{m}^3$	54.81 (49.80, 59.56)
NO_X Levels $\mu\text{g}/\text{m}^3$	77.72 (68.16, 86.07)
$PM_{2.5}$ Levels $\mu\text{g}/\text{m}^3$	29.68 (28.44, 30.58)
PM_{10} Levels $\mu\text{g}/\text{m}^3$	32.54 (31.11, 33.68)
Temperature °C	21 (20.09, 21.94)
Road Coverage %	2.68 (0.00, 3.82)

Table 2 Summary of covariate effects: Bayesian point estimates (interval estimate) of the regression parameters and Bayesian estimates of a positive association between the covariates and the SGA outcome (see Section A.2.3 in Supplementary Material for more information about Posterior Mean and Probability of a positive association with the outcome)

Covariate	Posterior mean (IQR) of OR	Prob (OR > 1)
<i>PM</i> _{2.5}	1.153 (0.853, 1.556)	0.621
Mother's Age	0.995 (0.977, 1.014)	0.432
Deprivation Index	1.075 (1.028, 1.125)	0.856
NDVI	1.007 (1.002, 1.011)	0.845
Temperature	0.996 (0.969, 1.026)	0.467
Road Coverage	1.001 (0.993, 1.011)	0.563

an 85% posterior probability of being greater than 1. The mother's age shows an OR of 0.995 (IQR 0.977–1.014), with a 43% posterior probability of being greater than 1. Temperature has a mean OR of 0.996 (IQR 0.969–1.026), while Road Coverage has a mean OR of 1.001 (0.993–1.011).

7 Discussion

Our study highlights the association between air pollution, specifically *PM*_{2.5} exposure, and the number of SGA births in Milan. These findings align with existing literature suggesting that air pollution adversely affects fetal growth through mechanisms such as placental dysfunction, oxidative stress, and systemic inflammation (Ghio et al. 2012; Møller et al. 2014; Nobles et al. 2019; Zhu et al. 2022a). Given the significant health risks associated with being born SGA, including increased perinatal mortality and long-term developmental challenges, our results emphasize the need for targeted public health interventions and urban planning strategies to mitigate exposure to air pollutants.

Our data exhibit relevant spatial variability (see Figure 1 and 2 and Table A1 for the Moran's I), indicating potential differences in risk factors across the area considered. Therefore, it is crucial to quantitatively assess the association between risk factors and being born SGA.

The results presented in this paper indicate a positive association between *PM*_{2.5} and SGA births with a 15% increase in the odds of being born SGA for every 10 $\mu\text{g}/\text{m}^3$ increase in *PM*_{2.5} levels. The effect of *PM*_{2.5} on SGA throughout the entire pregnancy shows significant heterogeneity in the literature, making meta-analysis challenging (Grabowski et al. 2024). Reported effects range from approximately 2% (Chen et al. 2023, 2022; Zhu et al. 2022b), to nearly 20% (Mitku et al. 2023; Shen et al. 2022). Similarly, the Deprivation Index is strongly associated with higher SGA rates, likely reflecting the impact of socioeconomic conditions on neonatal health. These findings align with existing literature, indicating that women residing in socioeconomically disadvantaged neighborhoods face a greater risk of term low birth weight and SGA births compared to those in more affluent areas (Ashorn et al. 2023; Janevic et al. 2010).

Our analysis suggests a slightly positive association between NDVI and the number of SGA cases per area, with almost a 1% increase in the odds of being born SGA for a 0.01 increase in NDVI. The posterior probability of the regression coefficient

associated with NDVI being positive is relatively high (84%). This result contrasts with existing literature where an increase in residential greenness was statistically significantly associated with lower odds of SGA (Akaraci et al. 2020). Our different result may be explained by the spatial distribution of green areas in Milan. In particular, greener areas tend to be located on the outskirts of the city, where socioeconomic deprivation is generally higher. Consequently, the observed effect of NDVI might reflect, at least in part, the underlying pattern of deprivation, which is a well-known determinant of adverse birth outcomes such as SGA.

In the literature, the association between maternal age and SGA births exhibits a U-shaped pattern, with higher risks observed for both younger (Eo 2021) and older mothers compared to those of middle age (Eo 2021; Palatnik et al. 2020; Desplanches et al. 2019), without a clearly defined threshold of maternal age that denotes harm. In our study, average maternal age in a neighborhood was not associated with being born SGA. A possible explanation could be the narrow distribution of maternal age, with an IQR between 32 and 35 years, suggesting that our cohort primarily consisted of relatively young mothers. Moreover, the limited variability in maternal age may also be a consequence of the spatial aggregation process, as aggregating individual-level data into areal units tends to smooth out variations and reduce the overall dispersion of the variable.

In our study, we found no statistically significant association between surface temperature, Road Coverage, and being born SGA. Both the interquartile range of the odds ratio (OR) and posterior probability consistently indicate a lack of relationship with the outcome. Kloog et al. (2018) reported that lower ambient temperatures during pregnancy may increase the risk of SGA, while higher temperatures may decrease this risk among singleton term infants. Our findings align with their results, suggesting that the average temperatures observed in our study also show no association with the outcome. Similarly, Ha et al. (2017) found no consistent association between temperature and SGA.

The spatial correlation observed in the random effects confirms a spatial dependence in the SGA rates since the posterior distribution of the spatial correlation parameter ρ is shifted toward higher values (closer to 1) compared to the prior.

Although the choice of covariates was informed by the literature, we acknowledge that the available variables may not fully capture the complexity of maternal, social, and environmental determinants of SGA. Moreover, the spatial nature of the data and the lack of individual-level information (e.g., maternal smoking during pregnancy) limited the range of covariates that could be included in the model. Nevertheless, including maternal age, socioeconomic deprivation, green areas, temperature, and road traffic helped reduce potential confounding in the association between air pollution and SGA. In addition, the a priori exclusion of fragile populations—such as mothers with medical disorders during pregnancy and infants with major fetal conditions—strengthens the validity of our findings by supporting an unbiased estimate of the association observed.

Our study has several strengths, including the use of a Bayesian spatial model that accounts for geographical correlations and provides robust uncertainty quantification. Additionally, the integration of multiple environmental and socioeconomic variables allows for a comprehensive assessment of risk factors. However, some limitations

must be acknowledged. The reliance on aggregated areal data rather than individual-level exposure measures may introduce ecological bias. Nonetheless, our results, in line with previous literature, suggest that this bias is unlikely to have significantly impacted our findings.

Future research about our data in Milan should focus on refining exposure assessment methods, incorporating more granular data on maternal health behaviors, and exploring potential interactions between air pollution and socioeconomic factors. Longitudinal studies that track individuals over time could provide more conclusive evidence on the causal pathways linking air pollution to adverse birth outcomes. Additionally, investigating potential policy interventions, such as air quality regulations and urban planning strategies in Milan, could offer valuable insights into mitigating environmental risks for vulnerable populations.

8 Conclusion

Our findings suggest that air pollution in Milan, particularly $PM_{2.5}$, may contribute to an increased risk of SGA births, though further research is needed to confirm the strength and consistency of this association. Socioeconomic deprivation appears to be a significant determinant of SGA prevalence, highlighting the need for targeted public health interventions. Addressing environmental and social determinants of health in urban settings is essential for improving perinatal outcomes and reducing health inequalities.

Supplementary Information The online version contains supplementary material available at <https://doi.org/10.1007/s10651-025-00685-3>.

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Author contributions AGR, RM, and ST conceived the study and guided the epidemiological approach. SC and AG guided the methodological strategy. RM and ST contributed to the dataset preparation. SC performed the statistical analysis, processed satellite data, and managed the areal data. AGR and AG supervised the study, ensuring alignment with epidemiological and public health priorities (AGR) and providing methodological insights for the epidemiological application (AG). SC, RM, and AG drafted the manuscript, with substantial input and revisions from all authors. All authors critically reviewed and approved the final version of the manuscript.

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Data availability Data cannot be shared for ethical/privacy reasons.

Declarations

Conflict of interest The authors declare no competing interests.

Ethical approval Ethics approval and consent to participate were not required, as this is an observational study based on data routinely collected by the Agency for Health Protection (ATS) of Milan, a public body of the Regional Health Service-Lombardy Region. The ATS has among its institutional functions, established by the Lombardy Region legislation (R.L. 23/2015), the government of the care pathway at the individual level in the regional social and healthcare system, the evaluation of the services provided to, and the outcomes of, patients residing in the covered area. This study is also ethically compliant with the National Law (D.Lgs. 101/2018) and the “General Authorisation to Process Personal Data for Scientific Research Purposes” (n.8 and 9/2016, referred to in the Data Protection Authority action of 13/12/2018). Data were anonymized with a unique identifier in the different datasets before being used for the analyses.

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References

- Akaraci S, Feng X, Suesse T, Jalaludin B, Astell-Burt T (2020) A systematic review and meta- analysis of associations between green and blue spaces and birth outcomes. *Int J Environ Res Public Health* 17(8):2949
- Ashorn P, Ashorn U, Muthiani Y et al (2023) Small vulnerable newborns—big potential for impact. *Lancet* 401(10389):1692–1706
- Bell ML, Ebisu K, Belanger K (2007) Ambient air pollution and low birth weight in Connecticut and Massachusetts. *Environ Health Perspect* 115(7):1118–1124

- Besag J (1974) Spatial interaction and the statistical analysis of lattice systems. *J R Stat Soc Ser B Stat Methodol* 36(2):192–225
- Chen J, Li PH, Fan H, Li C, Zhang Y, Ju D, Deng F, Guo X, Guo L, Wu S (2022) Weekly- specific ambient fine particulate matter exposures before and during pregnancy were associated with risks of SGA and large for gestational age: results from project elephant. *Int J Epidemiol* 51(1):202–212
- Chen X, Chen S, Zhu Z, Luo J, Wang H, Wulayin M, Huang C, Zhao W, Wang Q (2023) Identifying the critical windows and joint effects of temperature and PM_{2.5} exposure on SGA. *Environ Int* 173:107832
- Coker E, Ghosh J, Jerrett M, Gomez-Rubio V, Beckerman B, Cockburn M, Liverani S, Su J, Li A, Kile ML et al (2015) Modeling spatial effects of PM_{2.5} on term low birth weight in Los Angeles county. *Environ Res* 142:354–364
- Desplanches T, Bouit C, Cottenet J, Szczepanski E, Quantin C, Fauque P, Sagot P (2019) Combined effects of increasing maternal age and nulliparity on hypertensive disorders of pregnancy and SGA. *Pregnancy Hypertens* 18:112–116
- Eo O (2021) Maternal risk factors for small-for-gestational-age newborns in Mexico: analysis of a nationwide representative cohort. *Front Public Health* 9:707078
- Ghio AJ, Carraway MS, Madden MC (2012) Composition of air pollution particles and oxidative stress in cells, tissues, and living systems. *J Toxicol Environ Health, B* 15(1):1–21
- Grabowski B, Feduniw S, Orzel A, Drab M, Modzelewski J, Pruc M, Gaca Z, Szarpak L, Rabijewski M, Baran A, Scholz A (2024) Does exposure to ambient air pollution affect gestational age and newborn weight?—A systematic review. *Healthcare* 12(12):1176
- Ha S, Zhu Y, Liu D, Sherman S, Mendola P (2017) Ambient temperature and air quality in relation to SGA and term low birthweight. *Environ Res* 155:394–400
- Harris G, Thompson WD, Fitzgerald E, Wartenberg D (2014) The association of pm_{2.5} with full term low birth weight at different spatial scales. *Environ Res* 134:427–434
- Hocquette A, Durox M, Wood R, Klungsoyr K, Szamotulska K, Berrut S, Rihs T, Kyprianou T, Sakkeus L, Lecomte A et al (2021) International versus national growth charts for identifying small and large-for-gestational age newborns: a population-based study in 15 european countries. *The Lancet Regional Health-Europe*. <https://doi.org/10.1016/j.lanepe.2021.100167>
- ISTAT. Natalità e fecondità della popolazione residente, anno 2022. URL [it/it/files/2023/10/Report-natalita-26-ottobre-2023.pdf](https://www.istat.it/it/files/2023/10/Report-natalita-26-ottobre-2023.pdf) <https://www.istat.it>
- Janevic T, Stein CR, Savitz DA, Kaufman JS, Mason SM, Herring AH (2010) Neighborhood deprivation and adverse birth outcomes among diverse ethnic groups. *Ann Epidemiol* 20(6):445–451
- Katz J, Lee AC, Kozuki N, Lawn JE, Cousens S, Blencowe H, Ezzati M, Bhutta ZA, Marchant T, Willey BA et al (2013) Mortality risk in preterm and small-for-gestational-age infants in low-income and middle-income countries: a pooled country analysis. *Lancet* 382(9890):417–425
- Kloog I, Novack L, Erez O, Just AC, Raz R (2018) Associations between ambient air temperature, low birth weight and SGA in term neonates in southern Israel. *Environ Health* 17:1–9
- Loveland TR, Irons JR (2016) Landsat 8: The plans, the reality, and the legacy. *Remote Sensing of Environment* 185:1–6. <https://doi.org/10.1016/j.rse.2016.07.033>
- Li L, Laurent O, Wu J (2016) Spatial variability of the effect of air pollution on term birth weight: evaluating influential factors using Bayesian hierarchical models. *Environ Health* 15:1–12
- Liu Y, Xu J, Chen D, Sun P, Ma X (2019a) The association between air pollution and preterm birth and low birth weight in Guangdong, China. *BMC Public Health* 19:1–10
- Liu Q, Yang H, Sun X, Li G (2019b) Risk factors and complications of SGA. *Pak J Med Sci* 35(5):1199
- Mitku AA, Zewotir T, North D, Jeena P, Asharam K, Muttoo S, Naidoo RN (2020) The spatial modification of the non-linear effects of ambient oxides of nitrogen during pregnancy on birthweight in a south African birth cohort. *Environ Res* 183:109239
- Mitku AA, Zewotir T, North D, Jeena P, Asharam K, Muttoo S, Tularam H, Naidoo RN (2023) Impact of ambient air pollution exposure during pregnancy on adverse birth outcomes: generalized structural equation modeling approach. *BMC Public Health* 23(1):45
- Møller P, Danielsens PH, Karottki DG, Jantzen K, Roursgaard M, Klingberg H, Jensen DM, Christophersen DV, Hemmingsen JG, Cao Y et al (2014) Oxidative stress and inflammation generated DNA damage by exposure to air pollution particles. *Mutation Research/reviews in Mutation Research* 762:133–166
- Ngwira A (2019) Spatial quantile regression with application to high and low child birth weight in Malawi. *BMC Public Health* 19:1–11

- Nobles CJ, Grantz KL, Liu D, Williams A, Ouidir M, Seeni I, Sherman S, Mendola P (2019) Ambient air pollution and fetal growth restriction: physician diagnosis of fetal growth restriction versus population-based small-for-gestational age. *Sci Total Environ* 650:2641–2647
- Ochiai M, Nakayama H, Sato K, Iida K, Hikino S, Ohga S, Tsukimori K, Wake N, Masumoto K, Taguchi T et al (2008) Head circumference and long-term outcome in small-for-gestational age infants. *J Perinat Med* 36(4):341–347
- Palatnik A, De Cicco S, Zhang L, Simpson P, Hibbard J, Egede LE (2020) The association between advanced maternal age and diagnosis of SGA. *Am J Perinatol* 37(01):037–043
- Pedersen M, Giorgis-Allemand L, Bernard C, Aguilera I, Andersen AMN, Ballester F, Beelen RM, Chatzi L, Cirach M, Danileviciute A et al (2013) Ambient air pollution and low birthweight: a European cohort study (escape). *Lancet Respir Med* 1(9):695–704
- Proietti E, Röööls M, Frey U, Latzin P (2013) Air pollution during pregnancy and neonatal outcome: a review. *J Aerosol Med Pulm Drug Deliv* 26(1):9–23
- Risnes KR, Vatten LJ, Baker JL, Jameson K, Sovio U, Kajantie E, Osler M, Morley R, Jokela M, Painter RC et al (2011) Birthweight and mortality in adulthood: a systematic review and meta-analysis. *Int J Epidemiol* 40(3):647–661
- Rosano A, Pacelli B, Zengarini N, Costa G, Cislighi C, Caranci N (2020) Update and review of the 2011 Italian deprivation index calculated at the census section level. *Epidemiol Prev* 44(2–3):162–170
- Shen Y, Wang C, Yu G, Meng X, Wang W, Kan H, Zhang J, Cai J (2022) Associations of ambient fine particulate matter and its chemical constituents with birth weight for gestational age in China: a nationwide survey. *Environ Sci Technol* 56(12):8406–8415
- Shim YS, Park HK, Yang S, Hwang IT (2013) Age at menarche and adult height in girls born SGA. *Ann Pediatr Endocrinol Metab* 18(2):76
- Song I, Kim OJ, Choe SA, Kim SY (2020) Spatial heterogeneity in the association between particulate matter air pollution and low birth weight in South Korea. *Environ Res* 191:110096
- Spada E, Peila C, Coscia A (2024) Italian neonatal birthweight charts derived from infants not separated by birth order. *Ital J Pediatr* 50(1):89
- Stieb DM, Chen L, Hystad P, Beckerman BS, Jerrett M, Tjepkema M et al (2016) A national study of the association between traffic-related air pollution and adverse pregnancy outcomes in Canada, 1999–2008. *Environ Res* 148:513–526
- Tu J, Tu W, Tedders SH (2016) Spatial variations in the associations of term birth weight with ambient air pollution in Georgia, USA. *Environ Int* 92:146–156
- Tunesi S, Bergamaschi W, Russo AG (2024) Estimated number of deaths attributable to NO_2 , PM_{10} , and $PM_{2.5}$ pollution in the municipality of Milan in 2019. *Epidemiol Prev* 48(1):12–23
- World Health Organization (2006) In WHO child growth standards: length/height-for-age, weight-for-age, weight-for-length, weight-for-height and body mass index-for-age: methods and development. *Acta Paediatr* 95:76–85
- Zhao H, Zhang X, Wang W, Shi J, Lai W, Li Y, Zhang C, Guo L, Gong J, Li L et al (2023) Global, regional, and national burden of ambient and household $PM_{2.5}$ -related neonatal disorders, 1990–2019. *Ecotoxicol Environ Saf* 252:114560
- Zhong X, Zheng Y, Peng W, Huang Y, Wang L, Xia C et al (2025) Associations of prenatal exposure to fine particulate matter and its constituents with SGA risk: A twin study in China. *Ecotoxicol Environ Saf* 293:118001
- Zhu Z, Hu H, Benmarhnia T, Ren Z, Luo J, Zhao W et al (2022a) Gestational $PM_{2.5}$ exposure may increase the risk of SGA through maternal blood pressure and hemoglobin: a mediation analysis based on a prospective cohort in China, 2014–2018. *Ecotoxicol Environ Saf* 242:113836
- Zhu Z, Hu H, Benmarhnia T, Ren Z, Luo J, Zhao W, Chen S, Wu K, Zhang X, Wang L et al (2022b) Gestational $PM_{2.5}$ exposure may increase the risk of SGA through maternal blood pressure and hemoglobin: a mediation analysis based on a prospective cohort in China, 2014–2018. *Ecotoxicol Environ Saf* 242:113836

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