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Ambient air pollution, urban green space and childhood overweight and obesity: A health impact assessment for Barcelona, Spain

Huyen Nguyen Thi Khanh [a,1], Mariona Rigau-Sabadell [b,1], Sasha Khomenko [b,c,d], Evelise Pereira Barboza [b,c,d], Marta Cirach [b,c,d], Talita Duarte-Salles [e,f], Mark Nieuwenhuijsen [b,c,d], Martine Vrijheid [b,c,d], Natalie Mueller [b,c,2], Jeroen de Bont [a,2,*]

[a] *Institute of Environmental Medicine, Karolinska Institutet, Stockholm, Sweden*
[b] *Pompeu Fabra University, Barcelona, Spain*
[c] *Institute for Global Health, Barcelona, Spain*
[d] *CIBER Epidemiología y Salud Pública (CIBERESP), Madrid, Spain*
[e] *Fundació Institut Universitari per a la Recerca a l'Atenció Primària de Salut Jordi Gol i Gurina (IDIAPJGol), Barcelona, Spain*
[f] *Department of Medical Informatics, Erasmus University Medical Centre, Rotterdam, the Netherlands*

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ABSTRACT

Background: The burden of childhood overweight and obesity attributable to ambient air pollution and a lack of urban green spaces (UGS) remains unknown. This study aimed to estimate the attributable cases of childhood overweight and obesity due to air pollution and insufficient UGS exposure in Barcelona, Spain.

Methods: We applied a quantitative health impact assessment approach. We collected childhood overweight and obesity prevalence levels and exposure data from 69 spatial basic health zones in Barcelona. We estimated particulate matter ($PM_{2.5}$) and nitrogen dioxide (NO_2) levels using land use regression models, normalized difference vegetation index (NDVI) levels using remote sensing and percentage of green area (%GA) using land use. We estimated relative risks, population attributable fractions, and preventable overweight/obesity cases in children under following scenarios: Compliance of World Health Organization (WHO) air quality guidelines (AQGs) for (1) $PM_{2.5}$ and (2) NO_2; achieving (3) city-target NDVI levels and (4) 25% green area (%GA) recommendations. The analyses were stratified by socioeconomic deprivation index (in quintiles). Uncertainty was quantified using Monte Carlos simulations.

Results: Compliance of WHO AQGs could prevent 0.4% [253 (95%CI, −604; 1086)] and 4.2% [3000 (95%CI, 1009; 4943)] of childhood overweight/obesity cases due to excess $PM_{2.5}$ and NO_2 levels in Barcelona, respectively. Compliance of NDVI and %GA targeted levels could prevent 6% [4094 (95%CI, 1698; 6379)] and 10% [6853 (95%CI, 1440; 12779)] of childhood overweight/obesity cases respectively. The preventable burdens of childhood overweight/obesity cases were slightly higher in middle-class socioeconomic areas due to the higher adverse exposure levels at baseline (high air pollution, less UGS).

Discussion: Compliance with WHO AQGs and achieving UGS targets can reduce childhood overweight and obesity levels in Barcelona, and potentially in other locations as well. This underscores the need for policies that foster healthier urban environments of high environmental quality in order to protect child health.

1. Introduction

Cities worldwide already host 55% of the world's population, and this share is expected to increase to almost 70% by 2050 (Canton, 2021). Urban environments have become hotspots of pollution, such as ambient air pollution and the loss of natural environments, such as green spaces. Ambient air pollution is considered the most harmful environmental risk factor for mortality (World Health Organization, 2021a) and is a determinant of numerous diseases, including cardiovascular and respiratory diseases, cancer, and metabolic diseases, among others (Al-Kindi

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* Corresponding author. Institute of Environmental Medicine, Karolinska Institutet, SE-17177 Stockholm, Sweden.
E-mail address: jeroen.de.bont@ki.se (J. de Bont).

[1] Shared first authorship.

[2] Shared last authorship.

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et al., 2020; Dominski et al., 2021). Overweight and obesity in children continue to be major global public health concerns, affecting 18% of children between the ages of 5 and 19 years (World Health Organization, 2020). Spain is among the countries with the highest prevalence levels of obesity and overweight in Europe, with roughly 18% and 39% of children between the ages of 6 and 9 years having these conditions, respectively (de Bont et al., 2022; World Health Organization, 2021a). Childhood overweight and obesity are further linked with multiple chronic disease outcomes in later life, including type 2 diabetes, cardiovascular diseases, cancer, stroke, and mental health disorders, and also link to premature mortality (Bleich et al., 2018; World Health Organization, 2020).

Exposure to green space in urban environments (hereafter referred to as urban green space, or UGS) has been associated with positive effects on health and well-being, including metabolic health and weight status in children (Grant et al., 2019; Patwary et al., 2024; World Health Organization, 2017). UGS likely serves as a proxy for various health pathways linked to improved child health outcomes, such as providing a safe, natural environment where children can engage in independent play, play with peers, socialize, and participate in physical activity—factors that have all been associated with lower rates of childhood obesity (Lee et al., 2015; Pachucki, Mark C, & Goodman, 2015). Additionally, UGS exposure has been shown to influence perceptions about healthy diets. A quasi-experimental study, found that participants who regularly walked in parks and green environments consumed healthier foods compared to those who walked in urban settings (Langlois and Chandon, 2024). Furthermore, greener areas are linked to less traffic and reduced levels of air (and noise) pollution (Lee et al., 2015).

There is a growing body of evidence that independently links increased levels of ambient air (and noise) pollution in cities to increased overweight and obesity in children and adolescents (Bloemsma et al., 2019; Cai et al., 2020; de Bont et al., 2021; Malacarne et al., 2022; Niu et al., 2022; Seo et al., 2020). While the exact mechanisms connecting air pollution to childhood overweight and obesity remain unclear, research from animal studies and epidemiological data suggests that air pollution contributes to oxidative stress and inflammation in fat tissue, which increases the risk of obesity in children (An et al., 2018). Moreover, exposure to air pollution has been linked to issues such as sleep disturbances, depression, and anxiety, all of which are associated with weight gain (Parasin et al., 2021).

Furthermore, lower socioeconomic status (SES) and higher levels of deprivation have consistently been associated with increased rates of overweight and obesity in Europe (De Bont et al., 2020; Moreno, 2011). However, in Europe, lower SES populations are not always more adversely exposed in terms of environmental exposures (e.g. high air pollution and little UGS) than more affluent populations. European cities such as Vienna (Khomenko et al., 2020), Barcelona, or Madrid (Iungman et al., 2021), often exhibit different spatial dynamics compared to North American cities, where social segregation is more pronounced. In European cities, SES strata are more spatially mixed, and lower SES populations tend to live either in more peripheral, less well-connected but less polluted areas, or more centric, in heavily trafficked areas where they may be exposed to higher levels of pollution (Hajat, Hsia, & O'Neill, 2015; Iungman et al., 2021; Khomenko et al., 2020). The effects of ambient air pollution and UGS on childhood overweight and obesity in urban settings, and across different SES groups, have been understudied. A study in Catalonia, Spain, which included both urban and rural areas, found that air pollution levels were similar in the most and least deprived areas. However, the association between air pollution and childhood obesity was stronger for children living in the most deprived areas (de Bont et al., 2021).

Reducing levels of ambient air pollution and increasing UGS in cities could be effective prevention measures to reduce the prevalence of overweight and obesity in children (and later adulthood) and associated adverse health consequences. Moreover, children are a particularly vulnerable population as they are dependent on others to care for and protect them, which emphasizes the need for public policies that create safe and healthy environments for children, and this is irrespective of socioeconomic background. But also, protecting particularly socio-economically vulnerable children is important to reduce health and socio-economic inequities.

Previous studies have primarily focused on the epidemiological associations between air pollution, UGS, and childhood overweight and obesity, but have not evaluated the attributable burden of overweight and obesity under real-world exposure levels, nor the distribution of these exposures among the child population — both of which are crucial for policymakers in defining targeted interventions. To better understand the magnitude of the impact of air pollution and lack of UGS on childhood overweight and obesity in Barcelona, Spain, we aimed to estimate the attributable burden of childhood overweight and obesity due to high levels of air pollution and insufficient UGS exposure in the city. Furthermore, we assessed the role of socioeconomic deprivation in the associations between air pollution, UGS exposure, and childhood overweight and obesity by estimating the spatial distribution of exposures and attributable cases across different levels of deprivation.

We are conducting this health impact assessment (HIA) study with the understanding that cities need local insight into their specific problems, including where these issues are most prevalent and who is most adversely affected (e.g., by socioeconomic vulnerability) in order to define targeted policies to improve the situation. Although this study is specific to Barcelona, the findings provide broader implications for other cities, offering insights into the links between urban design, the environment, and health, as well as ideas for defining health-promoting environmental policies aimed at improving child health outcomes.

2. Material and methods

We applied a quantitative health impact assessment (HIA) framework to estimate attributable childhood overweight and obesity cases due to excess ambient air pollution, including particulate matter <2.5 μm ($PM_{2.5}$) and nitrogen dioxide (NO_2) levels, and lack of UGS, focusing on the normalized difference vegetation index (NDVI) and the percentage of green area (%GA), in Barcelona, Spain. Our unit of analysis was the 69 basic health zones (i.e., Àrea Bàsica Sanitaria (ABS) in Catalan) for the year 2015, which serve as the basic territorial units through which primary health care is organized and provided to the population of Barcelona (Department of health, 2006), and for which childhood overweight and obesity data were available. Barcelona is an area known to have high levels of childhood obesity with approximately 33% of children are overweight and 12% are obese (De Bont et al., 2019). All analyses were performed using statistical software R 4.1.2 and QGIS software v3.16.

2.1. Child population, overweight and obesity

We obtained data on the childhood population from the Catalan Statistics Institute, which includes 218,976 children between the ages of 2 and 17 years, as well as the number of children at the ABS level for Barcelona (Catalan Statistics Institute, 2016). We did not include data for children under the age of 2 years, as it is not recommended to classify children as overweight or obese before that age (Kumar and Kelly, 2017). We further obtained data on childhood overweight and obesity levels from the Information System for Research in Primary Care (SIDIAP) (Recalde et al., 2022). SIDIAP is a large de-identified electronic health record database with longitudinal data collected since 2006, it covers up to 75% of the total population living in Catalonia that are assigned to a primary health care. Choosing the ABS as our unit of analysis had to do with the fact that the ABS accommodate the primary health care centres the SIDIAP database corresponds to. Lower spatial units were not feasible due to confidentiality and privacy concerns.

From SIDIAP, we obtained height and weight measurements for children aged 2–17 years old, recorded between 2008 and 2017in primary care centres in Barcelona (De Bont, Márquez, et al., 2021). We only included individuals with at least one height and weight record available (SIDIAP, 2014). In Spain, height and weight are routinely-measured by paediatricians in the primary health care centres (Recalde et al., 2022). We chose 2015 as our temporal unit of analysis since this was the year used by SIDIAP to link children to their ABS in our study.

We estimated overweight and obesity prevalence using the body mass index (BMI; calculated as weight in kilograms divided by height in meters squared) from the collected height and body weight measures. Then, we calculated age- and sex-specific BMI z-scores using the WHO growth standard and growth reference and we classified children into overweight including obesity, hereafter written as overweight/obesity (for children below 5 years old zBMI $> +2$SD and $\leq +3$SD, and above 5 years between $> +1$SD and $\leq +2$SD), and obesity categories (for children below 5 years old zBMI $>$ 3SD, and above 5 years zBMI $> +2$SD) (World Health Organization, 2017). We estimated the standardized prevalence rates of childhood overweight/obesity and obesity per 100 children for each of the 69 ABS in Barcelona for three age groups: 2–5 years, 6–11 years, and 12–17 years. If a child had multiple height and weight measurements within the same age group, the unhealthiest BMI z-score measurement was chosen to identify children who are at most risk and to avoid underestimating the prevalence of overweight and obesity. The estimated childhood overweight/obesity and obesity prevalence levels for the three age groups were used as underlying background rates in the HIA framework.

2.2. Air pollution and green space exposure assessment

We derived annual air pollution baseline data for $PM_{2.5}$ and NO_2 from land use regression (LUR) models developed at a 100 × 100m grid cell scale for 2010 as part of the of the Effects of Low-Level Air Pollution: a Study in Europe (ELAPSE) project (De Hoogh et al., 2018). Briefly, the models were based on airbase routine monitoring data, and incorporated chemical transport model estimates, satellite derived data, plus a range of other predictor variables (i.e., roads, land use, altitude). The LUR models explained 72% and 59% of the spatial variation in the measured concentration for $PM_{2.5}$ and NO_2, respectively (Strak et al., 2021). Briefly, this method estimated the concentration ratio between year 2015 and the model reference year (2010). Then this ratio is applied to the spatial component (LUR Exposure). The time-series air pollution data for 2010–2015 were obtained using a representative background monitoring station from the XVPCA (Department of Climate Action, 2024) to estimate annual mean air pollution levels at the ABS level, we estimated the average concentration of all grid cells falling within each ABS area.

We estimated two proxies of baseline UGS exposure at ABS level (Barboza et al., 2021). First, we estimated NDVI levels, which represent the amount of surrounding greenness (i.e., street trees, green corridors, and general vegetation in public and private spaces). NDVI levels were obtained for each 250mx250m grid using the Terra Moderate Resolution Imaging Spectroradiometer (MODIS) Vegetation Indices (MOD13Q1) obtained from US Geological Survey (Barboza et al., 2021) and generated every 16 days (Brown, 2018). NDVI levels range from -1 to 1, with positive and higher values indicating more greenery. Negative values were set to zero, as they correspond to waterbodies. We averaged the estimated NDVI values of all 250mx250m grid cells that fell within each ABS to obtain NDVI levels at the ABS level.

Second, the %GA was calculated as the percentage of land area covered by green land use within an ABS, derived from land cover maps available in CORINE Land Cover 2012; European Environment Agency (2000). The land use categories chosen in CORINE were those describing UGS generally accessible to the public (i.e., parks, plazas, public gardens) (Barboza et al., 2021; Husqvarna-Group, 2020). Based on its native resolution, CORINE 2012 might represent any land use feature greater than 0.5 ha in urban areas. To obtain %GA at the ABS level, we averaged the %GA within each ABS (Barboza et al., 2021; Jia, 2021; Siljeg et al., 2020). For both NDVI and %GS we added an extra 300-m buffer to the ABS to account for surrounding greenness, as done by previous studies (Barboza et al., 2021).

2.3. Deprivation data

We extracted a deprivation index designed by the Catalan regional government to determine resource allocation needs within the ABS, as an indicator for socioeconomic status (SES) (Catalan Statistics Institute, 2016). The index is composed of the following variables: percentage of population with manual jobs, percentage of population with an insufficient level of education, premature mortality rate (<75 years), rate of avoidable hospitalizations (for pathologies associated with deprivation), percentage of the population exempt from pharmaceutical co-payment, percentage of the population with a brutto income below 18,000 euros per year, percentage of population with a bruto income of more than 100,000 euros per year, percentage of unemployed/inactive population, percentage of foreign population coming from low income countries, and percentage of elderly people living alone (Catalan Statistics Institute, 2016). We classified the deprivation index into quintiles, where quintile one (Q1) and quintile five (Q5) represents the least deprived and the most deprived ABS, respectively.

2.4. HIA framework and counterfactual scenarios

As done in previous work (Mueller et al., 2017), we followed the comparative risk assessment framework and estimated the preventable childhood overweight/obesity and obesity burden under compliance with following counterfactual exposure scenarios.

Scenario 1. Compliance with the recommended 5 $\mu g/m^3$ annual mean for $PM_{2.5}$ based on the 2021 World Health Organization (WHO) air quality guidelines (AQGs) (World Health Organization, 2021b);

Scenario 2. Compliance with the recommended 10 $\mu g/m^3$ annual mean for NO_2 based on the 2021 WHO AQGs (World Health Organization, 2021b);

Scenario 3. Compliance with the Barcelona city-target NDVI level of 0.3111 (95% CI: 0.301–0.321) based on the city-specific translation of the WHO 300m distance to nearest greenspaces recommendation into NDVI by a previous, large-scale European city study (Barboza et al., 2021);

Scenario 4. Compliance with the evidence-based recommendation of 25% equally-distributed green land use (%GA), based on the translation of the WHO 300m distance to nearest greenspaces recommendation into %GA (Khomenko et al., 2020; Konijnendijk, 2023; Mueller et al., 2017, 2018)

Detailed information of counterfactual exposure scenarios are presented in Table S1. We present our risk assessment framework in Fig. S1. We obtained exposure-response function (Zheng et al., 2023) from meta-analyses quantifying the associations between air pollution, UGS and childhood overweight and obesity in children and adolescents aged 2–17 years, respectively. For air pollution, we obtained odds ratio (OR) from a recent meta-analysis by Zheng et al. (2023). The ORs from Zheng et al. showed OR 1.18 (1.10; 1.28) per 10 $\mu g/m^3$ $PM_{2.5}$ and OR 1.12 (1.05; 1.19) per 10 $\mu g/m^3$ NO_2. However, we observed that included studies from Europe were limited, inconsistent and mainly cross-sectional compared to those conducted in Asia. Thus, we decided that the risk estimates provided by Zheng et al. were unsuitable for HIA pruposes in European city contexts. To overcome this, we conducted a meta-analysis that included only the European studies both cross-sectional and longitudinal studies included in Zheng et al.'s systematic review (Zheng et al., 2023). Given that until now the evidence has been limited and inconsistent, we believe it is important to include as many relevant European studies as possible, as this approach offers a more robust and comprehensive understanding of the association, rather than establishing one cross-sectional exposure-response association for Barcelona city. We did not find any new European studies published in PubMed between August 9, 2023 and June 30, 2024. With our meta-analysis of exclusively European studies, we obtained a OR 1.006 per 10 μg/m³ $PM_{2.5}$ (0.972; 1.042) and OR 1.013 per 10 μg/m³ NO_2 [0.999; 1.027] (Fig. 1) that were used in our subsequent HIA analysis. The meta-analytical effect estimate was mostly driven by a longitudinal study conducted in the Catalunya wider Barcelona region, including children of Barcelona city (de Bont et al., 2021).

For NDVI we obtained a OR 0.91 per 0.1 NDVI [95% CI: 0.84, 0.98] from a meta-analysis of mostly European studies (Ye et al., 2022). The ERF for %GA was obtained from a cohort study in the Netherlands for overweight including obesity and was relative risk (RR) 0.86 per 29% GA [95% CI 0.71–1.03] (Bloemsma et al., 2019). The meta-analyses conducted for air pollution and NDVI did not distinguish between the effects of these exposures on overweight (including obesity) and on obesity specifically. In addition, a previous study conducted in Catalonia (de Bont et al., 2021) observed almost identical hazard ratios (HR) when evaluating the associations between air pollution and overweight (including obesity) and those children who developed obesity. Consequently, we applied the same ERF when calculating attributable cases for both the overweight/obesity and obesity categories.

Using the ERFs, we scaled ORs to each exposure level difference at the ABS level, resulting from the comparison of the baseline situation with the counterfactual scenario. Next, at the ABS level, we calculated population attributable fractions (PAFs) for each exposure level difference, and finally, we multiplied the PAF by the baseline overweight/obesity and obesity cases to calculate the cases attributable to the current noncompliance of recommended exposure levels. We further stratified the estimated attributable cases of childhood overweight and obesity by age groups (2–5 years, 6–11 years, and 12–17 years) and deprivation index (i.e. quintiles).

Assuming the same validity of ERFs across different population groups with varying vulnerabilities (e.g., by SES, sex, age, co-morbidities, etc.) is a general limitation in HIA studies. Therefore, as sensitivity analyses, we obtained stratified ERFs to quantify the preventable childhood overweight/obesity and obesity burden due to excess air pollution exposure using socioeconomic deprivation-specific ERFs, obtained from a study conducted in Catalonia (Spain) (de Bont et al., 2021). This study classified the deprivation index in tertiles rather than quintiles, as in our study, where tertile one (T1) represents the least deprived and tertile three (T3) represents the most deprived. This study showed that children from more deprived communities had a higher risk of developing overweight/obesity due to NO_2 exposure (HR 1.07 [95% CI,1.05–1.08]), compared to children from less deprived communities (HR 0.99 [95% CI, 0.98–1.00]). There were no differences in effect estimates for $PM_{2.5}$ by levels of deprivation (Table S2). We did not present this sensitivity analysis as our primary result because the results were based on a single study, and generally, (stratified) ERFs derived from meta-analyses are preferred. Additionally, there were no stratified ERFs for UGS exposure (i.e., ERFs are $PM_{2.5}$ and NO_2-specific).

2.5. *Estimating confidence intervals – uncertainty analysis*

To estimate our confidence intervals, we accounted for several uncertainty distribution of the parameters included in the HIA analyses such as ABS-specific overweight and obesity levels, ABS population age structures, error from the air pollution and UGS models and the confidence intervals of the ERFs. For overweight and obesity levels we considered the standard deviation of yearly prevalence levels between 2008 and 2018. For age structure we considered the proportion of population in each age group (2–5, 6–11 and 12–17) among ABS included in the analyses. For the air pollution models we considered the Root Mean Square Error of the ELAPSE PM2.5 and NO2 models, and for the UGS we considered the reported standard deviation ± 0.02 for the NDVI estimations (Khomenko et al., 2021; Mumah et al., 2020). We considered the reported confidence intervals of the ERF assuming log-normal distribution. Finally, To account for the uncertainty in our exposure, risk estimates, and health outcome data, we applied Monte Carlo simulations to obtain point estimates and confidence intervals (CIs). We applied 500 repetitions to obtain a point estimate (by the mean) and the confidence interval (using the 2.5th and 97.5th percentiles). For each iteration, we randomly sampled values for each parameter from their respective uncertainty distributions and recalculated the HIA each time. This process yielded a distribution of results from which we derived our estimates (Mangla et al., 2014). The number of Monte Carlo replications was chosen considering the optimal balance between computational time and representative sampling results.

3. Results

In Barcelona, the overall prevalence of overweight/obesity and obesity in children between 2 and 17 years was 32.7% and 11.9%, respectively (Table 1). The highest baseline prevalence was observed between the ages of 6 and 11 years (42.3% overweight/obesity and 26% obesity), and in the most socioeconomically deprived population group (Q5) (38.3% overweight/obesity and 16.4% obesity) (Table S3). The highest and lowest prevalence of overweight/obesity and obesity levels were observed in the Northern and Western areas of the city, respectively (Fig-2A).

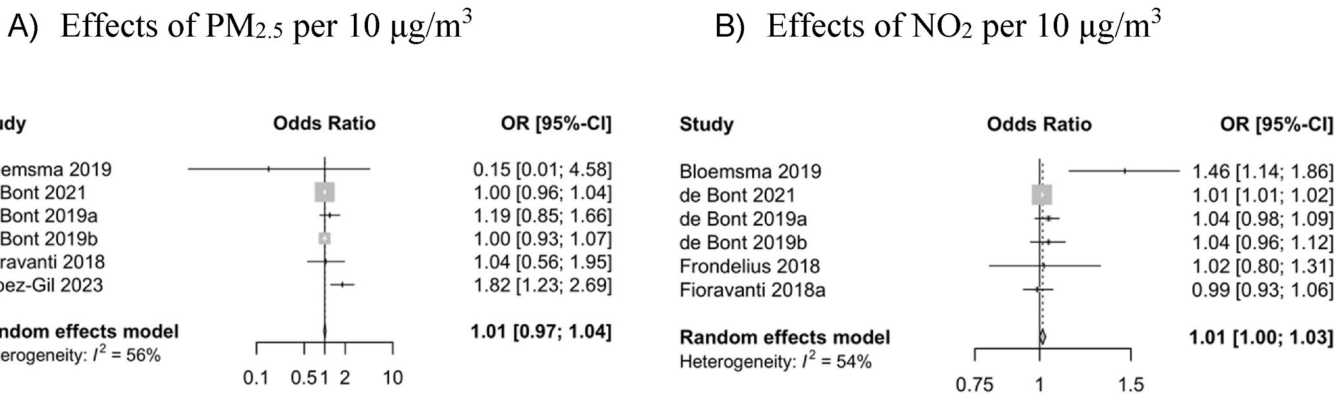

Fig. 1. Meta-analyses of the association between $PM_{2.5}$ (A) and NO_2 (B) on the risk of overweight in children and adolescents using only European studies from the Zheng et al. meta-analysis and using random effects model.

Table 1
Percentage and number of expected overweight/obesity and obesity cases preventable under compliance of air pollution and urban green spaces exposure level recommendations.

Counterfactual scenario	Exposure level threshold under counterfactual scenario	Overweight/obesity			Obesity		
		Baseline prevalence	Preventable overweight/obesity cases	PAF (%)	Baseline prevalence	Preventable obesity cases	PAF (%)
		N (%)	N (95% CI)		N (%)	N (95% CI)	
Scenario 1- WHO AQGs 2021	$PM_{2.5}$: 5 μg/m^3	71,603 (32.7%)	253 (−604; 1086)	0.4	26,222 (11.9%)	91 (−236; 436)	0.3
Scenario 2 - WHO AQGs 2021	NO_2: 10 μg/m^3		3000 (1009; 4943)	4.2		1097 (309; 1883)	4.2
Scenario 3 - NDVI	NDVI: 0.311		4094 (1698; 6379)	5.7		1470 (623; 2442)	5.6
Scenario 4 - %GA	%GA: 25%		6853 (1440; 12,779)	9.5		2467 (290; 4668)	9.4

Footnote: AQGs: air quality guidelines; CI: Confidence Interval; NDVI: Normalized Difference Vegetation Index; PAF: population attributable fractions; NO_2: nitrogen dioxide; $PM_{2.5}$: particulate matter less than 2.5 μm of diameter; WHO: World Health Organization; %GA: percentage of green spaces.

3.1. Scenario 1: $PM_{2.5}$

In 2015, $PM_{2.5}$ annual city-average was 14.9 μg/m^3 (range: 11.4–16.3 μg/m^3) (Fig. 2B). The highest levels of $PM_{2.5}$ were observed in the North-Central parts of the city, while the lowest levels in the South-Western parts. For scenario 1, under WHO AQG compliance for $PM_{2.5}$ levels, we estimated that 253 (95%CI, −604; 1086) overweight/obesity cases (0.4%) and 91 (95%CI, −236, 436) obesity cases (0.3%) were preventable (Table 1). The highest absolute numbers of preventable cases of overweight/obesity (136 [95% CI, −530; 807]) and obesity (60 [95% CI, −248; 345]) were found in the age group 6–11 years (Table S4).

3.2. Scenario 2: NO_2

In 2015, NO_2 annual city-average was 42.4 μg/m^3 (range: 28.1–56.1 μg/m^3) (Fig. 2B). The highest levels of NO_2 were observed in the northern parts of the city, while the lowest levels were found in the western parts. For scenario 2, under WHO AQG compliance for NO_2 levels, we estimated that 3000 (95%CI, 1009; 4943) overweight/obesity cases (4.2%) and 1097 (95%CI, 309; 1883) obesity cases (4.2%) were preventable (Table 1). The highest absolute numbers of preventable cases were found in the age group 6–11 years, with 1521 (95% CI, 5; 3092) cases of overweight/obesity and 636 (95% CI, −73; 1278) cases of obesity (Table S4).

3.3. Scenario 3: NDVI

In 2015, the city average NDVI level was 0.27 (range:0.16–0.68) (Fig. 2C). The highest NDVI levels were observed in the Western parts of the city, while the lowest levels in the city centre. For scenario 3, under compliance of city-target NDVI levels (i.e. 0.3111 NDVI), we estimated that 4094 (95%CI, 1698; 6379) overweight/obesity cases (5.7%) and 1470 (95%CI, 623; 2442) obesity cases (5.6%) were preventable (Table 1). The highest absolute numbers of preventable cases of overweight/obesity and obesity were found in the age group 6–11 years, with 2036 (95% CI, 338; 3972) and 815 (95% CI, 133; 1571) preventable cases, respectively (Table S4).

3.4. Scenario 4: %GA

In 2015, the city-average %GA was 17.6% (range: 0.0–79.8%) (Fig. 2C). Similar to NDVI, the highest %GA levels were observed in the Western parts of the city, while the lowest levels in city centre. For scenario 4, under compliance of targeted %GA levels, we estimated that 6853 (95%CI, 1440; 12779) overweight/obesity cases (9.6%) and 2467 (95%CI, 290; 4668) obesity cases (9.4%) were preventable (Table 1). The highest absolute numbers of preventable cases of overweight/obesity and obesity were found in the age group 6–11 years, with 3481 (95% CI, 371; 7568) and 1371 (95% CI, 365; 3296) preventable cases, respectively (Table S4).

3.5. Deprivation index in quintiles

At baseline, we observed the highest overweight/obesity and obesity attributable levels (38.3% and 16.5%, respectively) in the most deprived areas (Q5) and lowest prevalence levels (25.8% and 7.9%, respectively) in the least deprived areas (Q1) (Table 2). We observed that air pollution and UGS levels were the highest and the lowest, respectively, in the third quintile of deprivation (Q3) (i.e., $PM_{2.5}$ 15.4 μg/m^3, NO_2 45.4 μg/m^3, NDVI 0.3, %GA 4.4). Air pollution and NDVI exposure were quite similar in Q1 (least deprived) and Q5 (most deprived) ($PM_{2.5}$ 14.4 vs 14.8 μg/m^3, NO_2 41.0 vs 41.4 μg/m^3, NDVI 0.3 vs 0.3, respectively), except for %GA that was lower in Q1 (%GA 11.7) compared to Q5 (%GA 16.5).

We estimated the most preventable cases (in %) of overweight/obesity and obesity under recommended exposure level compliance (Scenario 1–4) in Q3. The least and most deprived areas (Q1 and Q5) had similar preventable cases (due to similar exposure levels), except for %GA where the %GA levels were lower in the least deprived areas (Q1) and more cases were preventable there compared to the most deprived areas (Q5). When accounting for the stratified ERF by levels of deprivation in tertiles, we estimated the most preventable cases (12.5%) of overweight/obesity and obesity under the recommended exposure level for NO_2 in the most deprived areas (T3) (Table 3).

4. Discussion

To our knowledge, this is the first HIA study estimating the burden of childhood overweight and obesity due to excess levels of air pollution and lack of UGS. Our findings indicate that 0.4% and 4.2% of childhood overweight/obesity cases could be prevented if Barcelona met the WHO AQGs for $PM_{2.5}$ and NO_2, respectively. Furthermore, adherence to target levels for NDVI and %GA could prevent 5.7% and 9.6% of childhood overweight/obesity cases, respectively. Although the most deprived areas showed higher baseline levels of childhood obesity, the exposure levels to air pollution and UGS were quite similar between the least and most deprived areas. The preventable burdens of childhood overweight/obesity and obesity due to non-compliance with WHO AQGs and UGS target levels were slightly higher in middle-class socioeconomic ABS (Q3), attributable to the higher adverse exposure levels at baseline (i.e., higher air pollution and lower UGS levels). However, when applying stratified effect response functions (ERFs) for air pollution, we observed that the most preventable cases were estimated for the most deprived areas.

Previous HIA studies have demonstrated the effect of environmental exposure levels and urban policies on premature mortality, cancer, stroke, diabetes, respiratory diseases, including asthma, and mental health (Brønnum-Hansen et al., 2018; Khomenko et al., 2021; Mueller

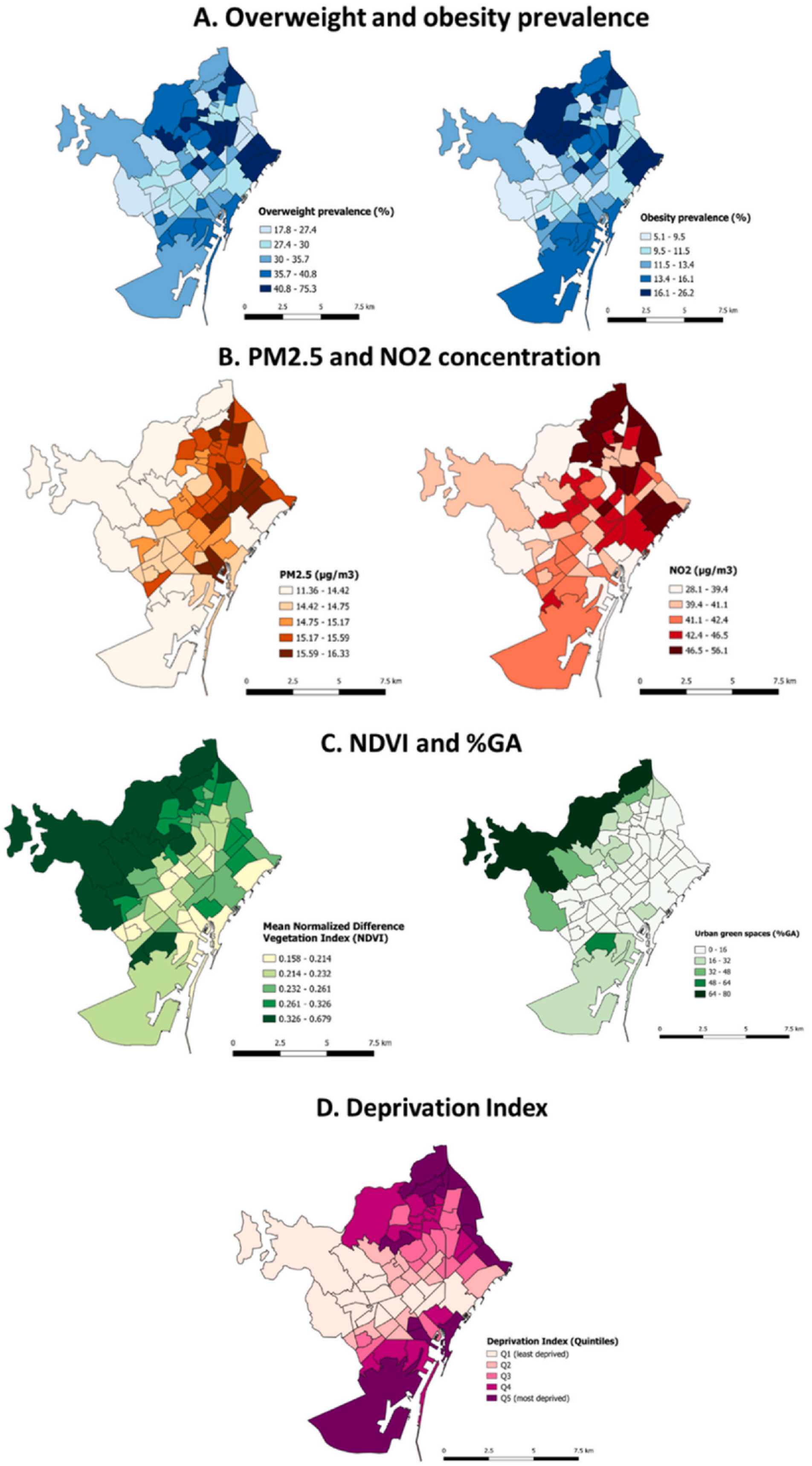

Fig. 2. Maps by ABS areas (in quintiles) for: A. overweight/obesity and obesity prevalence (%); B. $PM_{2.5}$ and NO_2 annual mean concentrations; C. NDVI and %GA levels; D socioeconomic deprivation.

Footnote: ABS: area bàsica de salut; NDVI: Normalized Difference Vegetation Index; NO_2: nitrogen dioxide; $PM_{2.5}$: particulate matter less than 2.5 μm of diameter; %GA: percentage of green spaces.

Table 2

Expected number of overweight/obesity and obesity cases attributed to ambient air pollution and urban green spaces by deprivation index using the main exposure-response functions.

	Mean exposure level	Overweight/obesity			Obesity		
		Baseline prevalence	Preventable cases		Baseline prevalence	Preventable cases	
		N (%)	N (95% CI)	%	N (%)	N (95% CI)	%
Scenario 1 of $PM_{2.5}$ = 5 µg/m^3							
Q1 (least deprived)	14.4 µg/m^3	14,693 (25.8%)	44 (−127; 203)	0.3	4497 (7.9%)	14 (−42; 65)	0.3
Q2	14.9 µg/m^3	13,729 (32.0%)	45 (−125; 201)	0.3	4617 (10.7%)	14 (−44; 72)	0.3
Q3	15.4 µg/m^3	15,777 (33.8%)	56 (−162; 254)	0.4	5800 (12.4%)	20 (−60; 94)	0.3
Q4	14.9 µg/m^3	14,219 (37.4%)	46 (−129; 208)	0.3	5634 (14.8%)	18 (−55; 87)	0.3
Q5 (most deprived)	14.8 µg/m^3	13,185 (38.3%)	36 (−113; 197)	0.3	5674 (16.5%)	15 (−50; 84)	0.3
Scenario 2 of NO_2 = 10 µg/m^3							
Q1 (least deprived)	41.0 µg/m^3	14,693 (25.8%)	584 (175; 962)	4.0	4497 (7.9%)	179 (44; 304)	4.0
Q2	42.7 µg/m^3	13,729 (32.0%)	570 (168; 946)	4.1	4617 (10.7%)	192 (45; 341)	4.2
Q3	45.4 µg/m^3	15,777 (33.8%)	701 (217; 1169)	4.4	5800 (12.4%)	257 (68; 434)	4.4
Q4	41.4 µg/m^3	14,219 (37.4%)	560 (172; 925)	4.0	5634 (14.8%)	221 (57; 379)	3.9
Q5 (most deprived)	41.4 µg/m^3	13,185 (38.3%)	516 (185; 891)	3.9	5674 (16.5%)	222 (75; 390)	3.9
Scenario 3 of NDVI = 0.311 units							
Q1 (least deprived)	0.3 NDVI	14,693 (25.8%)	711 (334; 1194)	4.8	4497 (7.9%)	221 (96; 392)	4.9
Q2	0.2 NDVI	13,729 (32.0%)	1201 (561; 2007)	8.4	4617 (10.7%)	401 (160; 741)	8.6
Q3	0.3 NDVI	15,777 (33.8%)	1216 (579; 1999)	7.7	5800 (12.4%)	450 (79; 773)	7.8
Q4	0.3 NDVI	14,219 (37.4%)	398 (188; 691)	2.8	5634 (14.8%)	158 (71; 285)	2.8
Q5 (most deprived)	0.3 NDVI	13,185 (38.3%)	645 (319; 1071)	4.9	5674 (16.5%)	274 (133; 457)	4.8
Scenario 4 of %GA = 25%							
Q1 (least deprived)	11.7 %	14,693 (25.8%)	1443 (264; 2745)	9.8	4497 (7.9%)	432 (73; 830)	9.6
Q2	4.5 %	13,729 (32.0%)	1575 (239; 2995)	11.4	4617 (10.7%)	541 (106; 1096)	11.7
Q3	4.4 %	15,777 (33.8%)	1863 (334; 3540)	11.8	5800 (12.4%)	687 (111; 1312)	11.8
Q4	16.8 %	14,219 (37.4%)	937 (165; 1744)	6.6	5634 (14.8%)	366 (62; 699)	6.5
Q5 (most deprived)	16.5 %	13,185 (38.3%)	987 (170; 1834)	7.5	5674 (16.5%)	425 (56; 808)	7.5

Footnote: $PM_{2.5}$: particulate matter less than 2.5 µm of diameter; NDVI: Normalized Difference Vegetation Index; NO_2: nitrogen dioxide; %GA: percentage of green spaces; CI: Confidence Interval.

Table 3

Expected number of overweight/obesity and obesity cases attributed to ambient air pollution by deprivation index using stratified exposure-response functions.

	Mean exposure level	Overweight/obesity			Obesity		
		Baseline prevalence	Preventable cases		Baseline prevalence	Preventable cases	
		N (%)	N (95% CI)	%	N (%)	N (95% CI)	%
Scenario 1 of $PM_{2.5}$ = 5 µg/m^3							
Q1 (least deprived)	14.6 µg/m^3	22,718 (31.7%)	−304 (202; 424)	−1.3	7244 (27.6%)	−97 (62; 136)	−1,3
Q2	15.3 µg/m^3	25,940 (36.2%)	0 (−240; 231)	0	9335 (35.6%)	2 (−88; 90)	0
Q3 (most deprived)	14.7 µg/m^3	22,945 (32.1%)	0 (−202; 191)	0	9643 (36.8%)	0 (−88; 86)	0
Scenario 2 of NO_2 = 10 µg/m^3							
Q1 (least deprived)	41.4 µg/m^3	22,718 (31.7%)	−497 (−163;-894)	−2.2	7244 (27.6%)	−159 (−46;-295)	−2.2
Q2	45.0 µg/m^3	25,940 (36.2%)	2294 (1812; 2831)	8.8	9335 (35.6%)	829 (613; 1078)	8.9
Q3 (most deprived)	40.9 µg/m^3	22,945 (32.1%)	2859 (2257; 3552)	12.5	9643 (36.8%)	1205 (931; 1499)	12.5

Footnote: $PM_{2.5}$: particulate matter less than 2.5 µm of diameter; NDVI: Normalized Difference Vegetation Index; NO_2: nitrogen dioxide; %GA: percentage of green spaces; CI: Confidence Interval.

et al., 2021). However, most HIAs were done for adult populations, with very few addressing children (Harris-Roxas et al., 2012). One HIA conducted in Barcelona estimated the attributable burden of childhood asthma due to air pollution, finding that 18% of childhood asthma cases were attributable to NO_2 and 19% to $PM_{2.5}$ in the city (Pierangeli et al., 2020). The variation in attributable/preventable asthma (18–19%) and overweigth/obesity (0.4–4.2%) cases is linked to the differences in strength of association between the air pollutants and the outcomes (i.e. asthma vs overweight/obesity), as expressed by the ERFs.

Recent urbanization processes have prompted research to examine how urban environments impact child health (Huang et al., 2022). Children are more vulnerable to air pollution (and other environmental risk factors) than other population groups (Mathiarasan and Hüls, 2021), particularly corncrning their respiratory system, immune status, brain development and cardiometabolic health (Dominski et al., 2021; Johnson et al., 2021; Tainio et al., 2021). This vulnerability arises because children are continuously undergoing physical and cognitive development, and environmental risk factors, such as air pollution, can disrupt these developmental processes. Although the mechanisms of air pollution linking with childhood overweight and obesity are not fully understood, animal and epidemiological studies suggest that air pollution increases oxidative stress and inflammatory responses in adipose tissue (An et al., 2018). Additionally, exposure to air pollution may lead to sleep problems, depression, and anxiety, which are associated with weight gain (Parasin et al., 2021). We also observed a higher number of cases attributable to excess exposure to NO_2 compared to $PM_{2.5}$. This difference may be explained by the larger exposure gradient between baseline and counterfactual NO_2 levels (mean 42.4 vs 10 µg/m^3) compared to baseline and counterfactual $PM_{2.5}$ exposure (mean 14.9 µg/m^3 vs 5 µg/m^3). The elevated NO_2 levels in Barcelona serve as an indicator of the city's dense motorized traffic, with approximately 6000 cars circulating per square kilometer (Repensar Barcelona, 2024). Our results showed that a significant number of childhood overweight/obesity cases could be prevented if the ambitious AQG were complied with, highlighting the importance of clean air in cities for child health.

Regarding UGS exposure, multiple studies suggest beneficial associations between increased UGS (or NDVI) and lower levels of childhood overweight and obesity (Bloemsma et al., 2019; Luo et al., 2020). We estimated that Barcelona could prevent 5.7% and 9.6% of childhood overweight/obesity annual cases if NDVI and %GA target values were achieved, respectively (Table 1). The higher estimated impact of %GA may be explained by its representation of more officially designated green spaces, such as public parks. These areas provide opportunities for physical activity, independent play and social interactions among children, which is associated with lower risks of overweight and obesity (Chen et al., 2022; El-Kholy et al., 2022; Mytton et al., 2012). In contrast, NDVI measures surrounding greenness, which does not always correspond to large, accessible areas for physical activity, play and social interaction; factors that appear to be particularly important for preventing childhood overweight and obesity (Alberti et al., 2019; Bilgili et al., 2013; Gascon et al., 2016). Nevertheless, while green parks are potentially more important than surrounding greenness in the pathways to childhood overweight and obesity prevention, surrounding greenness in gerneral is linked with improved mental health and well-being in children. This improved well-being in children can help reduce stress levels, which is associated with unhealthy eating behaviours (Vanaken and Danckaerts, 2018). In addition, more UGS is associated with less traffic and, consequently, lower air pollution and noise levels, while air (and noise) pollution independently link to childhood overweight and obesity (Ojeda Sánchez et al., 2023).

Our study revealed an even distribution of air pollution and UGS impacts on childhood overweight and obesity across the city by levels of socioeconomic deprivation (i.e., SES). ABS classified as Q3 (i.e., middleclass areas) showed slightly higher adverse environmental exposure levels (greater air pollution and lower UGS) at baseline, resulting in the highest number of preventable cases under the counterfactual scenarios. This findings aligns with the current evidence for European cities, which reports heterogeneous distributions of air pollution and UGS exposure levels by SES (Robinson et al., 2018). In contrast, evidence from North American cities often show that socioeconomically-deprived communities experience higher levels of air pollution and lower levels of UGS (Hajat, Hsia, & O'Neill, 2015). The ABS comprising Q3 often encompass highly-trafficked and densely-constructed streets and areas of Barcelona, such as Gran Via de les Corts Catalanes and Avinguda Meridiana. However, these central locations also offer proximity to daily living services and amenities. This suggests that spatial social deprivation patterns in Barcelona (and other European cities) are more mixed and differ from those of North America cities, where social segregation is much higher. In Barcelona middleclass populations (Q3) choose to reside in well-connected areas, close to services and amenities, even if it means being more adversely exposed to environmental risks (i.e., more air pollution and less UGS). Hence, we estimated the highest number of childhood overweight and obesity cases attributable to air pollution and lack of UGS attributable in the Q3 ABS. Importantly though, the most socioeconomically-deprived ABS (Q5) had the highest baseline overweight and obesity prevalence levels. This highlights that other socioeconomic and lifestyle factors, such as nutrition and physical activity, also play important roles in the development of childhood overweight and obesity outcomes. These factors require simultaneous consideration along with targeted interventions and policy actions to reduce childhood overweight and obesity.

We further estimated that the 6 to 11-years age group had the highest number of preventable overweight and obesity cases. This can be attributed to the fact that baseline prevalence levels were the highest in this age group, which is consistent with current literature identifying mid-childhood as the period with the highest rates of overweight and obesity (De Bont et al., 2020). Therefore, this age range is crucial for public health prevention and intervention efforts, such as promoting healthy diets and physical activity in the school but also family environments.

5. Limitations and strengths

This HIA study has certain limitations that should be acknowledged. First, in our main analysis, we employed generalized ERFs quantifying the associations between air pollution, UGS and childhood overweight and obesity, irrespective of levels of deprivation. To address this limitation, we conducted a sensitivity analysis incorporating a stratified ERF for air pollution exposure, based on levels deprivation in tertiles. Our findings revealed higher attributable cases of overweight and obesity in the most deprived areas, diverging from the results of our primary analyses. However, these results should be interpreted cautiously, as we obtained the stratified ERF from a study including data from the whole of Catalonia, including rural and urban areas, where deprivation levels might not be comparable with the levels of deprivation in our study area of Barcelona. Furthermore, the ERFs were derived from a single study rather than from meta-analysis, as in our main analysis. The development of future epidemiological research and policy initiatives should prioritize the establishment and incorporation of stratified ERFs, including stratification by socioeconomic variables, since applying a single, general ERF might misestimate the true health effect experienced by various population groups with differing vulnerabilities. Further, the ERF of both air pollutants were estimated by our group by only including European studies from a previously published meta-analysis combining both cross-sectional and longitudinal studies (Zheng et al., 2023). Given that current evidence regarding the association between ambient air pollution and childhood obesity is still limited and inconsistent in Europe, our estimates should be interpreted with caution, and we encourage further research efforts to better establish these associations.

We obtained exposure and health outcome data at the ABS level ($N = 69$), which is not the smallest administrative unit in Barcelona, but was the smallest unit of analysis for which the childhood overweight and obesity prevalence rates were available for this study. We assume high representativeness of the SIDIAP childhood overweight and obesity data as SIDIAP cover around 75% of the total population living in Catalonia (those assigned to a primary care centre of the Catalan Institute of Health). We believe that the ABS level sufficiently captured the variability in exposure levels and childhood overweight and obesity outcomes. However, by using the ABS level as our unit of analysis—and this applies to any choice of spatial units—we must acknowledge the modifiable areal unit problem (MAUP). This issue arises because the relationships between variables (e.g., exposure levels, SES, and health outcomes) can vary depending on the level of aggregation and the reassignment of variables (and hence relationships) according to the chosen spatial boundaries. In addition, we must address the issue of potential double-counting of health burdens. Ambient air pollution and UGS are correlated, which means our risk estimates and attributable childhood overweight and obesity cases may not be independent, leading to an overestimation of the total burden. Therefore, further research is needed to consider the high correlation of environmental exposures and to establish multi-risk factor models that account for these interactions, thereby avoiding the overestimation of health burdens. Finally, another limitation of this study is the potential misclassification between the air pollution and UGS exposure data (2015) and childhood overweight and obesity data (2008–2017). However, evidence suggests that air pollution levels (annual means) and green space availability (land use) in Barcelona remained relatively stable during this period (Nieuwenhuijsen et al., 2018).

As strengths to mention, we applied a comprehensive and robust uncertainty analysis to estimate our confidence intervals accounting for the multiple uncertainties derived from the different databases such as the ABS-specific overweight and obesity levels, ABS population age structures, error from the air pollution and UGS models and the confidence intervals from the ERFs. Moreover, we considered socioeconomic impacts with respect to baseline and counterfactual exposure levels and childhood overweight and obesity cases and were able to pinpoint where in the city the preventable burden appears to be the highest (i.e. Q3, ABS with dense traffic and high environmental burdens).

6. Policy implications

Ambitious policies are needed in Barcelona to reduce air pollution levels and expand UGS, particularly to protect children's health and, in our case, address childhood overweight and obesity outcomes.A combination of policies is recommended to reduce local air pollution levels, including measures to decrease motorized traffic volumes, such as congestion pricing, reducing parking spaces, implementing low emission zones, and expanding superblocks (Mueller et al., 2020). Additionally, promoting alternative transport modes, such as walking, cycling, and increased use of public transportation (Mueller et al., 2015), is crucial. Given the multiple benefits of UGS for child health, including overweight and obesity reductions, ambitious urban greening policies are needed in Barcelona and in cities worldwide. A concrete urban greening policy proposal was defined by the Barcelona City Council as the "Eixos Verds/Green Corridors" plan, which was foreseen to increase Barcelona Street greenery significantly, and additionally was assessed to be beneficial for the population's mental health (Yañez et al., 2023) and childrens' cognitive and behavioural development (Opbroek et al., 2024). But with a change in government and political cycle, this policy proposal is currently on hold. Alternatives like interior patio greening and green rooftops are currently under discussion, though their accessibility for children and the general population remains unclear. Additionally, other greening proposals should be implemented in Barcelona and beyond, including more street trees, small gardens, pocket parks, widespread city greening (including vertical gardens), and equitably distributed green playgrounds for children.(Mueller et al., 2020).

Stratifying our analysis by level of deprivation demonstrated that particularly Q3, meaning middle-class ABS located in areas with dense motor traffic and built environment, were the areas where adverse exposure levels were the highest (meaning high air pollution and little UGS) and resulted in the largest number of preventable childhood overweight and obesity cases. This highlights the urgent need for rigorous intervention and policy attention in the city center to reduce air pollution levels—primarily by decreasing motorized traffic—and to increase UGS, aiming for better and more equitable childhood overweight and obesity outcomes. Furthermore, the fact that ABS in Q5 (the most deprived areas) showed the highest baseline rates of overweight and obesity underscores the necessity for additional social and health policies. These policies should address other determinants of childhood overweight and obesity, such as nutrition and physical activity, alongside efforts to improve environmental quality through reduced air pollution and enhanced UGS.

In conclusion, the results of our HIA underscore the critical need for ambitious environmental quality policies aimed at reducing air pollution (and noise) levels and increasing UGS. The benefits of such policies are wide-ranging, from enhanced environmental quality and climate-change resilience to improved livability and public health, particularly child health, as demonstrated by our findings. With all policies and intervention proposals for improving air quality and greening of the city, the city should keep in mind health equity and environmental justice impacts and thus needs to consider distributional aspects and analyse where in the city intervention is most urgently needed, what type of intervention and who will benefit from this.

7. Conclusions

A significant reduction in childhood overweight and obesity cases can be achieved in Barcelona by lowering air pollution levels (between 0.4 and 4.4%) and increasing UGS levels (between 5.7 and 9.6%) to meet internationally recommended levels. The preventable burden of childhood overweight and obesity, under compliance with these recommended exposure levels, was slightly higher in middle-class socioeconomic areas, which also had the highest levels of air pollution exposure and the least amounts of UGS available at baseline. There is a need for policy intervention aimed at creating healthier urban environments of high environmental quality to particularly protect child health. Given that children are especially vulnerable to environmental risk factors and rely on adults to advocate for health-protecting policies, it is crucial to incorporate their needs into urban planning and public health initiatives.

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CRediT authorship contribution statement

Huyen Nguyen Thi Khanh: Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation. **Mariona Rigau-Sabadell:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Sasha Khomenko:** Writing – review & editing, Methodology, Conceptualization. **Evelise Pereira Barboza:** Writing – review & editing, Methodology, Conceptualization. **Marta Cirach:** Writing – review & editing, Data curation, Conceptualization. **Talita Duarte-Salles:** Writing – review & editing, Resources, Project administration, Funding acquisition. **Mark Nieuwenhuijsen:** Writing – review & editing, Methodology, Conceptualization. **Martine Vrijheid:** Writing – review & editing, Resources, Project administration, Methodology, Funding acquisition, Conceptualization. **Natalie Mueller:** Writing – review & editing, Writing – original draft, Validation, Methodology, Conceptualization. **Jeroen de Bont:** Writing – review & editing, Writing – original draft, Validation, Resources, Methodology, Funding acquisition, Conceptualization.

Declaration of competing interest

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Appendix A. Supplementary data

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Data availability

Data will be made available on request.

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