Environment International 199 (2025) 109493

Contents lists available at ScienceDirect

Environment International

journal homepage: www.elsevier.com/locate/envint

Full length article

# Residential greenspace and lung function throughout childhood and adolescence in five European birth cohorts. A CADSET initiative

Carlos A. Valencia-Hernández [a,b], Zhebin Yu [c,d], Ulrike Gehring [e], Gerard H. Koppelman [f], Marie Standl [g,h,i], Claudia Flexeder [g,h,j], Tamara Schikowski [k,l], Sara Kress [k], Erik Melén [m], Olena Gruzieva [c,d], Mare Lõhmus [c,d], Rosa Faner [n], Alvar Agusti [n,o], Jadwiga A. Wedzicha [a], Judith Garcia-Aymerich [p,q,r], Sarah Koch [p,r,s], Mark Nieuwenhuijsen [p,q,r], Aitana Lertxundi [r,t,u], Ana Esplugues [r,v,w], Ferran Ballester [r,v,w], Ane Arregi [x,y], Iana Markevych [z,aa,ab], Chloe I. Bloom [a,ac,1], Elaine Fuertes [a,ac,1,*], on behalf of the CADSET Clinical Research Collaboration

[a] National Heart and Lung Institute, Imperial College London, London, UK
[b] School of Medicine, Universidad de Los Andes, Bogotá, Colombia
[c] Institute of Environmental Medicine, Karolinska Institutet, Stockholm, Sweden
[d] Centre for Occupational and Environmental Medicine, Region Stockholm, Stockholm, Sweden
[e] Institute for Risk Assessment Sciences, Utrecht University, Utrecht, the Netherlands
[f] University of Groningen, University Medical Center Groningen, Beatrix Children's Hospital, Department of Pediatric Pulmonology and Pediatric Allergology, and Groningen Research Institute of Asthma and COPD, Groningen, the Netherlands
[g] Institute of Epidemiology, Helmholtz Zentrum München, German Research Center for Environmental Health, Neuherberg, Germany
[h] Comprehensive Pneumology Center Munich (CPC-M), Member of the German Center for Lung Research (DZL), Munich, Germany
[i] German Center for Child and Adolescent Health (DZKJ), partner site Munich, Munich, Germany
[j] Institute and Clinic for Occupational, Social and Environmental Medicine, University Hospital, Ludwig-Maximilians-Universität München, Munich, Germany
[k] IUF - Leibniz Research Institute for Environmental Medicine, Düsseldorf, Germany
[l] School of Public Health, Department of Environmental and Health, University of Bielefeld, Bielefeld, Germany
[m] Department of Clinical Science and Education Södersjukhuset, Karolinska Institutet, Stockholm, Sweden
[n] Respiratory Institute, Clinic Barcelona, FCRB-IDIBAPS, University of Barcelona, Barcelona, Spain
[o] CIBER Enfermedades Respiratorias, Spain
[p] ISGlobal, Barcelona, Spain
[q] Universitat Pompeu Fabra (UPF), Barcelona, Spain
[r] CIBER Epidemiología y Salud Pública (CIBERESP), Spain
[s] Department of Sport, Exercise, and Health, University of Basel, Switzerland
[t] Preventive Medicine and Public Health Department, University of Basque Country (UPV/EHU), Basque Country, Spain
[u] Health Research Institute-BIOGipuzkoa, Basque Country, Spain
[v] Epidemiology and Environmental Health Joint Research Unit, FISABIO-Universitat Jaume I-Universitat de València, València, Spain
[w] Department of Nursing, Universitat de València, Valencia, Spain
[x] Faculty of Psychology, University of the Basque Country, San Sebastian, Spain
[y] Environmental Epidemiology and Child Development Group, Biogipuzkoa Health Research Institute, San Sebastian, Spain
[z] Institute of Psychology, Jagiellonian University, Krakow, Poland
[aa] Research Group "Health and Quality of Life in a Green and Sustainable Environment", Strategic Research and Innovation Program for the Development of MU - Plovdiv, Medical University of Plovdiv, Plovdiv, Bulgaria
[ab] Environmental Health Division, Research Institute at Medical University of Plovdiv, Medical University of Plovdiv, Plovdiv, Bulgaria
[ac] MRC Centre for Environment and Health, Imperial College London, London, UK

*Abbreviations:* ALSPAC, Avon Longitudinal Study of Parents and Children; BAMSE, Children, Allergy, Milieu, Stockholm, Epidemiological Survey; CADSET, Chronic airway diseases early stratification; $FEV_1$, Forced expiratory volume in the first second; FVC, Forced vital capacity; GINIplus, German Infant Study on the Influence of Nutrition Intervention plus Air pollution and Genetics on Allergy Development; INMA, Infancia y Medio Ambiente; LISA, Influence of Lifestyle factors on the development of the Immune System and Allergies in East and West Germany; NDVI, Normalized difference vegetation index; $NO_2$, Nitrogen dioxide; PIAMA, Prevention and incidence of asthma and mite allergy; $PM_{2.5}$ mass, Particulate matter 2.5 μm or less in diameter; $PM_{10}$ mass, Particulate matter 10 μm or less in diameter.

* Corresponding author at: Emmanuel Kaye Building, 1B Manresa Road, London SW3 6LR, UK.
*E-mail address:* e.fuertes@imperial.ac.uk (E. Fuertes).
[1] Shared senior authorship.

https://doi.org/10.1016/j.envint.2025.109493
Received 6 November 2024; Received in revised form 11 March 2025; Accepted 22 April 2025
Available online 25 April 2025

ARTICLE INFO

Handling Editor: Adrian Covaci

*Keywords:*
Adolescence
Children
Cohort
Greenspace
Greenness
Lung function

ABSTRACT

Whether greenspace affects lung function is unclear. We explored associations between the level of greenness or presence of urban green space near the home with lung function measures taken repeatedly during childhood and adolescence in five European birth cohorts.

Lung function was measured by spirometry between six and 22 years (2–3 times), and 9,206 participants from BAMSE (Sweden), GINI/LISA South and GINI/LISA North (Germany), PIAMA (The Netherlands) and INMA (Spain) contributed at least one lung function measurement. The mean Normalized Difference Vegetation Index (NDVI) in a 300 m buffer and presence of urban green space within a 300 m buffer (yes/no) were estimated at the home address at the time of each spirometry measurement. Cohort-specific associations were assessed using adjusted linear mixed models and combined in a random-effects *meta*-analysis.

Residential greenness was not associated with forced expiratory volume in one second ($FEV_1$), forced vital capacity (FVC) or $FEV_1$/FVC in the *meta*-analysis (2.3 ml [-3.2, 7.9], 6.2 ml [-3.4, 15.7] and −0.1 [-0.3, 0.1] per 0.1 increase in NDVI, respectively), nor was having a nearby urban green space (−8.6 ml [–22.3, 5.0], −7.6 ml [-24.7, 9.4] and 0.0 [-0.4, 0.3], respectively). Heterogeneity was low to moderate ($I^2 = 0$ –39 %). Asthma, atopy, air pollution, sex, socioeconomic status and urbanization did not modify the null associations.

Using repeated data from five large independent European birth cohorts, we did not find associations between vegetation levels around the home or the presence of an urban green space and lung function levels during childhood and adolescence.

## 1. Introduction

Lung function is an important marker of respiratory, cardiovascular and mental health and is associated with reduced premature death (Agustí et al., 2017). Lung development starts early in pregnancy and continues throughout childhood and adolescence, peaking around 20–25 years of life, before declining due to physiological ageing. This growth trajectory can be influenced both positively and negatively by genetic and environmental factors (Melén et al., 2024).

In the face of climate change and rapid urbanization, greening our cities may be one pathway to design urban environments that maximize health, including respiratory health (van Daalen et al., 2024; Nieuwenhuijsen et al., 2024; Zhao et al., 2025). However, how best to achieve this remains unclear as greenspace (a term used here to refer to all types of vegetation exposure metrics) can have several roles. For example, it may represent areas of lower air pollution and may promote healthy lifestyles and immune development. However, greenspace can also contain higher amounts of allergic vegetation, which can aggravate allergic and respiratory symptoms among those sensitized.

The epidemiological evidence linking greenspace and lung function is so far limited and mixed. Most existing studies investigating the link between greenspace and lung function in children and adolescents are cross-sectional and their results are inconsistent. Some studies report greenspace is associated with better values of at least one lung function parameter (Almeida et al., 2022; Cilluffo et al., 2022; Fernandes et al., 2024; Hartley et al., 2022; Paciência et al., 2019; Squillacioti et al., 2020; Zhou et al., 2021), while others report mixed (both positive and negative) associations (Ye et al., 2023), null associations (Agier et al., 2019; Boeyen et al., 2017) or significant associations that become null once air pollution levels are considered (Yu et al., 2021). Although they have advantages, cross-sectional studies are unable to assess temporality in cause and effect, are more susceptible to certain biases such as self-selection (in this case, healthier people choosing to live in greener places) and inferring causality is difficult (Wang and Cheng, 2020).

Only one study has so far utilized repeated data on greenspace metrics and lung function parameters and reported that participants of the English Avon Longitudinal Study of Parents and Children (ALSPAC) birth cohort with higher greenness levels close to their homes and nearby urban green spaces had higher forced expiratory volume in the first second ($FEV_1$) and forced vital capacity (FVC) up to 24 years of age. Some associations were greater among those living in cities and areas of high air pollution (Fuertes et al., 2020).

Given the mixed results from cross-sectional studies and the limited number of studies with repeated data, this analysis investigates associations between the level of greenness and the presence of urban green spaces near the home with repeated lung function measurements obtained using spirometry during childhood and adolescence in five large and independent European birth cohorts. This work is part of the 'Chronic Airway DiSeases Early sTratification' (CADSET) network, which brings together European birth cohorts with high-quality lung function data (Agusti et al., 2019).

## 2. Methods

### 2.1. Study population

This study includes data from five large independent European birth cohorts: Children, Allergy, Milieu, Stockholm, Epidemiological Survey (BAMSE, Sweden) (Mitselou et al., 2022), Prevention and Incidence of Asthma and Mite Allergy (PIAMA, Netherlands) (Wijga et al., 2014), German Infant Study on the Influence of Nutrition Intervention plus Air pollution and Genetics on Allergy Development (GINIplus, Germany) (von Berg et al., 2013, 2010), Influence of Lifestyle factors on the development of the Immune System and Allergies in East and West Germany (LISA, Germany) (Heinrich et al., 2002) and INfancia y Medio Ambiente (INMA, Spain) (Gascon et al., 2017; Guxens et al., 2012). Given their similar study designs and follow-ups, the two German cohorts are combined and analysed separately by geographical region (GINI/LISA North and GINI/LISA South), as usually done in environmental epidemiological analyses of these data (e.g. (Fuertes et al., 2016, 2015; Gehring et al., 2013)). The analyses in INMA were carried out separately for each geographically distinct sub-cohort (Gipuzkoa, Sabadell and Valencia in Spain).

Information on each cohort's study design, geographical coverage and greenspace data sources is summarized in Table S1. Ethical approval was granted to each cohort individually by their local research ethics committees.

### 2.2. Lung function parameters

Lung function testing was performed without bronchodilation using spirometry by trained personnel and calibrated equipment according to the American Thoracic Society and European Respiratory Society guidelines existing at the time (Beydon et al., 2007a; Miller et al., 2005). FVC, as a parameter of lung volume, $FEV_1$, and $FEV_1$/FVC, as a measure of airway obstruction, were used as the primary outcomes. In a

secondary analysis and to allow international comparisons, standard deviation scores (z-scores) for $FEV_1$ and FVC derived using reference equations for spirometry from the Global Lung Function Initiative (https://www.lungfunction.org) were calculated, as were percent predicted volumes (Quanjer et al., 2012).

The ages at which lung function testing was conducted varied by cohort but covered most of later childhood and into adolescence (overall age range six to 22 years). Specifically, testing occurred at approximately 8, 16 and 22 years in BAMSE, 8, 12 and 16 years in PIAMA, 6, 10 and 15 years in GINI/LISA North, 6 and 15 years in GINI/LISA South and 7/8 and 10/11 years in INMA (Table S2). As in a previous analysis of these data (Gehring et al., 2013), for the 6-year time point in GINI/LISA North and South, we used forced expiratory volume in 0.5 s instead of $FEV_1$ as young children can usually perform reliable spirometry but often have short expiratory times (hence a reliable $FEV_1$ cannot always be determined). We also did not use the FVC for this time point in these two German cohorts as young children often have difficulties fulfilling the guidelines for FVC (Beydon et al., 2007b). Individuals who contributed at least one lung function measurement at any time point were included in the analysis to maximize the use of available data.

### 2.3. Greenspace exposures

Mean residential greenness within a 300 m buffer was estimated using the Normalized Difference Vegetation Index (NDVI) (Rhew et al., 2011). Briefly, using remote sensing technology, the amount of green vegetation was calculated based on the difference between near infrared light, reflected by the green vegetation, and red light, not reflected by green vegetation. The values of NDVI range from + 1, which corresponds to dense green vegetation, to −1 which corresponds to water. For all cohorts, NDVI values were calculated at a resolution of 30 m by 30 m from cloud-free Landsat Thematic Mapper satellite images obtained from the Global Visualisation viewer from the U.S. Geological Survey. NDVI data used in the study were based on satellite images taken during the spring/summer to capture the greatest variation in vegetation levels. For nearly all cohorts this involved combining cloud free images over a few months close in time to the year of lung function measurement, whereas for the INMA sub-cohorts, a 5-year rolling average was calculated. Details of the months and years used to assign the satellite images to each lung function measurement per cohort are provided in Table S1.

Using these images, mean NDVI values within 300 m circular buffers surrounding the participants' places of residence at each lung function measurement were calculated. We chose the NDVI as a measure of interest to facilitate comparisons with other studies as it is the most commonly used greenspace metric in health research, and the 300 m buffer as this size is used as an accessibility threshold and is the World Health Organization standard (Annerstedt van den Bosch et al., 2016; World Health Organization, 2017). Mean NDVI values in 500 m and 1000 m circular buffers were used in sensitivity analyses.

The proportion of urban green space within a 300 m buffer around the home addresses was estimated from land use classification data (sources and years summarized in Table S1). This information was dichotomized as yes (i.e. any presence, proportion > 0) vs no (i.e. proportion = 0). These data were only available for a 500 m buffer for the GINI/LISA North and South cohorts and were unavailable in BAMSE. For GINI/LISA North and South as well as INMA − Gipuzkoa, data from a single year were available and assigned to all addresses across time, explicitly assuming the spatial distribution of the urban green spaces remained constant throughout each cohort's follow-up. For the remaining cohorts, urban green space data for two years were available and that closest in time to the lung function measurements were used (Table S1). Urban green spaces correspond to public green areas used predominantly for recreation. We selected this measure for analysis due to the increasing percentage of the population living in urban areas and because it has been previously associated with better lung function up to 24 years (Fuertes et al., 2020).

### 2.4. Statistical analysis

Using the R package 'lme4' (Bates et al., 2015; R Core Team, 2023), linear mixed models were used to estimate separate associations between repeated measures of the two greenspace indicators (mean NDVI within a 300 m buffer and the presence of an urban green space within a 300 m buffer) and the three lung function parameters ($FEV_1$, FVC, and $FEV_1$/FVC) in each cohort (Detry and Ma, 2016). Models were adjusted for age, age-squared (to capture non-linear lung function growth), weight, height, second-hand smoke exposure in the home as time-varying covariates (value provided at each follow-up), sex, a measure of socioeconomic status, older siblings, and maternal smoking during pregnancy as time-invariant covariates (value provided at birth). Models also included individual as a random intercept. Socioeconomic status was defined using parental education in BAMSE, PIAMA, GINI/LISA North and South, categorized into a 3-level variable (low, intermediate, high) with the low level corresponding to completing the compulsory level of education in each country, and using parental occupation in the INMA sub-cohorts (Office of Population Census and Survey, 1991). There were also additional adjustments made for certain cohorts due to their study design: study region in BAMSE and cohort/intervention in GINI/LISA North and South. All covariates were collected using parent-completed or self-completed questionnaires and harmonised for inferential comparability (Benet et al., 2019), except for height and weight which were measured. For FVC and $FEV_1$/FVC in GINI/LISA South for which data were available for only one time point (15 years), we used simple linear regression models adjusted for the same covariates collected at the time of lung function testing.

Cohort-specific associations were combined using an individual-participant data random-effects *meta*-analysis, to allow for potential within- and between-cohort heterogeneity (DerSimonian and Laird, 1986). Effect estimates from the models for mean NDVI are presented per 0.1 unit increase in mean NDVI. Effect estimates from the models of urban green space are presented comparing the presence (versus absence) of urban green space. The $I^2$ statistic was used to examine the statistical heterogeneity among cohort-specific effect estimates and can be interpreted as the percentage of the variability in effect sizes attributable to the between-study variability rather than sampling error (Huedo-Medina et al., 2006). Values between 30–60 %, 50–90 % and 75–100 % represent moderate, substantial and considerable heterogeneity, respectively (Higgins and Green, 2011). Cochran's Q test was used to test for significant heterogeneity.

### 2.5. Additional analyses

The role of air pollution is complex as it may act as a confounder, effect modifier or may lie in the causal pathway (mediator) between greenspace and respiratory health (Markevych, 2021). We assumed at least partial mediation (Yu et al., 2021), and thus the main analyses were not adjusted for air pollution. To test to which extent long-term air pollution can be a confounder, models were further (separately) adjusted for annual average levels of nitrogen dioxide ($NO_2$) and particulate matter 2.5 μm or less in diameter ($PM_{2.5}$) at the home address corresponding to the time of lung function measurement, derived from existing land-use regression models (Beelen et al., 2013; Cyrys et al., 2012; Eeftens et al., 2012a, 2012b). To test whether long-term air pollution may be an effect modifier, we introduced interaction terms between each pollutant and greenspace variable and stratified the models by cohort-specific tertiles of $NO_2$ and $PM_{2.5}$ concentrations. To account for potential confounding by short-term air pollution levels, models were adjusted for the average of the daily concentrations of $NO_2$ and particulate matter 10 μm or less in diameter ($PM_{10}$) in the seven days prior to lung function testing (not available for the 6-year follow-up of GINI/LISA North and South, and $PM_{2.5}$ mass used in the INMA sub-cohorts due to better data availability). These daily pollution data were derived from routine regional and urban background sites of air

quality monitoring networks in the study areas, as done previously (Gehring et al., 2013).

To assess whether vulnerable subgroups exist, we introduced an interaction term between sex, self-report of doctor diagnosis of asthma (assessed by questionnaire, all time points considered), and atopic sensitization (positive reaction defined as having any allergen-specific IgE level $\geq$ 0.35 kU/l, with testing conducted against a set of common outdoor and indoor aeroallergens that varied slightly by cohort (Fuertes et al., 2016)). As socioeconomic status and urbanization may modify associations between greenness and health, we tested for effect modification by these factors using data obtained at the earliest time point of lung function measurement in each cohort (urbanization was categorized as a 3-level variable based on tertiles of population density (BAMSE, PIAMA, INMA sub-cohorts) or rural/suburbs/cities (GINI/LISA North and South)). We conducted stratified models when interaction terms were statistically significant (p-interaction $<$ 0.05).

To assess the impact of potential exposure misclassification, we (i) restricted the sample to those who did not move and (ii) replicated the models using mean NDVI values within 500 m and 1000 m buffers (data for the 1000 m buffer are unavailable in the INMA sub-cohorts).

Finally, to assess the robustness of our models to the selected modelling strategy in some cohorts, we 1) adjusted for 'study region' in the PIAMA cohort and 2) analysed the INMA cohort as a single study and adjusted for 'region', rather than analysing these data as three separate sub-cohorts. We also replicated the main analyses restricting to the 4,568 participants who contributed at least two lung function measurements.

## 3. Results

### 3.1. Study population and lung function measurements

Overall, 9,206 individuals contributed at least one lung function measurement to the analysis (3,071 in BAMSE, 1,887 in PIAMA, 1,455 in GINI/LISA North, 1,588 in GINI/LISA South, 369 in INMA-Gipuzkoa, 422 in INMA-Sabadell and 414 in INMA-Valencia). Demographic information including the mean and standard deviation of the lung function parameters per cohort and age at time of measurement is summarized in Table 1. All mean $FEV_1$/FVC values were $>$ 83 % for all time points and cohorts, indicating limited evidence of obstruction in these population-based child/adolescent participants.

### 3.2. Greenness and urban green space

The distribution of mean NDVI values in 300 m buffers per cohort is depicted in Fig. 1. The correlation between mean NDVI estimates in a 300 m buffer and those in the alternative 500 m and 1000 m buffers was high for all cohorts (Pearson's r $>$ 0.91 and $>$ 0.71, respectively, Table S3). When examining those who had moved during the study period, the correlation between mean NDVI estimates in a 300 m buffer across each reported address at the different timepoints was moderate to high across cohorts (Pearson's r ranged from 0.47 to 0.92).

The percentage of participants with an urban green space within 300 m of their home at the earliest time of lung function measurement was 58.1 % in PIAMA, 56.1 % in GINI/LISA North, 76.6 % in GINI/LISA South, 30.1 % in INMA-Gipuzkoa, 75.3 % in INMA-Sabadell and 72.9 % in INMA-Valencia.

### 3.3. Associations between residential greenness and $FEV_1$, FVC and $FEV_1$/FVC

No associations were identified in the *meta*-analysis between greenness and any of the spirometry-based measures considered (2.3 ml [-3.2, 7.9], 6.2 ml [-3.4, 15.7] and −0.1 [-0.3, 0.1] for $FEV_1$, FVC and $FEV_1$/FVC, respectively, per 0.1 increase in mean greenness, Fig. 2). Heterogeneity between studies was low to moderate ($I^2$ = 0——39 %). When considering cohort-specific analyses, associations were only significant for the PIAMA cohort (14.0 ml [0.9, 27.1], 23.8 ml [9.3, 38.4] and (−0.3 [-0.5, 0.0] for $FEV_1$, FVC and $FEV_1$/FVC, respectively, per 0.1 increase in mean greenness). When excluding the PIAMA cohort from the *meta*-analysis, there was no heterogeneity between studies for $FEV_1$ and FVC ($I^2$ = 0 %) and very little for $FEV_1$/FVC (20.3 %).

### 3.4. Associations between urban green space and $FEV_1$, FVC and $FEV_1$/FVC

There were no associations in the *meta*-analysis between the presence (versus absence) of an urban green space and $FEV_1$, FVC and $FEV_1$/FVC (−8.6 ml [−22.3, 5.0], −7.6 ml [-24.7, 9.4] and 0.0 [-0.4, 0.3], respectively, Fig. 2), with no heterogeneity observed between cohorts ($I^2$ = 0 %). All cohort-specific associations were null.

### 3.5. Additional analyses

Additionally adjusting the models for long-term annual average $NO_2$ (Fig. S1) and $PM_{2.5}$ mass (Fig. S2) or short-term 7-day averages of $NO_2$ (Fig. S3) and $PM_{10}$ mass (Fig. S4) did not greatly change the combined effect estimates. However, the adjustment for long-term $NO_2$ did attenuate the previously statistically significant associations observed with greenness in the PIAMA cohort, suggesting some potential confounding by air pollution in this study area (7.7 ml [-7.9, 23.3], 17.3 ml [0.0, 34.5] and −0.1, [-0.4, 0.2] for $FEV_1$, FVC and $FEV_1$/FVC per 0.1 increase in greenness, respectively, Fig. S1). A small attenuation was observed in this cohort for $FEV_1$ when adjusting for long-term $PM_{2.5}$ mass (10.4 ml [-3.3, 24.0] per 0.1 increase in greenness, Fig. S2).

There was little evidence of effect modification by long-term $NO_2$ and $PM_{2.5}$ mass. All p-values for the interaction terms between these pollutants and greenspace variables were large (p-interaction $>$ 0.05) in the *meta*-analysis, except for between greenness and $PM_{2.5}$ mass (p-interaction = 0.033) for FVC. Models stratified by tertiles of long-term $PM_{2.5}$ mass did not yield a clear trend (−4.0 ml [-18.9, 10.8], 16.8 ml [4.6, 29.0] and 7.3 ml [-20.6, 35.3] increase in FVC per 0.1 increase in greenness, in low, medium and high tertiles of $PM_{2.5}$ mass, respectively).

No susceptible subgroups were identified as interaction terms between both greenspace indicators and sex, socioeconomic status, asthma, sensitization and urbanization were not statistically significant (p-interaction $>$ 0.05) in the *meta*-analysis, except that between asthma and urban green space (p-interaction = 0.037) for $FEV_1$. Although larger negative effect estimates were observed among participants with asthma in stratified models, confidence intervals substantially overlapped between the two groups (−34.7 ml [-77.1, 7.7] and −5.2 ml [-19.7, 9.4] change in $FEV_1$ for those with an urban greenspace nearby compared to those without, among participants with and without asthma, respectively).

There were several differences between movers and non-movers, and these varied by cohort. However, the results remained null when restricting to those who did not move (3,378 participants, Fig. S5). Finally, the findings did not change when repeating the analyses using mean greenness values in 500 m and 1000 m buffers (Fig. S6), using z-scores or percent predicted values of $FEV_1$ or FVC as the outcomes (Figs. S7 and S8, respectively), restricting the sample to those with at least two lung function measurements (N = 4,568, Fig. S9), analysing the INMA cohort as a single study and adjusting for 'region' or adjusting the PIAMA models for 'region'.

## 4. Discussion

In this study of five large independent European birth cohorts, analysed both individually and combined in a *meta*-analysis, we found no evidence that having higher greenness levels around the home or an urban green space close to the home is associated with lung function from childhood into adolescence. We also did not identify any

**Table 1**
Characteristics of the study population. The number of individuals who contributed at least one lung function measurement to the analysis is indicated in bold per cohort.

| Characteristic | Time point[1] | BAMSE (N = 3071) | | PIAMA (N = 1887) | | GINI/LISA North (N = 1455) | | GINI/LISA South (N = 1588) | | INMA – Gipuzkoa (N = 369) | | INMA – Sabadell (N = 422) | | INMA – Valencia (N = 414) | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | n or mean | % or SD | n or mean | % or SD | n or mean | % or SD | n or mean | % or SD | n or mean | % or SD | n or mean | % or SD | n or mean | % or SD |
| Male | Birth | 1473 | 48.0 | 936 | 49.6 | 740 | 50.9 | 787 | 49.6 | 171 | 46.3 | 216 | 51.2 | 206 | 49.8 |
| Older siblings | Birth | 1458 | 47.5 | 927 | 49.1 | 718 | 49.3 | 1065 | 67.1 | 155 | 42.0 | 157 | 40.8 | 178 | 43.2 |
| Mother smoked in pregnancy | Birth | 365 | 11.9 | 286 | 15.3 | 215 | 15.0 | 195 | 12.5 | 81 | 22.5 | 110 | 26.4 | 145 | 35.0 |
| High social class[2] | Birth | 1670 | 54.4 | 1048 | 55.6 | 727 | 50.1 | 1233 | 77.8 | 185 | 50.1 | 131 | 33.9 | 119 | 28.7 |
| Age (years) | 1 | 8.3 | 0.5 | 8.1 | 0.3 | 6.3 | 0.2 | 6.1 | 0.1 | 7.9 | 0.2 | 7.4 | 1.2 | 7.6 | 0.2 |
| | 2 | 16.7 | 0.6 | 12.7 | 0.4 | 10.3 | 0.2 | – | – | 10.8 | 0.3 | 11.1 | 0.6 | 10.6 | 0.2 |
| | 3 | 22.7 | 0.6 | 16.4 | 0.2 | 15.2 | 0.3 | 15.3 | 0.3 | – | – | – | – | – | – |
| $FEV_1$ (ml) | 1 | 1776.1 | 272.0 | 1798.1 | 247.5 | 1096.9* | 162.3* | 1088.1* | 157.7* | 1608.8 | 225.3 | 1149.9 | 264.2 | 1543.7 | 214.6 |
| | 2 | 3930.2 | 749.0 | 2697.5 | 426.6 | 2162.3 | 291.1 | – | – | 2104.8 | 308.3 | 2193.9 | 376.8 | 2076.4 | 282.7 |
| | 3 | 4010.5 | 798.3 | 3944.6 | 714.0 | 3480.5 | 614.6 | 3526.9 | 632.2 | – | – | – | – | – | – |
| FVC (ml) | 1 | 2066.0 | 327.0 | 2005.1 | 298.5 | – | – | – | – | 1902.6 | 280.7 | 1645.9 | 301.0 | 1743.2 | 253.3 |
| | 2 | 4640.7 | 940.8 | 3204.0 | 502.3 | 2386.1 | 348.0 | – | – | 2439.9 | 366.8 | 2608.4 | 443.7 | 2463.4 | 353.2 |
| | 3 | 4850.1 | 1060.2 | 4701.2 | 857.7 | 4079.8 | 768.7 | 4055.9 | 766.4 | – | – | – | – | – | – |
| $FEV_1$/FVC | 1 | 86.2 | 5.7 | 90.0 | 6.2 | – | – | – | – | 84.9 | 6.1 | 86.5 | 6.1 | 88.8 | 5.8 |
| | 2 | 85.3 | 6.5 | 84.4 | 5.7 | 90.9 | 5.6 | – | – | 86.5 | 5.9 | 84.3 | 5.4 | 84.5 | 4.9 |
| | 3 | 83.3 | 6.2 | 84.2 | 6.2 | 85.7 | 6.4 | 87.4 | 6.4 | – | – | – | – | – | – |
| Height (cm) | 1 | 132.2 | 5.9 | 133.3 | 5.8 | 121.1 | 5.1 | 119.4 | 4.6 | 127.9 | 5.3 | 125.2 | 8.9 | 126.0 | 5.4 |
| | 2 | 172.7 | 9.1 | 160.0 | 7.7 | 144.5 | 6.4 | – | – | 144.8 | 6.4 | 145.9 | 7.7 | 142.5 | 6.7 |
| | 3 | 174.3 | 9.5 | 175.6 | 8.7 | 172.5 | 8.2 | 170.8 | 8.2 | – | – | – | – | – | – |
| Weight (kg) | 1 | 30.2 | 5.4 | 29.2 | 4.9 | 23.5 | 3.6 | 21.9 | 2.9 | 28.5 | 5.0 | 27.4 | 7.3 | 28.1 | 5.8 |
| | 2 | 65.2 | 11.5 | 48.3 | 9.3 | 37.9 | 7.4 | – | – | 39.5 | 7.6 | 42.0 | 10.3 | 40 | 9.5 |
| | 3 | 70.5 | 14.0 | 64.3 | 10.2 | 63.8 | 12.8 | 60.4 | 10.9 | – | – | – | – | – | – |
| Secondhand smoke | 1 | 322 | 17.6 | 240 | 13.4 | 267 | 21.6 | 157 | 10.6 | 36 | 9.8 | 121 | 28.7 | 148 | 35.7 |
| | 2 | 257 | 12.4 | 169 | 10.1 | 212 | 19.4 | – | – | 27 | 7.3 | 66 | 15.6 | 86 | 20.8 |
| | 3 | 59 | 2.9 | 41 | 5.5 | 153 | 13.1 | 88 | 6.3 | – | – | – | – | – | – |
| $PM_{2.5}$ mass ($\mu g/m^3$) | 1 | 9.5 | 0.9 | 16.3 | 0.7 | 17.3 | 0.6 | 13.3 | 0.9 | 11.1 | 0.9 | 13.1 | 1.6 | 8.5 | 0.5 |
| | 2 | 7.8 | 1.1 | 16.3 | 0.7 | 17.4 | 0.7 | – | – | 10.6 | 0.5 | 12.7 | 1.4 | 9.7 | 0.5 |
| | 3 | 4.7 | 1.2 | 16.2 | 0.7 | 17.4 | 0.7 | 13.3 | 0.9 | – | – | – | – | – | – |
| $NO_2$ ($\mu g/m^3$) | 1 | 20.2 | 6.2 | 23.0 | 6.6 | 23.5 | 3.0 | 20.1 | 5.3 | 12.2 | 2.2 | 32.1 | 11.0 | 16.8 | 6.9 |
| | 2 | 17.9 | 6.7 | 22.5 | 6.2 | 23.8 | 3.3 | – | – | 11.7 | 1.9 | 31.1 | 10.6 | 19.9 | 8.5 |
| | 3 | 16.3 | 6.0 | 20.7 | 5.3 | 23.6 | 3.0 | 19.9 | 5.1 | – | – | – | – | – | – |
| High urbanization[3] | 1 | 859 | 28.1 | 568 | 34.4 | 281 | 19.8 | 689 | 43.6 | 114 | 32.4 | 140 | 34.1 | 130 | 32.9 |
| Ever asthma[4] | All | 736 | 24.0 | 280 | 14.9 | 159 | 12.6 | 152 | 10.4 | 44 | 12.0 | 23 | 5.5 | 45 | 10.9 |
| Atopic sensitization[5] | All | 1586 | 51.6 | 775 | 45.0 | 538 | 39.2 | 792 | 51.2 | – | – | 24 | 5.7 | 56 | 13.5 |
| Did not move | All | 624 | 20.3 | 748 | 39.6 | 752 | 54.2 | 571 | 36.5 | 313 | 84.8 | 285 | 67.5 | 327 | 79.0 |

– = not available; *FEV0.5 used for 6-year time point instead of FEV1; [1] Time points correspond to approximately 8, 16 and 22 years in BAMSE, 8, 12 and 16 years in PIAMA, 6, 10 and 15 years in GINI/LISA North and South, and 7/8 and 10/11 years in the INMA subcohorts; [2] Defined using parental education in BAMSE, PIAMA, GINI/LISA North and South, and parental occupation in the INMA sub-cohorts; [3] Categorized as a 3-level variable based on tertiles of population density (BAMSE, PIAMA, INMA sub-cohorts) or rural/suburbs/cities (GINI/LISA North and South); [4] Defined as ever self-reported doctor diagnosis of asthma at any follow-up; [5] Any allergen-specific IgE level $\geq$ 0.35 kU/l, with testing conducted against a set of common outdoor and indoor aeroallergens that varied slightly by cohort. Testing was done at each time point for BAMSE, PIAMA, GINI/LISA North and GINI/LISA South, but only at age 4 years for INMA-Sabadell and 7 years for INMA-Valencia.

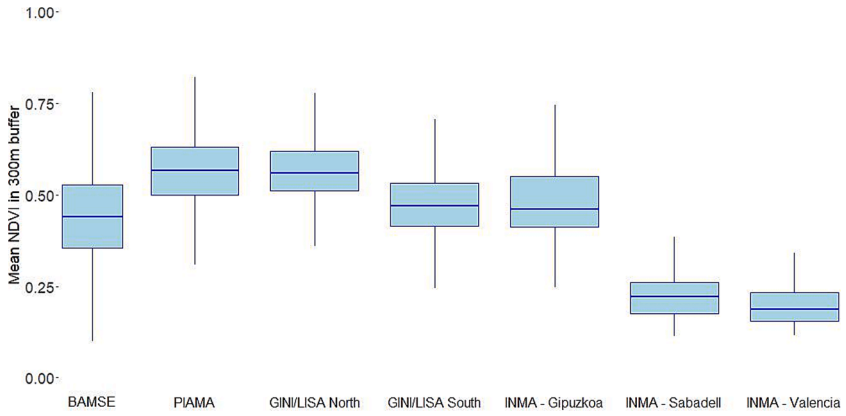


**Fig. 1.** Cohort-specific distribution of mean greenness values in a 300 m buffer around the home addresses at the earliest time point of lung function measurement. Direct comparisons across cohorts are not appropriate as it was not possible to obtain cloud-free images on the same days for all cohorts.

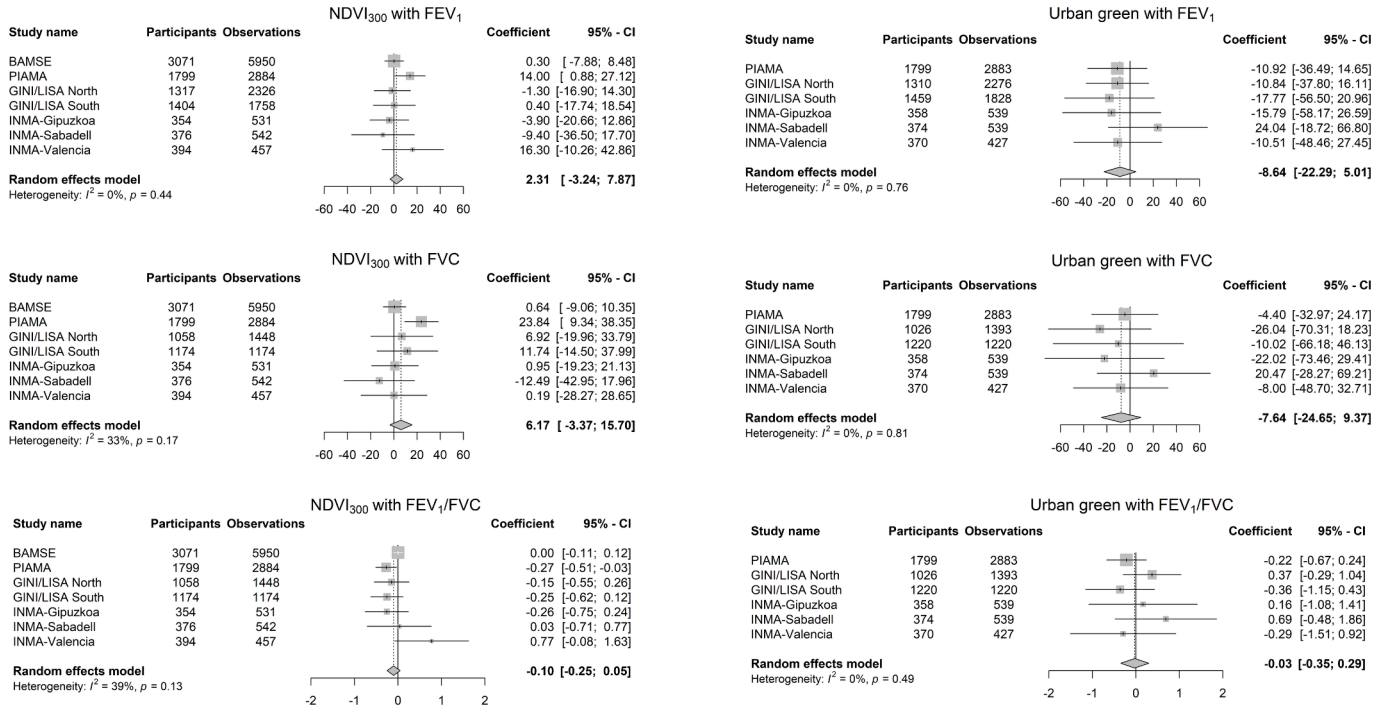


**Fig. 2.** Adjusted associations between $FEV_1$ (top), FVC (middle), and $FEV_1$/FVC (bottom) and mean NDVI values in a 300 m buffer (left) and the presence of an urban green space within a 300 m buffer (right).

vulnerable subgroups, in terms of disease (asthma, atopic sensitization), demographics (sex, socioeconomic status) and environmental factors (pollution, urbanization).

### 4.1. *Interpretation of findings*

Several pathways have been proposed to explain how greenspaces may be associated with lung function. Greenspaces may represent areas with low air pollution, although this relationship is complex (Venter et al., 2024). In the PIAMA cohort, which was the only cohort in which statistically significant beneficial associations were observed in the main models, effect estimates were substantially attenuated when adjusting for annual average $NO_2$, suggesting some confounding by long-term air pollution in this study area. Air pollutants may also modify potential associations between greenspaces and lung function. For example, previous studies have reported beneficial associations between lung function and urban green space in the ALSPAC cohort that were greater among those living in cities and in areas of high $PM_{10}$ concentrations (Fuertes et al., 2020), whereas the opposite was observed in a cross-sectional study in northeastern China (Zhou et al., 2021) (i.e. greening urban areas promotes lung health only in areas with low-moderate air pollution levels). In the current analysis, no effect modification by long-term air pollution was observed.

It is generally suspected that having greenspaces nearby promotes a healthier lifestyle, including increased physical activity (and consequently better respiratory muscle strength and body composition) and better diets (Koch et al., 2024). Some data also suggest that greenspaces may expose children to beneficial microbiota which could contribute to immune system development and better overall respiratory health (Rook, 2013; Zhang et al., 2024). Given the overall null findings observed in this study and because the relevant data are not available for many participants (e.g. accelerometery-based physical activity only available for smaller subsets), these potential underlying pathways were not explored in additional (i.e. mediation) analyses.

If any association does exist between greenspaces and lung function, it is likely that features of the greenspace itself such as type, quality, facilities, cleanliness, accessibility, safety, ecological quality and vegetation species will affect the causal pathways. For example, greenness levels representing all vegetation types may be more important for pathways affecting immune system development whereas structured urban green space may be more relevant for pathways linked to physical activity. However, these hypotheses remain to be tested in the context of greenspace effects on lung function. Moving beyond the two measures considered in this analysis, identifying which allergenic species of trees and plants are present may be particularly relevant for allergic respiratory symptoms and disease (Parmes et al., 2020), if pollen exposure leads to reduced lung function among those sensitized and/or with allergic asthma (Baumbach et al., 2024; Idrose et al., 2021). In the current analysis, only the interaction term between asthma and urban green space was statistically significant for $FEV_1$. Given the number of tests conducted, this may reflect a chance finding, especially as stratified analyses did not reveal a clear at-risk group.

Our null findings are consistent with some previous cross-sectional studies which report no associations after full model adjustments (Agier et al., 2019; Boeyen et al., 2017; Yu et al., 2021). However, other cross-sectional studies report positive (Almeida et al., 2022; Cilluffo et al., 2022; Fernandes et al., 2024; Hartley et al., 2022; Paciência et al., 2019; Squillacioti et al., 2020) or mixed (both positive and negative) associations (Ye et al., 2023). Of note is a recent large cross-sectional *meta*-analysis using lung function data (6–8 years) from four young European birth cohorts, in which $FEV_1$ and FVC values were positively associated with mean greenness in a 300 m buffer (Fernandes et al., 2024). One of the four contributing cohorts in this analysis is the large ALSPAC cohort, for which positive associations were previously reported in a longitudinal analysis (Fuertes et al., 2020). Another was INMA for which cross-sectional associations at approximately seven years of age were positive but not statistically significant (Fernandes et al., 2024). We were able to replicate this finding using the 7/8-year lung function data in INMA (consistent with (Fernandes et al., 2024)), but not the 10/11-year data (e.g. 4.7 [-2.7, 12.2] and −8.7 [-20.9, 3.5] per 0.1 increase, respectively, for the association between greenness in a 300 m buffer and $FEV_1$). This observation emphasizes the importance of longitudinal analyses. It is difficult to determine why a positive association was observed in the longitudinal analysis of the English ALSPAC cohort (Fuertes et al., 2020) but not in any of the five cohorts considered here. Differences in vegetation species, climatic conditions, air pollutants and numerous cultural and contextual factors that vary by study area/country are likely to be contributing factors.

### 4.2. Strengths and limitations

This study included several well characterized large European cohorts with repeated objective measure of lung function obtained using spirometry, which has been called for in greenspace research (Markevych et al., 2017). The inclusion of data from diverse cohorts and study areas likely enhanced the generalizability of our findings. It is indeed notable that in this analysis of data from seven distinct study areas which likely differ in terms of greenspace characteristics and climatic conditions, heterogeneity in the *meta*-analysis was low to moderate and associations were consistently null across cohorts, especially after adjusting for long-term air pollution.

All cohorts collected information using standardized and comprehensive assessment tools including parent- or self-completed questionnaires, which enhanced the reliability of the estimates within cohorts. We chose to combine cohort-specific associations using an individual-participant data *meta*-analysis which allowed a tailored set of confounders to be considered in each cohort (a common list of confounders in all cohorts plus study design variables when necessary), and for differences in the number of times and ages at which lung function was measured across cohorts.

This study does however have limitations. First, not all participants contributed two or more lung function measurements, which could lead to some selection bias. However, results remained null when restricting the study sample to the 4,568 participants who contributed at least two lung function measurements. The ages at which lung function was measured varied by cohort, with the three Spanish cohorts contributing data up to around 11 years and the Swedish BAMSE cohort providing data up to 22 years of age. If the underlying mechanisms linking greenspace to lung function are age-specific, this could have affected our results. However, we observed generally null findings across all cohorts (and consequently ages) considered. Second, questionnaire data may be subject to recall or misclassification bias. Third, it is never possible to fully account for all relevant covariates, so residual confounding (e.g. by socioeconomic status) remains possible.

Fourth, although we attempted to use the same set of limited exposure variables across cohorts, defined *a priori,* in some cases the data were derived from different sources and years (Table S1), with likely differences in sensitivity and spatial resolution, both within a greenspace metric (e.g. how urban green space was defined across cohorts) and between the two metrics used (greenness and urban green space). This may have contributed some heterogeneity to the results. We tried as much as possible to match the year of the greenspace data to that of the lung function measurement, but this was not always feasible, especially for the urban green spaces for which data were only available at one or two years depending on the cohort. Fifth, although exposure misclassification is possible because of moving during the follow-ups and the size of the selected buffer, results remained null when restricting to those who did not move and when using larger buffer sizes of 500 m and 1000 m. Nonetheless, some exposure misclassification remains likely as we only considered greenspaces around homes and did not consider exposures that may occur at schools or during other parts of a participant's daily routine. Finally, we also were unable to consider specific qualities of the greenspaces (such as type, quality, facilities, cleanliness, accessibility, safety) which may have affected whether and how participants interact with them, as well as the extent of allergic plant species present which could lead to adverse effects on lung function among those sensitized (Parmes et al., 2020).

### 4.3. Conclusions

This individual-level participant data *meta*-analysis, including repeated data from five birth cohorts across Europe, did not find associations between greenspace around the home and lung function levels during childhood and adolescence.

## Data statement

Due to data protection reasons the datasets generated and/or analyzed during the current study cannot be made publicly available. The datasets are available to interested researchers from the corresponding author on reasonable request (e.g. reproducibility), provided the release is consistent with the consent given by the participants of each cohort. Ethical approval might be obtained for the release and a data transfer agreement from the respective legal departments may be required.

## CRediT authorship contribution statement

**Carlos A. Valencia-Hernández:** Writing – review & editing, Writing – original draft, Visualization, Resources, Project administration, Methodology, Investigation, Formal analysis, Data curation. **Zhebin Yu:** Writing – review & editing, Resources, Investigation, Formal analysis, Data curation. **Ulrike Gehring:** Writing – review & editing, Resources, Investigation, Data curation. **Gerard H. Koppelman:** Writing – review & editing, Resources, Investigation, Data curation. **Marie Standl:** Writing – review & editing, Resources, Investigation, Data curation.

**Claudia Flexeder:** Writing – review & editing, Resources, Investigation, Data curation. **Tamara Schikowski:** Writing – review & editing, Resources, Investigation, Conceptualization. **Sara Kress:** Writing – review & editing, Resources, Investigation, Data curation. **Erik Melén:** Writing – review & editing, Resources, Investigation, Funding acquisition, Data curation. **Olena Gruzieva:** Writing – review & editing, Resources, Investigation, Data curation. **Mare Lõhmus:** Writing – review & editing, Resources, Investigation, Data curation. **Rosa Faner:** Writing – review & editing, Resources, Investigation, Funding acquisition, Data curation. **Alvar Agusti:** Writing – review & editing, Resources, Investigation, Funding acquisition, Data curation. **Jadwiga A. Wedzicha:** Writing – review & editing, Resources, Investigation, Funding acquisition, Data curation. **Judith Garcia-Aymerich:** Writing – review & editing, Resources, Investigation, Data curation. **Sarah Koch:** Writing – review & editing, Resources, Investigation, Data curation. **Mark Nieuwenhuijsen:** Writing – review & editing, Resources, Investigation, Data curation. **Aitana Lertxundi:** Writing – review & editing, Resources, Investigation, Data curation. **Ana Esplugues:** Writing – review & editing, Resources, Investigation, Data curation. **Ferran Ballester:** Writing – review & editing, Resources, Investigation, Data curation. **Ane Arregi:** Writing – review & editing, Resources, Investigation, Data curation. **Iana Markevych:** Writing – review & editing, Resources, Investigation, Data curation. **Chloe I. Bloom:** Writing – review & editing, Visualization, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Data curation, Conceptualization. **Elaine Fuertes:** Writing – review & editing, Writing – original draft, Visualization, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization.

## Funding

Funding for this work was provided by the CADSET ERS Clinical Research Collaboration, which has been supported by financial and other contributions from the following consortium partners: European Respiratory Society (ERS), AstraZeneca UK Ltd, Chiesi Farmaceutici, GlaxoSmithKline LLC, Menarini and Sanofi-Genzyme. The BAMSE study was supported by the Swedish Research Council, the Swedish Heart–Lung Foundation, the Region Stockholm (ALF and database maintenance), the Swedish Environmental Protection Agency, and the Swedish Research Council for Health Working Life and Welfare. The PIAMA study is supported by The Netherlands Organization for Health Research and Development, The Netherlands Organization for Scientific Research, The Netherlands Asthma Fund, The Netherlands Ministry of Spatial Planning, Housing, and the Environment, The Netherlands Ministry of Health, Welfare and Sport and the National Institute for Public Health and Environment (RIVM). The GINIplus study was mainly supported for the first 3 years of the Federal Ministry for Education, Science, Research and Technology (intervention arm) and Helmholtz Zentrum München (former GSF) (observation arm). The 4-year, 6-year, 10-year, 15-year and 20-year follow-up examinations of the GINIplus study were covered from the respective budgets of the 5 study centres (Helmholtz Zentrum München (former GSF), Research Institute at Marien-Hospital Wesel/EVK Düsseldorf, LMU Munich, TU Munich and from 6 years onwards also from IUF – Leibniz Research-Institute for Environmental Medicine at the University of Düsseldorf) and a grant from the Federal Ministry for Environment (IUF Düsseldorf, FKZ 20462296). Further, the 15-year follow-up examination of the GINIplus study was supported by the Commission of the European Communities, the 7th Framework Program: MeDALL project. The 15-year and 20-year follow-up examinations were additionally supported by the companies Mead Johnson and Nestlé. The LISA study was mainly supported by grants from the Federal Ministry for Education, Science, Research and Technology and in addition from Helmholtz Zentrum München (former GSF), Helmholtz Centre for Environmental Research – UFZ, Leipzig, Research Institute at Marien-Hospital Wesel, Pediatric Practice, Bad Honnef for the first 2 years. The 4-year, 6-year, 10-year, 15-year and 20-year follow-up examinations of the LISA study were covered from the respective budgets of the involved partners (Helmholtz Zentrum München (former GSF), Helmholtz Centre for Environmental Research – UFZ, Leipzig, Research Institute at Marien-Hospital Wesel, Pediatric Practice, Bad Honnef, IUF – Leibniz-Research Institute for Environmental Medicine at the University of Düsseldorf) and in addition by a grant from the Federal Ministry for Environment (IUF Düsseldorf, FKZ 20462296). Further, the 15-year follow-up examination of the LISA study was supported by the Commission of the European Communities, the 7th Framework Program: MeDALL project. The INMA project has been supported by the Instituto de Salud Carlos III, Red de Centros de investigación en Epidemiología y Salud Pública (RCESP) and CIBER Epidemiología y Salud Pública (CIBERESP), and in part by the Fondo de Investigación Sanitaria, the European Union's 6th and 7th Framework Programmes (Hiwate, Escape, Hitea and Contamed projects), the Ministerio de Educación y Ciencia, the Generalitat de Catalunya, the Centre for Research in Environmental Epidemiology (CREAL) of Barcelona, the Fundació La Caixa, the Fundació Roger Torné, the Consejería de Salud de Andalucía, the Junta the Andalucía, the Conselleria de Sanitat de la Generalitat Valenciana, the CAJASTUR—Caja Asturias, the Spanish Association against the Cancer (AECC) (Delegación Provincial Asturias), the Departamento de Sanidad-Gobierno Vasco, the Diputación Floral de Gipuzkoa, the University of Oviedo, the KUTXA – Caja Gipuzkoa San Sebastián and the city councils of Zumarraga, Urretxu, Legazpi, Azpeitia, Beasain and Azkoitia in Gipuzkoa. ISGlobal acknowledges support from the grant CEX2018-000806-S funded by MCIN/AEI/ https://doi.org/10.13039/501100011033, and support from the Generalitat de Catalunya through the CERCA Program. EF is supported by the Imperial College Research Fellowship. MS has received funding from the European Research Council (ERC) under the European Union's Horizon 2020 research and innovation programme (Grant Agreement No. 949906). IM is supported by the National Science Centre, Poland (grant number 2023/50/E/HS6/00102) and "Strategic research and innovation program for the development of Medical University – Plovdiv" N⁰ BG-RRP-2.004–0007-C01, Establishment of a network of research higher schools, National plan for recovery and resilience, financed by the European Union – NextGenerationEU".

## Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Gerard H. Koppelman reports relationships that include: board membership, funding grants, and speaking and lecture fees. Gerard H. Koppelman reports grant support from the Netherlands Lung Foundation, ZON-MW (VICI grant), European Union, TEVA the Netherlands, GSK and Vertex outside the submitted work (Money to Institution). GHK participated in advisory boards or gave lectures supported by AZ, PURE-IMS, Boehringer Ingelheim and Sanofi (money to Institution).

Jadwiga A. Wedzicha reports relationships that include: board membership, consulting or advisory, funding grants, and speaking and lecture fees. Jadwiga A. Wedzicha reports outside submitted work research grants from Astra Zeneca, Boehringer, Chiesi, GSK, Novartis, fees for lectures and/or advisory boards from AZ, GSK, Sanofi, Gilead, Empirico, Epiendo, Boehringer, Chiesi, Pieris, Pulmatrix.

The other authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Acknowledgements

We thank all families and participants in the BAMSE, PIAMA, GINIplus, LISA and INMA cohorts, and the respective study teams, for their hard work and effort.

## Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envint.2025.109493.

## Data availability

The authors do not have permission to share data.

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