



Full length article

## Neighborhood allergenic trees and lung function from early adolescence up to early adulthood in Germany

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### ABSTRACT

**Introduction:** We investigated whether having more birch trees or more allergenic trees around home in early adolescence was related to worse lung function up to early adulthood in the German cities of Munich and Dresden.

**Methods:** The analytic sample included 1539 participants from the population-based ISAAC II/SOLAR II study who were aged 9–11 at baseline and 19–24 at follow-up. Forced expiratory volume in one second (FEV<sub>1</sub>), forced vital capacity (FVC), and FEV<sub>1</sub>/FVC were measured by spirometry at both time points. The number of birch trees, allergenic trees, and total trees, along with tree cover density and the normalized difference vegetation index (NDVI) were calculated in 300 m buffers around home at baseline. The associations were assessed by generalized least squares regressions with a variance-covariance structure accounting for heteroscedasticity and within-subject correlations.

**Results:** Participants living close to birch trees around age 10 tended to have slightly lower FEV<sub>1</sub> and FVC up to early adulthood. These associations were not restricted to participants with asthma or hay fever. Similar, though much attenuated, associations were found for allergenic trees. No associations were found for the other exposures of interest. We saw some effect modification by ozone, nitrogen dioxide (NO<sub>2</sub>), and study town, but only for associations of NDVI with FEV<sub>1</sub>.

**Discussion:** Birch trees around the childhood home, as proxy of long-term exposure to allergenic birch pollen, were associated with slightly lower lung function up to early adulthood. Future studies on health effects of greenspace exposure should include species of plants.

### 1. Introduction

Increasing construction of housing and infrastructure is pushing

nature out of cities (Zhao et al., 2025). Available urban vegetation is not only limited in its spatial occurrence. It is also endangered due to rapidly changing temperature and precipitation conditions (Esperon-Rodriguez

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et al., 2022). Vegetation species that are typically planted in cities are not only very vulnerable to challenges posed by climate change but are oftentimes suboptimal for respiratory health due to their allergenic potential (Zhao et al., 2025; Nieuwenhuijsen et al., 2024; Markevych et al., 2020). Therefore, careful selection of plant species for cities must, on the one hand, take into account the species' resilience to climate change and, on the other hand, their potential negative impact on respiratory health (Zhao et al., 2025; Nieuwenhuijsen et al., 2024).

Our knowledge of long-term impacts of various plant species on the human respiratory system is surprisingly limited. Published epidemiological research has correlated respiratory health outcomes, such as lung function parameters, with metrics of overall vegetation, like vegetation indices, measurements of tree cover, and with areas covered by nature (e.g., Agier et al., 2019; Cilluffo et al., 2022; Markevych et al., 2023; Paciência et al., 2019; Squillacioti et al., 2019; Xiao et al., 2022; Yu et al., 2021; Zhou et al., 2021). Only one study delved into the interrelation between tree genera and lung function (Baumbach et al., 2024). That study, however, contained an adult population with matured lungs and declining lung function. No such longitudinal studies in younger populations with growing lungs exist, to the best of our knowledge.

In the present effort, we used data from a well-established German population-based cohort with repeated lung function measurements from early adolescence and early adulthood. We used data from tree registries to compute the number of birch trees, allergenic trees, and the total number of trees around home. We supplemented the tree count exposures with two conventional vegetation metrics, the normalized difference vegetation index (NDVI) and the tree cover density around home. We hypothesized that residing in proximity to more allergenic trees during early adolescence would be associated with worse lung function in early adolescence and early adulthood because allergenic trees are a potent source of air pollution (Idrose et al., 2022). We further hypothesized that the detrimental association between allergenic trees and lung function would be stronger in (a) settings with high ozone or nitrogen dioxide (NO<sub>2</sub>) levels (since ozone and NO<sub>2</sub> might increase pollen allergenicity (Sénéchal et al., 2015)) and (b) in participants with asthma or hay fever (since allergenic pollen can exacerbate already existing allergies (Erbas et al., 2018) and thereby decrease lung function).

## 2. Methods

### 2.1. Study design and population

In 1995/6, children aged 9–11 from Dresden and Munich were recruited as part of Phase II of the International Study of Asthma and Allergies in Childhood (ISAAC II) using community-based random samples (Weiland et al., 1999; Weiland et al., 2004). In 2002/3, participants were recontacted for the first time for the Study on Occupational Allergy Risks I (SOLAR I) when they were aged 16–18 years. The second follow-up happened in SOLAR II (Heinrich et al., 2011) from 2007 to 2009 when participants were aged 19–24 years. Of the 6399 children who participated in ISAAC II, 3785 participated in SOLAR I, and, of those, 2051 participated in SOLAR II. ISAAC II and SOLAR II included a questionnaire and a clinical examination, SOLAR I only a questionnaire. Since our analysis required lung function measurements, we used data from ISAAC II and SOLAR II, but none from SOLAR I. To make their chronological order obvious, we shall use the term “baseline” to refer to ISAAC II and the term “follow-up” to refer to SOLAR II in the remainder of the text.

996 baseline and 1081 follow-up participants had complete data for lung function outcomes, spatial exposures of interest, and adjustment variables and were used in our analysis. Supplementary Table S1 details the stepwise construction of the analytic sample. 458 participants contributed only baseline, 543 only follow-up, and 538 both baseline and follow-up lung function data to the analysis. Further information about the structure of the analytic sample can be found in

Supplementary Table S2.

The Ethical Committees of the Medical Faculty of the University of Dresden and of the Bavarian Chamber of Physicians approved all phases of the study. Written informed consent, including permission to link the data from all study phases, was obtained from the participants' legal guardians at baseline and from the participants at follow-up.

### 2.2. Lung function outcomes

We considered three lung function outcomes, all based on spirometry before bronchial challenge. The forced expiratory volume in one second (FEV<sub>1</sub>) measures the maximum volume of air that a person can forcefully exhale within the first second after having taken a deep breath. The forced vital capacity (FVC) measures the maximum total volume of air that a person can forcefully exhale after having taken a deep breath. The FEV<sub>1</sub>/FVC ratio, a parameter reflecting airway obstruction, was included as a secondary outcome. Lung function was measured at baseline (ISAAC II) and at follow-up (SOLAR II) according to American Thoracic Society criteria (American Thoracic Society, 1995). In addition, we used the `zscore_GLI` function from R's (version 4.5.0; R Core Team, 2025) `rspirometry` package (version 0.5) to compute z-scores according to the 2012-equations from the Global Lung Function Initiative (GLI; Quanjer et al., 2012).

### 2.3. Exposures

All exposures were assessed around or at the participant's baseline home address in the year of the baseline lung function measurements.

#### 2.3.1. Tree counts

We used tree registry data to determine the number of birch trees, the number of allergenic trees, and the total number of trees in 300 m buffers. We selected the 300 m buffer radius following recommendations in Zare Sakhvidi et al. (2025) because it is large enough to be a good approximation for the neighborhood around home in compact European cities while being small enough to account for the limited mobility of our study participants who were aged around 10 at baseline when exposures were assessed. We also conducted sensitivity analyses for 100 m, 500 m, and 1000 m buffers to check the robustness of results as described below. The Dresden tree registry data were provided by the city's authority for urban greening and waste management (“Amt für Stadtgrün und Abfallwirtschaft”) in August 2023 and contained 112,690 individual trees. The year of planting was known for 80.2% of trees and included years between 1423 and 2022. The tree genus that was required for identifying birch trees and for classifying trees into allergenic and non-allergenic as described below was known for 95.9% of trees. The Munich tree registry data were provided by the city's construction department's horticulture division (“Baureferat Gartenbau”) in July 2024 and contained 172,266 individual trees. In Munich, tree genus and year of planting were only available for those trees of the tree registry that were located inside the area enclosed by the “Mittlerer Ring” ring road that surrounds the central part of Munich. From now on, we will refer to this area, which corresponds to 14.3% of the city's total area and contains 45.3% of the trees listed in the tree registry, simply as “central Munich”. For 42.9% of the tree registry trees in central Munich, we knew whether they had been standing at their current location for 0–3, 3–15, 15–30, 30–60, or more than 60 years, and for 94.2% the genus was known.

When assigning tree counts around the participants' baseline home addresses in the year of the baseline lung function measurements, we ignored trees that had not yet been planted according to the tree registries. When the year of planting was missing for a tree, we assumed that the tree was too old for its year of planting to be known and included the tree in the tree counts. Trees without information on genus were ignored when counting birch trees and allergenic trees. Because information on tree genus was only available for central Munich, participants from Munich with baseline addresses outside this area had to

be excluded from analyses involving these tree-genus-based exposures.

The classification of tree genera into allergenic and non-allergenic was taken from Markeyvych et al. (2020), where it was developed for use in a German context in a collaboration of epidemiologists and plant biologists. In brief, a tree had to satisfy three criteria to be classified as allergenic. First, its genus had to be among the tree genera whose tree pollen were routinely monitored in Germany (see the pollen calendar at <http://www.pollenstiftung.de/pollenvorhersage/pollenflug-kalender>). Second, there had to be at least one tree species of the same genus as the tree whose pollen allergens had previously been described in a published study, or whose pollen was characterized in a published study as causing allergic reactions on contact, or whose sensitization or allergenicity rates had been reported. Third, for at least one tree species of the same genus as the tree [www.allergen.org](http://www.allergen.org) had to list an aeroallergen. By this definition, the following tree genera occurring in the Dresden and Munich tree registries were classified as allergenic: *Alnus* (alder), *Betula* (birch), *Carpinus* (hornbeam), *Corylus* (hazel), *Fagus* (beech), and *Fraxinus* (ash). This list very closely matches the list of tree genera with very strong, strong, or moderate allergenicity that De Weger et al. (2024) produced independently for the neighboring Netherlands. Of the trees in the respective tree registry, 13.1% were classified as allergenic in Dresden and 15.7% in central Munich.

### 2.3.2. Tree cover density

We assigned tree cover density, i.e., the percentage of an area covered by tree canopy, for 300 m buffers. Assignments were based on the earliest available tree cover density data from the European Union's Copernicus program found at <https://land.copernicus.eu>. The data had a resolution of 20 m and were computed using satellite images from 2011 through 2013 (<https://doi.org/10.2909/91687ef2-f907-4f84-81f7-c9c81980c306>).

### 2.3.3. Greenness

We approximated the degree of vegetation around home using the normalized difference vegetation index (NDVI; Tucker, 1979). NDVI is based on the fact that the fractions of spectral reflectance of the near-infrared band (NIR) and the red band (RED) differ for areas with different land cover and is computed from these fractions as  $NDVI = (NIR - RED) / (NIR + RED)$ . The index ranges from -1, for water-covered areas, over 0, for areas without vegetation, to +1, for areas fully covered by vegetation. In a first step, we created maps of NDVI values around baseline covering the Dresden and Munich study areas. For this purpose, we used Landsat 5 Thematic Mapper Collection 2 Level 2 satellite images with a resolution of 30 m that were provided by the United States Geological Survey at <https://earthexplorer.usgs.gov/>. Our choice of satellite images from the pool of available images was guided by several considerations. Images had to be from around the time when baseline lung function was measured. The time gap between the images covering Dresden and Munich had to be minimal to increase comparability. Images had to be from the warm season of the year when vegetation contrasts are largest. Images had to be free of clouds, at least in areas around baseline addresses. In the end, we selected images for Dresden and Munich that were taken on August 7, 1997, and August 14, 1997, respectively (see Supplementary Table S3). Before using the values from the near-infrared and red bands of the chosen satellite images to compute the NDVI values according to the above formula, we followed the specifications in the Landsat product guide (U.S. Geological Survey, 2021) by setting values outside the valid range (7273–43636) to missing, multiplying by a scale factor (0.0000275), and adding an offset (-0.2). In a second step, we used the previously created NDVI maps to assign each participant the average NDVI value computed over a 300 m buffer.

### 2.3.4. Air pollution

We included ozone and NO<sub>2</sub> in the analysis since there is experimental evidence that they can increase pollen allergenicity (Sénéchal

et al., 2015). Mean annual ozone and NO<sub>2</sub> concentrations (in µg/m<sup>3</sup>) for the year when baseline lung function was measured were assigned directly at the baseline home address. The assignments were based on air pollution maps for 2010 at a 100 m resolution developed by the Effects of Low-Level Air Pollution: A Study in Europe project (ELAPSE; [www.elapseproject.eu](http://www.elapseproject.eu)) (de Hoogh et al., 2018). Historical annual air pollution concentrations modelled by the Danish Eulerian Hemisphere Model (DEHM; Brandt et al., 2012) at a coarser resolution of 26 km and subsequently rescaled to the NUTS-1 administrative regions of the study towns (Saxony for Dresden, Bavaria for Munich) were used to back extrapolate the 2010 ELAPSE air pollution estimates to baseline years using the difference method in line with Baumbach et al. (2024).

## 2.4. Statistical analysis

The associations between the three lung function outcomes (FEV<sub>1</sub>, FVC, FEV<sub>1</sub>/FVC) and the five exposures of interest (number of birch trees, number of allergenic trees, total number of trees, tree cover density, NDVI) were assessed in separate linear regressions. This gave rise to 15 main models. All five exposures of interest were baseline exposures: they were assessed at baseline in 300 m buffers around the participant's baseline home address. Lung function outcomes were measured at baseline and at follow-up. Not all participants had their lung function measured twice, some had measurements only at baseline and some only at follow-up.

Based on literature research and in line with previous studies, we identified the following set of adjustment variables: sex (female vs. male), age (in years), height (in cm), weight (in kg), parental socioeconomic status (SES; low vs. high), pollen season at the time of lung function measurement (no pollen season from October through January vs. tree pollen season from February through April vs. grass pollen season from May through July vs. ragweed and mugwort pollen season from August through September; see Markeyvych et al. (2020) and the pollen calendar at <http://www.pollenstiftung.de/pollenvorhersage/pollenflug-kalender>), study town (Dresden vs. Munich), and study time point (baseline vs. follow-up). Of these adjustment variables, only the values of age, height, weight, pollen season, and study time point differed between baseline and follow-up.

Since lung function was measured around age 10 and then again around age 22, when it had increased substantially, lung function outcomes were not only correlated within subjects but also had different variances at baseline and follow-up. Both within-subject correlation and heteroscedasticity violate assumptions of Ordinary Least Squares (OLS) regression. If not explicitly modeled they can make OLS inefficient and produce biased effect estimates and invalid standard errors. To find an appropriate variance-covariance and fixed-effects structure for the linear models that would account for heteroscedasticity and within-subject correlation and omit superfluous model terms (main effects and interactions), we followed the approach outlined in Zuur et al. (2009). In short, we started from a model with a minimal variance-covariance structure, i.e., uncorrelated errors with constant variance, and a maximal fixed-effects structure consisting of the above set of adjustment variables as well as candidate interaction terms identified with the help of R's `interaction.plot` function: two-way interaction terms for study time point with sex, age, and study town, and for sex with study town, and a three-way interaction term for study time point, study town, and sex. In the next step, we used regression residual diagnostics to incrementally augment the variance structure until the regression residuals were homoscedastic and uncorrelated. This resulted in a block-diagonal variance-covariance matrix for the error terms with one block per participant and only zeros off the block diagonal. The block size was 1×1 for participants for whom lung function was available at only one time point and 2×2 for participants with lung function available at baseline and follow-up. The latter 2×2 blocks allowed for a non-zero covariance between error terms for baseline and follow-up lung function outcomes, which models the within-person correlation of lung

function values over time. Error terms for (i) baseline lung function outcomes, (ii) follow-up lung function outcomes of female participants, and (iii) follow-up lung function outcomes of male participants were allowed to have different variances. This reflected the fact that the sex-specific differences in lung function were small at baseline around age 10 but pronounced at the time of the follow-up around age 22, when men tended to have noticeably larger lungs than women. In total, the error term's variance-covariance matrix had four free parameters: one covariance and three variances. In a final step, we used stepwise backward selection in an attempt to simplify the fixed-effects structure by dropping, one by one, the three-way interaction term and variables not appearing in interaction terms. Only the removal of the parental SES variable did not deteriorate the model fit as judged by likelihood ratio tests on nested models. We decided to keep the parental SES variable anyway because it is a potential confounder and the cost of estimating the single free parameter that it added to the models is negligible. Therefore, the maximal fixed-effects structure that we described above was adopted unchanged for the main models. Models were estimated using Generalized Least Squares (GLS) regressions as implemented in the *gls* function of R's *nlme* package (version 3.1-168; Pinheiro and Bates, 2000).

In addition, we estimated Generalized Additive Models (GAMs) with a smooth (cubic regression spline) effect for the exposure of interest and otherwise the same fixed-effects and variance structure as the main models to explore potential non-linear exposure-outcome relationships. These models were fitted using the *gamm* function of R's *mgcv* package (version 1.9-1; Wood, 2017).

To check for effect modification by ozone and NO<sub>2</sub> tertiles (low vs. medium vs. high), asthma (never vs. ever), hay fever (never vs. ever), and study town (Dresden vs. Munich), we analyzed the respective strata separately.

In addition to the GLS regressions with exposures assessed in 300 m buffers around home, we conducted the following sensitivity analyses both for the main models and for the stratified analyses. To ensure that results do not depend on the method of estimation, we estimated all models with Generalized Estimating Equations (GEE) using the *geeglm* function of R's *geepack* package (version 1.3.12; Halekoh et al., 2006), where we specified a block-diagonal variance-covariance matrix with one block per participant, non-zero correlation between baseline and follow-up, and different variances for baseline, follow-up women, and follow-up men that we specified as proportional to the variance of the outcome variable in the corresponding subset of the data. We used GEE only in sensitivity analyses and otherwise preferred GLS because the latter estimates variance parameters from the data while the former requires them to be known a priori. To check the robustness of associations with respect to changes of the buffer size used to assess exposures around home, we estimated models with exposures of interest assessed in 100 m, 500 m, and 1000 m buffers. Cross-sectional associations at baseline and follow-up were assessed with models that used only baseline or only follow-up lung function measurements. In line with the variance structure described above, the models that used only follow-up lung function measurements allowed for different error term variances for female and male participants.

For the main models only, we assessed the degree of confounding by ozone and NO<sub>2</sub> via additional adjustment for mean annual concentration of ozone and NO<sub>2</sub> at the baseline home address, respectively. We also estimated the main models with the three lung function outcomes replaced by their respective GLI-2012 z-scores.

We present effect estimates as point estimates accompanied by 95% confidence intervals (CIs) (e.g., Nuzzo, 2014; Wasserstein and Lazar, 2016; Wasserstein et al., 2019). We considered an association to have an effect direction in a given analysis if at least three quarters of the exposure's effect estimate's 95% CI were either positive or negative. Similarly, we considered two stratified analyses for the same outcome and exposure but different strata of a stratifying variable to show evidence of effect modification if the 95% CIs of the exposure's effect

estimates overlapped by no more than one quarter of their respective widths. To increase the robustness of findings, we concentrated on results that could be reproduced in at least half of the conducted analyses. In the main models, we concentrated on reproducible effect directions, in the stratified analyses, on reproducible effect differences.

### 3. Results

Descriptive statistics of the analytic sample can be found in Supplementary Table S4. A comparison in terms of demographic characteristics of participants who contributed both baseline and follow-up lung function measurements to the analysis, participants who contributed only baseline, and participants who contributed only follow-up lung function measurements did not reveal any differences for sex, age, or study town but found the proportion of participants from parents with high SES to be consistently higher in participants who participated in the follow-up study than in participants who participated only in the baseline study (62% vs. 53%). Visual inspection of the smooth exposure-outcome relationships estimated by GAMs did not reveal any non-linearities and justified the choice of linear models.

#### 3.1. Main models

Fig. 1 depicts the exposure effect estimates for the 15 main models. They show lower FEV<sub>1</sub> and FVC values in participants with birch trees around home. Every additional 10 birch trees in the 300 m buffer around the baseline home address changed FEV<sub>1</sub> by -20.5 mL on average; possible values for the true average FEV<sub>1</sub> change that were most compatible with our data, given our statistical model, ranged from -38.9 to -2.0 mL (95% CI). This corresponds to 37.8% of the difference between mean FEV<sub>1</sub> in 10- and 11-year-olds in our study sample. The average change for FVC was -28.1 mL with 95% CI from -49.1 to -7.2 mL, which corresponds to 49.5% of the difference between mean FVC in 10- and 11-year-olds in our study sample.

Table 1 shows that both associations had consistent effect direction when estimated using GEE (Supplementary Fig. S1), with exposures assessed in 500 m and 1000 m buffers (Supplementary Figs. S3 and S4), in cross-sectional models using only baseline or only follow-up outcomes (Supplementary Fig. S5 and S6), under additional adjustment for ozone and NO<sub>2</sub> (Supplementary Fig. S7), and when using GLI-based z-scores of the lung function outcomes (Supplementary Fig. S8). The association of birch trees with FEV<sub>1</sub> was also reproduced with exposures assessed in 100 m buffers (Supplementary Fig. S2).

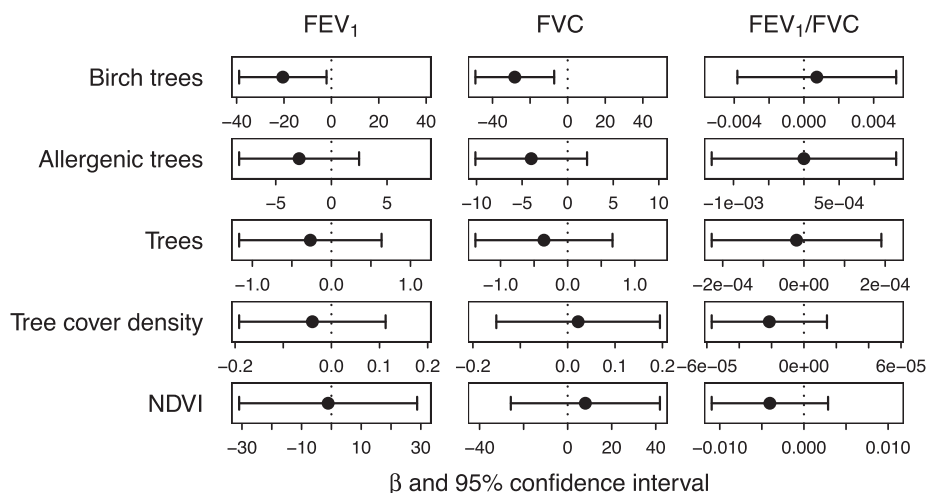
Associations of allergenic trees with FEV<sub>1</sub> and FVC, though reproduced in the majority of analyses, had noticeably smaller effect sizes than those of birch trees. Two other associations that were consistent across analyses were those of tree cover density and NDVI with the FEV<sub>1</sub>/FVC ratio. However, their effect sizes were very small.

Supplement 2 (CSV file) contains the numeric values for all exposure effect estimates.

#### 3.2. Effect modification

In the stratified analyses, we saw a "harmful" association between NDVI and FEV<sub>1</sub> for participants who had a baseline home address with mean annual ozone concentration in the high ozone tertile and a "beneficial" association for participants who had a baseline home address with mean annual ozone concentration in the low ozone tertile (Supplementary Table S5 and Figs. S9–S15). For NO<sub>2</sub> we observed the opposite, i.e., a "beneficial" association between NDVI and FEV<sub>1</sub> in low NO<sub>2</sub> settings and a "harmful" association in high NO<sub>2</sub> settings (Supplementary Table S6 and Figs. S16–S22).

No reproducible indications of effect modification were found for asthma (Supplementary Table S7 and Figs. S23–S29). A suggestive effect modification of the association between allergenic trees and FEV<sub>1</sub> by hay fever was not robust because reproducibility across buffer sizes was



**Fig. 1. Main models in 300 m buffers.** Tree counts were scaled by 10 trees, tree cover density by 10%, and NDVI by 0.2. Abbreviations: FEV<sub>1</sub> — forced expiratory volume in one second, FVC — forced vital capacity, NDVI — normalized difference vegetation index.

**Table 1**

**Summary of main (= unstratified) analyses.** Rows represent types of analyses. Columns represent exposure-outcome combinations. Cells with dark (light) gray background mark analyses in which at least three quarters of the values in the 95% confidence interval (CI) of the exposure’s effect estimate were negative (positive). In other words, dark gray cells mark “harmful tendencies”, light gray cells “beneficial tendencies.” Abbreviations: FEV<sub>1</sub> — forced expiratory volume in one second, FVC — forced vital capacity, GEE — generalized estimating equations, GLI — Global Lung Function Initiative, NDVI — normalized difference vegetation index, NO<sub>2</sub> — nitrogen dioxide.

	FEV <sub>1</sub>	FVC	FEV <sub>1</sub> /FVC	
	Birch trees	Birch trees	Birch trees	Details in Figure
	Allergenic trees	Allergenic trees	Allergenic trees	
	Trees	Trees	Trees	
	Tree cover density	Tree cover density	Tree cover density	
	NDVI	NDVI	NDVI	
300 m buffers				
GEE				
100 m buffers				
500 m buffers				
1000 m buffers				
Only baseline outcomes				
Only follow-up outcomes				
Additionally adjusted for ozone				
Additionally adjusted for NO <sub>2</sub>				
GLI-2012 z-scores				

weak (Supplementary Table S8 and Figs. S30–S36). NDVI was found to have a “harmful” association with FEV<sub>1</sub> in participants from Dresden and a “beneficial” association in participants from Munich (Supplementary Table S9 and Figs. S37–S43). In participants from Dresden, NDVI had a “harmful” association with the FEV<sub>1</sub>/FVC ratio that was either “beneficial” or null in participants from Munich, but in both cases the effect size was tiny.

It is worth emphasizing that we saw no indications of effect modification for the “harmful” association of birch trees with FEV<sub>1</sub> and FVC. In particular, the association was also “harmful” in participants without history of asthma and in participants without history of hay fever, though typically with a weaker effect size than in participants with history of asthma or hay fever. Both study towns showed a “harmful” association with an effect size that seemed stronger in central Munich than in Dresden.

Supplement 2 (CSV file) contains the numeric values for all exposure effect estimates.

## 4. Discussion

### 4.1. Main study findings

The results of this population-based study on 1539 participants from Dresden and Munich with up to two lung function measurements spread about 10 years apart showed that children living close to birch trees around age 10 tended to have lower lung function around age 10 and around age 22. Similar but much attenuated associations were seen for allergenic trees. For the association between NDVI and FEV<sub>1</sub> we saw effect modification by ozone, NO<sub>2</sub>, and study town.

The “harmful” associations of exposure to birch trees at baseline with FEV<sub>1</sub> and FVC were reproduced in cross-sectional analyses that used only baseline or only follow-up lung function values and produced effect estimates pointing in the same direction and of very similar sizes. In other words, the impact of exposure to birch trees around, and most likely before, age 10 is already seen in the lung function values around age 22 except that CIs were unsurprisingly widened by 12 more years of life’s statistical noise. One possible explanation of the observed associations would be that there is a window of vulnerability to exposure to birch trees around or before age 10 and that the decrease in lung function due to exposure to birch trees is not compensated between ages 10 and 22. However, due to the observational nature of our data, the long time between baseline and follow-up, and the absence of information on residential mobility and longitudinal exposure trajectories, we cannot rule out the alternative explanations of sustained exposure or exposure misclassification. The small effect sizes that are statistically detectable but too small to be relevant in a clinical context are another reason not to overinterpret our findings.

We found no trustworthy signs of effect modification by NO<sub>2</sub>, ozone, asthma, hay fever, or study town. The evidence for effect modification by NO<sub>2</sub>, ozone, and study town that we saw for the association of NDVI with FEV<sub>1</sub> is weak because it was not replicated for the closely related FVC outcome. The fact that the association of birch trees with FEV<sub>1</sub> and FVC was also “harmful” in participants without history of asthma and in participants without history of hay fever, though typically with a weaker effect size than in participants with history of asthma or hay fever, might suggest that non-allergy-mediated as well as allergy-mediated pathways play a role.

### 4.2. Comparison with other studies

We are not aware of other studies on lung function that explored the

association with long-term exposure to birch trees, allergenic trees, total number of trees, or tree cover density in a study population whose lung function is still growing. In a previous study, we looked at these associations in populations living in the German cities of Hamburg and Erfurt whose lung function had either plateaued or was in decline (Baumbach et al., 2024). We found “harmful” associations for exposure to birch trees with FEV<sub>1</sub> and FVC whose effect sizes were very similar to those found in the present study. No associations with allergenic trees, total number of trees, tree cover density, or NDVI were found, again in line with the present study.

Our observed null findings for NDVI and lung function are in line with two previous studies in children, adolescents, and young adults. A study using 1033 children aged 6 to 12 from the population-based HELIX cohort consisting of six cohorts from the UK, France, Spain, Lithuania, Norway, and Greece found no associations with percent predicted value of FEV<sub>1</sub> (Agier et al., 2019). Also, Valencia-Hernández et al. (2025) reported recently null findings after having conducted a meta-analysis including 9206 participants from five birth cohorts from Sweden, the Netherlands, Germany, and Spain who had their lung function measured up to three times between ages 6 and 22.

The majority of studies, however, found beneficial associations for NDVI. Fernandes et al. (2024) used the most recent lung function measurement taken between ages 3 and 12 of almost 8000 children from the EU Child Cohort Network from the Netherlands, the UK, France, and Spain in a meta-analysis and reported higher NDVI around home to be associated with higher FEV<sub>1</sub> and FVC z-scores. Fuertes et al. (2020) analyzed data of 7094 children from the ALSPAC birth cohort from the UK where lung function was measured at ages 8, 15, and 24 and reported that higher NDVI was associated with higher FEV<sub>1</sub> and FVC values. A US study by Hartley et al. (2022) on 617 children from the CCAPS birth cohort with lung function measured at age 7 found higher percent predicted values of FEV<sub>1</sub> and FVC in children with higher NDVI around their current home address. Queiroz Almeida et al. (2022) analyzed data of 3278 children from the Porto Metropolitan Area in Portugal who had their lung function measured at age 10 and found that children whose home addresses from birth to age 10 showed a steeper trend toward higher NDVI had higher FEV<sub>1</sub>. However, this association was only seen for 100 m buffers around home but not for 250 m or 500 m buffers. A cross-sectional Chinese study (Zhou et al., 2021) in 6740 children who had their lung function measured once between ages 6 and 15 revealed a link between higher NDVI around schools and higher FEV<sub>1</sub> and FVC. In another Chinese study, Ye et al. (2023) had data on 913 school children with an average age of 11.6 years and used a time-weighted average of NDVI around home, school, and the commuting route as greenness exposure. In their data, FEV<sub>1</sub> tended to be higher in children from medium compared to low greenness settings. We might speculate that some of the inconsistent findings between exposure to NDVI and lung function might be due to the presence or absence of allergenic tree pollen like birch pollen across the different study settings.

We observed the association of NDVI with FEV<sub>1</sub> to be “beneficial” in low and “harmful” in high NO<sub>2</sub> settings. For ozone the effect modification went in the opposite direction, which is not surprising given the strong negative correlation between the two pollutants in our data. However, the fact that we see effect modification for FEV<sub>1</sub> but not for FVC, even though both are measures of lung volume, might indicate that the observed effect modifications are spurious. The CIs that Zhou et al. (2021) reported for their analyses stratified by NO<sub>2</sub> show null associations of NDVI with FEV<sub>1</sub> and FVC in low-to-medium NO<sub>2</sub> settings that turn “beneficial” in high NO<sub>2</sub> settings. Some studies discovered effect modifications by air pollutants other than ozone and NO<sub>2</sub> (Fuertes et al., 2020; Zhou et al., 2021).

#### 4.3. Strengths and limitations

A major strength of this study is the use of tree registry data. With information on individual trees, we were able to apply a sophisticated

classification of trees into allergenic and non-allergenic trees (Markevych et al., 2020) and to count birch and allergenic trees around participant homes. As proxies of long-term exposure to allergenic tree pollen these exposures allowed us to explore a potential pathway between exposure to vegetation and lung function on which allergenicity-unaware indicators like tree counts, tree cover density, or NDVI cannot shed light.

Another strong point are the high-quality, repeated spirometer-based lung function measurements from the well-known ISAAC II and SOLAR II studies covering a period of more than 10 years. The sophisticated statistical modelling, the number of sensitivity analyses, and their use not only for main models but also for stratified analyses are another strength of this study that should increase the robustness of its findings.

We consider the consistent findings on harmful effects of exposure to birch trees between the two study regions Dresden and Munich as another strength of our study. Moreover, our study findings in children are in line with results of a similar study in adults (Baumbach et al., 2024).

The unavailability of follow-up home addresses and the subsequent limitation to baseline exposures is less unfortunate than it might seem. First, even if follow-up home addresses had been available, on their own, they would have been of little use. The statistical problem of accounting for participants having lived a different number of years at baseline and follow-up addresses would have remained and would have required more detailed address histories to solve. Second, the baseline exposures are the more relevant ones. Not only do they precede the lung function measurements; they also represent a much longer window of exposure for most participants. The young adults of the follow-up study were at the beginning of their careers and more likely to have recently moved to their follow-up address than the children of the baseline study who lived with their parents at the baseline address, often for many years.

Even though total number of trees and tree cover density should be positively correlated, their observed Pearson correlations in 300 m buffers around baseline home addresses were negative: −0.14 in Dresden and −0.33 in Munich. A plausible explanation of these, at first sight, counter-intuitive correlations is based on the fact that every tree that a municipal authority digitalizes by recording its location, species, year of planting, height, circumference, health state, etc., represents a financial cost. The ensuing economic incentives would favor digitalization of trees that have high priority for the municipal authority, e.g., trees standing next to roads, and trees that the municipal authority can digitalize with minimal effort, e.g., trees that they planted themselves. By the same logic, trees in non-public green spaces, e.g., private gardens, inner courtyards, and housing estates, trees in public green spaces planted before the age of widespread digitalization, e.g., trees in old parks, or trees of little interest, e.g., trees in city forests, would be less likely to be found in municipal tree registries. These types of tree agglomerations—accurately captured by the objective satellite images underlying tree cover density but systematically underrepresented in municipal tree registries—may produce, and could thus explain, the observed negative correlations. To produce the expected positive correlations, explicit efforts would be needed to make tree registry coverage more comprehensive and more homogeneous. As it happens, such efforts, in the form of a separate digitalization campaign to collect more data on more trees, were invested in central Munich (see section 2.3.1). As a result, the observed Pearson correlation between total number of trees and tree cover density in 300 m buffers around the 129 baseline home addresses in central Munich was 0.48. The most unfortunate consequence of the “blind spots” in the Dresden and Munich tree registries is that tree counts and the satellite-image-based tree cover density and NDVI become incommensurable (Baumbach et al., 2024).

We made the plausible assumption that most tree registry trees without data on year of planting were simply too old for their year of planting to be known and therefore present at baseline. This will inevitably have led to the inclusion of some trees whose year of planting was missing for reasons other than old age and that had not been planted at

baseline. The resulting exposure misclassification goes in the opposite direction of the exposure misclassification introduced by the systematic underrepresentation of certain types of trees in the tree registries and should be minor compared to the latter.

It is important to keep in mind that this study assesses only environmental proximity to sources of tree pollen. It does not include direct measurements of pollen exposure, sensitization status, or inflammatory markers. This severely limits the evidential support that this study can lend to theories of biological pathways linking exposure to tree pollen to lung function.

The tree cover density exposure is likely to have some degree of measurement error due to the temporal mismatch between the Copernicus tree cover data that did not exist for years before 2011 and the baseline study period of 1995/6. Similarly, the fact that, due to lack of cloud-free satellite images, we could not compute NDVI maps as averages over several satellite images but used a single satellite image for each study area introduces some measurement error in the NDVI exposures. However, with spatial contrasts in vegetation being rather stable over time (e.g., de Hoogh et al., 2025; Fuertes et al., 2016; Dadvand et al., 2012), we consider our tree cover density and NDVI exposures useful approximations that are unlikely to have biased our results.

## 5. Conclusions

Using data from local tree registries in two German cities, we observed that children who resided close to birch trees—a proxy for long-term exposure to highly allergenic birch tree pollen—had slightly lower lung function up to early adulthood. Future studies on health effects of greenspace exposure should include species of plants, which might be able to clarify inconsistent findings of the association between NDVI and lung function across different study settings.

## Declaration of generative AI in scientific writing

No generative AI and AI-assisted technologies were used during the preparation of this work.

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## CRediT authorship contribution statement

**Clemens Baumbach:** Writing – review & editing, Writing – original draft, Visualization, Software, Methodology, Formal analysis, Data curation, Conceptualization. **Felix Forster:** Writing – review & editing, Data curation. **Ursula Berger:** Writing – review & editing. **Kees de Hoogh:** Writing – review & editing, Data curation. **Gudrun Weinmayr:** Writing – review & editing, Funding acquisition, Data curation. **Jon Genuneit:** Writing – review & editing, Funding acquisition, Data curation. **Dennis Nowak:** Writing – review & editing, Funding acquisition. **Erika von Mutius:** Writing – review & editing, Funding acquisition. **Christian Vogelberg:** Writing – review & editing, Funding acquisition. **Katja Radon:** Writing – review & editing, Funding acquisition. **Joachim Heinrich:** Writing – review & editing, Supervision.

## Declaration of competing interest

The 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.

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## Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.envint.2026.110259>.

## Data availability

Data will be made available on request.

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