Environmental Research 263 (2024) 120068

Contents lists available at ScienceDirect

Environmental Research

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

Does living close to allergenic street trees affect lung function in German adults?

Clemens Baumbach [a], Ursula Berger [b], Katja Radon [a], Dennis Nowak [a,c], Joachim Heinrich [a,c,d,1,*]

[a] Institute and Clinic for Occupational, Social and Environmental Medicine, University Hospital, Ludwig Maximilian University, Munich, Germany
[b] Institute for Medical Information Processing, Biometry and Epidemiology, Ludwig Maximilian University, Munich, Germany
[c] Comprehensive Pneumology Center Munich (CPC-M), German Center for Lung Research (DZL), Munich, Germany
[d] Allergy and Lung Health Unit, School of Population and Global Health, University of Melbourne, Melbourne, Australia

A R T I C L E I N F O

Keywords:
Spirometry
Birch trees
Tree cover density
Greenness
NDVI
Epidemiology

A B S T R A C T

Introduction: Studies on greenspace and lung function in adults produced divergent results. Some of the adverse findings could be due to long-term exposure to allergenic tree pollen. We investigated whether having more birch trees or more allergenic trees around home is related to worse lung function and whether these exposures confound the association between greenspace and lung function.

Methods: The analytic sample consisted of 874 adults aged 20–44 years at baseline from the German study centers, Erfurt and Hamburg, of the ECRHS cohort study. Spirometric lung function was measured in 1991/92, 2000/01, and 2011/12. We counted trees based on tree registries and classified them into allergenic and non-allergenic. We assessed exposure to greenspace with the normalized difference vegetation index (NDVI), tree cover density, and total number of trees in a 300 m buffer around home. Linear mixed models were used.

Results: The forced expiratory volume in 1 s (FEV_1) and the forced vital capacity (FVC) were decreased in the presence of more birch trees after adjusting for confounders and co-exposures. For every 10 additional birch trees in a 300 m buffer around home, the average change in FEV_1 was −27.6 mL (95% confidence interval (CI): [-58.7, 3.5]). For FVC the average change was −28.2 mL (95% CI: [-62.0, 5.6]). No consistent associations were found for allergenic trees, total trees, tree cover density, or NDVI. Unlike other associations, those of birch trees with FEV_1 and FVC were not moderated by allergic sensitization to birch pollen, history of asthma symptoms or nasal allergies including hay fever, ozone, NO_2, or age.

Discussion: Living close to birch trees had an adverse long-term association with lung function. That tree registries were limited to street trees prevented us from answering the question of a potential confounding of greenspace effects by allergenic neighborhood trees.

1. Introduction

Low lung function has been a recognized risk factor for increased mortality for many years (e.g., Hole et al., 1996). More recently, studies found that even small deviations in lung function parameters, that are still in a range considered clinically normal, were associated with increased mortality risk and later respiratory and cardiovascular problems (Agustí et al., 2017; Vasquez et al., 2017). This makes the search for determinants of low lung function and the development of suitable interventions a worthwhile undertaking.

An umbrella review on greenspace exposure and a broad spectrum of health indicators showed rather consistent beneficial associations with birth weight, physical activity, mental health, cardiometabolic factors, total cardiovascular disease morbidity, and stroke-specific and all-cause mortality (Yang et al., 2021). Studies on greenspace and lung function have reported mixed results showing sometimes beneficial, sometimes

---

[*] Corresponding author. Institute and Clinic for Occupational, Social and Environmental Medicine, University Hospital, Ludwig Maximilian University, Munich, Germany.

E-mail address: Joachim.Heinrich@med.uni-muenchen.de (J. Heinrich).

[1] Postal address: Prof. Dr. Joachim Heinrich, Institute and Clinic for Occupational, Social and Environmental Medicine, University Hospital, LMU Munich, Ziemssenstraβe 5, 80336 Munich, Germany.

https://doi.org/10.1016/j.envres.2024.120068
Received 24 May 2024; Received in revised form 5 September 2024; Accepted 25 September 2024

adverse, and sometimes no associations (Mueller et al., 2022). This leaves room for speculation about the reasons behind these observed inconsistent associations. Suggested explanations include between-study differences in methodology (cross-sectional vs. longitudinal), exposure assessment (normalized difference vegetation index (NDVI) vs. other greenspace metrics), lung function definitions (absolute vs. percent predicted based on prediction equations from the European Respiratory Society Global Lung Function Initiative (ERS-GLI)), climatic conditions (green only in warm season vs. all year round), exposure windows (early life vs. lifetime vs. current), and consideration and levels of co-exposures (e.g., ambient air pollution).

In this study, we focus on one speculative explanation of the mixed results seen for effects of long-term exposure to greenspace on lung function: long-term exposure to allergenic tree pollen (Markevych et al., 2017; World Health Organization, 2016). If the long-term effects of exposure to allergenic pollen turned out to be detrimental for lung function as was previously suggested for short-term effects (Idrose et al., 2022), then the beneficial effects that are typically associated with exposure to greenspace (Markevych et al., 2017), e.g., mitigation of exposure to air pollutants and capacity building by encouraging physical activity in parks that results in better lung function, might be outweighed by the adverse long-term effects of exposure to allergenic pollen in and around green spaces with higher allergenic pollen load. While conventional greenspace metrics like vegetation indices or tree cover density capture vegetation and are, therefore, indirectly also proxies of the long-term exposure to the pollen emitted by this vegetation, they fail to distinguish between allergenic and non-allergenic pollen; they are allergenicity-unaware. To overcome this limitation, we used data on individual trees from municipal tree registries and a previously developed allergenicity classification (Markevych et al., 2020) to count the number of birch trees, whose pollen are very strongly allergenic, and the number of allergenic trees around residential addresses. The two resulting allergenicity-aware greenspace metrics are proxies of long-term exposure to allergenic tree pollen. Our goal with this study was to investigate, first, whether there was an adverse association between long-term exposure to allergenic tree pollen and lung function and, second, whether long-term exposure to allergenic tree pollen was a confounder of the associations between conventional, allergenicity-unaware greenspace metrics and lung function that might explain the observed adverse associations of previous studies.

2. Methods

2.1. Study design and population

The analytic sample consisted of a subset of the Erfurt and Hamburg participants who were recruited for the multi-center, population-based European Community Respiratory Health Survey (ECRHS). Participants were drawn at random from lists of the Offices of Population Censuses. At baseline in 1991/92 (ECRHS I), participants were aged 20–44 years. Since then there were two follow-ups, in 2000/01 (ECRHS II) and 2011/12 (ECRHS III). In Erfurt, 731 participants took part in the ECRHS I medical examination. For ECRHS II, 715 were recontacted and 287 took part in the medical examination. For ECRHS III, 697 were recontacted and 336 took part in the medical examination. In Hamburg, 1251 participants took part in the ECRHS I medical examination. For ECRHS II, a random subset of 900 of these 1251 participants were recontacted and 303 took part in the medical examination. For ECRHS III, 857 of the same 900 randomly selected participants were recontacted and 287 took part in the medical examination. In the end, the analytic sample consisted of 874 subjects, 637 from Erfurt and 237 from Hamburg, with complete data for lung function outcomes, spatial exposures, and confounders. Supplementary Table S1 explains the stepwise construction of the analytic sample. Participants from Erfurt had data from up to three study time points. For participants from Hamburg home addresses at baseline were unknown. Due to the ensuing lack of spatial exposures at baseline, participants from Hamburg contributed to the analyses only with data from the two follow-ups. Supplementary Table S2 contains a detailed listing of the number of participants in the analytic sample with observations from one, two, or three study time points.

Both study centers obtained ethical approval from the appropriate local ethics committees, and participants provided their informed written consent.

2.2. Lung function

In 1991/92, 2000/01, and 2011/12, lung function was measured with spirometry according to a standardized protocol as previously described (Nowak et al., 1996; ECRHS II Steering Committee, 2002; Roca et al., 1998). Briefly, five forced expiratory manoeuvers were performed plus up to four additional manoevers if among the first five manoeuvers there were fewer than two that were considered technically satisfactory. The measured lung function parameters were the forced expiratory volume in 1 s (FEV_1) and the forced vital capacity (FVC). After breathing in as deeply as possible, FEV_1 measures the volume of air that can be exhaled in the first second, while FVC measures the total volume of air that can be forcefully exhaled. Too low FEV_1 values can be a sign of obstructive lung disease where the airways are narrowed and thereby hinder the free flow of air. Too low FVC values can be a sign of restrictive lung disease where lung volume is reduced due to loss of elasticity in the lung tissue or due to factors outside the lungs that limit the expansion of the chest wall or diaphragm. The ratio FEV_1/FVC, which we considered as a secondary outcome, is typically low in patients with chronic obstructive pulmonary disease and is used as a diagnostic tool by medical practitioners.

2.3. Asthma and allergic symptoms

Sensitization to birch allergen was assessed at baseline using a Phazet skin prick test on the forearm using histamine-coated and uncoated Phazets as positive and negative controls, respectively. The test was considered positive if the birch allergen and the positive control had wheal diameters no less than 3 mm and the negative control a wheal diameter less than 3 mm. At each of the three study time points, participants were asked whether, in the last 12 months, (a) they had wheezing and whistling in the chest, (b) were woken with a tight chest, (c) by an attack of shortness of breath, or (d) by an attack of coughing. Anyone who at least once answered affirmatively to at least one of these four questions was considered having a history of asthma symptoms. Similarly, participants who at least once gave an affirmative answer to the question “Do you have nasal allergies including hay fever?” were considered having a history of nasal allergies.

2.4. Greenness

Greenness was assessed with NDVI (Tucker, 1979). This non-specific metric for degree of vegetation exploits the fact that areas with different land cover show characteristic light reflectance patterns. NDVI is computed as (NIR - RED)/(NIR + RED), where NIR and RED are the fractions of spectral reflectance for the near-infrared and red bands, respectively, that are measured using satellite images. NDVI values range from -1 for water over 0 for barren land to 1 for areas completely covered by vegetation.

We used Landsat 5 Thematic Mapper Collection 2 Level 2 satellite images provided by the United StatesGeological Survey (https://earthexplorer.usgs.gov/; last accessed on 2024-03-04). The data came as raster images at 30 m resolution. We selected images taken during the warm season because they show the biggest contrast between areas covered and areas not covered by vegetation. Only images where the areas of interest were free of clouds were chosen. To match the study-specific times of data collection, different satellite images were selected for ECRHS I, II, and III (see Supplementary Table S3). NDVI was computed from the values of the red and near-infrared bands using the above-mentioned formula after replacing values outside the valid range (7273–43636) by zero, multiplying by a scale factor (0.0000275), and adding an offset (−0.2) as specified in the Landsat product guide (U.S. Geological Survey, 2021). Mean NDVI was computed for buffers around home of 300 m radius in line with World Health Organization recommendations (Annerstedt van den Bosch et al., 2016).

2.5. Tree cover density

Tree cover density refers to the percentage of an area that is covered by trees. We used high-resolution tree cover density data from the European Union's Copernicus program that were freely available at https://land.copernicus.eu (last accessed on 2024-04-22). The data came as raster images at 20 m resolution and were available for the years 2012, 2015, and 2018. We used the 2012 dataset (https://doi.org/10.2909/91687ef2-f907-4f84-81f7-c9c81980c306), which is based on satellite images from 2011 to 2013, because it was closest in time to ECRHS III data collection. Mean tree cover density was computed for 300 m buffers around home addresses.

2.6. Tree counts

We used tree registry data to compute the total number of trees, the number of allergenic trees, and the number of birch trees for 300 m buffers around home. The tree counts are specific to the year of lung function measurements because they ignore trees planted after the respective year of lung function measurement. The data for Erfurt were from August 2023 and were provided by the city's authority for gardens and cemeteries ("Garten- und Friedhofsamt"). The Hamburg data were from February 2014, were supplied by the city's authority for environment, climate, energy, and agriculture ("Behörde für Umwelt, Klima, Energie und Agrarwirtschaft"), and are publicly available at https://suche.transparenz.hamburg.de/dataset/strassenbaumkataster-hamburg11 (last accessed on 2024-03-04).

We used the classification of tree genera into allergenic and non-allergenic genera developed by Markevych et al. (2020) in a collaboration between epidemiologists and plant biologists. Briefly, a tree satisfying the following three criteria was classified as allergenic. The first criterion was satisfied by a tree if its genus's tree pollen were monitored in Germany on a regular basis (see the pollen calendar at http://www.pollenstiftung.de/pollenvorhersage/pollenflug-kalender; last accessed on 2024-03-04). The second and third criterion were based on species and were satisfied by a genus if, among the trees of the same genus, there was at least one belonging to a species that satisfied the criterion. The second criterion was satisfied by a species if a published study had described its pollen allergens, or if a published study had described its pollen as causing allergic reactions on contact, or if sensitization or allergenicity rates were reported. The third criterion was satisfied by a species for which www.allergen.org listed at least one aeroallergen. The following genera found in Erfurt and Hamburg were classified as allergenic: *Alnus* (alder), *Betula* (birch), *Carpinus* (hornbeam), *Corylus* (hazel), *Fagus* (beech), and *Fraxinus* (ash). This list is nearly identical with the list of genera with very strong, strong, and moderate allergenicity that De Weger et al. (2024) independently produced for the Netherlands. The Erfurt tree registry contained about 59,000 trees, 18% of which were classified as allergenic. For the Hamburg tree registry, the numbers were 224,000 and 17%.

2.7. Air pollution

We also considered nitrogen dioxide (NO_2) and ozone around home because there is experimental evidence showing that these two air pollutants increase pollen allergenicity (Sénéchal et al., 2015). Average annual concentrations (in $\mu g/m^3$) of NO_2 and ozone at home addresses for the years of lung function measurements were computed based on air pollution maps for 2010 that were produced by the Effects of Low-Level Air Pollution: A Study in Europe project (ELAPSE; www.elapseproject.eu) (de Hoogh et al., 2018) and came at a resolution of 100 m. Using year- and NUTS-1-area-specific air pollution concentrations from the Danish Eulerian Hemispheric Model as reference values we were able to forward and backward extrapolate the 2010-values using the difference and ratio methods to obtain air pollution concentration estimates for the years of lung function measurements (Brandt et al., 2012). Since the correlation between values extrapolated using the difference and ratio methods was 0.92 for NO_2 and 1.00 for ozone, we made the arbitrary choice to use air pollution concentrations based on the difference method in all analyses. The resulting average annual air pollution concentrations were assigned directly at the home address.

2.8. Statistical analysis

To assess the associations between the five greenspace metrics (number of birch trees, number of allergenic trees, total number of trees, tree cover density, and NDVI) and the lung function outcomes (FEV_1, FVC, and FEV_1/FVC), we fitted a linear mixed model with a random intercept for subject to each of the 15 outcome-exposure combinations and adjusted for age, sex, height, pollen season at the time of lung function measurements (no pollen from October to January, tree pollen from February to April, grass pollen from May to July, and ragweed and mugwort pollen from August to September; see Markevych et al. (2020) and the pollen calendar at http://www.pollenstiftung.de/pollenvorhersage/pollenflug-kalender), education (measured by age at end of full-time education: up to 20 years vs. older than 20 years), study town (Erfurt vs. Hamburg), and study time point (ECRHS I vs. II vs. III). Confounders were selected based on literature search and in line with previous studies on ECRHS data. A directed acyclic graph of the conceptual model is shown in Supplementary Fig. S1. Linear mixed models were fitted using the lmer function in the lme4 package (version 1.1–35.1; Bates et al., 2015) of the statistical software R (version 4.1.2; R Core Team, 2021). Hereinafter, we shall refer to the above 15 models and their adjustment set as the main model.

We assessed the impact of confounding in the above models by using main models additionally adjusted for annual average ozone and NO_2 concentrations and for frequency (never/less than once a month/once a month vs. once a week/2–3 times a week vs. 4–6 times a week/every day) and duration (never/30 min vs. 1 h/2–3 h vs. 4–6 h/7 h or more) of moderate to vigorous physical activity (MVPA). The main model co-adjusted for MVPA was fitted to the subset of ECRHS II and III participants for whom physical activity variables were available. We focused on associations that showed consistent directionality in main and sensitivity analyses instead of dichotomizing results according to an arbitrary statistical significance criterion (Nuzzo, 2014; Wasserstein and Lazar, 2016; Wasserstein et al., 2019).

We ran stratified analyses to check for moderation by allergic sensitization to birch pollen at baseline, by history of asthma symptoms or nasal allergies including hay fever, as well as by ozone tertiles, NO_2 tertiles, study town, and age group (20–29 vs. 30–39 vs. 40–49 vs. 50–65 years). We concluded on effect modification based on 95% confidence intervals (CIs) of effect estimates with no or limited overlap between stratified groups and disregarding statistical significance of the effect estimates.

To check that the results do not depend on the choice of statistical model, we refitted the main models using generalized estimating equations (GEE) models as implemented in the geeglm function of R's geepack package (version 1.3.10; Halekoh et al., 2006). The possibility of non-linear relationships between spatial exposures and lung function outcomes was visually assessed by looking at the estimated smoothing curves produced by generalized additive mixed models (GAMM) as implemented in the gamm function of R's mgcv package (version 1.8–39; Wood, 2017). We checked for spatial autocorrelation using Moran's I autocorrelation index implemented in the Moran.I function of

R's ape package (version 5.7–1; Paradis and Schliep, 2019) and using semivariograms implemented in the Variogram function of R's nlme package (version 3.1–155; Pinheiro and Bates, 2000). The impact of different buffer sizes was examined by also running the main models with greenspace metrics assessed in 500 m and 1000 m buffers.

Mutual confounding between allergenicity-aware and allergenicity-unaware greenspace metrics was assessed by comparing effect estimates between single-exposure and two-exposure models.

3. Results

Table 1 summarizes characteristics of the analytic sample. Study town specific versions of this table can be found in Supplementary Tables S4 and S5. Pearson correlations between lung function outcomes and spatial exposures can be found in Supplementary Figs. S2–4. Besides the expected correlations between FEV_1 and FVC (positive), ozone and NO_2 (negative), and total number of trees and number of allergenic trees (positive), we saw a correlation of only −0.02 between total number of trees and tree cover density that was driven by the Hamburg subset where the correlation was −0.22 compared to 0.27 in Erfurt.

The main results both for single- and for two-exposure models are shown in Fig. 1 and numeric values can be found in Supplementary Table S6. In the single-exposure models, we found that FEV_1 and FVC were decreased in the presence of more birch trees. For every 10 additional birch trees in a 300 m buffer around home, the average change in FEV_1 was −27.6 mL; possible values for the true average FEV_1 change that were most compatible with our data, given our statistical model, ranged from −58.7 to 3.5 mL (95% CI). For FVC the average change was −28.2 mL (95% CI: [−62.0, 5.6]). FVC was increased slightly in the presence of more trees and more allergenic trees. The average change in FVC was 1.4 mL (95% CI: [−0.2, 2.9]) for every 10 additional trees and 6.1 mL (95% CI: [−0.4, 12.6]) for every 10 additional allergenic trees.

The comparison of single- and two-exposure models shows how exposure effect estimates changed when a second exposure of opposite allergenicity awareness was added to the model. All associations were rather robust under co-adjustment for a second exposure.

The above associations from single-exposure models remained after additional adjustment for ozone and NO_2 (Supplementary Fig. S5). Additional adjustment for MVPA did not reveal confounding of the exposure-outcome associations by MVPA (Supplementary Fig. S6). Since MVPA variables existed only for ECRHS II and III, the MVPA-adjusted models had to be compared with a main model that was fitted to the ECRHS II + III subset of the data consisting of observations from 588 participants. In this data subset, the associations of birch trees with FEV_1 and FVC remained virtually unchanged. Allergenic trees and total number of trees no longer had a beneficial association with FVC but instead showed adverse associations with FEV_1/FVC and, to a lesser extent, with FEV_1. Tree cover density had an adverse association with FVC and, to a lesser extent, with FEV_1.

We saw evidence of moderation by allergic sensitization to birch pollen at baseline (Fig. 2). The clearest differences were seen for number of allergenic trees and FVC, tree cover density and both FEV_1 and FEV_1/FVC, and NDVI and FEV_1/FVC, where data of the 92 participants who were sensitized to birch allergen at baseline consistently showed adverse associations while data of the 759 participants without allergic sensitization to birch pollen at baseline resulted in null or even beneficial associations. Similar tendencies were observed for number of allergenic trees and FEV_1, total number of trees and both FEV_1 and FVC, tree cover

Table 1
Characteristics of the analytic sample.

Characteristic	Category	ECRHS I		ECRHS II		ECRHS III	
		N/Mean	%/SD	N/Mean	%/SD	N/Mean	%/SD
Town	Erfurt	574	100%	239	71.6%	262	60.9%
	Hamburg			95	28.4%	168	39.1%
Pollen season during lung function measurement	No pollen season	363	63.2%	121	36.2%	73	17%
	Tree pollen season	207	36.1%	104	31.1%	144	33.5%
	Grass pollen season	4	0.7%	94	28.1%	168	39.1%
	Ragweed and mugwort pollen season			15	4.5%	45	10.5%
Sex	Female	301	52.4%	156	46.7%	227	52.8%
	Male	273	47.6%	178	53.3%	203	47.2%
Age in years		32.7	6.7	42.3	6.5	54.0	6.9
Height in cm		170.5	8.8	172.2	9.3	171.0	9.4
Weight in kg		70.3	13.3	75.3	14.2	81.5	18.8
Age at end of full-time education	Up to 20 years	390	67.9%	185	55.4%	266	61.9%
	Over 20 years	184	32.1%	149	44.6%	164	38.1%
History of asthma symptoms	No	454	79.9%	229	68.6%	284	66.7%
	Yes	114	20.1%	105	31.4%	142	33.3%
History of nasal allergies including hay fever	No	498	86.8%	263	78.7%	326	75.8%
	Yes	76	13.2%	71	21.3%	104	24.2%
Allergic sensitization to birch pollen at baseline	No	521	91.6%	287	88.3%	366	88.4%
	Yes	48	8.4%	38	11.7%	48	11.6%
MVPA frequency	Never/Less than once a month/Once a month			172	51.5%	211	49.1%
	Once a week/2–3 times a week			136	40.7%	193	44.9%
	4-6 times a week/Every day			26	7.8%	26	6%
MVPA duration	Never/30 min			172	51.7%	197	45.9%
	1 h/2–3 h			123	36.9%	180	42%
	4–6 h/7 h or more			38	11.4%	52	12.1%
FEV_1 in mL		3839.6	828.9	3647.5	813.0	2990.1	778.4
FVC in mL		4642.2	988.8	4516.1	1001.1	3989.8	948.2
FEV_1/FVC in %		82.9	6.2	81.0	5.9	74.8	7.2
Mean NDVI in 300 m buffer		0.375	0.068	0.384	0.101	0.489	0.105
Tree cover density in 300 m buffer		12.5	6.5	16.6	12.0	19.3	14.0
Total number of trees in 300 m buffer		264.0	151.8	228.9	143.6	214.2	143.5
Number of allergenic trees in 300 m buffer		43.3	35.8	38.4	36.0	35.0	35.2
Number of birch trees in 300 m buffer		5.2	6.5	4.3	5.7	5.3	8.8
Mean annual NO_2 in $\mu g/m^3$		38.7	7.1	37.5	6.8	24.1	5.0
Mean annual ozone in $\mu g/m^3$		64.2	2.9	59.4	3.7	65.6	4.0

For numeric variables, mean and standard deviation (SD) are reported, for categorical variables, the number (N) and percentage (%) of participants in each category. Abbreviations: FEV_1 — forced expiratory volume in 1 s, FVC — forced vital capacity, MVPA — moderate to vigorous physical activity, NO_2 — nitrogen dioxide.

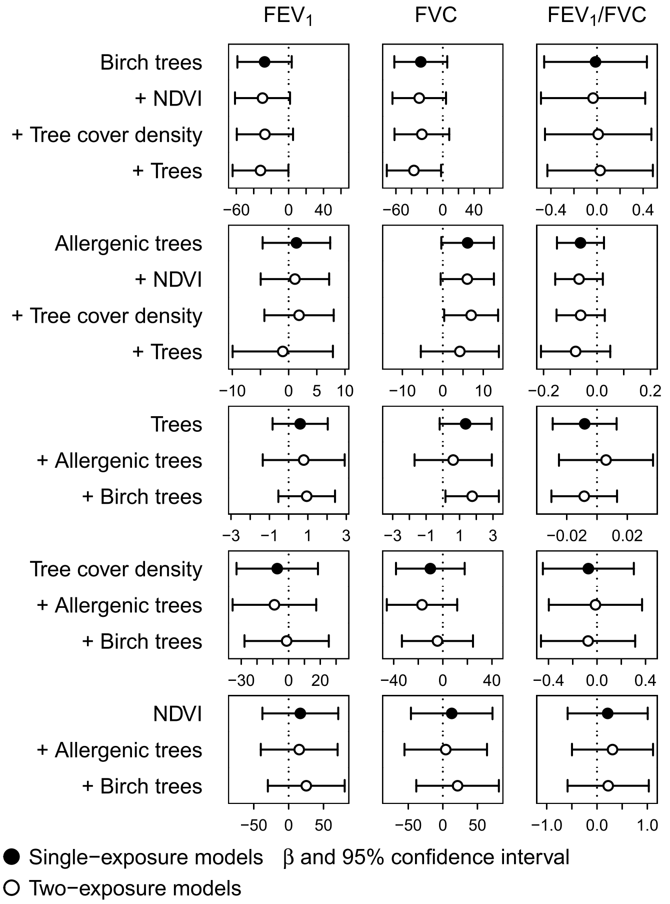

Fig. 1. Comparison of exposure-outcome associations between single- and two-exposure models. Associations of number of birch trees, number of allergenic trees, total number of trees, tree cover density, and NDVI in 300 m buffers around home addresses with lung function outcomes. Estimates are based on linear mixed models with a random intercept for subject. All associations shown in the same subplot refer to the same exposure variable whose name is mentioned in the topmost y-axis label. In each subplot, the estimate at the top comes from the main (single-exposure) model, the other estimates from co-adjusted models in which a second exposure variable was added whose name is mentioned in the respective y-axis label after the "+" sign. Single- and two-exposure models were adjusted for age, sex, height, pollen season, education, study town, and study time point. Models were fitted to the analytic sample of 874 participants. Tree counts were rescaled such that their β estimates represent the average change in the outcome for every 10 additional trees. Similarly, tree cover density was rescaled such that its β estimate represents the average change in the outcome given a 10% increase in tree cover density. NDVI was rescaled such that its β estimates represent the average change in the outcome given a 0.2-unit increase in NDVI. Abbreviations: FEV_1 — forced expiratory volume in 1 s, FVC — forced vital capacity, NDVI — normalized difference vegetation index.

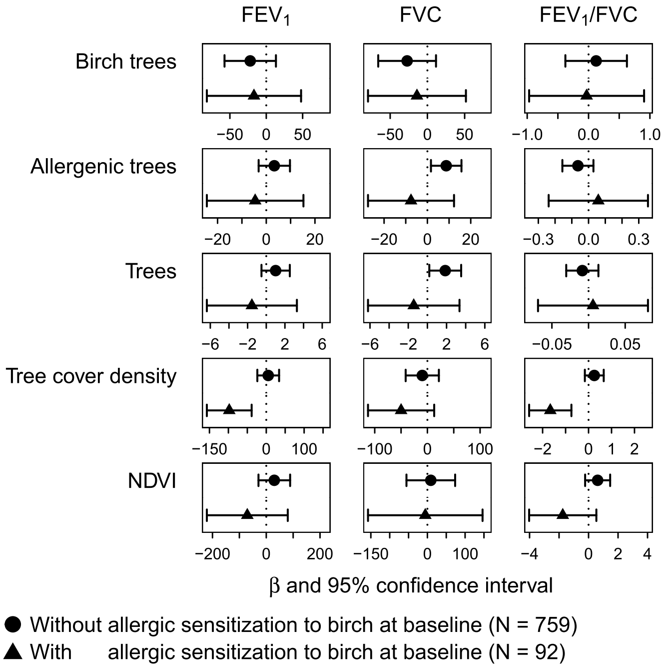

Fig. 2. Stratified by allergic sensitization to birch pollen at baseline. Associations of number of birch trees, number of allergenic trees, total number of trees, tree cover density, and NDVI in 300 m buffers around home addresses with lung function outcomes. Estimates are based on linear mixed models with a random intercept for subject. All models were adjusted for age, sex, height, pollen season, education, study town, and study time point. The models with effect estimates marked by circles were fitted to the subset of 759 participants who were not sensitized to birch allergen at baseline. The models with effect estimates marked by triangles were fitted to the subset of 92 participants who were sensitized to birch allergen at baseline. Tree counts were rescaled such that their β estimates represent the average change in the outcome for every 10 additional trees. Similarly, tree cover density was rescaled such that its β estimate represents the average change in the outcome given a 10% increase in tree cover density. NDVI was rescaled such that its β estimates represent the average change in the outcome given a 0.2-unit increase in NDVI. Abbreviations: FEV_1 — forced expiratory volume in 1 s, FVC — forced vital capacity, NDVI — normalized difference vegetation index.

density and FVC, and for NDVI and FEV_1. Surprisingly, there were no noticeable differences in the effect estimates for number of birch trees. In those with a history of asthma symptoms or nasal allergies including hay fever, we saw adverse associations of tree cover density and NDVI with FEV_1/FVC compared to beneficial associations in participants without such history (Supplementary Fig. S7). Except for an adverse association of tree cover density with FEV_1/FVC in the third and a beneficial association in the second ozone tertile as well as a negative association of total number of trees with FEV_1/FVC in the third and a beneficial association in the second NO_2 tertile, the stratification by ozone and NO_2 tertiles did not show signs of moderation (Supplementary Figs. S8–9). In the Hamburg subset, tree cover density and NDVI had beneficial associations with FEV_1/FVC while the same associations were adverse and null, respectively, in the Erfurt subset (Supplementary Fig. S10). Though the differences were less pronounced, the adverse associations of birch trees on FEV_1 and FVC were stronger in the Hamburg subset. Stratification by age group did not show any marked differences (Supplementary Fig. S11).

Refitting the main single-exposure models using GEE models produced results similar to those obtained using linear mixed models (Supplementary Fig. S12). The GAMM plots (not shown) confirmed that the relationship between exposures and lung function outcomes can be modeled using linear models. Moran's I showed that unlike the spatial exposures which, by definition, showed high spatial autocorrelation, the lung function outcomes — except for FEV_1 and FVC in the ECRHS I Erfurt subset — were not spatially autocorrelated. Semivariograms of the regression residuals showed no signs of spatial autocorrelation which suggests that a statistical model without explicit modeling of spatial autocorrelation is adequate.

Supplementary Figs. S13–14 show the exposure effect estimates from the main models with exposures assessed in 500 m and 1000 m buffers, respectively. Compared to the 300 m buffer, the adverse associations of birch trees with FEV_1 and FVC were attenuated in the 500 m buffer and disappeared in the 1000 m buffer. Since this pattern of attenuation applied to the other exposure effect estimates as well, the 500 m and 1000 m buffers revealed no new associations.

4. Discussion

4.1. Main study findings

In our population-based sample of 874 participants from the German ECRHS cohorts from Erfurt and Hamburg, the number of birch trees in a 300 m buffer around home, as a proxy for long-term exposure to birch pollen, showed the hypothesized harmful association with lung function outcomes FEV_1 and FVC. This association was not limited to or driven by participants who were sensitized to birch allergen at baseline. While no robust adverse associations with FEV_1 and FVC were found for the number of allergenic trees in the full dataset, they appeared in the subset of participants sensitized to birch allergen at baseline. Two-exposure models did not reveal the hypothesized confounding of the associations between allergenicity-unaware greenspace metrics and lung function by allergenicity-aware greenspace metrics.

4.2. Interpretation

Caution is needed when interpreting the results since both tree count and tree cover density variables are afflicted by negative measurement error. A visual comparison of tree cover density with tree locations in the geographic information system software QGIS (QGIS.org, 2024) revealed two issues. First, the tree registries are focused on street trees and contain comparatively few non-street trees, especially in Hamburg. Second, the tree cover density data captured larger groups of trees as found, e.g., in parks, forests, or gardens of housing estates, but often missed street trees, presumably because they were not clustered enough. It follows that the greater the number of non-street trees in an area — a number that is roughly proportional to tree cover density and NDVI — the more our tree count variables underestimated the actual tree counts. Similarly, the greater the number of street trees in an area, the more our tree cover density variable underestimated the actual tree cover density. The measurement error will be more severe in the case of tree count variables because the non-street trees that are omitted in the tree count variables grow more densely than the street trees that are ignored by the tree cover density variable. The above observations explain why the correlation between total number of trees and tree cover density, instead of being strongly positive, was only weakly positive in Erfurt and even weakly negative in Hamburg.

How exposure effect estimates in single-exposure models are biased by the above measurement errors depends a) on the slope of the observed exposure-outcome association and b) on the distribution of the measurement errors over the range of the exposure variable. The impact of b) can be illustrated using the example of the adverse association of birch trees with FEV_1. If areas with fewer street birch trees had more non-street birch trees than areas with more street birch trees, the association identified by our model would be weaker than the true effect birches have. Conversely, more non-street birch trees in areas with more street birch trees would mean that the identified association is stronger than the true effect. However, assuming that the numbers of non-street and street birch trees are independent, the measurement errors would not bias the effect estimate. For two-exposure models, the consequences for exposure effect estimates are more complex and the resulting biases hard to predict because the interdependencies introduced by the measurement errors interact with the confounding relationship on which the two-exposure models were meant to throw light. Therefore, we do not take the overall very similar exposure effect estimates in single- and two-exposure models to suggest absence of confounding between allergenicity-unaware and allergenicity-aware greenspace metrics. Instead, we speculate that the nature of the measurement errors in our tree count variables makes them unsuitable for use in two-exposure models together with tree cover density and NDVI.

4.3. Comparison with other studies

We are not aware of any other studies on adults that explored the long-term effects of allergenic pollen on lung function. However, there are a few studies about the long-term effects of exposure to greenspace on lung function in adults. Chaparro et al. (2018) used data on 16,347 adults from the Understanding Society: The UK Household Longitudinal Survey (UKHLS) and found a beneficial association between the percentage of public green space in the Census Area Statistic ward of residence and the percent predicted FEV_1 based on ERS-GLI prediction equations. Xiao et al. (2022) had data on 50,991 Chinese adults aged 20 and 89 years and saw beneficial associations between NDVI around home and FEV_1, FVC, and FEV_1/FVC. In another Chinese study, Zhang et al. (2023) analyzed data from 2768 adults aged 40 years and older and found beneficial associations between NDVI and both FEV_1 and FVC. In their sample of 3428 adults aged 18–40 years from Norway and Sweden, Nordeide Kuiper et al. (2020) observed that higher NDVI increased the risk of FEV_1 and FVC being below the lower limit of normal as defined using ERS-GLI prediction equations. Markevych et al. (2023) analyzed ECRHS data from 22 study centers and 11 EU countries comprising 5559 adults above the age of 25 and found that higher NDVI was associated with a faster decline in FVC and that having urban green spaces close to home was associated with a faster decline in FEV_1. The lack of any robust associations of NDVI, tree cover density, or total number of trees with lung function that we observed in our data adds to these mixed findings. Moreover, it cannot be excluded that other studies with similar null findings or even studies with, at first sight, counter-intuitive adverse associations fell victim to publication bias and are underrepresented in the literature.

4.4. Strengths and limitations

We consider the use of tree registry data to construct exposure proxies for the long-term exposure to allergenic tree pollen a major strength of this study. Theoretically, long-term exposure to allergenic tree pollen can also be approximated using data from pollen monitoring stations that measure day-to-day variations in pollen counts. But the sparsity of monitoring stations — often no more than one per region — means that spatial exposure contrasts, e.g., within a city, cannot be captured with this approach. Data derived from pollen monitoring sites are important to study short-term health effects, but can hardly be used on their own for the assessment of long-term effects. We did not have time series of daily pollen counts for the times of data collection for the two study towns. If such data were available, one might consider combining spatial data about tree locations with temporal data about pollen counts for spatio-temporal exposure modeling. In addition to birch trees we were able to count allergenic trees in general by making use of a sophisticated classification of trees into allergenic and non-allergenic that was the result of a previous fruitful collaboration between epidemiologists and plant biologists (Markevych et al., 2020). The fact that an independent effort recently produced a nearly identical classification for the Netherlands (De Weger et al., 2024) suggests that the classification is robust. With NDVI, tree cover density, and total number of (mostly street) trees, we used a selection of metrics that capture different aspects of greenspace. The rich data from the ECRHS study is another strength of this study. ECRHS is population-based, has up to three time points per participant over a time window of 20 years, includes potential confounders and effect modifiers, and, with its focus on respiratory health, produced reliable, good-quality, spirometry-based lung function measurements.

However, the ECRHS study was not specifically designed with focus on environmental exposures. No complete lifelong residential histories were recorded. Home addresses are only known at the times of lung function measurements. Information on exposures at home addresses before the start of the study, at school, at work, or while traveling was not available which might have introduced measurement bias. The unfortunate lack of baseline home addresses for Hamburg meant that more than 850 baseline observations could not be used for analysis. The number of participants with data at two or three time points and thus statistical power were further reduced by the fact that the numbers of participants in the follow-ups were noticeably smaller than in the baseline examination.

Besides tree pollen, long-term exposure to allergenic grass or weed pollen might also be an important factor that could help explain the mixed associations between greenspace and lung function. But at least for our study towns, Erfurt and Hamburg, the data on the spatial distribution of grass or weed species or genera, that would allow such an analysis, did not exist.

The 2012 tree cover density data that we used for lack of earlier tree cover datasets reflects the state around the time of ECRHS III data collection. Since the study area's number of trees tends to change rather slowly and since canopy growth is similar over the area, spatial contrasts in tree cover density will be rather stable over time. Therefore, we consider the possible changes over time in tree cover density as a minor point of potential bias.

Above we already mentioned the measurement errors in the exposure variables. An additional source of measurement error in the counts of street trees is due to trees that had to be removed over time, e.g., because of storm damage or poor health. These trees might once have been present in the tree registry but were deleted after they had been removed. Since the resulting underestimation in past tree counts is likely to apply more or less evenly to the study area, spatial contrasts should not be much affected and we consider the increase in risk of bias to be small. The restriction of many tree registries to street trees that is responsible for the underestimated tree counts is a known issue, but not an insurmountable obstacle for using the data for research (e.g., Lai and Kontokosta (2019)). Another promising approach is the classification of trees into dominant tree species with the help of satellite images and phenological reference data as Welle et al. (2022) did for Germany. Unfortunately, the resulting classification into spruce, pine, Douglas fir, larch, beech, oak, and "other broadleaf" omits too many allergenic species as to be useful for answering our study questions.

Another concern in greenspace research is bias due to residential self-selection. Health-conscious, and thus potentially healthier, people might be more likely to move to greener areas because of reduced air pollution and opportunities for physical activity. People who are affected by aeroallergens emitted by green spaces might move away to less green neighborhoods. There might even be reverse causation when people with impaired lung function move to greener neighborhoods in an attempt to reduce their exposure to air pollutants. Inasmuch as greener urban neighborhoods are more expensive to live in and thus favor wealthier citizens, their residents are likely to be healthier than residents of less green areas (Mueller et al., 2022).

5. Conclusions

Using data from municipal tree registries, we found that long-term exposure to birch pollen as approximated by living in areas with more birch trees was associated with decreased lung function in German adults, independent of whether or not they were sensitized to birch pollen. The tree registries' primary focus on street trees prevented us from investigating potential confounding between allergenicity-unaware and allergenicity-aware greenspace metrics. Inclusion of more non-street trees in tree registries would further increase the value of these data for greenspace research.

Funding

This study was specifically funded by the German Research Foundation (G.Z.: KA 4737/2–1 | NO 262/13–1 | HE 3294/12–1) and the Comprehensive Pneumology Center Munich (CPC-M), German Center for Lung Research (DZL), Munich, Germany. In addition, the data used were generated with the financial support of several funding institutions:

ECRHS I: Bundesminister für Forschung und Technologie.

ECRHS II Erfurt: GSF—National Research Centre for Environment and Health, Deutsche Forschungsgemeinschaft (grant code FR 1526/1-1).

ECRHS II Hamburg: GSF—National Research Centre for Environment and Health, Deutsche Forschungsgemeinschaft (grant code MA 711/4–1).

ECRHS III Erfurt: German Research Foundation (grant code HE 3294/10–1).

ECRHS III Hamburg: German Research Foundation (grant codes MA 711/6–1, NO 262/7–1).

The aforementioned funding sources had no involvement in the design of the study, collection, analysis and interpretation of data, writing of the report and decision to submit the article for publication.

CRediT authorship contribution statement

Clemens Baumbach: Writing – review & editing, Writing – original draft, Visualization, Software, Methodology, Formal analysis, Data curation, Conceptualization. **Ursula Berger:** Writing – review & editing. **Katja Radon:** Writing – review & editing. **Dennis Nowak:** Writing – review & editing, Resources, Funding acquisition. **Joachim Heinrich:** Writing – review & editing, Supervision, Resources, Funding acquisition.

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.

Data availability

Data will be made available on request.

Acknowledgments

We thank Annette Wagner from Hamburg's "Behörde für Umwelt, Klima, Energie und Agrarwirtschaft" for pointing us to the website with Hamburg's tree registry data and for sharing links to additional information related to trees and pollen allergens.

We thank Ricarda Schmidt and Dr. Döll from Erfurt's "Garten- und Friedhofsamt" for providing the data of Erfurt's tree registry.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envres.2024.120068.

References

Agustí, A., Noell, G., Brugada, J., Faner, R., 2017. Lung function in early adulthood and health in later life: a transgenerational cohort analysis. Lancet Respir. Med. 5 (12), 935–945. https://doi.org/10.1016/S2213-2600(17)30434-4. Epub 2017 Nov 14. PMID: 29150410.

Annerstedt van den Bosch, M., Mudu, P., Uscila, V., Barrdahl, M., Kulinkina, A., Staatsen, B., Swart, W., Kruize, H., Zurlyte, I., Egorov, A.I., 2016. Development of an urban green space indicator and the public health rationale. Scand J Public Health 44 (2), 159–167. https://doi.org/10.1177/1403494815615444. Epub 2015 Nov 16. PMID: 26573907.

Bates, D., Mächler, M., Bolker, B., Walker, S., 2015. Fitting linear mixed-effects models using Lme4. J. Stat. Soft. 67, 1–48. https://doi.org/10.18637/jss.v067.i01.

Brandt, J., Silver, J.D., Frohn, L.M., Geels, C., Gross, A., Hansen, A.B., Hansen, K.M., Hedegaard, G.B., Skjøth, C.A., Villadsen, H., Zare, A., Christensen, J.H., 2012. An integrated model study for Europe and North America using the Danish Eulerian Hemispheric Model with focus on intercontinental transport of air pollution. Atmos. Environ. 53, 156–176. https://doi.org/10.1016/j.atmosenv.2012.01.011.

Chaparro, M.P., Benzeval, M., Richardson, E., Mitchell, R., 2018. Neighborhood deprivation and biomarkers of health in Britain: the mediating role of the physical environment. BMC Publ. Health 18 (1), 801. https://doi.org/10.1186/s12889-018-5667-3. PMID: 29945580; PMCID: PMC6020450.

de Hoogh, K., Chen, J., Gulliver, J., Hoffmann, B., Hertel, O., Ketzel, M., Bauwelinck, M., van Donkelaar, A., Hvidtfeldt, U.A., Katsouyanni, K., Klompmaker, J., Martin, R.V., Samoli, E., Schwartz, P.E., Stafoggia, M., Bellander, T., Strak, M., Wolf, K., Vienneau, D., Brunekreef, B., Hoek, G., 2018. Spatial PM2.5, NO2, O3 and BC models for western Europe - evaluation of spatiotemporal stability. Environ. Int. 120, 81–92. https://doi.org/10.1016/j.envint.2018.07.036. Epub 2018 Jul 31. PMID: 30075373.

De Weger, L.A., Bakker-Jonges, L.E., De Groot, H., Kuppen, H.H.J.M., Batenburg, W.W., Van Leeuwen, A., Koenders, M., Van Vliet, A.J.H., 2024. Method to develop a regional guide for the allergenic potential of tree pollen. Sci. Total Environ. 926, 171575. https://doi.org/10.1016/j.scitotenv.2024.171575. Epub 2024 Mar 9. PMID: 38461999.

European Community Respiratory Health Survey II Steering Committee, 2002. The European community respiratory health Survey II. Eur. Respir. J. 20 (5), 1071–1079. https://doi.org/10.1183/09031936.02.00046802. PMID: 12449157.

Halekoh, U., Højsgaard, S., Yan, J., 2006. The R package geepack for generalized estimating equations. J Stat Softw 15 (2), 1–11. https://doi.org/10.18637/jss.v015.i02.

Hole, D.J., Watt, G.C., Davey-Smith, G., Hart, C.L., Gillis, C.R., Hawthorne, V.M., 1996. Impaired lung function and mortality risk in men and women: findings from the Renfrew and Paisley prospective population study. BMJ 313 (7059), 711–715. https://doi.org/10.1136/bmj.313.7059.711. PMID: 8819439; PMCID: PMC2352103.

Idrose, N.S., Lodge, C.J., Erbas, B., Douglass, J.A., Bui, D.S., Dharmage, S.C., 2022. A review of the respiratory health burden attributable to short-term exposure to pollen. Int J Environ Res Public Health 19 (12), 7541. https://doi.org/10.3390/ijerph19127541. PMID: 35742795; PMCID: PMC9224249.

Lai, Y., Kontokosta, C.E., 2019. The impact of urban street tree species on air quality and respiratory illness: a spatial analysis of large-scale, high-resolution urban data. Health Place 56, 80–87. https://doi.org/10.1016/j.healthplace.2019.01.016. Epub 2019 Jan 31. PMID: 30711775.

Markevych, I., Schoierer, J., Hartig, T., Chudnovsky, A., Hystad, P., Dzhambov, A.M., de Vries, S., Triguero-Mas, M., Brauer, M., Nieuwenhuijsen, M.J., Lupp, G., Richardson, E.A., Astell-Burt, T., Dimitrova, D., Feng, X., Sadeh, M., Standl, M., Heinrich, J., Fuertes, E., 2017. Exploring pathways linking greenspace to health: theoretical and methodological guidance. Environ. Res. 158, 301–317. https://doi.org/10.1016/j.envres.2017.06.028. Epub 2017 Jun 30. PMID: 28672128.

Markevych, I., Ludwig, R., Baumbach, C., Standl, M., Heinrich, J., Herberth, G., de Hoogh, K., Pritsch, K., Weikl, F., 2020. Residing near allergenic trees can increase risk of allergies later in life: LISA Leipzig study. Environ. Res. 191, 110132. https://doi.org/10.1016/j.envres.2020.110132. Epub 2020 Aug 24. PMID: 32853665.

Markevych, I., Zhao, T., Fuertes, E., Marcon, A., Dadvand, P., Vienneau, D., Garcia Aymerich, J., Nowak, D., de Hoogh, K., Jarvis, D., Abramson, M.J., Accordini, S., Amaral, A.F., Bentouhami, H., Jacobsen Bertelsen, R., Boudier, A., Bono, R., Bowatte, G., Casas, L., Dharmage, S.C., Forsberg, B., Gislason, T., Gnesi, M., Holm, M., Jacquemin, B., Janson, C., Jogi, R., Johannessen, A., Keidel, D., Leynaert, B., Maldonado Perez, J.A., Marchetti, P., Migliore, E., Martínez-Moratalla, J., Orru, H., Pin, I., Potts, J., Probst-Hensch, N., Ranzi, A., Sánchez-Ramos, J.L., Siroux, V., Soussan, D., Sunyer, J., Urrutia Landa, I., Villani, S., Heinrich, J., 2023. Residential greenspace and lung function decline over 20 years in a prospective cohort: the ECRHS study. Environ. Int. 178, 108036. https://doi.org/10.1016/j.envint.2023.108036. Epub 2023 Jun 12. PMID: 37336027.

Mueller, W., Milner, J., Loh, M., Vardoulakis, S., Wilkinson, P., 2022. Exposure to urban greenspace and pathways to respiratory health: an exploratory systematic review. Sci. Total Environ. 829, 154447. https://doi.org/10.1016/j.scitotenv.2022.154447. Epub 2022 Mar 11. PMID: 35283125.

Nordeide Kuiper, I., Svanes, C., Markevych, I., Accordini, S., Bertelsen, R.J., Bråbäck, L., Heile Christensen, J., Forsberg, B., Halvorsen, T., Heinrich, J., Hertel, O., Hoek, G., Holm, M., de Hoogh, K., Janson, C., Malinovschi, A., Marcon, A., Miodini Nilsen, R., Sigsgaard, T., Johannessen, A., 2021. Lifelong exposure to air pollution and greenness in relation to asthma, rhinitis and lung function in adulthood. Environ. Int. 146, 106219. https://doi.org/10.1016/j.envint.2020.106219. Epub 2020 Oct 27. PMID: 33126061.

Nowak, D., Heinrich, J., Jörres, R., Wassmer, G., Berger, J., Beck, E., Boczor, S., Claussen, M., Wichmann, H.E., Magnussen, H., 1996. Prevalence of respiratory symptoms, bronchial hyperresponsiveness and atopy among adults: west and east Germany. Eur. Respir. J. 9 (12), 2541–2552. https://doi.org/10.1183/09031936.96.09122541. PMID: 8980967.

Nuzzo, R., 2014. Scientific method: statistical errors. Nature 506 (7487), 150–152. https://doi.org/10.1038/506150a. PMID: 24522584.

Paradis, E., Schliep, K., 2019. Ape 5.0: an environment for modern phylogenetics and evolutionary analyses in R. Bioinformatics 35, 526–528. https://doi.org/10.1093/bioinformatics/bty633.

Pinheiro, J.C., Bates, D.M., 2000. Mixed-Effects Models in S and S-PLUS. Springer, New York. https://doi.org/10.1007/b98882.

QGIS.org, 2024. QGIS Geographic Information System. QGIS Association. http://www.qgis.org. (Accessed 24 May 2024).

R Core Team, 2021. R: A Language and Environment for Statistical Computing. R Foundation for Statistical Computing, Vienna, Austria. URL. https://www.R-project.org/. Last accessed on 2024-05-24.

Roca, J., Burgos, F., Sunyer, J., Saez, M., Chinn, S., Antó, J.M., Rodríguez-Roisin, R., Quanjer, P.H., Nowak, D., Burney, P., 1998. References values for forced spirometry. Group of the European community respiratory health Survey. Eur. Respir. J. 11 (6), 1354–1362. https://doi.org/10.1183/09031936.98.11061354. PMID: 9657579.

Sénéchal, H., Visez, N., Charpin, D., Shahali, Y., Peltre, G., Biolley, J.P., Lhuissier, F., Couderc, R., Yamada, O., Malrat-Domenge, A., Pham-Thi, N., Poncet, P., Sutra, J.P., 2015. A review of the effects of major atmospheric pollutants on pollen grains, pollen content, and allergenicity. Sci. World J. 2015, 940243. https://doi.org/10.1155/2015/940243. Epub 2015 Dec 24. PMID: 26819967; PMCID: PMC4706970.

Tucker, C.J., 1979. Red and photographic infrared linear combinations for monitoring vegetation. Rem. Sens. Environ. 8 (2), 127–150. https://doi.org/10.1016/0034-4257(79)90013-0.

U.S. Geological Survey. Landsat 4-7 Collection 2 (C2) Level 2 Science Product (L2SP) Guide, Version 4.0, September 2021, Sioux Falls, South Dakota, USA. URL https://www.usgs.gov/media/files/landsat-4-7-collection-2-level-2-science-product-guide (Last accessed on 2024-06-27).

Vasquez, M.M., Zhou, M., Hu, C., Martinez, F.D., Guerra, S., 2017. Low lung function in young adult life is associated with early mortality. Am. J. Respir. Crit. Care Med. 195 (10), 1399–1401. https://doi.org/10.1164/rccm.201608-1561LE. PMID: 28504596; PMCID: PMC5443902.

Wasserstein, R.L., Lazar, N.A., 2016. The ASA statement on p-values: context, process, and purpose. Am. Stat. 70 (2), 129–133. https://doi.org/10.1080/00031305.2016.1154108.

Wasserstein, R.L., Schirm, A.L., Lazar, N.A., 2019. Moving to a world beyond “$p < 0.05$”. Am. Stat. 73 (Suppl. 1), 1–19. https://doi.org/10.1080/00031305.2019.1583913.

Welle, T., Aschenbrenner, L., Kuonath, K., Kirmaier, S., Franke, J., 2022. Mapping dominant tree species of German forests. Remote Sens 14 (14), 3330. https://doi.org/10.3390/rs14143330.

Wood, SN, 2017. Generalized Additive Models: An Introduction with R, 2nd edition,. Chapman and Hall/CRC. https://doi.org/10.1201/9781315370279.

World Health Organization, 2016. Urban green spaces and health - a review of evidence. Available at: https://www.who.int/europe/publications/i/item/WHO-EURO-2016-3352-43111-60341. Last accessed on 2024-03-19.

Xiao, Y., Gu, X., Niu, H., Meng, X., Zhang, L., Xu, J., Yang, L., Zhao, J., Zhang, X., Bai, C., Kang, J., Ran, P., Shen, H., Wen, F., Huang, K., Chen, Y., Sun, T., Shan, G., Lin, Y., Wu, S., Zhu, J., Wang, R., Shi, Z., Xu, Y., Ye, X., Song, Y., Wang, Q., Zhou, Y., Ding, L., Li, D., Yao, W., Guo, Y., Xiao, F., Lu, Y., Peng, X., Zhang, B., Xiao, D., Wang, Z., Zhang, H., Bu, X., Zhang, X., An, L., Zhang, S., Cao, Z., Zhan, Q., Yang, Y., Liang, L., Cao, B., Dai, H., Wu, T., He, J., Kan, H., Chen, R., Yang, T., Wang, C., 2022. Associations of residential greenness with lung function and chronic obstructive pulmonary disease in China. Environ. Res. 209, 112877. https://doi.org/10.1016/j.envres.2022.112877. Epub 2022 Feb 4. PMID: 35131324.

Yang, B.Y., Zhao, T., Hu, L.X., Browning, M.H.E.M., Heinrich, J., Dharmage, S.C., Jalaludin, B., Knibbs, L.D., Liu, X.X., Luo, Y.N., James, P., Li, S., Huang, W.Z., Chen, G., Zeng, X.W., Hu, L.W., Yu, Y., Dong, G.H., 2021. Greenspace and human health: an umbrella review. Innovation 2 (4), 100164. https://doi.org/10.1016/j.xinn.2021.100164. PMID: 34622241; PMCID: PMC8479545.

Zhang, W., Peng, W., Cai, J., Jiang, Y., Zhou, C., Zha, Z., Mi, J., 2023. Residential surrounding greenness is associated with improved lung function in adults: a cross-sectional study in eastern China. BMC Publ. Health 23 (1), 632. https://doi.org/10.1186/s12889-023-15473-6. PMID: 37013488; PMCID: PMC10069091.