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Residential greenspace and lung function decline over 20 years in a prospective cohort: The ECRHS study

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ABSTRACT

Background: The few studies that have examined associations between greenspace and lung function in adulthood have yielded conflicting results and none have examined whether the rate of lung function decline is affected.
Objective: We explored the association between residential greenspace and change in lung function over 20 years in 5559 adults from 22 centers in 11 countries participating in the population-based, international European Community Respiratory Health Survey.
Methods: Forced expiratory volume in 1 s (FEV_1) and forced vital capacity (FVC) were measured by spirometry when participants were approximately 35 (1990–1994), 44 (1999–2003), and 55 (2010–2014) years old. Greenness was assessed as the mean Normalized Difference Vegetation Index (NDVI) in 500 m, 300 m, and 100 m circular buffers around the residential addresses at the time of lung function measurement. Green spaces were defined as the presence of agricultural, natural, or urban green spaces in a circular 300 m buffer. Associations of these greenspace parameters with the rate of lung function change were assessed using adjusted linear mixed effects regression models with random intercepts for subjects nested within centers. Sensitivity analyses considered air pollution exposures.
Results: A 0.2-increase (average interquartile range) in NDVI in the 500 m buffer was consistently associated with a faster decline in FVC (−1.25 mL/year [95% confidence interval: −2.18 to −0.33]). These associations were especially pronounced in females and those living in areas with low PM_{10} levels. We found no consistent associations with FEV_1 and the FEV_1/FVC ratio. Residing near forests or urban green spaces was associated with a faster decline in FEV_1, while agricultural land and forests were related to a greater decline in FVC.
Conclusions: More residential greenspace was not associated with better lung function in middle-aged European adults. Instead, we observed slight but consistent declines in lung function parameters. The potentially detrimental association requires verification in future studies.

1. Introduction

Lungs undergo development, growth, plateau, and decline phases. Any adverse or protective factors during these stages can influence the lifetime lung function trajectory (Agusti and Faner, 2019). Several studies have investigated the trajectories both in children and adults (Okyere et al., 2021). A study investigating lung function trajectories from childhood to adulthood showed children whose lung function peak was below average, as well as adults with lung function accelerated decline, are related to adult multi-morbidity, including chronic obstructive pulmonary disease (COPD) (Bui et al., 2018). Other epidemiological studies have shown that even a mild decline in lung function parameters of young adults within clinically normal ranges can predict respiratory and cardiovascular abnormalities and increased mortality (Agustí et al., 2017; Vasquez et al., 2017). The search for modifiable factors of low lung function has received much attention in the recent past.

Among potential environmental modifiers of lifetime lung function, a lot of research went into the impact of long-term exposure to ambient air pollutants on lung function in children (Zhang et al., 2022) and adults (Edginton et al., 2019; Masroor et al., 2021), but few studies have explored a potential role of greenspace exposure, although greenspace has been hypothesized to affect lung function through a reduction of hazardous pollutants and facilitation of physical activity (Markevych et al., 2017). Only three studies have examined associations between greenspace and lung function in adults (Xiao et al., 2022 Nordeide Kuiper et al., 2021; Sarkar et al., 2019) and delivered mixed results. While exposure to greenspace was associated with better lung function in a large Chinese study (Xiao et al., 2022), a multicenter study in Norway and Sweden showed the opposite (Nordeide Kuiper et al., 2021). A UK Biobank study found an inverse J-shaped association between exposure to greenspace and lung function (Sarkar et al., 2019). Similar inconsistent findings were reported for COPD, a disease characterized by a reduced ratio of forced expiratory volume in 1 s (FEV_1) to forced vital capacity (FVC). Residential greenness was associated with lower odds of COPD in the UK Biobank study (Sarkar et al., 2019) but higher odds in a large Chinese study (Fan et al., 2020). A further Chinese study reported that greenness was associated with overall lower odds of COPD, but this finding was not consistent across regions (Xiao et al., 2022).

A recent comprehensive systematic review on exposure to urban greenspace (defined mainly as greenness from satellite remote sensing data or green spaces from land use maps) and respiratory health reported that the most consistent beneficial health effect appears to be a reduction in respiratory mortality (Mueller et al., 2022). However, the review was not conclusive regarding the effects of greenspace exposure on lung function in adults. Apart from the differences in study areas, types of vegetation or green spaces, and sociodemographic characteristics, one possible explanation for the existing uncertainty is the wide

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methodological heterogeneity across the reviewed studies, which differed markedly in study design (panel, cross-sectional, case-control, and cohort), confounder control (ambient air pollution, smoking, pollen exposure, occupational exposures), greenspace indicators (Normalized Difference Vegetation Index (NDVI), proximity to green space, green views), exposure buffers (100 m, 200 m, 300 m, 400 m, 500 m, 1000 m), and exposure metrics (e.g., one-time or repeated measurements). Furthermore, no study has used repeated lung function measurements to assess how greenspace exposures are related to an age-related decline in lung function. Understanding the role of greenspace in lung function trajectories can inform the development of evidence-based strategies to promote lung health and reduce the adverse impacts of low lung function.

We sought to fill this gap and explore whether residing in greener areas could slow down lung function decline in adults over the course of 20 years. Furthermore, we tested whether sociodemographic and residential factors, such as ambient air pollution concentrations, could affect this presumed association.

2. Methods

2.1. Study design and population

The European Community Respiratory Health Survey (ECRHS; https://www.ecrhs.org) is a prospective multicenter cohort study initiated in 1990–1994 (baseline, ECRHS I). Participants aged 20 to 44 years were randomly recruited from population-based registries (random sample), with an oversampling of subjects with respiratory symptoms (symptomatic sample) (Janson et al., 2001). ECRHS I consisted of a questionnaire survey (stage 1) and a medical examination (stage 2). Two follow-ups have taken place: ECRHS II in 1999–2003 and ECRHS III in 2010–2014 (Burney et al., 1994; The European Community Respiratory Health Survey II Steering Committee, 2002). Ethical approval was obtained by all centers from the appropriate ethics committees, and participants provided written informed consent.

As the focus of the current analysis was lung function decline, the study population was restricted to participants with at least two lung function measurements and greenness assigned to their corresponding residential addresses. Participants younger than 25 years were excluded because lung growth continues up to approximately 20–25 years (Agusti and Faner, 2019). Thus, the analytic sample consisted of 5559 participants from 22 study centers in 11 countries: Reykjavik in Iceland, Umeå, Uppsala, and Gothenburg in Sweden, Bergen in Norway, Tartu in Estonia, Norwich and Ipswich in the UK, Antwerp city and South Antwerp in Belgium, Erfurt in Germany, Paris and Grenoble in France, Basel in Switzerland, Verona, Pavia, and Turin in Italy, and Oviedo, Galdakao, Barcelona, Albacete, and Huelva in Spain. Fig. 1 plots the geographic locations of the included study centers. Fig. S1 depicts the flowchart of the study population.

2.2. Lung function

FEV_1 and FVC repeatable to 150 mL from at least two of a maximum of five correct manoeuvres that met the recommendations of the American Thoracic Society and the European Respiratory Society (Miller et al., 2005) for repeatability, as well as the FEV_1/FVC ratio, were used as the outcomes of interest. Four different models of spirometers were used across centers at ECRHS I and ECRHS II, while the same spirometer was used by all but two centers at ECRHS III (Table S1). Measurement bias due to the use of different spirometers had been corrected (Accordini et al., 2020; Bridevaux et al., 2015). All lung function measures were taken without bronchodilation.

Fig. 1. Included study centers and availability of greenspace data across them.

2.3. Residential greenspace

2.3.1. Greenness

Greenness (i.e., vegetation degree) was defined by the NDVI (Tucker, 1979), which is calculated based on the knowledge that plants absorb visible red light (Red) for use in photosynthesis and reflect near-infrared light (NIR) to prevent overheating. The equation for NDVI is based on spectral reflectance measurements acquired in corresponding light wavelengths and reads as $NDVI = (NIR - Red) / (NIR + Red)$. As NIR and Red are ratios of the reflected over absorbed light and their values range from 0 to +1, NDVI values range from −1 to +1, with +1 indicating a highly vegetated area (Weier and Herring, 2000).

NDVI was calculated from Landsat 4–5 Thematic Mapper (TM) satellite images (https://earthexplorer.usgs.gov). For all 22 study areas, cloud-free Landsat 4–5 TM satellite images with a spatial resolution of 30 m × 30 m, taken during the most vegetation-rich months close to each of the ECRHS surveys, were retrieved, and NDVI images were calculated. Thus, three NDVI images were created to correspond to the time of each of the three ECRHS surveys for each center. The list of the Landsat 4–5 TM satellite images that were used is provided in Table S2.

Residential greenness was defined as the mean of the NDVI values in a circular 500 m buffer around each participant's residential address. As NDVI values were extracted at each of the three ECRHS surveys, they are time-specific, meaning that one and the same home address can have up to three different NDVI values over time. Associations with NDVI in 100 m and 300 m buffers were also tested in sensitivity analyses.

2.3.2. Green spaces

Green spaces within proximity to each residence were used as secondary exposure variables. Green spaces were assessed using the Urban Atlas land use data for the year 2006 (https://www.eea.europa.eu/data-and-maps/data/urban-atlas) and defined as the presence (yes vs. no) of each of agricultural, natural (forest), or urban green spaces (1) of any size and (2) of at least one hectare in a circular 300 m buffer around participants' residential addresses as per WHO recommendations (Annerstedt van den Bosch et al., 2016). As the Urban Atlas only covers large metropolitan areas with a population of $\geq$ 100,000 inhabitants, these variables were available for 13 ECRHS centers only (Fig. 1).

2.4. Main analysis

Associations of greenspace with change in FVC, FEV_1, and FEV_1/FVC were estimated using multivariable mixed linear regression models with random intercepts for subjects nested within centers (lmer function from lme4 package (Bates et al., 2014) in the statistical program R, version 3.6.1 (R Core Team, 2022). We checked deviations from linearity by treating NDVI as quartiles and tertiles, but found no indication of non-linearity (data not shown). An interaction term between the greenspace variable and age at lung function measurement was included in the models to capture the effect of greenspace on the rate of change of the lung function parameters over the course of the study.

A set of covariates was selected a priori. Minimally adjusted models included type of sample (random, symptomatic), sex, age (years; at each survey), age squared (at each survey), and height (cm; at each survey). Main models were additionally adjusted for age at completion of full-time education as a marker of socioeconomic status (SES) (the oldest age reported across ECRHS I and II: 17 years, 17–20 years, > 20 years), occupation as an additional marker of SES (the highest level reported across ECRHS II and III: management/professional/non-manual, technical/professional/non-manual, other non-manual, skilled manual, semi-skilled/unskilled manual, other/unknown), weight (kg; at each survey), and smoking status and lifetime pack-years (at each survey; never smoker, ex-smoker < 15 pack-years, ex-smoker $\geq$ 15 pack-years, current smoker < 15 pack-years, current smoker $\geq$ 15 pack-years). Continuous variables were centered over the data from all surveys.

2.5. Sensitivity analyses

Several sensitivity analyses were performed to test the robustness of our findings against a number of assumptions. First, the main models were further adjusted for: (1) body mass index (BMI; kg/m^2) instead of weight, (2) spirometer model, (3) baseline lung function, to control for possible "regression to the mean" (Barnett et al., 2005), (4) urbanicity, as there is spatial interrelation with amount and types of greenspace, and (5) air pollutants, as greener areas typically have fewer air pollution sources (Markevych et al., 2017). A model with fixed effects for centers was built as well.

Residential urbanicity for sensitivity analyses (at each time point) was defined according to the standard EU Degree of Urbanisation (DEGURBA) (European Commission, 2011) classification for the year 2001, which corresponds to the ECRHS II survey. Briefly, DEGURBA classifies all municipalities (LAU2) into three categories: cities (densely populated areas), towns and suburbs (intermediate density areas), and rural areas (thinly populated areas). Air pollution exposures were assigned to each of the residential addresses from existing land use regression (LUR) models for Western Europe that are based on satellite and ground measurements (de Hoogh et al., 2016; Vienneau et al., 2013). These exposures reflected annual average concentrations of nitrogen dioxide (NO_2) for the year 2005, particulate matter with an aerodynamic diameter < 2.5 µm ($PM_{2.5}$) for the year 2010, and particulate matter with aerodynamic diameter < 10 µm (PM_{10}) for the year 2007. Information from > 1500 AIRBASE monitoring sites that covered background, industrial, and traffic environments were combined with spatial information on land use characteristics, population density, road length, altitude, distance to sea, and satellite-based air pollution measurements to create a single LUR model per pollutant that was applied and mapped on a 100 m × 100 m grid across Western Europe. Model validation, based on evaluation at independent monitoring locations, were $R^2 = 0.58$, 0.58, and 0.49 for NO_2, $PM_{2.5}$, and PM_{10}, respectively.

Second, the analytic population was restricted to (1) the random sample, (2) participants who had lung function and greenspace data at all three ECRHS surveys, and (3) a sample without the Spanish centers, for which addresses at ECRHS I could not be retrieved and geocoded.

2.6. Stratified analyses

We conducted several stratified analyses to test potential effect modification by: (1) sex, (2) age group at ECRHS I ($\leq$ 35 years, > 35 years), (3) age at completion of full-time education (< 17 years, 17–20 years, > 20 years), (4) residential air pollution levels at ECRHS I (low defined as $\leq$ 75th percentile of NO_2/$PM_{2.5}$/PM_{10}, high defined as > 75th percentile (Fuertes et al., 2018), (5) urbanicity at ECRHS I (urban, suburban/rural, as there were too few suburban residents), (6) asthma at ECRHS I, defined as having had an asthma attack in the last 12 months or currently taking asthma medication, (7) hay fever or any respiratory allergy at ECRHS I, (8) geographic area: Northern Europe (Reykjavik, Umeå, Uppsala, Gothenburg, Bergen, Tartu), Central Europe (Norwich, Ipswich, Antwerp city, South Antwerp, Erfurt, Paris, Grenoble, Basel, Verona, Pavia, Turin), and Southern Europe (Oviedo, Galdakao, Barcelona, Albacete, Huelva), and (9) ever changed their place of residence (ever movers, never movers). Effect modification was considered only if there were differences in point estimates and little to not overlapping confidence intervals.

3. Results

3.1. Personal and residential characteristics of the study population

Descriptive characteristics of the study population are shown in Table 1. About half of the study participants were males (48 %). The mean time of follow-up since baseline was nine years at ECRHS II and 20 years at ECRHS III. Accordingly, the mean ages of the study participants were 35, 44, and 55 years at ECRHS I, II, and III, respectively. All lung function parameters were the highest at ECRHS I and lowest at ECRHS III. Mean FEV_1 was 3725, 3440, and 2962 mL at the three follow-ups, respectively, while mean FVC was 4571, 4328, and 3922 mL, respectively. Also, 9% and 28% suffered from asthma and nasal allergies at baseline, respectively.

Over half of the participants changed their place of residence at least once. Seventy-eight percent resided in urban settings at baseline, with this proportion decreasing over time to 66%. Mean residential greenness across all buffers was the highest at ECRHS I, followed by ECRHS III, and ECRHS II. Correlations between NDVI variables across surveys ranged from 0.48 to 0.62 across the entire population and from 0.78 to 0.92 in non-movers. Across 22 study centers, the lowest residential NDVI was observed for the Spanish centers of Barcelona, Albacete, and Huelva, and the centers of Antwerp city and Paris (Fig. 2). The highest residential greenness was oberved for the Swedish, Norwegian, and UK centers. The north-to-south gradient in greenness from higher to lower was most pronounced at ECRHS III. At baseline, 35%, 28%, and 70% of participants resided within 300 m of agricultural land, forests, or urban green spaces, respectively (Table 1). At the follow-ups, more people lived close to agricultural land and forests, while fewer people had urban green spaces nearby. Residential air pollution levels were the lowest at the time of the last survey, but differences in air pollution levels across surveys were very slight.

3.2. Residential greenness and lung function change

Residing in more vegetated places was associated with a faster

Table 1
Characteristics of the analytic sample (n = 5559).

Characteristic	ECRHS I		ECRHS II		ECRHS III	
	n/N or N	% or mean ± SD	n/N or N	% or mean ± SD	n/N or N	% or mean ± SD
Geographic area						
Northern Europe	2097/5559	37.7				
Central Europe	2818/5559	50.7				
Southern Europe	644/5559	11.6				
Symptomatic sample	805/5559	14.5				
Male sex	2655/5559	47.8				
Age, years	5559	35.3 ± 6.0	5278	44.2 ± 6.0	4047	55.4 ± 6.1
Time of follow-up since baseline			5109	8.9 ± 0.8	3873	20.1 ± 0.9
Age at completion of full-time education						
< 17 years			1022/5488	18.6		
17–20 years			1861/5488	33.9		
> 20 years			2605/5488	47.5		
Occupation						
Management/professional/non-manual					1340/5541	24.2
Technical/professional/non-manual					998/5541	18.0
Other non-manual					1471/5541	26.5
Skilled manual					545/5541	9.8
Semi-skilled/unskilled manual					673/5541	12.1
Other/unknown					514/5541	9.3
Height, cm	5391	170.4 ± 9.6	5104	170.3 ± 9.6	3792	169.5 ± 9.7
Weight, kg	5391	70.1 ± 13.7	5083	74.5 ± 15.3	3766	78.2 ± 16.1
BMI, kg/m^2	5390	24.0 ± 3.8	5082	25.6 ± 4.4	3766	27.2 ± 4.9
Smoking						
Never	2343/5466	42.9	2137/4813	44.4	1498/3167	47.3
Ex-smoker with < 15 pack-years	989/5466	18.1	919/4813	19.1	614/3167	19.4
Ex-smoker with ≥ 15 pack-years	325/5466	5.9	513/4813	10.7	544/3167	17.2
Current smoker with < 15 pack-years	1015/5466	18.6	411/4813	8.5	110/3167	3.5
Current smoker with ≥ 15 pack-years	794/5466	14.5	833/4813	17.3	401/3167	12.7
Asthma	469/5540	8.5				
Hayfever or other nasal allergy	1564/5527	28.3				
FEV_1, mL	4707	3724.6 ± 815.8	5019	3439.8 ± 796.6	3673	2961.7 ± 741.8
FVC, mL	4656	4571.1 ± 1019.9	4988	4328.4 ± 988.8	3628	3921.7 ± 943.1
FEV_1/FVC, %	4625	81.7 ± 7.1	4971	79.7 ± 6.9	3611	75.6 ± 6.7
NDVI in 500 m buffer	4625	0.276 ± 0.141	4971	0.261 ± 0.155	3611	0.270 ± 0.147
NDVI in 300 m buffer	4625	0.270 ± 0.143	4971	0.255 ± 0.157	3611	0.264 ± 0.149
NDVI in 100 m buffer	4625	0.253 ± 0.150	4971	0.244 ± 0.159	3611	0.251 ± 0.155
Agricultural green spaces in 300 m buffer	920/2596	35.4	1079/2744	39.3	966/2314	41.7
Forests in 300 m buffer	713/2596	27.5	811/2744	29.6	713/2314	30.8
Urban green spaces in 300 m buffer	1820/2596	70.1	1775/2744	64.7	1504/2314	65.0
NO_2, μg/m^3	4398	29.7 ± 13.4	5004	28.2 ± 13.0	4321	26.7 ± 13.0
PM_{10}, μg/m^3	3941	22.9 ± 8.6	4554	23.6 ± 8.6	3927	22.6 ± 8.5
$PM_{2.5}$, μg/m^3	4397	15.4 ± 5.5	5003	15.1 ± 5.2	4321	14.4 ± 5.2
Ever changed place of residence					3248/5559	58.4
Urbanicity						
Urban	3368/4343	77.6	3535/4942	71.5	2860/4313	66.3
Semi-urban	199/4343	4.6	537/4942	10.9	571/4313	13.2
Rural	776/3434	17.9	870/4942	17.6	882/4313	20.4

BMI – body mass index; ECRHS - European Community Respiratory Health Survey; FEV_1 - forced expiratory volume in 1 s; FVC – forced vital capacity; NDVI – Normalized Difference Vegetation Index; NO_2 – nitrogen dioxide; PM_{10} - particulate matter with aerodynamic diameter < 10 μm; $PM_{2.5}$ – particulate matter with aerodynamic diameter < 2.5 μm; SD – standard deviation.

decline in FVC (−1.25 mL/year [95% Confidence Interval: −2.18 to −0.33] per 0.2 increase [mean of interquartile ranges] in NDVI in a 500 m buffer; main model, Table 2). Adjusting for BMI instead of weight, correcting for spirometer model, additionally adjusting for urbanicity, NO_2, or $PM_{2.5}$, restricting to the random sample, excluding participants who did not participate in all three surveys, or using fixed effects for centers did not materially change this association (change in estimate < 20%, Table 2 and Table S4). Adjusting for PM_{10} levels strengthened this effect estimate to −1.62 (−2.57 to −0.68) mL/year (Table 2), as did excluding the Spanish centers without greenness data at baseline. A similar association with FVC was observed for mean NDVI in 300 m and 100 m buffers (Table S3). There was no consistent association between greenness and FEV_1 or the FEV_1/FVC ratio (Table 2 and Table S3).

In stratified analyses, we found suggestive evidence of potentially stronger associations between higher greenness and a larger decline in FVC for females and for participants with lower levels of residential PM_{10} at baseline. This association was also slightly stronger for participants ≤ 35 years at baseline, with low or high education levels, with asthma at baseline, and from Southern and Northern Europe, but confidence intervals overlapped. When the analysis was stratified by change of residence across follow-ups, the association with FVC was unchanged for ever movers and was slightly attenuated to −0.95 (−2.48 to 0.57) in the group of never movers (Fig. 3). Analyses stratified by levels of NO_2 or $PM_{2.5}$ revealed no clear patterns of associations (Fig. 3). An association between higher greenness and a larger decline in FEV_1 was observed for participants with low education levels, females, ever movers, and residents of Southern Europe (Fig. S2).

3.3. *Green space proximity and lung function change*

Having forest and urban green spaces of any size in a circular 300 m buffer around home was associated with a faster decline in FEV_1 (−2.25 [−4.02 to −0.47] and −1.98 [−3.66 to −0.31] mL/year, respectively; Table 3). Similarly, residing near agricultural land and forests was

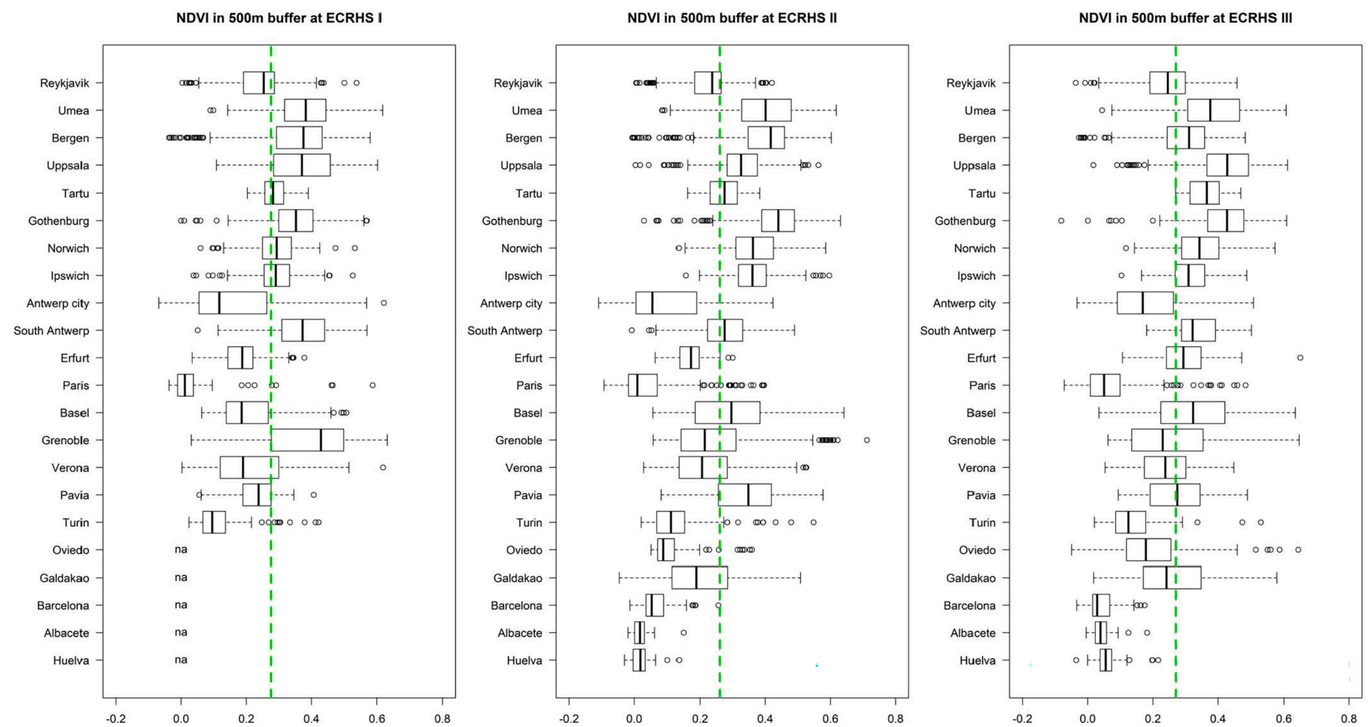

Fig. 2. Distribution of residential greenness (NDVI) in a 500 m buffer around home of the ECRHS participants, by survey. ECRHS centers are ordered north (top) to south (bottom). For each area, the median value is indicated by a bold black line and the box summarizes the 25th to 75th percentiles. The dashed green vertical line represents the overall mean.

Table 2
Associations between residential greenness (NDVI) in a 500 m buffer around home and lung function change over a 20-year period[1], assessed by mixed linear models. Effect estimates are expressed as change following a 0.2-increase in NDVI.

Population, model	FEV_1 (mL/year)			FVC (mL/year)			FEV_1/FVC (%/year)		
	n	ß	95% CI	n	ß	95% CI	n	ß	95% CI
All, minimally adjusted[2]	5559	−0.71	(−1.44 to 0.02)	**5559**	**−1.41**	**(−2.30 to −0.52)**	5559	0.011	(−0.001 to 0.023)
All, main[3]	5316	−0.54	(−1.30 to 0.23)	**5316**	**−1.25**	**(−2.18 to −0.33)**	5316	0.012	(−0.001 to 0.025)
All, main + spirometer	5316	−0.68	(−1.47 to 0.10)	**5316**	**−1.46**	**(−2.41 to −0.50)**	5316	0.011	(−0.002 to 0.024)
All, main + baseline lung function	**5095**	**−1.37**	**(−2.03 to −0.71)**	**5056**	**−1.79**	**(−2.53 to −1.05)**	5027	0.000	(−0.011 to 0.010)
All, main + urbanicity	4782	−0.70	(−1.50 to 0.09)	**4782**	**−1.39**	**(−2.35 to −0.43)**	4782	0.012	(−0.001 to 0.026)
All, main + NO_2	4842	−0.66	(−1.43 to 0.11)	**4842**	**−1.41**	**(−2.35 to −0.47)**	4842	0.013	(−0.000 to 0.026)
All, main + $PM_{2.5}$	4842	−0.64	(−1.41 to 0.13)	**4842**	**−1.40**	**(−2.34 to −0.46)**	**4842**	**0.013**	**(0.000 to 0.027)**
All, main + PM_{10}	4464	−0.71	(−1.49 to 0.07)	**4464**	**−1.62**	**(−2.57 to −0.68)**	**4464**	**0.016**	**(0.002 to 0.029)**
Random sample, main	4550	−0.59	(−1.38 to 0.21)	**4550**	**−1.41**	**(−2.38 to −0.45)**	**4550**	**0.014**	**(0.001 to 0.027)**
Without Spanish centers, main	**4706**	**−0.85**	**(−1.67 to −0.03)**	**4706**	**−1.81**	**(−2.79 to −0,80)**	4706	0.013	(−0.000 to 0.027)
Participants of all three surveys, main	2056	−0.35	(−1.37 to 0.68)	**2056**	**−1.45**	**(−2.67 to −0.23)**	**2056**	**0.017**	**(0.000 to 0.034)**

CI – confidence interval; FEV_1 - forced expiratory volume in 1 s; FVC – forced vital capacity; NDVI – Normalized Difference Vegetation Index; NO_2 – nitrogen dioxide; PM_{10} - particulate matter with aerodynamic diameter < 10 μm; $PM_{2.5}$ – particulate matter with aerodynamic diameter < 2.5 μm.
Boldface indicates p-value < 0.05.

[1] An interaction term between the greenness variable and age at lung function measurements captures the effect of greenness on the rate of change of lung function parameter.

[2] With random intercepts for subjects nested within centers, and adjusted for sample, sex, age, age squared, and height.

[3] With random intercepts for subjects nested within centers, and adjusted for sample, sex, age, age squared, height, age at completion of full-time education, occupation, weight, and smoking status and lifetime pack-years smoked.

associated with a greater decline in FVC (−2.56 [−4.48 to −0.69] and −4.87 [−6.96 to −2.78] mL/year, respectively; Table 3). No consistent associations were observed with the FEV_1/FVC ratio. Counting only green spaces of at least one hectare in the same 300 m buffer showed similar associations with lung function (Table S5).

4. Discussion

4.1. Main study findings

Our longitudinal analysis over the course of 20 years in 5559 European adults across 22 centers in 11 countries suggests that residing in places with more vegetation is consistently related to a faster decline in FVC and less consistently to a decline in FEV_1. Having green spaces nearby was associated with a faster decline in both FVC and FEV_1. Measures of associations were larger in females whereas the role of airborne particulate matter in modifying these associations was less clear. No consistent associations were observed for the FEV_1/FVC ratio.

4.2. Interpretations and comparisons with other studies

To the best of our knowledge, this is the first study to investigate the

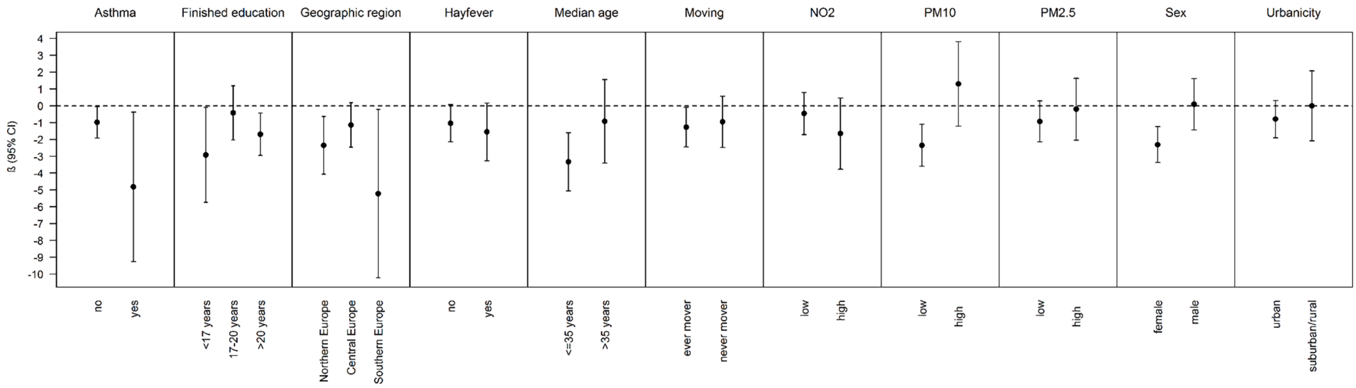

Fig. 3. Associations between residential greenness (NDVI) in a 500 m buffer around home and FVC change (mL/year) over a 20-year period, assessed by adjusted mixed linear models (with random intercepts for subjects nested within centers, and adjusted for sample, sex, age, age squared, height, age at completion of full-time education, occupation, weight, and smoking status and lifetime pack-years smoked) and stratified by potential effect modifiers. All potential modifiers refer to ECRHS I data except moving; moving history (ever mover, never mover) considered all ECRHS data across three surveys. Effect estimates are expressed as change following a 0.2-increase in NDVI.

Table 3
Associations between presence of green space of any size in a 300 m buffer[1] around home and lung function change over a 20-year period[2], assessed by mixed linear models.

Model/type of green spaces	FEV_1 (mL/year)			FVC (mL/year)			FEV_1/FVC (%/year)		
	n	ß	95% CI	n	ß	95% CI	n	ß	95% CI
Minimally adjusted[3]									
Agricultural	2821	−0.65	(−2.18 to 0.87)	**2820**	**−2.20**	**(−4.01 to −0.39)**	**2820**	**0.026**	**(0.000 to 0.052)**
Forest	**2821**	**−2.26**	**(−3.92 to −0.59)**	**2820**	**−4.71**	**(−6.68 to −2.73)**	2820	0.027	(−0.002 to 0.055)
Urban green	**2821**	**−2.24**	**(−3.80 to −0.67)**	2820	−1.25	(−3.12 to 0.61)	**2820**	**−0.029**	**(−0.056 to −0.003)**
Main[4]									
Agricultural	2744	−0.56	(−2.20 to 1.08)	**2744**	**−2.56**	**(−4.48 to −0.69)**	**2742**	**0.035**	**(0.007 to 0.064)**
Forest	**2744**	**−2.25**	**(−4.02 to −0.47)**	**2744**	**−4.87**	**(−6.96 to −2.78)**	2742	0.025	(−0.006 to 0.056)
Urban green	**2744**	**−1.98**	**(−3.66 to −0.31)**	2744	−0.33	(−2.32 to 1.65)	**2742**	**−0.037**	**(−0.066 to −0.007)**

CI – confidence interval; FEV_1 - forced expiratory volume in 1 s; FVC – forced vital capacity.
Boldface indicates p-value < 0.05.
[1] Reference is no green spaces.
[2] An interaction term between the green spaces variable and age at lung function measurements captures the effect of green spaces on the rate of change of lung function parameter.
[3] With random intercepts for subjects nested within centers, and adjusted for sample, sex, age, age squared, and height.
[4] With random intercepts for subjects nested within centers, and adjusted for sample, sex, age, age squared, height, age at completion of full-time education, occupation, weight, and smoking status and lifetime pack-years smoked.

relationship between greenspace and age-related lung function decline in middle-aged adults using repeated lung function measurements. Few existing studies on greenspace and lung function in adults reported a potentially detrimental effect of greenspace exposure on lung function (Nordeide Kuiper et al., 2021; Sarkar et al., 2019). Despite the overall consistent findings, there are several methodological differences between our study and the previously published studies, which hamper a direct comparison. For example, the mean age in the study by Nordeide Kuiper et al. (2021) was 28 years whereas ours ranged from 35 to 55 years across surveys. In addition, their study modeled the impact of greenness exposure on lung function measured once and dichotomized as below or above the lower limit of normal lung function, while our study used repeatedly measured lung function data modeled as continuous variables. Another major difference is related to the window of exposure. The study by Nordeide Kuiper et al. (2021) considered lifetime exposure up to 28 years, while our study considered greenspace exposures beyond the age of 25 years capturing the age-related lung function decline phase over a longer period.

Our study results contradict the overall positive association between residential greenness exposure and lung function observed in adults in a multicenter study in China (Xiao et al., 2022). In addition to differences in climatic conditions and regional heterogeneity, covariates like air pollutants, vegetation types, and subject characteristics, the study by Xiao et al. (2022) is also cross-sectional and measured lung function only once. Our findings are also not in line with the only study with repeated lung function tests taken at ages 8, 15, and 24 years (Fuertes et al., 2020). In that study, lifetime exposure to greenspace (NDVI and proximity to green space) was associated with higher FVC and FEV_1 levels at 24 years in a cohort of young adults living in the UK. Aside from other differences in methodology, the study by Fuertes et al. (2020) was based upon much younger subjects who were in the life stage of lung growth, while our study included older adults and captured the decline phase.

The potentially detrimental associations of increased exposure to greenness on lung function in our study might be supported by findings on the COPD. A nationwide cross-sectional study in China observed higher odds of COPD for people living in green neighborhoods (Fan et al., 2020). Another multicenter study in China found higher odds of COPD for people living in greener areas in some of their centers, but the overall association was beneficial (Xiao et al., 2022). The UK Biobank study found a beneficial association between living in green neighborhoods and COPD (Sarkar et al., 2019), while another European study by Nordeide Kuiper et al. (2021) reported opposite findings. Particularly, the cross-sectional data of the UK Biobank study showed an inverse J-shaped association between NDVI and FEV_1/FVC, where the detrimental effect of NDVI in a 500 m buffer starts at levels above 0.21 (Sarkar et al., 2019). The globally potentially detrimental effect of NDVI on lung function observed in our study might be due to the fact that our mean NDVI values were substantially higher than those in the UK Biobank study (0.27 vs. 0.18). Neverthelss, our analyses showed no consistent associations for the FEV_1/FVC ratio and, therefore, were unable to clarify the association between greenspace and COPD. The direction of the association between greenspace and COPD remains inconclusive and warrants further clarification.

4.3. Possible interpretation

Being aware of previous mixed findings on greenspace and allergic and respiratory outcomes in children (Fuertes et al., 2016; Lambert et al., 2017; Tischer et al., 2018) and adolescents (Ferrante et al., 2020), we initially anticipated different scenarios on how greenspace could be related to lung function decline. Since the observed association in our study is not beneficial, the suggested pathways linking greenspace to positive health outcomes, including physical activity facilitation (Lachowycz and Jones, 2011), inverse spatial correlation with air pollution levels and urbanicity (Markevych et al., 2017), or increased biodiversity (Marselle et al., 2021; Rook, 2013), are not likely to be relevant.

Mechanisms that could explain our results include greenspace as a source of hazards, e.g., increased pesticide and pollen exposure (Markevych et al., 2017). Occupational exposure to pesticides has been found to reduce lung function indicators in the short and long term (de Jong et al., 2014; Sapbamrer et al., 2020; Sham'a et al., 2015) and short-term pollen exposure has been suggested to reduce lung function by some (Gruzieva et al., 2015; Krug et al., 2003) but not all (Bake et al., 2014; Roberts et al., 2004) studies. Future research is warranted to clarify whether these exposures may contribute to the observed associations, as previous studies reporting similar adverse associations have failed to provide convincing explanations for their results (Sarkar et al., 2019).

Surprisingly, the point estimates for higher greenness and lung function decline were greatest in settings with lower PM_{10} levels, although confidence intervals partially overlapped (Fig. 3 and S2). On the one hand, as no such observation was made for $PM_{2.5}$ and NO_2, this might be a chance finding. On the other hand, people with respiratory problems might move to areas with less pollution, thereby creating self-selection bias (Biele et al., 2019). Although our air pollution exposure estimates were from different years and did not entirely cover the period of ECRHS surveys, several studies have reported high stability of the air pollution exposure surfaces over time (Eeftens et al. 2011; Gulliver et al., 2013). Thus we do not anticipate the used air pollution data to be a major source of bias.

It is worth noting that greenspace might play different roles throughout the life course. Whilst the study by Fuertes et al. (2020) showed increased lung function growth associated with higher greenness exposure up to 24 years, our study showed a faster decline during the life period of general worsening of respiratory health. Further longitudinal studies that cover different life stages are required to elucidate a more definite explanation for age-specific roles of greenspace exposure on respiratory health.

4.4. Strengths and limitations

ECRHS is a large population-based prospective study with participants followed for up to 20 years, with broad geographic representation across Europe. As ECRHS has been specifically designed to collect information on respiratory health, we had good quality data on repeated lung function measurements and could control our analyses for many established confounders and check for potential effect modification. Despite the generally small effect size and an uncertain clinical meaning, the observed associations of this study could be important from a public health perspective and should encourage more research on the quality of greenspace and cofactors like the emission of pollen from allergenic trees and pesticide usage.

Nevertheless, our study should be seen in light of its limitations. Since ECRHS was not meant to investigate associations with geographic exposures, including greenspace, we did not have all the necessary information to exclude the possibility of residual confounding, especially by time-varying factors, and to validate the potential underlying pathways. Most of all, this concerns area-level socioeconomic status, as more affluent areas tend to have more greenspace and/or greenspace of better quality (Astell-Burt et al., 2014; Rigolon et al., 2021) and to be safer. We did not know how much time participants spent in their neighborhood or at work. Importantly, we did not have the full residential history of the participants throughout their life course to check susceptibility windows. Since addresses were available from the time points of the three surveys, we could only explore the impact of contemporary greenspace exposure, but not of early life exposure. We were also unable to retrieve and geocode the addresses of five Spanish centers at ECRHS I. Due to extensive cloud cover in many study centers, especially the Nordic ones, we computed NDVI during vegetation-rich seasons to capture maximum contrast between vegetated and non-vegetated areas instead of using annual averages. We could not look into more detail why greenspace was related to a slight but consistent decline in lung function. Beyond testing the role of spatial correlation with air pollution and urbanicity, NDVI provides only very general information on vegetation degree but not on vegetation types. Likewise, the Urban Atlas data used to define green spaces did not provide information on vegetation types and were only available for a subset of participants in this analysis. Accounting for pollen and pesticide exposure around the time of lung function measurements and exploring the link between spatial contrasts of allergenic species (e.g., McInnes et al., 2017; Markevych et al., 2020) and lung function could shed more light on the reported associations, but we unfortunately lacked these data.

5. Conclusion

Living in areas with more greenspace was not associated with better lung function in middle-aged European adults. Instead, we observed a slight but consistent decline in lung function parameters with exposure to greenspace, although the decline might be clinically irrelevant. Further research is needed to investigate beneficial and potentially harmful associations of different types of greenspace and possible mechanisms.

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CRediT authorship contribution statement

Iana Markevych: Conceptualization, Data curation, Formal analysis, Methodology, Software, Visualization, Writing – original draft, Writing – review & editing. **Tianyu Zhao:** Conceptualization, Software, Validation, Visualization, Writing – original draft, Writing – review & editing. **Elaine Fuertes:** Methodology, Writing – original draft, Writing – review & editing. **Alessandro Marcon:** Methodology, Writing – review & editing. **Payam Dadvand:** Methodology, Writing – review & editing. **Danielle Vienneau:** Methodology, Writing – review & editing. **Judith Garcia Aymerich:** Methodology, Writing – review & editing. **Dennis Nowak:** Writing – review & editing. **Kees de Hoogh:** Data curation, Writing – review & editing. **Deborah Jarvis:** Funding acquisition, Writing – review & editing. **Michael J. Abramson:** Writing – review & editing. **Simone Accordini:** Writing – review & editing. **Andre FS Amaral:** Writing – review & editing. **Hayat Bentouhami:** Writing – review & editing. **Randi Jacobsen Bertelsen:** Writing – review & editing. **Anne Boudier:** Writing – review & editing. **Roberto Bono:** Writing – review & editing. **Gayan Bowatte:** Writing – review & editing. **Lidia Casas:** Writing – review & editing. **Shyamali C Dharmage:** Writing – review & editing. **Bertil Forsberg:** Writing – review & editing. **Thorarinn Gislason:** Writing – review & editing. **Marco Gnesi:** Writing – review & editing. **Mathias Holm:** Writing – review & editing. **Benedicte Jacquemin:** Writing – review & editing. **Christer Janson:** Writing – review & editing. **Rain Jogi:** Writing – review & editing. **Ane Johannessen:** Writing – review & editing. **Dirk Keidel:** Writing – review & editing. **Benedicte Leynaert:** Writing – review & editing. **José Antonio Maldonado Perez:** Writing – review & editing. **Pierpaolo Marchetti:** Writing – review & editing. **Enrica Migliore:** Writing – review & editing. **Jesús Martínez-Moratalla:** Writing – review & editing. **Hans Orru:** Writing – review & editing. **Isabelle Pin:** Writing – review & editing. **James Potts:** Writing – review & editing. **Nicole Probst-Hensch:** Writing – review & editing. **Andrea Ranzi:** Writing – review & editing. **José Luis Sánchez-Ramos:** Writing – review & editing. **Valerie Siroux:** Writing – review & editing. **David Soussan:** Writing – review & editing. **Jordi Sunyer:** Writing – review & editing. **Isabel Urrutia Landa:** Writing – review & editing. **Simona Villani:** Writing – review & editing. **Joachim Heinrich:** Conceptualization, Funding acquisition, Methodology, Supervision, Writing – original draft, Writing – review & editing.

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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Data availability

Data will be made available on request.

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Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envint.2023.108036.

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