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Exposure to urban greenspace and pathways to respiratory health: An exploratory systematic review

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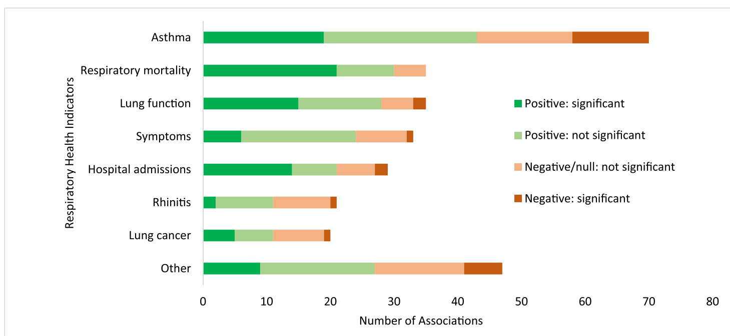
HIGHLIGHTS

- We identified 108 papers examining greenspace and respiratory health.
- A wide range of health indicators were included, with asthma being the most common.
- Positive associations were most strongly related to reduced respiratory mortality.
- For other health outcomes, effect estimates were often inconsistent or imprecise.

GRAPHICAL ABSTRACT



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ABSTRACT

Background/objective: Urban greenspace may have a beneficial or adverse effect on respiratory health. Our objective was to perform an exploratory systematic review to synthesise the evidence and identify the potential causal pathways relating urban greenspace and respiratory health.

Methods: We followed PRISMA guidelines on systematic reviews and searched five databases for eligible studies during 2000–2021. We incorporated a broad range of urban greenspace and respiratory health search terms, including both observational and experimental studies. Screening, data extraction, and risk of bias, assessed using the Navigation Guide criteria, were performed independently by two authors. We performed a narrative synthesis and discuss suggested pathways to respiratory health.

Results: We identified 108 eligible papers ($n = 104$ observational, $n = 4$ experimental). The most common greenspace indicators were the overall greenery or vegetation (also known as greenness), green land use/land cover of physical area classes (e.g., parks, forests), and tree canopy cover. A wide range of respiratory health indicators were studied, with asthma prevalence being the most common. Two thirds ($n = 195$) of the associations in these studies were positive (i.e., beneficial) with health, with 31% ($n = 91$) statistically significant; only 9% ($n = 25$) of reported associations were negative (i.e., adverse) with health and statistically significant. The most consistent positive evidence was apparent for respiratory mortality. There were $n = 35$ (32%) 'probably low' and $n = 73$ (68%) 'probably high' overall ratings of bias. Hypothesised causal pathways for health benefits included lower air pollution, more physically active populations, and exposure to microbial diversity; suggested mechanisms with poorer health included exposure to pollen and other aeroallergens.

Conclusion: Many studies showed positive association between urban greenspace and respiratory health, especially lower respiratory mortality; this is suggestive, but not conclusive, of causal effects. Results underscore the importance of contextual factors, greenspace metric employed, and the potential bias of subtle selection factors, which should be explored further.

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Contents

1. Introduction

As more of the global population moves to inhabit cities, urban greenspace will provide an important and accessible source of nature. Urban greenspace, also referred to as greenness or green infrastructure, can involve parks and forests, as well as street trees, gardens, and numerous other arrangements of vegetation. Systematic reviews have identified beneficial associations between greenspace and specific health outcomes, notably mental health (van den Berg et al., 2015), all-cause and cardiovascular disease mortality (Gascon et al., 2016), physical activity (Kondo et al., 2018), and other indicators of health and wellbeing (Twohig-Bennett and Jones, 2018). While there are likely many mechanisms by which greenspace or biodiversity could affect health, four major domains have been proposed: reducing harm (e.g., mitigating air pollution), restoring capacities (e.g., attention restoration), building capacities (e.g., encouraging physical activity), and causing harm (e.g., allergens) (Markevych et al., 2017; Marselle et al., 2021). All of these pathways may be relevant for respiratory health, particularly reducing harm from air pollution. Although systematic reviews of greenspace have focussed on specific aspects of respiratory health, such as childhood asthma (Hartley et al., 2020) and allergic respiratory diseases in children (Lambert et al., 2017) and youth (Ferrante et al., 2020), a review has not to date been undertaken focussing on the potential relationships and pathways across respiratory health outcomes.

The respiratory system is composed of the upper (e.g., nasal passages) and lower (e.g., trachea, lungs) respiratory tracts and functions to provide exchange of oxygen and carbon dioxide. Its development and healthy maintenance appear to involve an intricate web of environmental and genetic factors, with specific susceptibility to harm in early life (Stocks et al., 2013). The respiratory system includes a complex suite of microbiota, including bacteria, viruses, and fungi, that are affected by various environmental exposures and are believed to play a key role in fighting off pathogens and promoting overall health (Man et al., 2017). For example, the risk of childhood asthma was found to be lower in those residing on traditional farms, which was linked to enhanced microbial diversity in these settings (Ege et al., 2011). Adverse environmental exposures throughout the life course can cause demonstrable harm: the inhalation of particulate matter of <2.5 μm ($PM_{2.5}$) resulted in over 2 million respiratory-related deaths globally in 2017 (Bu et al., 2021), and the leading causes of global disability-adjusted life years for chronic respiratory diseases are smoking for men and household/ambient air pollution for women (Soriano et al., 2020). Therefore, it would be useful to gain a better understanding of the role of greenspace to mitigate exposures to air pollution, as well as with other potential pathways to health.

Although greener areas may entail better air quality due to fewer pollution sources, there are also a number of physical mechanisms by which vegetation may filter the air. Leaves contain stomata, which can absorb gases, including SO_2, NO_2, and O_3, and also provide an effective, broad surface area on which to accumulate PM through deposition (Salmond et al., 2016). At the same time, trees can contribute ambient pollutants via the release of biogenic volatile organic compounds (bVOCs), such as terpenes and isoprenes, leading to precursors for O_3 and secondary organic aerosols

(Eisenman et al., 2019). Dense tree canopies may prevent dispersion of traffic-related air pollutants in street canyon environments, causing higher street-level air pollution concentrations (Abhijith et al., 2017). Trees and grasses can release large volumes of pollen and fungal spores, potentially leading to allergic reactions (Dadvand et al., 2014), and in urban settings with high traffic volume, pollen can bind to diesel exhaust particles, which may exacerbate inflammatory responses to allergens (Esposito et al., 2012).

In addition to air quality, there are other possible links between urban greenspace and respiratory health, including more direct pathways. For example, green areas in urban environments may offer positive contact to microbiota (Ruokolainen et al., 2015); insufficient exposure to such biotic factors at a young age may lead to improperly developed immune systems (Rook et al., 2013), with linkage to inflammatory conditions, including asthma, as noted earlier (Haahtela et al., 2013). Although physical activity may induce breathing difficulties in those with compromised respiratory systems, known as exercise-induced bronchoconstriction, reviews suggest an overall positive effect of exercise, including lung function improvements in asthmatic children (Wanrooij et al., 2014). Vegetation and tree canopies could alleviate urban heat island effects (Gunawardena et al., 2017), leading to fewer adverse respiratory health events during periods of extreme heat (Takaro et al., 2013). Nevertheless, green areas are not always synonymous with better health. For example, research identified differential effects of greenspace with adverse associations of eyes and nose symptoms in urban settings, but protective relationships in rural environments, potentially due to more high allergenicity plants in cities (Fuertes et al., 2014b). With this mix of interrelated pathways, it is unsurprising that broad reviews on health have suggested the overall respiratory benefits of trees and other vegetation are not so clear-cut (Fong et al., 2018; Kondo et al., 2018).

Here, we focus on the association of respiratory health with urban greenspace, as opposed to greenspace in rural areas, as the role of greenspace in more built-up urban areas may have an even more important role for population health (Lachowycz and Jones, 2013). Therefore, our objective was to perform an exploratory systematic review to synthesise the evidence relating urban greenspace and respiratory health, and investigate the overall direction and magnitude of reported associations. We then used this evidence to help identify potential causal pathways linking urban greenspace components to respiratory health outcomes.

2. Methods

We followed the PRISMA guidelines on systematic reviews (Moher et al., 2009) and published our review protocol on the OSF registry (https://osf.io/jvs46).

2.1. Search strategy

We searched the following five databases for studies in English: Medline, Embase, Global Health, Scopus, and the Cochrane Library. The study period included the following dates: 01 January 2000 to 31 December 2018. A streamlined update of the search was performed using the Scopus database from January 2019 to October 2021, following peer review. References from eligible studies, as well as from any relevant review papers identified in the search, were scanned for additional eligible studies. Any other references known by the research team that met the eligibility criteria, but were not identified from the above search strategy, were also included. We did not search grey literature. Our greenspace search terms and medical subject headings focussed on urban areas and were intentionally broad to capture a wide array of studies.

The main health outcome for the search included disease coding of the respiratory system (i.e., International Coding of Disease-10 [ICD-10] C30-C39 [malignant neoplasms of respiratory and intrathoracic organs], J00-J99 [diseases of the respiratory system]), including mortality, morbidity, and hospital admissions. In addition to the main health outcomes, other indicators of respiratory health were eligible for the review, such as lung function measurements (e.g., Forced Expiratory Volume in 1 s [FEV_1]), asthma (or other respiratory) medication use, respiratory symptoms, asthma control, and any other related respiratory health outcomes identified during the course of the review. To be as inclusive as possible with this broad range of health indicators, we did not pre-specify summary measures. The full list of search terms for each database and PECO (population, exposure, comparator, outcome) statement are presented in Table S1.

2.2. Selection eligibility

Observational studies were to include one or more objective measurements of, or proximity to, urban greenspace/greenness/greenery, including but not limited to, parks, gardens, street trees, and urban forests. Exposure assessment could have been based on residential/work or other address, and also may have included personal monitoring, including visits to or use of greenspace. For intervention/experimental studies, the setting needed to include an area with urban greenspace (e.g., park, forest), and non-green/urban setting comparator. As an example, study subjects may have spent time or engaged in a specific activity in urban greenspace, which was then compared to doing the same in a non-green/urban environment. Table 1 presents the selection eligibility criteria.

2.3. Data extraction & risk of bias

All search results from each of the databases were pooled in EndNote. After duplicates were removed, two reviewers (WM + PW/JM/ML/SV) first screened each title and abstract for relevant papers. A similar process was then followed whereby two authors reviewed independently the full text of all relevant papers using the above eligibility criteria. Any discrepancies were discussed and decided by a third reviewer, if needed. The following data were extracted independently by two reviewers from the eligible papers using a template data extraction sheet: author, year, study design, sample size, study population, setting, time period, description of greenspace exposure (including distance/area measure), greenspace exposure metric, control exposure (for experimental studies), health outcome, source of health outcome, number of cases, confounders/covariates, effect estimate measure, main results. Where it was possible, we standardised effect estimates per 0.1-unit increase in surrounding NDVI or 10% increase in tree canopy or green land use/land cover. In summary figures, we indicate whether reported exposure-outcome effect estimates and confidence intervals (CI) are positive (i.e., beneficial) or negative (i.e., adverse)/null for a given respiratory health indicator. For studies examining multiple buffer radii, we include either the main reported results or those closest to a radius of 250 m, a commonly used metric. We report results specifically for urban populations, if available, and prioritise results representing the longest period of follow-up in a given study.

The risk of bias in the studies was assessed independently by two authors using the Navigation Guide methodology and criteria for making risk of bias determinations, as set out in Johnson et al. (2016). This rating involved the assignment of 'low', 'probably low', 'probably high', 'high',

Table 1
The eligibility criteria used to identify relevant papers.

#	Criteria
1	Empirical peer-reviewed studies.
2	For observational studies, exposure includes one or more objective measurements of, or proximity to, urban greenspace/greenness/greenery.
3	For experimental/intervention studies, setting must include a green area, i.e. park, forest, and non-green/urban setting comparator.
4	Outcome must include respiratory health, i.e., ICD − 10 C00-C14, C30-C39, J00-J99 mortality/morbidity, hospital admissions, lung function measurements, medication use, asthma control.
5	Assesses empirically the association between greenspace metric and respiratory health outcome.
6	Studies that use human participants.
7	Studies in English.
8	Contains most complete data if also published elsewhere.

Table 2
The Navigation Guide criteria used to assess the risk of study bias.

#	Criteria
1	Are the study groups free from baseline differences?
2	Was knowledge of the exposure groups adequately prevented during the study?
3	Were exposure assessment methods robust?
4	Were outcome assessment methods robust?
5	Were confounding and effect modification adequately addressed?
6	Were incomplete outcome data adequately addressed?
7	Are reports of the study free of suggestion of selective outcome reporting?
8	Was the study free of support from a company, study author, or other entity having a financial interest in any of the exposures studied?
9	Was the study apparently free of other problems that could put it at a risk of bias?

or 'not applicable' to the nine criteria outlined in Table 2. For criterion #5 (confounding), we specified as tier 1 (important) confounders: age, sex, socioeconomic status (SES), and tobacco smoking (including exposure to secondhand smoke [e.g., in studies of children]). Tier 2 (other potentially relevant) confounders included air pollution exposure and physical activity; however, these may be on the causal pathway to respiratory health and therefore should also include a mediation analysis (only relevant for statistically significant results). All tier 1 and 2 covariates needed to be adjusted for in multivariate models for a study to be assigned a 'low' rating (with mediation analysis if associations were statistically significant). Adjustment for all tier 1 and fewer than two tier 2 confounders (with mediation analysis) would be assigned a 'probably low' rating, and adjusting for some tier 1 or performing only crude analyses would be rated as 'probably high' or 'high' risk of bias, respectively (Eick et al., 2020). If multiple health outcomes were included in a single study, we assigned to the study the highest bias rating for any of the individual outcomes (i.e., criterion #4 in Table 2). Each study was then assigned an overall grading based on the highest bias category allotted to the nine criteria. We evaluated the overall quality and strength of evidence for each health outcome, according to the Navigation Guide as detailed in Johnson et al. (2016) and Pega et al. (2020). One author (WM) conducted an initial evaluation of quality and strength; studies were assumed to be of a moderate quality and subsequently downgraded or upgraded according to set criteria, which was then used in part to inform the overall strength of evidence (see Tables S2 & S3 for criteria). These assessments were revised following discussion and agreement with all other authors.

Finally, we completed a narrative synthesis of multiple respiratory health outcomes to examine the overall direction of association and also to comment on the overall quality and potential biases in the eligible studies (Campbell et al., 2020). To support our exploratory review, we illustrate hypothesised pathways for which urban greenspace may affect health. Given the broad inclusion of greenspace exposure indicators, buffer sizes, and respiratory health outcomes included in our review scope, we concluded that it would not be appropriate to undertake meta-analysis of published coefficients of association.

3. Results

The initial database search identified 15,667 unique studies, after the removal of duplicates, to which we added two studies from the manual search of references. From the screening of titles and abstracts of these papers, we identified 236 potentially eligible studies. We inspected the full text of these studies and after applying the exclusion criteria (Table S4), we identified 108 eligible papers to assess the evidence of urban greenspace exposure and respiratory health outcomes (see Fig. 1).

3.1. Study characteristics

Characteristics of the reviewed studies, including greenspace exposures, health outcomes, and main respiratory health results, are presented in Tables 3-10. The years of publication of the studies ranged from 2007 (n = 1) to 2022 (n = 1), with the highest number published in 2021 (n = 24) and none published in 2011. Most (n = 104) of the eligible studies were observational, with the remaining four having an experimental design. The observational studies included both ecological (i.e., aggregated health data) (n = 36) and individual-level (n = 68) health data (n = 32 cross-sectional; n = 19 cohort/longitudinal; n = 8 birth cohort; n = 7 case-crossover/case-control; n = 2 panel). The statistical sample size of observational studies ranged dramatically, from 8 urban areas (Bernat et al., 2016) to 26,455 urban residential areas (Alcock et al., 2017) in the ecological studies, and from 57 (Cole-Hunter et al., 2018) to 10.5 million (Klompmaker et al., 2021) where studies used individual-level health data. The number of participants included in experimental studies ranged from 24 (Moshammer et al., 2019) to 119 (Sinharay et al., 2018). Study demographics included children, adults, and older adults, as well as the general population. The maximum follow-up time for a longitudinal study

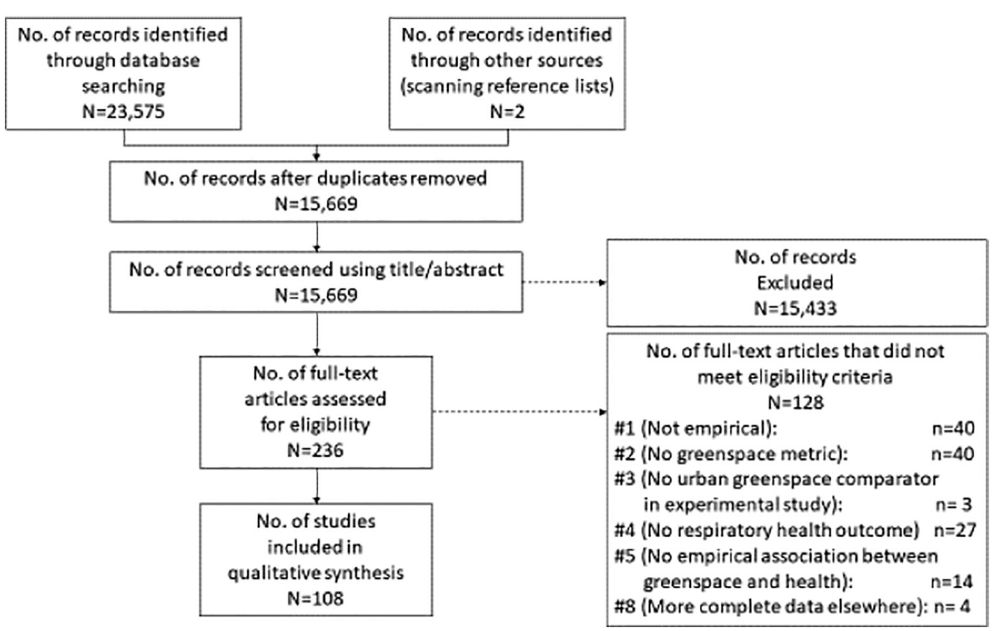

Fig. 1. A flow diagram of the search results, with reasons for excluded studies.

Table 3
Study characteristics of the respiratory mortality studies, ordered by risk of bias and year.

First author, year	Study type	Sample size/# of cases	Study population and setting	Greenspace data/exposure metric	Respiratory health outcome	Confounders/covariates	Main results (95% CI)	Overall risk of bias
Richardson, 2010	Ecological	n = 6432 wards (population of 28.6 M)	Adults in the UK aged 16–64 years	2 Land use datasets (Generalised Land Use Dataset, CORINE), % of greenspace by area	Respiratory mortality	Age-group, income deprivation, air pollution and country, synthetic estimates of smoking for English wards only	IRR of respiratory mortality for >75% vs <25%: GS 0·89 (0·83 to 0·96) males 0.96 (0.88 to 1.05) females	Probably Low
Villeneuve, 2012	Cohort	n = 574,840	Adults aged 35 + years in 10 urban areas in Ontario, Canada	NDVI - Landsat (30 m cell); residential levels at cohort inception; 500 m residential buffer	Non-malignant respiratory disease (J00-J99) mortality	Age, sex, income, marital status, ambient air pollution, and contextual neighbourhood characteristics. Also estimated smoking and physical activity.	Rate Ratio per 0.1 NDVI (500 m buffer) increase* = 0.96 (95% CI 0.95 to 0.97)	Probably Low
James, 2016	Cohort	n = 108,630	US Nurses (women) in 11 US states	NDVI vegetation (MODIS); NDVI with 250/1250 m home buffers; current season NDVI and cumulative average NDVI	Respiratory mortality	Race/ethnicity, smoking status, smoking, fixed individual-level SES, area-level SES, weight status, region, urbanicity, physical activity, air pollution, social engagement, and mental health	Continuous NDVI (250 m) (per 0.1-unit increase): 0.73 (0.59 to 0.90) Mediation analysis with air pollutants and physical activity explained <10% of association.	Probably Low
Crouse, 2017	Cohort	n = 1,265,000	Non-immigrant adults (aged ≥19 years) in 30 Canadian cities	NDVI vegetation (MODIS); Annual residential max NDVI at 250 m & 500 m buffers	Respiratory mortality	Aboriginal and minority status, marital status, education, employment, income, population density, air pollution	Hazard Ratio per 0.1-unit NDVI (250 m)*: 0.93 (0.91 to 0.95)	Probably Low
Wang, 2017	Cohort	n = 3544	Adults aged ≥65 years in Hong Kong	NDVI vegetation (IKONOS) 15 m resolution; % of greenspace within 300 m of home (counting cells >0.1 NDVI)	Respiratory disease mortality	Age, sex, marital status, years lived in Hong Kong), SES, lifestyle factors (smoking, alcohol intake, diet quality), self-rated health and housing type, physical activity, mental health	Hazard Ratio (per 10% increase in 300 m buffer): Respiratory disease mortality: 1.004 (0.928 to 1.087)	Probably Low
Kim, 2019	Ecological	n = 73 districts	General population in 7 cities in Korea	NDVI (MODIS; 250 m); Median value of NDVI for the summer period (May–October)	Age and sex standardised respiratory disease (J00–99) and chronic lower respiratory disease (J40–47) mortality	PM10, neighbourhood SES, smoking rates, and healthcare infrastructure status	% increase with IQR increase: Respiratory disease = 1.85% (−0.76% to 4.52%); Chronic lower respiratory disease = −3.75% (−8.50% to 1.24%)	Probably Low
Kasdagli, 2021	Ecological	n = 1035 municipal units	General population in Greece	NDVI greenness (MODIS; 1 km); Mean NDVI in May per municipal unit	Respiratory mortality	Air pollutants (PM2.5, NO2, BC and O3), % unemployed, % working with education; % born in Greece, lung cancer mor-tality (proxy for smoking)	Relative risk for IQR increase in NDVI: NDVI: RR = 0.92 (0.89 to 0.95)	Probably Low
Hu et al., 2007	Ecological	20 zipcodes	General population, Pensacola metropolitan region of Florida.	Greenness (Landsat), 1.5 km buffers around randomly selected points	Asthma mortality	Point source pollution sites and emissions, traffic count	Quantitative results not presented: 'modeling of mortality rates shows the similar relationship [with hospitalisations]'. See results in Table 5 below.	Probably High
Donovan, 2013	Ecolo-gical	n = 1296 counties	General adult population in USA (15 states)	% of county covered by ash tree canopy	Chronic lower respiratory tract (J40–47) mortality	Race/ethnicity, income, education, poverty, years of ash borer infestation	Mortality rate (per 100,000) per 10% increase in ash canopy*: −52.2 (−77.9 to −26.4)	Probably High
Gronlund et al., 2015*	Case-cross-over	n = 344 zip codes	Adults aged 65 years and older in Michigan, USA	Green land cover (30 m resolution) classified as green and non-green% greenspace in each zipcode	Respiratory mortality	Sex, age, deprivation, education, ethnicity, age of building, air quality, temperature	OR in areas of high and low greenspace: No quantitative results given for respiratory mortality, but graphs indicate positive association; CIs cross 1.0 during extreme heat days	Probably High
Vienneau, 2017	Cohort	n = 4,284,680	General population in Switzerland	NDVI summer vegetation values (Landsat, 30 m resolution), Green land use; Residential buffers of	Respiratory mortality (J00-J99)	Civil status, job position, education, neighbourhood socio-economic position	Hazard Ratio per 0.1-unit NDVI: 0.94 (0.93 to 0.96) per 10% Green land use: 0.98 (0.98 to 0.99)	Probably High

(continued on next page)

Table 3 (*continued*)

First author, year	Study type	Sample size/# of cases	Study population and setting	Greenspace data/exposure metric	Respiratory health outcome	Confounders/covariates	Main results (95% CI)	Overall risk of bias
				500 m		(SEP), geographic region, area type, altitude, air pollution (PM10), and transportation noise		
Shen and Lung, 2017	Ecolo-gical	n = 48 administrative districts	General population in Taipei, Taiwan	Proportion of greenspace patches, mean distance between patches, patch density	Pneumonia mortality, chronic lower respiratory disease mortality	Air pollutants, mean annual temperature	Partial least squares model coefficients: Largest Patch Percentage: − 0.131 Landscape Proportion: − 0.010 Patch Distance: 0.027 Fragmentation: 0.112	Probably High
Xu, 2017	Ecolo-gical	n = 199 (Tertiary Planning Units)	Adults aged 20 + years in Hong Kong	NDVI vegetation (30 m resolution); Mean NDVI of Tertiary Planning Unit (TPU)	Chronic respiratory disease mortality	Age, gender, population density, and area-level socio-economic variables	RR per 0.1-unit NDVI:* Chronic respiratory disease mortality = 0.98 (0.95 to 1.00)	Probably High
Orioli, 2019	Cohort	n = 1,263,721	Adults aged 30 + years in Rome, Italy	Leaf area index (LAI) NDVI (greenness) (Landsat; 30 m); Residential buffers of 300 m and 1000 m	Respiratory disease mortality (ICD-9:460–519)	Age, sex, education, marital status, occupational status, birthplace, area-level SEP, mediation for air pollution and noise, subset with smoking data	Hazard ratio for IQR increase in NDVI: LAI (300 m) HR = 1.014 (0.988 to 1.041) NDVI (300 m) HR = 1.011 (0.986 to 1.038)	Probably High
Wang, 2019	Ecological	n = 369 census tracts	General population in Philadelphia, US	Percentage of greenspace (PLAND), mean area of greenspace (AREA_MN), fragmentation of greenspace (PD), greenspace connectedness (COHESION), aggregation of the greenspace pattern (AI), and complexity of the shape of the greenspace (SHAPE_AM); Per census tract	Chronic lower respiratory disease mortality	Percentage of people aged 65 years and older, the percentage of females, the percentage of white residents, median household income, the percentage of holders of a bachelor's degree or higher, and population density	Percentage change in expected count of the studied causes of death: PLAND = -0.509 (−1.410, 0.401) AREA_MN = 0.001 (−0.004 to 0.005) PD = 0.200 (−0.060 to 0.461) COHESION = -35.609 (−46.688 to −22.221) AI = -8.552 (−16.222 to −0.180) SHAPE_AM = -5.190 (−9.697 to −0.459)	Probably High
Lee, 2020a	Ecological	n = 1,173,773 deaths (n units of analysis unspecified)	General population in Taiwan	NDVI (greenness) (MODIS; 250 m) Forest and park land cover (Taiwan Land-use Investigation); Mean NDVI in each township across the study period	Respiratory disease mortality	Total population, age, sex ratio, taxable income, precipitation, time trend, and temperature.	Risk ratio: NDVI Respiratory mortality: RR = 0.721 (0.632 to 0.824) Forest/park Respiratory mortality: RR = 0.903 (0.883 to 0.923)	Probably High
Jaafari, 2020	Ecological	n = 87 study units	General population in Tehran, Iran	Greenspace defined by total class area, cohesion index, patch density, shape index, and total edge; Greenspace metrics calculated at study unit (10 km2 area)	Respiratory mortality	Age-adjusted rates. Models adjusted for air pollutants (CO, NO2, O3, PM10, PM2.5, and SO2)	Path coefficients from structural equation modeling: Greenspace- > Respiratory mortality = −0.305 ($p < 0.001$)	Probably High
Sun, 2020	Case-crossover	n = 66,820 in the cohort (3159 deaths)	Adults aged 65 + years in Hong Kong	NDVI (2001, 2006; Landsat; 30 m); Mean NDVI in 250 m and 500 m residential buffers	Respiratory mortality	Ambient temperature, relative humidity, influenza epidemics, public holidays, and air pollution (with interaction term with low/high greenness)	Effect modification by residential greenness: Elders living in the low greenness areas were associated with a higher risk of pneumonia mortality attributed to NO2 (p = 0.049) and O3 (p = 0.025) – interactions	Probably High
Bauwelinck, 2021	Population cohort	n = 2,185,170	Adults aged 30 + years in urban areas in Belgium	Surrounding greenness [(NDVI) and modified soil adjusted vegetation index (MSAVI2)]; Surrounding greenspace (Urban Atlas (UA), CORINE (CLC)); NDVI, MSAVI2, UA, and CLC within residential buffers of 300 m, 500 m, 1000 m	Respiratory mortality (ICD-10: J00-J99)	Age, sex, marital status, country of birth, education level, employment status, area mean income, and air pollutants (PM2.5, PM10, NO2 and black carbon) with mediation analysis.	Hazard ratio (HR): NDVI (300 m): 0.95 (0.93–0.97) Greenspace (Urban Atlas) (300 m): 0.98 (0.96–0.99) Mediation analysis: 18–60% of association between residential green space and respiratory mortality is potentially partially mediated by	Probably High

Table 3 (*continued*)

First author, year	Study type	Sample size/# of cases	Study population and setting	Greenspace data/exposure metric	Respiratory health outcome	Confounders/covariates	Main results (95% CI)	Overall risk of bias
							$PM_{2.5}$.	
Klompmaker, 2021	Population cohort	n = 10,481,566	Adults aged 30 + years in Netherlands	NDVI (Landsat 30 m resolution) Greenspace (national land-use database of the Netherlands - TOP10NL); Residential buffers of 300 m and 1000 m	Respiratory disease mortality (J00-J99)	Age, sex, marital status, region of origin, standardised household income, PC4 composite SES, mean income neighbourhood, unemployment neighbourhood, percentage of immigrants neighbourhood, mean income region, unemployment region and percentage of immigrants region	Hazard ratio (HR) for IQR increase: Respiratory disease mortality: NDVI (300 m) = 0.954 (0.943 to 0.965) Greenspace (300 m) = 0.962 (0.951 to 0.972)	Probably High

GS = Greenspace; IRR = Incidence Rate Ratio; IQR = Interquartile Range; NDVI = Normalised Difference Vegetation Index; OR = Odds Ratios; RR = Relative Risk; SES/P = Socioeconomic Status/Position.

* Standardised from reported values.

design was 24 years (Fuertes et al., 2020). The research was undertaken in 26 countries across Europe, the Americas, Asia (including Australasia and South Asia), with one global analysis including data from 94 countries (Fuertes et al., 2014a).

3.2. Greenspace indicators

The three most frequent indicators were (1) the overall greenery or vegetation (also known as greenness), commonly characterised by the Normalised Difference Vegetation Index (NDVI) through satellite remote sensing, but also more recently through eye-level views (e.g., Yu et al., 2021a, 2021b); (2) green land use/land cover, including physical area classes such as parks and forests; and (3) the amount of tree cover or canopy, which also addressed specific types, such as ash tree canopy (Donovan et al., 2013) or allergenic species (Stas et al., 2021) (see Fig. 2). Other, less typical examples of greenspace indicators were biodiversity indices (Liddicoat et al., 2018) and domestic gardens (Alcock et al., 2017). Where data were available at the individual level, greenspace exposure was predominantly defined within circular buffers around the residential address (e.g., mean NDVI value, proportionate area of green land use/land cover), ranging from a radius of 100 m to 5 km, but most routinely from 200 m to 500 m. In some instances, greenspace was characterised also at the work (Hoehner et al., 2013) or school (Dzhambov et al., 2021) address. In studies relying on ecologic-level data, the amount of greenspace covering an administrative area was frequently defined as the exposure, which spanned much larger areas than those of residential buffers, for example, up to 59 km^2 (Fuertes et al., 2014a). Other greenspace metrics included the presence (Dadvand et al., 2014) or number (Hoehner et al., 2013) of parks within a certain distance to the residential address, and the fragmentation of surrounding vegetation cover (Prist et al., 2016). The time-period of greenspace exposure measurements, if stated, overlapped with the study period (typically a point in time), with NDVI mainly assessed during the summer (e.g., Andrusaityte et al., 2016), but in some cases, as annual (Pun et al., 2018) or lifetime (Fuertes et al., 2020) averages.

The four experimental studies involved visits to parks or forests to represent greenspace areas, all of which relied on urban streetscapes for the control environment. The duration of greenspace exposure ranged from 45 min (Cavalcante de Sá et al., 2016) to 2 h (Sinharay et al., 2018).

3.3. Health outcomes: overview

Of the 290 associations included in the studies, 195 (67%) included point estimates or coefficients of a positive association between greenspace and respiratory health; the CIs or reported p-values of 91 (31% overall) associations did not cross 1 or were below 0.05, respectively. The other one third (n = 95; 33%) suggested negative or null associations between greenspace and respiratory health, of which 25 (9% overall) included CIs or p-values that did not cross 1 or were below 0.05, respectively (Fig. 3).

The extent of analysis ranged from univariate methods indicating ecologic correlates between greenspace and health (e.g., Khan et al., 2010; Bernat et al., 2016) to more sophisticated multivariate models examining potential pathways to health through mediation analyses (e.g., James et al., 2016). Although most observational studies included a metric of greenspace as the exposure and a respiratory health indicator as the outcome, some incorporated the latter only as a mediator between greenspace and poor general health (Ulmer et al., 2016) or greenspace and stress (Pun et al., 2018); other analyses included greenspace as a covariate, rather than the primary exposure (Cole-Hunter et al., 2018). In the experimental research on greenspace, all 4 studies showed at least some positive association with exposure to greenspace compared to a trafficked road, though one found post-intervention lung function improvements only in healthy participants (i.e., not COPD patients) (Sinharay et al., 2018).

3.4. Risk of bias

In each of the risk of bias categories, the majority of the ratings were ‘Not Applicable’, ‘Low’, or ‘Probably Low’ (see Fig. S1). Disagreements on ratings were resolved by discussion and agreement with a third reviewer in 80 instances (8% of all ratings). At least one study was assigned a ‘probably high’ bias rating for criteria #1 (study groups free from baseline differences), #3 (robust exposure assessment), #4 (robust outcome assessment), #5 (confounding and effect modification), #6 (incomplete outcome data), and #9 (other sources of bias). There was the most potential for bias regarding #5 (confounding) (‘Probably High’/’High’ ratings: n = 57) and outcome assessment (#4) (‘Probably High’ ratings: n = 18). Thirteen studies included a ‘probably high’ rating in more than one criterion. Based on the highest bias grading in each study, there were 35 (32%) ‘Probably Low’ and 73 (68%) ‘Probably High’/’High’ overall ratings. The individual bias assessment categories and rationale for each study are included in Tables S5-S12.

3.5. Health outcomes: individual

3.5.1. Respiratory mortality

Respiratory mortality was an outcome in 20 studies (10 ecological studies, 8 cohort studies, and 2 case-crossover; see Table 3). Risk of bias was rated as “probably low” for 7 of these (4 cohort studies, 3 ecological studies) and “probably high” for the remaining 13. Confounder control included adjustment for all tier 1 confounders in the “probably low” studies, but only 2 fully adjusted for smoking at the individual level. One study included a

Table 4
Study characteristics of the lung cancer (incidence & mortality) studies, ordered by risk of bias and year.

First author, year	Study type	Sample size/# of cases	Study population and setting	Greenspace data/exposure metric	Respiratory health outcome	Confounders/covariates	Main results (95% CI)	Overall risk of bias
Li, 2008	Ecological	n = 47 prefectures	General population, Japan	% of forest coverage in each prefecture	Standardised Mortality Ratio of lung cancer	Smoking prevalence, Human Development Index (for SES)	Partial correlation coefficients between % forest cover and lung cancer SMR: −0.325 ($p < 0.05$) in females; −0.251 ($p >$ 0.05) in males	Probably Low
Richardson, 2010	Ecological	n = 6432 wards (population of 28.6 M)	Adults in the UK aged 16–64 years	2 Land use datasets (Generalised Land Use Dataset, CORINE), % of greenspace by area	Lung cancer mortality	Age-group, income deprivation, air pollution and country, synthetic estimates of smoking for English wards only	IRR of respiratory mortality for Lung cancer of 75% + GS vs <25%: 0.96 (0.90 to 1.02) males 1.02 (0.94 to 1.11) females	Probably Low
Richardson, 2010	Ecological	n = 1009 census area units (population of 1,546,405)	Adults aged 15–64 years in small urban areas, New Zealand	[1] Usable greenspace; [2] Non-usable greenspace; Quartiles of green land cover in census units (%)	Lung cancer mortality	Age, sex, socio-economic deprivation, smoking, air pollution and population density	IRR for Q4:Q1 greenspace (model 4): [1] total greenspace 1.12 (0.94 to 1.32); [2] usable greenspace 1.02 (0.90 to 1.15)	Probably Low
Kim, 2019	Ecological	n = 73 districts	General population in 7 cities in Korea	NDVI (MODIS; 250 m); Median value of NDVI for the summer period (May–October)	Age and sex standardised lung cancer (C33–34) mortality.	PM10, neighbourhood SES, smoking rates, and healthcare infrastructure status	% increase with IQR increase: Lung cancer = 1.10% (−1.22% to 3.47%)	Probably Low
Sakhvidi et al., 2021	Cohort	n = 19,408	Workers (age 35–50 years at baseline) at the French national electricity and gas company in France	NDVI (greenness) (Landsat; 30 m) (1989 Urban greenspace (artificial, non-agricultural vegetated areas) (European CORINE land use dataset); Mean NDVI during May–July at 100 m, 300 m, 500 m, 1000 m residential buffers (1989–2016) Residential distance to urban greenspace (1990, 2000, 2006, and 2012)	Lung cancer incidence	Smoking, passive smoking, alcohol drinking, socio-occupational status, marital status, body mass index, vegetable consumption, education, occupational exposure to carcinogens, age at enrolment, 10 years cumulative exposure to air pollution (PM2.5), distance to major roads, population density, and deprivation	Hazard ratio per IQR increase in NDVI or proximity to greenspace: NDVI (300 m) OR = 0.846 (0.653 to 1.095) Proximity to urban greenspace OR = 1.015 (0.882 to 1.169)	Probably Low
Mitchell and Popham, 2008	Ecological	n = 40,813,236	Adults <60 years (female) & 65 years (male), England	Proportion of Lower Super Output Area (LSOA) covered in greenspace	Lung cancer mortality	Age, sex, deprivation, population density, urban or rural classification.	Incidence Rate Ratio (IRR) Q5:Q1 Greenspace 0·96 (0·91 to 1·02)	Probably High
Richardson et al., 2012	Ecological	n = 49 cities in the US (43 M population)	General population	Green land cover (30 m resolution from the National Land Cover Database); % by area	Lung cancer mortality	Household income, race, air pollution, % car ownership, sprawl index	Change in mortality rate per 10 percentage point increase in city GS coverage*: Male: 2.2 (−4.4 to 8.7) Female: 0.6 (−3.9 to 5.0)	Probably High
Bixby et al., 2015	Ecological	n = 50 cities (~11 M population)	Adults aged 15–64 years in English cities with population > 100,000	Green land cover (20–30 m resolution); Proportion of city covered by green land (quintiles)	Lung cancer mortality (ICD − 10 C33–34)	Income, air pollution, age and sex distribution	RR: Q5 to Q1 greenness: Men: 0.97 (95% CI: 0.84 to 1.12) Women: 1.01 (95% CI: 0.84 to 1.22)	Probably High
Xu, 2017	Ecological	n = 199 (Tertiary Planning Units)	Adults aged 20 + years in Hong Kong	NDVI vegetation (30 m resolution); Mean NDVI of Tertiary Planning Unit (TPU)	Lung cancer mortality	Age, gender, population density, and area-level socio-economic variables	RR per 0.1-unit NDVI:* Lung cancer = 1.02 (0.99 to 1.04)	Probably High
Klompmaker, 2021	Population cohort	n = 10,481,566	Adults aged 30 + years in Netherlands	NDVI (Landsat 30 m resolution) Greenspace (national land-use database of the Netherlands - TOP10NL); Residential buffers of 300 m and 1000 m	Lung cancer mortality (C34)	Age, sex, marital status, region of origin, standardised household income, PC4 composite SES, mean income neighbourhood, unemployment neighbourhood, percentage of immigrants neighbourhood, mean income region, unemployment region and percentage of immigrants region	Hazard ratio (HR) for IQR increase: NDVI (300 m) = 0.926 (0.915 to 0.937) Greenspace (300 m) = 0.952 (0.942 to 0.963)	Probably High
Lee, 2020a	Ecological	n = 1,173,773 deaths (n units of analysis	General population in Taiwan	NDVI (greenness) (MODIS; 250 m) Forest and park land cover	Lung cancer mortality	Total population, age, sex ratio, taxable income, precipitation, time trend, and	Risk ratio: NDVI RR = 0.871 (0.735 to 1.032)	Probably High

Table 4 (*continued*)

First author, year	Study type	Sample size/# of cases	Study population and setting	Greenspace data/exposure metric	Respiratory health outcome	Confounders/covariates	Main results (95% CI)	Overall risk of bias
		unspecified)		(Taiwan Land-use Investigation); Mean NDVI in each township across the study period		temperature.	Forest/park RR = 0.885 (0.865 to 0.905)	
Sun et al., 2021	Ecological	n = 841 neighbourhood units	General population in Shanghai, China	NDVI (greenness) (1 km res); Mean NDVI in each neighbourhood	Lung cancer incidence	Urban form, road traffic, demographic factors, SES factors	Incidence Rate Ratio: NDVI IRR = 0.137 (0.057 to 0.329)	Probably High

GS = Greenspace; IQR = Interquartile Range; IRR = Incidence Rate Ratio; NDVI = Normalised Difference Vegetation Index; OR = Odds Ratios; RR = Relative Risk; SES = Socioeconomic Status; SMR = Standardised Mortality Ratio.

* Standardised from reported values.

mediation analysis with $PM_{2.5}$ and physical activity. Six of the 7 studies with a risk of bias rated as "probably low" include positive associations, of which 5 have CIs excluding 1, suggesting that living in a greener area was associated with lower respiratory mortality. The other study has a point estimate with a negative association, but the CI includes 1. Several longitudinal studies identified stronger associations of greenspace with lower respiratory mortality in younger ages (Villeneuve et al., 2012; Crouse et al., 2017; Vienneau et al., 2017).

3.5.2. Lung cancer

Lung cancer was the outcome for 12 studies (10 ecological, 2 cohort; see Table 4). Risk of bias was rated as "probably low" for 5 of these, with only 1 study (cohort) adjusting for individual-level smoking habits. Among the 5 studies with risk of bias rated as "probably low", point estimates are positive and negative; however all but one of the CIs include 1.

3.5.3. Respiratory hospital visits

Hospital visits were examined in 13 studies (10 ecological, 2 cohort, and 1 time series study; see Table 5). Risk of bias was rated as "probably low" for 3 of these and "probably high" for the remaining 10 (9 ecological, 1 time series). Adjustment for individual-level risk factors was possible only in the cohort studies. Among the 3 studies with risk of bias rated as "probably low", 1 includes point estimates of negative associations with CIs that exclude 1, suggesting areas with more greenspace have higher rates of hospital admission. The other 2 studies include negative and positive point estimates, with CIs for two positive estimates including 1.

3.5.4. Asthma (excluding mortality and hospital visits)

Asthma prevalence (also incidence, inhaler use, control) was the outcome for 38 studies (20 cross-sectional, 6 ecological, 8 cohort, 3 case-control, and 1 panel study; see Table 6). Risk of bias was rated as "probably low" for 8 of these (3 cross-sectional, 3 cohort, 1 case-control, and the panel study). Confounder control included adjustment for all tier 1 confounders in these 8 studies and smoking at an individual-level. Among those studies with risk of bias rated as "probably low", 6 include point estimates with a positive association, of which 5 have CIs that exclude 1, suggesting that living in an area with more greenspace is protective against asthma. However, 3 studies, including 2 of the above, present point estimates with negative associations and CIs that exclude 1, indicating higher asthma in areas with more greenspace.

3.5.5. Lung function

Lung function was the outcome for 14 studies (4 cross-sectional, 4 cohort, 3 experimental, 2 case-control, and 1 panel study; see Table 7). Risk of bias was rated as "probably low" for 6 of these (3 experimental, 1 case-control, 1 cross-sectional, and the panel study). Confounder control included adjustment for tier 1 confounders, with all studies either excluding smokers or controlling for smoking at an individual-level; 2 studies included mediation analysis with air pollution or physical activity. Among those studies with risk of bias rated as "probably low", 4 have point estimates of positive associations that exclude 1, suggesting better lung function in greener areas. The remaining 2 studies have point estimates with non-significant CIs.

3.5.6. Respiratory symptoms

Respiratory symptoms were the outcome for 12 studies (5 cross-sectional, 4 cohort, 3 experimental, 1 ecological, and 1 case-crossover study; see Table 8). Risk of bias was rated as "probably low" for 6 of these (4 cross-sectional, 1 cohort, and 1 experimental study). Adjustment included all tier 1 confounders in these 6 studies, which included control for parental smoking. Among those studies with risk of bias rated as "probably low", 2 studies have point estimates with CIs that exclude 1, suggesting positive associations with greenspace; however another study contains a negative point estimate with CIs that exclude 1. The remaining 3 studies have point estimates that are positive (2), or negative and positive (1), all with non-significant CIs.

3.5.7. Rhinitis

Rhinitis was the outcome for 12 studies (7 cohort, 3 cross-sectional, 1 ecological, and 1 case-control study; see Table 9). Risk of bias was rated as "probably low" for only 2 of the cohort studies, which adjusted for all tier 1 confounders, including parental smoking. These studies have point estimates indicating negative and positive associations, though the CIs include 1.

3.5.8. Other health indicators

There were 20 studies that examined indicators of health not previously mentioned, including cardiorespiratory fitness, respiratory infections, various biomarkers (e.g., exhaled NO), and Covid−19 mortality. Risk of bias was rated as "probably low" for 7 of these (5 cross-sectional and 2 experimental studies; see Table 10). Confounder control included adjustment for individual-level tier 1 confounders in these studies. Among those studies with risk of bias rated as "probably low", the results for 6 studies include point estimates, or other quantitative results, that suggest a positive association, of which 2 have a CI that excludes 1. Two studies, including 1 of the above, incorporate results indicating a negative association, of which 1 is statistically significant.

3.5.9. Overall quality & strength of evidence

We evaluated the overall quality of evidence separately for each health outcome using the eight criteria in the Navigation Guide. We assessed the evidence related to respiratory mortality to be of 'moderate' quality; we rated the quality of evidence for all other examined health outcomes to be 'low'. The most common reasons for downgrading the quality of evidence was due to the 'inconsistency' and 'imprecision' criteria for differing risk estimates and wide confidence intervals (see Tables 11, S13 & S14 for details). Similarly, we rated the overall strength of evidence of better health to be 'limited' for respiratory mortality, and 'inadequate' for the remaining respiratory health outcomes.

Table 5
Study characteristics of the hospital visits studies, ordered by risk of bias and year.

First author, year	Study type	Sample size/# of cases	Study population and setting	Greenspace data/exposure metric	Respiratory health outcome	Confounders/covariates	Main results (95% CI)	Overall risk of bias
Sbihi et al., 2017	Cohort	n = 68,195	Children aged ≤10 years (born 1999–2002) in Vancouver, Canada	NDVI vegetation (Landsat); Residential postal code NDVI during pregnancy using 100 m	Asthma trajectories	Sex, parity, First Nations status, birth weight, gestational duration, breastfeeding, mode of delivery, household income, maternal education, smoking, air pollutants.	Relative Risk Ratio NDVI - Q3 vs Q0: Transient: 0.91 (0.80 to 1.05) Late onset: 1.05 (0.90 to 1.23) Early onset: 1.01 (0.81 to 1.25)	Probably Low
Liddicoat, 2018	Ecological	n = 364 Local Government Areas (LGAs)	General population in Australia	Vegetation diversity, Proportion of Eucalyptus forest, Proportion of open trees; Average value within LGA (250 m grid metric data aggregated to 3 km radius)	Respiratory hospital admissions	SES, temperature, species richness, % overweight, % smoking, distance to coast, precipitation, land use mix, other biodiversity indicators	Standardised regression coefficients: Proportion of eucalyptus forests: −0.0270 p = 0.0055 Diversity of vegetation: −0.0324 p = 0.0033 Proportion of open trees: −0.0121 p = 0.3738	Probably Low
Lee, 2020b	Cohort	n = 11,281	Children at age 4 with allergic rhinitis recruited in Taiwan	NDVI (greenness) (MODIS; 250 m) Urban parks; Mean NDVI in each township across the study period during January, April, July, and October. Mean urban park % in each township	Allergic rhinitis outpatient visits	Air temperature, relative humidity, PM2.5 concentrations, socioeconomic status (income tax level as a proxy), road network, industrial area, population size, sex ratio, year, season, township urbanization level	Relative risk (1 unit increase in NDVI; 1% increase in urban parks): NDVI: RR = 1.084 (1.059, 1.111) Urban parks: RR = 1.057 (1.056–1.058)	Probably Low
Hu, 2007	Ecological	20 zipcodes	General population, Pensacola metropolitan region of Florida.	Greenness (Landsat), 1.5 km buffers around randomly selected points	Asthma hospitalisations	Point source pollution sites and emissions, traffic count	Association between greenness and Standardised Morbidity Ratio: Greenness effect −0.221 (p = 0.230) for spatial lag model; −0.2590 (p = 0.077) for spatial error model	Probably High
Lovasi, 2008	Ecological	n = 42 health service catchment areas	Children <15 years, New York City, USA	Street tree density in United Hospital Fund (UHF) area	Asthma hospitalisations	SES, race, population density, distance to pollution sources	Relative risk (RR) per SD of tree density: Hospitalisations RR = 0.89 (0.75 to 1.06)	Probably High
Ayres-Sampaio, 2014	Ecological	n = 278	General population in Portugal	NDVI Vegetation (MODIS); Seasonal average NDVI of each municipality	Asthma hospital admissions	Temperature, humidity, air pollution	Pearson correlation coefficients: r = −0.498, −0.407, −0.376, −0.439 for NDVI and winter, spring, summer, autumn admissions	Probably High
Lee, 2014	Ecological	n = 143	General population in Korea	Forest cover; Proportion of forest cover within a city	Number of outpatients, number of visits	Age distribution, air pollution, medical providers	Parameter estimate from structural equation model: Estimate = −0.05, p < 0.00	Probably High
Alcock, 2017	Ecological	n = 26,455 urban residential areas	General population, England	Green land use, % of greenspace and gardens in lower super output areas, density of mature trees	Emergency hospitalisations for asthma	Air pollution, deprivation, age structure	Mean change to asthma rate per % greenspace: Greenspace (+1%) −3.89 (−4.65 to −3.14) Gardens (+1%) −4.35 (−5.5 to −3.19) Trees (+50/km^2) -9.14 (−11.19 to −7.09)	Probably High
Alvarez-Mendoza, 2019	Ecological	892 hospital admissions	General population in Quito, Ecuador	NDVI; Monthly median NDVI in each parish	Chronic respiratory disease hospital admissions	SO2, surface reflectance (proxy for humidity and O3)	Odds ratio: 0.2395 (p = 0.219)	Probably High
Douglas, 2019	Ecological	n = 2347 census tracts	General population in Los Angeles County, US	Public parks and open space (Los Angeles County Department of Parks and Recreation); Acres of public parks and open space per census tract	Asthma emergency department visits	Diesel particulate matter, % poverty, % <10 years old, race/ethnicity	Regression coefficient: Public park and open space = −8.05 (p < 0.001)	Probably High
Lai, 2019	Ecological	n = 174 zip codes	General population in New York City, US	Street trees; Number of street trees per 1000 ft. street length	Asthma emergency department visits	Indoor/outdoor air pollution, tree allergenicity, age (<17 or > 65 years), % public housing	Geographically weighted regression coefficient: Street trees = −0.01 (p > 0.05)	Probably High
Heo, 2019	Time series	n = 364	Medicare enrollees	NDVI greenness; Population-average NDVI	Respiratory hospital	Median household income, percent of the population ≥	% change in hospitalization risk associated with a 1 IQR	Probably High

Table 5 (*continued*)

First author, year	Study type	Sample size/# of cases	Study population and setting	Greenspace data/exposure metric	Respiratory health outcome	Confounders/covariates	Main results (95% CI)	Overall risk of bias
			(>65 yrs) in U.S. counties with populations larger than 200,000	for each county (MODIS at 250 m resolution)	admissions	65 years, percent of persons >65 years in poverty, population density, mean of annual level of PM10 (or PM2.5), and latitude of the county	increase in NDVI: All respiratory disease: PM10: −1.29 (−3.36, 0.83) PM2.5: −0.01 (−1.03, 1.01)	
Kim, 2021	Ecological	$n = 2301$ census tracts	General population in Los Angeles County, US	Trees (Los Angeles Regional Imagery Acquisition Consortium) Greenspace (Los Angeles Regional Imagery Acquisition Consortium); Areas covered by trees; Median size of tree patch; Cluster of patches; % private greenspace; % recreational greenspace; % semi-public greenspace	Asthma emergency department visits	SES, air pollution	Regression coefficients: Spatial error model: Areas covered by trees = −52.911 ($p < 0.05$); Size of tree patch = −0.033 ($p < 0.05$); Cluster of patches = 15.232 ($p < 0.05$); % private greenspace = 13.428 ($p > 0.05$); % recreational greenspace = 9.543 ($p > 0.05$); % semi-public greenspace = 1.014 ($p > 0.05$)	Probably High

NDVI = Normalised Difference Vegetation Index; OR = Odds Ratios; RR = Relative Risk; SES = Socioeconomic Status; SD = Standard Deviation; SMR = Standardised Mortality Ratio.

4. Discussion

Our evidence review was aimed at summarising published evidence on the associations of urban greenspace with respiratory health and the hypothesised causal pathways that these associations may reflect. We searched five databases of peer-reviewed studies and identified 108 eligible papers, including 104 observational and four experimental studies. Two thirds of the associations in these studies were positive with health, with 31% positive and statistically significant; only 9% reported associations with health that were negative and statistically significant. The most consistent positive evidence was apparent for respiratory mortality. In the following discussion, we first highlight relevant pathways to health, as suggested in the reviewed studies; we then discuss the findings for each health outcome and assess the overall evidence.

4.1. Hypothesised causal pathways

A range of mechanisms with respiratory health were offered in the reviewed papers, though few studies actually tested these hypotheses. Positive pathways for health included the abatement of the urban heat island effect and outdoor air pollution; reduced exposure to indoor allergens (e.g., by encouraging more time outside and/or introducing more diverse microbiota); reduced stress (e.g., via reduced noise exposure/annoyance); and opportunities for physical activity. Suggested negative pathways for health were exposure to pollen and other aeroallergens, and monocultures, which may entail pesticide use and reduced biodiversity. In addition to suggesting these pathways, the studies underscored the importance of contextual factors when interpreting results, which may affect the exposure, health outcome, or their interrelationship. We illustrate some of the potential pathways and contextual factors for consideration in Fig. 4.

4.2. Respiratory mortality

The analyses of respiratory mortality (excluding that from lung cancer) showed the most consistent positive findings (i.e., a lowered risk) with greenspace, with some studies including a narrow list of causes of death (e.g., chronic lower respiratory disease [J40-J47] [Xu et al., 2017]) and others examining all respiratory diseases (i.e., J00-J99 [Vienneau et al., 2017]). This general trend agrees with a meta-analysis of greenspace and all-cause mortality in cohort studies, which estimated a 3%–6% lower risk of mortality per 0.1-unit increase in residential NDVI levels (Rojas-Rueda et al., 2019). A causal association with greenspace may reflect a combination of the pathways in Fig. 4 (e.g., less exposure to air pollution, greater opportunity for physical activity). Studies with mediation analysis found the individual contribution of some of these pathways explained from less than 10% (James et al., 2016; Vienneau et al., 2017) up to 60% ($PM_{2.5}$) (Bauwelinck et al., 2021) of observed associations. Potential benefits may not be universal, as one study suggested positive associations in men only (Richardson and Mitchell, 2010); concerns of perceived neighbourhood safety or greenspace quality may discourage greenspace utilisation, especially for women.

4.3. Lung cancer

The lung cancer studies showed a lower proportion of positive results than those for respiratory mortality. The most important risk factor for lung cancer is tobacco smoking (Alberg et al., 2013), but only one of the studies examining lung cancer could control for individual-level smoking habits. The latency period for lung cancer can span multiple decades (Shibuya et al., 2005), which would require the assessment of exposures over an extended period of time in epidemiological studies (Hystad et al., 2013). There is emerging evidence that the amount of surrounding residential greenspace may be associated with lower current smoking and higher smoking cessation, which would provide an effective pathway for reduced lung cancer (Martin et al., 2020). The lack of robust adjustment for smoking and application of ecological study design, where populations are likely to be dynamic over time, hinders the interpretation of the lung cancer evidence related to greenspace exposure.

4.4. Asthma & hospital visits

Context may play a key role in interpreting the mixed evidence presented in the studies on asthma. For example, in one study, asthma prevalence in areas of higher greenspace was found to be lower only in the presence of heavy traffic (Feng and Astell-Burt, 2017). While Andrusaityte et al. (2016) found higher childhood asthma prevalence in areas with higher NDVI and no such links with residential proximity to a park, Dadvand et al. (2014) found the opposite (i.e., higher asthma closer to parks [not forests], but no relationship to NDVI). Urban parks may be more likely to incorporate exotic flora, potentially contributing to higher allergenicity, than perhaps more native plants in forests. NDVI reflects all vegetation, much of which may not produce pollen; pollen can travel over long distances, though proximate taxa have shown to be influential for pollen concentration levels (Charalampopoulos et al., 2018). In addition, a number of

Table 6
Study characteristics of the asthma studies, ordered by risk of bias and year.

First author, year	Study type	Sample size/# of cases	Study population and setting	Greenspace data/exposure metric	Respiratory health outcome	Confounders/covariates	Main results (95% CI)	Overall risk of bias
Lovasi et al., 2013	Cohort	n = 492 (5 years) n = 427 (7 years)	African American and Dominican children aged <7 years in New York City, USA	Tree canopy from 2001 (LiDAR plus aerial imagery and vector data); % of area within 250 m of address	Asthma prevalence	Sex, age, ethnicity, maternal asthma, previous birth, other previous pregnancy, Medicaid enrolment, smoking, population density, percent poverty, percent park land, and estimated traffic volume.	Prevalence ratios (or RRs) per 10% increase in neighbourhood tree canopy*: Asthma at age 7: 1.22 (1.03 to 1.43)	Probably Low
Sbihi et al., 2015	Cohort	65,000 children (8214 cases)	Children aged 0–10 years old in Vancouver, Canada	NDVI vegetation during pregnancy were calculated for 100-m areas around residential postal codes	Asthma diagnosis	Individual covariates include the month/year of birth, sex, First Nations status, and maternal parity, age, smoking during pregnancy, and initiation of breastfeeding. Participants were assigned neighbourhood-level socioeconomic indicators (household income and maternal education), air pollutants	ORs per 0.1-unit increase in NDVI during pre-school years:* aOR = 0.96 (95% CI: 0.94 to 0.99) Distance to nearest park: aOR = 0.98 (0.95 to 1.00) No associations during school years.	Probably Low
Andrusaityte, 2016	Case-control	n = 1489 (n = 112 asthma cases, n = 1377 controls)	Children aged 4–6 years in Kaunas, Lithuania	[1] NDVI (Landsat), [2] land use (Urban Atlas); Average residential NDVI using 100 m, 300 m, 500 m buffers; Residential distance to park <1000 m (binary)	Parent report of clinically diagnosed asthma	Mother's age at childbirth, maternal education, parental asthma, maternal smoking during pregnancy, breastfeeding, antibiotic use, keeping a cat, living in a flat and ambient PM2.5 and NO2	Odds Ratio: Per 0.1-unit increase in NDVI − 100*: OR = 1.38 (1.09 to 1.75); Results non-significant when including park distance. Distance to a city park <1000 m: OR = 0.96 (0.55 to 1.68)	Probably Low
Su et al., 2017	Panel	n = 140 (5660 rescue inhaler use events)	Convenience sampled participants (<18 years) in Louisville, Kentucky, USA	Land cover: forest, shrub land, and grassland/ herbaceous cover; Land cover proportion when rescue inhaler used - 250 m buffer	Asthma rescue inhaler use	Air pollution, pollen, and mold spore counts, and meteorological information, land use. Smoking in sensitivity analysis.	Rate ratio per IQR of %: Vegetation cover: 0.829 (95% CI: 0.800 to 0.857) Tree cover: 0.825 (95% CI: 0.796 to 0.854)	Probably Low
Donovan, 2018	Cohort	n = 49,956	Children born in 1998 followed up from 0 to 18 years of age in New Zealand	NDVI vegetation (Landsat, max annual value) and Land cover (2012); Average lifetime NDVI in residential meshblocks (mean buffer ~255 m), Proportion of natural land cover in meshblocks	Asthma based on pharmacy (7 + prescriptions) and hospital discharge records (J45–46)	Air pollution (major road length, mean annual NO2), premature birth, low birth weight, antibiotic use, parental smoking, ethnicity, birth order, number of siblings, parental occupation, NZDep social deprivation index	OR per 0.1-unit increase in NDVI*: 0.93 (0.89 to 0.98) Per SD increase in land cover: Number of natural land cover types: 0.933 (0.885 to 0.985) Exotic conifer land cover: 1.042 (1.009 to 1.075) Gorse land cover: 1.032 (1.004 to 1.060)	Probably Low
Eldeirawi et al., 2019	Cross-sectional	n = 1915	Mexican American children in Chicago, US	NDVI (Landsat 30 m resolution); Residential buffers of 100 m, 250 m, 500 m	Parent-reported asthma	Age, sex, country, urban/rural, family history of asthma, smoking in the home, proximity to traffic arterials, population density, SES + others	Odds ratio for IQR increase in NDVI: NDVI (250 m): Lifetime asthma:	Probably Low

Table 6 (*continued*)

First author, year	Study type	Sample size/# of cases	Study population and setting	Greenspace data/exposure metric	Respiratory health outcome	Confounders/covariates	Main results (95% CI)	Overall risk of bias
							OR = 1.08 (0.82 to 1.42)	
Zeng, 2020	Cross-sectional	n = 59,754	Children aged 2–17 years in 7 cities in Northeast China	NDVI, Soil adjusted vegetation index (SAVI) (Both use Landsat; 30 m); Summer NDVI around each school at 100 m, 300 m, 500 m, and 1000 m buffers.	Current asthma	Age, gender, parental education, family income, breastfeeding, low birthweight, preterm, residential area, SHS, mold in home, home coal usage, and family history of asthma, PM10, NO2	Odds ratio (OR) per 0.1 unit increase in NDVI or SAVI.: NDVI (300 m) Current asthma OR = 0.87 (0.82 to 0.92) Air pollution was found to be a strong mediator for asthma	Probably Low
Dzhambov, 2021	Cross-sectional	n = 1251	School children, aged 8–12 years. in Alpine towns, Austria & Italy	NDVI (July–August 2003; Landsat, 30 m) Tree canopy cover (2000; Landsat; 30 m) Domestic garden (study questionnaire); Residential buffers of 100 m, 300 m, 500 m, school buffer of 100 m	Parent-reported current asthma symptoms, ever asthma symptoms	Age, gender, maternal education, low birth weight, maternal smoking during pregnancy, duration of breastfeeding, cumulative risk of secondhand smoking/pneumonia/bronchitis in the 1st year of life, number of green months during pregnancy, geographic region	Odds ratio for IQR increase: NDVI (500 m): Ever asthma: OR = 0.81 (0.64 to 1.03) Tree cover (500 m): Ever asthma: OR = 0.94 (0.73 to 1.22) Gardens (Presence): Ever asthma: OR = 0.71 (0.51 to 1.00)	Probably Low
Lovasi, 2008	Ecological	n = 42 health service catchment areas	Children <15 years, New York City, USA	Street tree density in United Hospital Fund (UHF) area	Asthma prevalence	SES, race, population density, distance to pollution sources	Relative risk (RR) per SD of tree density: Prevalence RR = 0.71 (0.64 to 0.79)	Probably High
Maas, 2009	Cross-sectional	n = 345,143 individuals	General population, Netherlands	Green land cover), % of greenspace within 1 km and 3 km around home postcode	Prevalence rate of Asthma, COPD	Age, sex, SES, urbanicity	Odds Ratio (OR) for 10% increase in greenspace within 1 km: Asthma, COPD: 0.97 (0.96 to 0.98)	Probably High
Khan, 2010	Cross-sectional	n = 987	General population in Karachi, Pakistan	Vegetative area (Landsat land cover;)Area of vegetative land in each union council	Asthma prevalence	None.	Correlation between asthma prevalence and vegetative land cover: r = 0.43	Probably High
Pilat, 2012	Ecological	n = 14 Metropolitan Statistical Areas (MSAs)	Children aged <17 years in Texas, USA	Mean NDVI vegetation & % tree canopy in MSAs	Asthma prevalence	Relative humidity, temperature, ozone, particulate matter, and ethnicity	Semipartial correlation between asthma residual and NDVI/tree canopy: NDVI: r = 0.052 (p = 0.880) Tree canopy: r = −0.328 (p = 0.325)	Probably High
Dadvand 2014	Cross-sectional	n = 3178	School children aged 9–12 years; Sabadell, Spain	NDVI Vegetation (Landsat), Land use (parks, forests); Mean NDVI 100 m, 250 m, 500 m, 1000 m residential buffers and Living within 300 m of a	Current asthma	SES, type of school, urban vulnerability, age, sex, exposure to environmental tobacco smoke, having older siblings, parental history of asthma	Adjusted ORs for 0.1-unit increase in NDVI (250 m): 1.02 (0.82 to 1.28)* Adjusted ORs for living within 300 m of: parks 1.60	Probably High

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Table 6 (*continued*)

First author, year	Study type	Sample size/# of cases	Study population and setting	Greenspace data/exposure metric	Respiratory health outcome	Confounders/covariates	Main results (95% CI)	Overall risk of bias
				park or forest			(1.09 to 2.36); forests 1.02 (0.56 to 1.87)	
Brokamp et al., 2016	Cohort	$n = 762$	Atopic children aged ≤7 years old in USA	NDVI vegetation; Mean of 400 m residential buffer	Asthma diagnosis at age 7	Air pollution, neighbourhood deprivation, race	Unadjusted OR (unit not given) = 0.15 (0.01 to 2.04)	Probably High
Bernat, 2016	Ecological	n = 8 urban areas	General population in 8 urban areas in Lithuania	Forest coverage, recreational forests, forest remoteness; % (coverage/ remoteness) or ha/1000 inhabitants in urban areas	Asthma cases per 1000	Other exposures included, e.g. air pollutants, but independent correlation analysis only	Correlations: Asthma Coverage: $r = -0.29$ Remoteness: $r = 0.17$ Recreational: $r = -0.63$	Probably High
Ulmer, 2016	Cross-sectional	$n = 7910$ in cohort $n = 4820$ in analysis	General population (adults <65 years of age) in California, USA	Tree cover (LIDAR data); 250 m residential buffer	Asthma included as a mediator	Sex, age, race, education, income, smoking status, park percentage near home, walkability	Mediation analysis, also assess association between asthma and tree canopy: Odds of asthma for 10% increase in tree canopy: OR = 0.90 (0.79 to 1.02)	Probably High
Chen et al., 2017	Cross-sectional	$n = 150$	Children aged 9–17 years with physician-diagnosed asthma in Chicago, USA	NDVI vegetation (Landsat) - averaged across year; 250 m residential buffer	Asthma control and functional limitations	SES, season, age, sex, ethnicity, asthma severity, medication use	Regression coefficients predicting asthma outcomes: Asthma control: 0.05 (−9.05 to 17.46); Asthma functional limitations: 0.02 (−4.27 to 5.27)	Probably High
Feng, 2017	Cross-sectional	$n = 4447$	Children aged 6–7 years old, Australia	Green land use (parkland); % of parkland in Statistical Areas stratified into 0–20%, 20–40%, >40%	Asthma prevalence	Age, gender, maternal education, area SES, geographic remoteness, traffic volume, perceived safety	OR of asthma with GS: >40% GS: 1.15 (0.73 to 1.82) OR of asthma with heavy traffic and GS: >40% GS: 0.32 (0.12 to 0.84)	Probably High
Tischer et al., 2017	Cohort	$n = 2472$	Children aged 4 years in Asturias, Gipuzkoa, Sabadell and Valencia, Spain	NDVI vegetation (Landsat), Green land use (Urban Atlas); Mean NDVI within 300 m home buffer (average between birth and age 4), Greenspace within 300 m of home	Asthma prevalence	Sex, maternal education, maternal allergy, breast feeding, pets at home, maternal smoking during pregnancy, second hand smoke, area deprivation, air pollution (NO2), sensitivity analysis with physical activity	ORs (3rd vs 1st tertile) of NDVI and distance (<300 m) to greenspace for all 4 regions combined: NDVI Asthma: 1.82 (0.71 to 4.67) Greenspace distance Asthma: 0.60 (0.31 to 1.18)	Probably High
Ihlebaek, 2018	Cross-sectional	$n = 8638$	Adults aged 30–76 years Oslo, Norway	[1] Vegetation cover greenness (VCG) from satellite data (10 m resolution), [2] land use greenness (LUG) from municipal plans; % of VCG and proportion of	Self-reported asthma	Circuit (area) level covariates: mean income, % living in an owned house and mean education. Individual: civil status, use of alcohol, smoking status, physical activity, type of work, number of negative life events, number of good friends and degree of interest from other people.	Men Q5:Q1 OR = [1] 0.94 (0.51 to 1.74) and [2] 0.73 (0.40 to 1.35) Women Q5:Q1 OR = [1] 0.81 (0.51 to 1.30) and [2]	Probably High

Table 6 (*continued*)

First author, year	Study type	Sample size/# of cases	Study population and setting	Greenspace data/exposure metric	Respiratory health outcome	Confounders/covariates	Main results (95% CI)	Overall risk of bias
				LUG in each 'circuit' (quintiles)			0.78 (0.50 to 1.23)	
Kurnia Febriawan and da Silva Sodre, 2018	Ecological	Not specified, only reported prevalence of asthma as %	General population in Western Australia	Enhanced Vegetation Index (EVI) from MODIS; Either positive or negative values	Asthma prevalence	Humidity, Rainfall, SES	Proportion high asthma in area of low EVI = 79.97%; high EVI = 20.03%	Probably High
Zock, 2018	Cross-sectional	n = 4450	General population in the Netherlands	Natural and agricultural green land use (from LGN-72012); Proportion of green land use within a neighbourhood	Asthma & COPD (combined) prevalence	Sex, age (continuous), household income and SES (individual level) and municipality and neighbourhood (group level), air pollution, noise, blue space	OR per 10% increase in green land use: Natural green = 0.92 (0.81 to 1.04) Total green = 0.97 (0.94 to 1.02)	Probably High
DePriest, 2019	Cross-sectional	n = 196	Children aged 3–12 years with persistent asthma in US	NDVI; Neighbourhood level	Asthma control	Age, sex, social risk index, season, medication, allergen sensitisation, secondhand smoke	Odds ratio (unit not given): 1.01 (0.93, 1.10)	Probably High
Li, 2019	Cross-sectional	n = 5643	Middle school students in Suzhou, China	NDVI (Greenness) (Landsat; 30 m), Parks; Mean NDVI from images in March, June, October, December 2014 at 100 m, 200 m, 500 m, 1000 m residential buffers; Distance from home to nearest park	Doctor-diagnosis of asthma	Age, sex, environmental tobacco smoke (ETS) at home, parental education, parental history of asthma, air pollution, pets in the home, and dampness and mold	Odds ratio for IQR increase in NDVI or Q4:Q1 distance to a park: NDVI (200 m) Ever asthma OR = 1.01 (0.88 to 1.16) Urban parks (Q4:Q1) Ever asthma OR = 0.70 (0.50 to 0.96)	Probably High
Hsieh, 2019	Case-control	n = 3520 cases n = 3520 controls	Children <18 years of age in Taiwan	Green cover (NDVI value ≥0.4) (Landsat and Thermal Infrared Sensor satellites); Quintile of green cover for township of residence	Asthma incidence	Matched on sex, age, first diagnosis year. Adjusted for air pollutants, urbanization degree, frequency of healthcare provider visits, and mean township family income	Odds ratio (reference: Q1 green cover): Q5:Q1 green cover: OR = 1.10 (0.92 to 1.32); p for trend = 0.0289	Probably High
Alasauskas, 2020	Cross-sectional	51,235 school children, including 3065 with asthma.	School children, aged 7–17 years. in Vilnius, Lithuania	Green spaces defined as areas with trees and bushes.; Distance to green space	Asthma prevalence	Adjusted for air pollutants, age, sex, proximity to roads, green spaces,	Odds ratio for distance to greenspace: 1.336 (1.060 to 1.653)	Probably High
Squillacioti, 2020	Cross-sectional	n = 187	Children (10–13 years old) in Turin, Italy	NDVI (greenness) (Landsat; 30 m); Mean NDVI in a 300 m residential buffer	Asthma prevalence	Air pollutants, namely PM10, NO2 and NO, age, sex, BMI and urinary cotinine levels	Odds ratio of tertile 3 (highest) to tertile 1 (lowest) NDVI (300 m) Asthma OR = 0.13 (0.02 to 0.70)	Probably High
Aerts, 2020	Ecological	n = 1872 census tracts	6–18 year old children in Belgium	Relative covers of forest, grassland and garden from the Belgian National Geographic Institute (NGI-IGN).; % cover in census tracts	Asthma prevalence (using sales data of reimbursed medication for obstructive airway disease)	Models were adjusted for air pollution (PM10), housing quality and administrative region	Parameter estimates per IQR increase of relative cover: Grassland β = 0.10 to 0.14 Garden β = 0.07 to 0.09 Forest: β = −0.013 to 0.010	Probably High

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Table 6 (*continued*)

First author, year	Study type	Sample size/# of cases	Study population and setting	Greenspace data/exposure metric	Respiratory health outcome	Confounders/covariates	Main results (95% CI)	Overall risk of bias
Kuiper, 2020	Cohort	*n* = 1106 parents *n* = 1949 children	Parents (exposure) Children (outcome) in Bergen (Norway) and Umea, Uppsala, and Gothenburg (Sweden)	NDVI (Greenness; Landsat); Mean NDVI in summer in 100 m, 300 m, 500 m and 1000 m during 0–18 years of age for parents and 0–10 years of age for offspring.	Early onset asthma (parent reported)	Grandparental education, grandparental asthma; parental asthma, offspring's own air pollution/greenness exposures and air pollution/greenness exposures during pregnancy were included as potential mediators	Odds ratio for tertile 3 to tertile 1 of parent's exposure: Early onset asthma: Mother: OR = 1.00 (0.59 to 1.72) Father: OR = 0.67 (0.31 to 1.42)	Probably High
Markevych et al., 2020	Cohort	*n* = 631	Children up to 15 years old in Leipzig, Germany	NDVI (greenness) (Landsat; 30 m), Trees (Stadt Leipzig, Amt für Geoinformation und Amt für Stadtgrün und Gewasser); Mean NDVI; Total number of trees, Number of allergenic trees in 100 m, 300 m, 500 m, and 1000 m around home birth address.	Asthma (parent reported of doctor diagnosis)	Age, sex, season of birth, parental atopy and parental education.	Odds ratio for tertile 3 to tertile 1 of birth exposure: NDVI (300 m) Asthma: OR = 0.61 (0.39 to 0.95) Trees (300 m) Asthma: OR = 0.80 (055 to 1.18) Allergenic trees (300 m) Asthma: OR = 1.49 (0.98 to 2.27)	Probably High
Commodore, 2021	Cross-sectional	*n* = 855	Multi-racial children aged 4–8 years old in Various US states: DE, NY, CA, NY, IL, NJ, AL	Public parks ascertained in the Preschool-aged Children's Physical Activity Questionnaire (Pre-PAQ); Presence of park	Parent-reported asthma/asthma-like symptoms	Sex, race-ethnic group, family history of asthma, Maternal education level, Obese status of child, pets, exposure to environmental tobacco smoke, traffic, urban-rural status	Odds ratio: Presence of parks: 2.65 (1.14, 6.15)	Probably High
Razavi-Termeh, 2021b	Cross-sectional	*n* = 872 cases	General population in Tehran, Iran	NDVI (2009–2019; Landsat; 30 m); Annual average	Asthma prevalence	Air pollution parameters (O3, CO, NO2, SO2, PM 10, and PM 2.5), meteorological parameters (rainfall, temperature, humidity, pressure, and wind speed), distance to streets	Gini index: Higher asthma prevalence in areas with lower NDVI	Probably High
Yu, 2021b	Cross-sectional	n = 59,754	Children aged 2–17 years in 7 cities in Northeast China	Eye-level greenness (Tencent map); Green view index (GVI) for grass, trees, overall around schools at 800 m and 1000 m buffers	Asthma prevalence	age, sex, parental education, family income, obesity, pet kept in home, and exercise time. Effect modification by PM2.5	Odds ratio per IQR increase in GVI (800 m): GVI (800 m) Doctor diagnosed asthma: Trees: OR = 0.76 (0.72 to 0.80) Grass: OR = 1.04 (1.00 to 1.08) (Overall: OR = 0.77 (0.73 to 0.81))	Probably High
Cavaleiro Rufo et al., 2021	Population cohort	*n* = 1050	Children at ages 4 and 7 years. in Porto, Portugal	NDVI; Residential buffers of 100 m, 200 m, 300 m during 2005–2006	Parent-reported asthma/asthma-like symptoms	Sex, maternal history of asthma, household crowding, maternal education, distance to nearest major road and neighbourhood SES.	Odds ratio: NDVI (100 m) (T3:T1): Asthma - age 4: 0.28 ($p > 0.05$) Asthma - age 7: 0.37 ($p > 0.05$) Wheezing - age 7: 0.49 ($p > 0.05$) Dry cough - age 7: 0.91 ($p > 0.05$) Rhinitis - age 7:	Probably High

Table 6 (*continued*)

First author, year	Study type	Sample size/# of cases	Study population and setting	Greenspace data/exposure metric	Respiratory health outcome	Confounders/covariates	Main results (95% CI)	Overall risk of bias
							0.37 ($p < 0.05$)	
Dong, 2021	Ecological	n = 140 neighbourhood units	General population in Toronto, Canada	1) Ratio of tree areas to shrub and grass areas (Toronto Parks, Forestry and Recreation), 2) Tree diversity, 3) Percentage of greenspace; Neighbourhood level	Asthma prevalence	Age, sex, air pollution (mediator), income, household size, % of visible minorities	Regression coefficients: Ratio of tree area to shrub/grasses: −0.19 ($p >$ 0.05) Tree diversity: 0.07 ($p > 0.05$) % of greenspace: 0.12 ($p > 0.05$)	Probably High
Donovan, 2021	Ecological	*n* = 498 cities, 26,367 census tracts	Adults in US cities	Plant diversity from Global Biodiversity Information Facility Overall greenness (NDVI) from USGS EROS Archive; Taxonomic diversity at census level. Maximum NDVI at census level.	Asthma prevalence	SES, race, ethnicity, air quality, climate zone, obesity %, PM2.5 (examined effect modification)	Standardised regression coefficients (per 1 SD): Taxonomic diversity = −0.0528 (−0.0638 to −0.0418) NDVI = 0.0383 (0.0290 to 0.0475)	Probably High
Kuiper et al., 2021	Matched case-control, cohort	*n* = 3428	Adults (age 18–40 years) in Norway, Sweden	NDVI (greenness) (Landsat; 30 m); Residential buffer of 300 m (mean value in May, June, July every 5 years from 1984 to 2014)	Asthma (self-reported of doctor diagnosis), asthma attack in the last 12 months	O3, NO2, parental education and parental asthma	Odds ratio for 0.1-unit increase in NDVI (asthma): NDVI (300 m) Physician diagnosed asthma OR = 1.00 (0.98 to 1.01) Asthma attack (lifetime) OR = 0.95 (0.77 to 1.17)	Probably High
Razavi-Termeh, 2021a	Cross-sectional	n = 872 cases	Children in Tehran, Iran	Parks; Distance to parks	Asthma prevalence	Air pollution parameters (O3, CO, NO2, SO2, PM 10, and PM 2.5), meteorological parameters (rainfall, temperature, humidity, pressure, and wind speed), distance to streets	Random forest model: Positive association between distance to park and asthma prevalence	High

GS = Greenspace; IQR = Interquartile Range; NDVI = Normalised Difference Vegetation Index; OR = Odds Ratios; RR = Relative Risk; SHS: Secondhand smoke; SES = Socioeconomic Status; SD = Standard Deviation; SMR = Standardised Mortality Ratio.

* Standardised from reported values.

studies included self-or parent-reported health information, which, unless a robust and validated questionnaire was used to ascertain health status (e.g., ISAAC), were assigned a 'probably high' bias rating. Self-reported health can vary by country (Jürges, 2007), and reports of child health have been shown to vary by parental gender (Waters et al., 2000). Therefore, this differential assessment of health may have hampered the interpretation of evidence on a multi-country scale via different study designs. Overall, the available evidence of greenspace exposure and asthma was too heterogeneous and inconsistent to make inferences on the direction or causality of associations; such contradictory findings could be attributed to different greenspace metrics or uncontrolled confounding, such as body mass index (Beasley et al., 2015).

4.5. Respiratory symptoms & rhinitis

Studies have examined respiratory symptoms related to asthma and rhinitis, with most unable to identify a clear association. There are different putative factors associated with the development of rhinitis, depending on the sub-type (i.e., allergic, infectious, chronic), including pollen, viruses, environmental tobacco smoke (Roberts et al., 2013), and other air pollutants (Lu et al., 2020). The lack of robust associations, and even inconsistent results in the same study, suggests the presence of more important underlying mechanisms, though a potential role for greenspace in causal pathways cannot be ruled out. Greenspace indicators may have been too crude to disentangle net effects to exposures that, for example, involve allergenic features linked to certain species, (e.g., birch tree pollen [Biedermann et al., 2019]).

4.6. Lung function & other health outcomes

While still somewhat inconsistent overall, some of the more recent studies indicated better lung function in school children with higher surrounding levels of greenspace (e.g., Yu et al., 2021a; Zhang et al., 2021; Zhou et al., 2021). The experimental studies examining lung function or mucociliary clearance also found better function in green areas compared

Table 7
Study characteristics of the lung function studies, ordered by risk of bias and year.

First author, year	Study type	Sample size/# of cases	Study population and setting	Greenspace data/exposure metric	Respiratory health outcome	Confounders/covariates	Main results (95% CI)	Overall risk of bias
Huang et al., 2016	Experimental	n = 40	Young, healthy college students in Beijing, China	2 h exposure in an urban park Control: Transport hub (high air pollution)	Pulmonary function: (FEV1) and peak expiratory flow (PEF))	Age, sex, BMI, day of week, time of measurement, site, temperature and relative humidity and air pollutants: PM2.5, BC, and CO.	Transport hub vs. park % change: FEV1 1 h − 3.48 (−4.43 to −2.53) vs. -0.32 (−1.28 to 0.64); PEF 1 h − 4.51 (−5.66 to −3.36) vs. −1.91 (−3.01 to −0.81);	Probably Low
Cole-Hunter, 2018	Panel	n = 57	Healthy adults aged 18–60 years in Barcelona, Spain	NDVI vegetation - spring (Landsat); NDVI using 100 m, 300 m, 500 m buffers around residential and occupational addresses	Lung function - spirometry {FEV1, FVC, SUM}	age, height, weight, BMI, sex, air pollution (NO2, NOx, O3, PM10, PMCoarse, PM2·5), noise, fungal and pollen spores, weather, total-PA, neighbourhood-greenness and noise	PM10 adjusting for greenness as a covariate: FVC $\beta = -0.22\%$, $p = 0.09$; FEV1 $\beta = -0.34\%$, $p = 0.15$	Probably Low
Sinharay, 2018	Experi-mental	n = 40 COPD; $n = 39$ IHD; $n = 40$ healthy controls	Men and women aged 60 years+ with (GOLD) COPD, and healthy volunteers in London, UK	2 h walk in an urban park (Hyde Park) Control: 2 h walk on a busy street (Oxford St)	Lung function up to 26 h after walking	Air pollution (main exposure), group, location, time of measurement, temperature, relative humidity, smoking history	No difference in lung function in COPD patients at the end of the walk between Oxford St and Hyde Park.	Probably Low
Moshammer, 2019	Experimental	n = 24	Students (age range 21–33) in Vienna	Park ("Augarten", a large park in the centre of Vienna); 1 h walk	Lung function	Single exposure models	Change in lung function in road vs park: FVC (24 h) = −50.03 ($p = 0.005$) FEV1 = −13.12 ($p = 0.49$)	Probably Low
Zhang, 2021	Case-control	$n = 1900$ cases $n = 87$ controls	Schoolchildren age 9–11 years in Tianjin, China	NDVI (2015–2017; Landsat; 30 m); Mean NDVI at 100 m, 300 m, 500 m residential buffer for three periods: lag1 (Jul-Sep), lag2 (Apr-Jun) and lag3 (Jan-Mar)	Impaired lung function (FEV1/FVC ≤ 0.8)	Sex, BMI, parental education, air pollution, road proximity, indoor factors (e.g. smoking, cooking fuel)	Odds ratio: NDVI (300 m): lag1: OR = 0.044 (0.022 to 0.065) lag2: OR = 0.036 (0.014 to 0.057) lag3: OR = 0.049 (0.027 to 0.070)	Probably Low
Zhou, 2021	Cross-sectional	$n = 6740$	School children aged 6–15 years. in 7 cities in Northeast China	NDVI, Soil adjusted vegetation index (SAVI) (Both use Landsat; 30 m); Mean NDVI around schools using 300 m, 500 m, 1000 m buffers.	Lung function: obstructive (FEV1/FVC <0.8), restrictive (FEV1/FVC ≥0.8 but FVC <80% of predicted)	Age, sex, height, weight, parent education level, family income, environment tobacco exposure, home coal use, pet keeping, home renovation, family history of atopy, prematurity and season.	Odds ratio (OR) for airflow obstruction/spirometric restrictions or change in FEV/FVC per IQR increase in NDVI: NDVI (300 m) Airflow obstruction OR = 0.99 (0.85 to 1.17) Spirometric restrictions: OR = 0.55 (0.45 to 0.68) FEV1: B = 61 (47 to 76) FVC B = 63 (41 to 71)	Probably Low
Boeyen et al., 2017	Cross-sectional	$n = 360$	Children aged 5–12 years in heavy industrial area in Western Australia	NDVI vegetation (Landsat at 30 m resolution); Residential means using buffers 100, 200, 300, 500 m	Lung function using Forced Oscillation Technique - respiratory system resistance and reactance, Area under reactance curve, resonant frequency, Frequency dependence of resistance	Personal (Age, height, weight, asthma, smoking history, pets, parent education) Housing (age, heating type, wood burning, distance to major road	Spearman Correlation Coefficient: NDVI within 500 m: Respiratory system resistance: −0.078, $p = 0.149$ Respiratory system reactance: 0.032, $p = 0.559$ Area under reactance curve −0.065, $p = 226$ Resonant frequency: −0.092, $p = 0.091$ Frequency dependence of resistance: 0.025, $p = 0.639$	Probably High
Lambert, 2019	Cohort	$n = 486$	Adolescents age 12 and 18 years in Melbourne, Australia	NDVI (greenness) (Landsat; 30 m); Residential buffers at 100 m, 500 m, 1000 m at	Lung function: pre (12,18 years)and post (18 years) bronchodilator spirometry (FEV1, FVC,	Age, height, sex, URTI before 5 weeks, mother's education.	Effect modification by residential greenness: In areas of high greenness, exposure to low pollen	Probably High

Table 7 (*continued*)

First author, year	Study type	Sample size/# of cases	Study population and setting	Greenspace data/exposure metric	Respiratory health outcome	Confounders/covariates	Main results (95% CI)	Overall risk of bias
				birth	FEV1/FVC)		grains in first 3 months associated with higher FEV1 and FVC.	
Squillacioti, 2020	Cross-sectional	n = 187	Children (10–13 years old) in Turin, Italy	NDVI (greenness) (Landsat; 30 m); Mean NDVI in a 300 m residential buffer	Lung function	Air pollutants, namely PM10, NO2 and NO, age, sex, BMI and urinary cotinine levels	Regression coefficient for lung function: NDVI (300 m) Lung function (FVC) B = -0.07 (−0.22 to 0.90)	Probably High
Fuertes, 2020	Birth cohort	*n* = 7094	15 and 24 year olds in Bristol, Bath & North East Somerset, North Somerset and South Gloucestershire, UK	NDVI greenness Proportion of green spaces (urban green spaces, forests and agricultural land); NDVI: buffers (100 − 1000 m) and proportion of green spaces within 300 m around birth, eight-, 15- and 24-year home addresses	Lung function	Sex, age, height, weight, older siblings, breast feeding daycare attendance, parental education, maternal smoking and reported smoking by the participants	Regression coefficients for IQR increase (NDVI) or presence (green space): Lifetime average NDVI (300 m): FEV1 = 21.5 (−14.3 to 57.4) FVC = 3.5(−38.7 to 45.8) Green space (urban): FEV = 14.4 (−16.6 to 45.4) FVC = −1.8 (−38.6 to 34.9)	Probably High
Lambert, 2020	Cohort	*n* = 160	Children with a family history of asthma or allergic disease, aged 8 and 14 years in Sydney, Australia	NDVI (greenness) (Landsat; 30 m); Residential buffers at 100 m and 500 m at same seasons of lung function measurement	Lung function	Atopy status, current asthma, daily PM2.5, daily NO2, smoking during pregnancy, maternal asthma and seasonality.	Effect modification by residential greenness: No clinically meaningful effect modification.	Probably High
Yu, 2021a	Cross-sectional	n = 6740	School children aged 6–15 years. in 7 cities in Northeast China	Eye-level greenness (Tencent map); Green view index around schools at 800 m, 1000 m, 1500 m buffers	Lung impairment	Age, sex, BMI, parental education, family income, low birthweight, preterm birth, exercise per week and keeping pets in the home. Mediation with (PM1, PM2.5, PM10, and NO2.)	OR of lung impairment per IQR increase in Green view index (GVI): GVI (800 m) FEV1 < 85% predicted: OR = 0.73 (0.63 to 0.84) FVC < 85% predicted: OR = 0.83 (0.74 to 0.93) Results were attenuated and mediated with addition of air pollutants.	Probably High
Lambert et al., 2021	Cohort	*n* = 2334	Adolescents age 15 years in Germany	NDVI (greenness) (Landsat; 30 m); Residential buffers at 100 m, 300 m, 500 m, 1000 m, 3000 m at birth and 15 years old	Lung function	Area, age, sex, height, weight, asthma sensitisation, birth factors, early lung infections and indoor second-hand smoke exposure; parental education; parental atopy; seasonally adjusted vitamin D	Effect modification by residential greenness: No effect modification on lung function (FEV1, FVC).	Probably High
Kuiper, 2021	Matched case-control, cohort	n = 3428	Adults (age 18–40 years) in Norway, Sweden	NDVI (greenness) (Landsat; 30 m); Residential buffer of 300 m (mean value in May, June, July every 5 years from 1984 to 2014)	Lung function (lower limit of normal)	O3, NO2, parental education and parental asthma	Odds ratio for 0.1-unit increase in NDVI NDVI (300 m) Low lung function FEV1: OR = 1.74 (1.15 to 2.63) FVC: OR = 1.57 (1.00 to 2.45)	Probably High

GS = Greenspace; IQR = Interquartile Range; NDVI = Normalised Difference Vegetation Index; OR = Odds Ratios; RR = Relative Risk; SES = Socioeconomic Status; SD = Standard Deviation; SMR = Standardised Mortality Ratio.

with urban/built environments; however, these differences could relate to lower exposure to air pollutants, or some intrinsic property, while in the green environment, or both.

4.7. Overall synthesis of evidence

From the synthesis of studies performed in our narrative review, the strongest evidence of a positive association between greenspace and health related to respiratory mortality. Although a minority of those studies (7/20) were assigned a 'probably low' rating of bias, five found indicative dose response relationships of decreased mortality with higher greenspace levels; the two showing increases were not statistically significant. Respiratory mortality as a health indicator represents a broad range of disease, for which nearly every pathway in Fig. 4 may apply, but so too can common biases, such as residential self-selection. While it appears that a beneficial association exists with mortality, and potentially respiratory hospital

Table 8
Study characteristics of the respiratory symptoms studies, ordered by risk of bias and year.

First author, year	Study type	Sample size/# of cases	Study population and setting	Greenspace data/exposure metric	Respiratory health outcome	Confounders/covariates	Main results (95% CI)	Overall risk of bias
Lovasi, 2013	Cohort	n = 492 (5 years) n = 427 (7 years)	African American and Dominican children aged <7 years in New York City, USA	Tree canopy from 2001 (LiDAR plus aerial imagery and vector data); % of area within 250 m of address	Asthma, wheeze, rhinitis, allergies (including grass and tree pollen)	Sex, age, ethnicity, maternal asthma, previous birth, other previous pregnancy, Medicaid enrolment, smoking, population density, percent poverty, percent park land, and estimated traffic volume.	Prevalence ratios (or RRs) per 10% increase in neighbourhood tree canopy*: Wheeze at age 7: 1.17 (0.96 to 1.41)	Probably Low
Cilluffo et al., 2018	Cross-sectional	n = 219	Children aged 8–10 years in Palermo, Italy	NDVI vegetation (ASTER); NDVI raster cell of residential address ($200m^2$)	Self-reported nasal, pulmonary symptoms	Gender, age (years), maternal and paternal education, parental history of allergy, breastfeeding, preterm birth, smoking, atopy, doctor diagnosed asthma and parental history of allergy, greyness, air pollution	Nasal symptoms OR Q4:Q1 0.99 (0.84 to 1.17) Pulmonary symptoms OR Q4:Q1 0.97 (0.78 to 1.20)	Probably Low
Sinharay, 2018	Experi-mental	n = 40 COPD; n = 39 IHD; n = 40 healthy controls	Men and women aged 60 years+ with (GOLD) COPD, and healthy volunteers in London, UK	2 h walk in an urban park (Hyde Park) Control: 2 h walk on a busy street (Oxford St)	Symptoms	Air pollution (main exposure), group, location, time of measurement, temperature, relative humidity, smoking history	COPD patients more likely to experience symptoms after Oxford St compared to Hyde Park. ORs: cough: 1.95 (0.96 to 3.95 sputum 3.15 (1.39 to 7.13) shortness of breath 1.86 (0.97 to 3.57) wheeze 4.00 (1.52 to 10.50)	Probably Low
Eldeirawi, 2019	Cross-sectional	n = 1915	Mexican American chil-dren in Chicago, US	NDVI (Landsat 30 m resolution); Residential buffers of 100 m, 250 m, 500 m	Parent-reported asthma-like symptoms	Age, sex, country, urban/rural, family history of asthma, smoking in the home, proximity to traffic arterials, population density, SES + others	Odds ratio for IQR increase in NDVI (250 m): Lifetime wheezing: OR = 0.93 (0.78 to 1.12) Current dry cough at night: OR = 1.12 (0.85 to 1.47)	Probably Low
Zeng, 2020	Cross-sectional	n = 59,754	Children aged 2–17 years in 7 cities in Northeast China	NDVI, Soil adjusted vegetation index (SAVI) (Both use Landsat; 30 m); Summer NDVI around each school at 100 m, 300 m, 500 m, and 1000 m buffers.	Current wheeze	Age, gender, parental education, family income, breastfeeding, low birthweight, preterm, residential area, SHS, mold in home, home coal usage, and family history of asthma, PM10, NO2	Odds ratio (OR) per 0.1 unit increase in NDVI (300 m) Current wheeze OR = 0.93 (0.89 to 0.98) Air pollution was found not to be a mediator for wheeze.	Probably Low
Dzhambov, 2021	Cross-sectional	n = 1251	School children, aged 8–12 years. in Alpine towns, Austra & Italy	NDVI (July–August 2003; Landsat, 30 m) Tree canopy cover (2000; Landsat; 30 m) Domestic garden (study questionnaire); Residential buffers of 100 m, 300 m, 500 m, school buffer of 100 m	Parent-reported ever allergic rhinitis symptoms	Age, gender, maternal education, low birth weight, maternal smoking during pregnancy, duration of breastfeeding, cumulative risk of secondhand smoking/pneumonia/bronchitis in the 1st year of life, number of green months during pregnancy, geographic region	Odds ratio for IQR increase: NDVI (500 m): OR = 0.83 (0.67 to 1.03) Tree cover (500 m): OR = 0.86 (0.68 to 1.09) Gardens (Presence): OR = 0.85 (0.62 to 1.17)	Probably Low
Fuertes, 2014b	Cohort	n = 5803	Children <10 years old; Germany	NDVI (summer values); Residential NDVI at 500 m, 800 m, 1000 m, 3000 m at birth, 6 and 10 years old.	Eyes and nose symptoms	Age, sex, parental history of atopy, older siblings, maternal smoking, parental education, air pollution, population density	Odds ratios (ORs) per IQR increase in greenness exposure. NDVI w/ 500 m buffer: Eyes/nose symptoms OR = 1.00 (0.88 to 1.14)	Probably High
Fuertes, 2014a	Ecological	n = 222 (population centres)	Children aged 6–7 and 13–14 years; Global (94 countries)	NDVI Vegetation (MODIS); Mean NDVI of ~59 km^2 area	Self/parent-reported intermittent and persistent rhinitis symptoms	Temperature, precipitation, vapour pressure, GNI per capita, population density, and climate type, air pollutants in sensitivity analysis	Mean difference in country/centre-level prevalence per 100 children per 0.1-unit NDVI* In country: Intermittent rhinitis 0.80 (−0.88 to 2.48) Persistent rhinitis 0.95 (−0.38 to 2.28) In centre: Intermittent rhinitis	Probably High

Table 8 (*continued*)

First author, year	Study type	Sample size/# of cases	Study population and setting	Greenspace data/exposure metric	Respiratory health outcome	Confounders/covariates	Main results (95% CI)	Overall risk of bias
							−0.13 (−1.08 to 0.83) Persistent rhinitis −0.29 (−1.14 to 0.56)	
Tischer, 2017	Cohort	n = 2472	Children aged 4 years in Asturias, Gipuzkoa, Sabadell and Valencia, Spain	NDVI vegetation (Landsat), Green land use (Urban Atlas); Mean NDVI within 300 m home buffer (average between birth and age 4), Greenspace within 300 m of home	Wheezing, bronchitis	Sex, maternal education, maternal allergy, breast feeding, pets at home, maternal smoking during pregnancy, second hand smoke, area deprivation, air pollution (NO2), sensitivity analysis with physical activity	ORs (3rd vs 1st tertile) of NDVI and distance (<300 m) to greenspace for all 4 regions combined: NDVI Wheezing: 0.96 (0.71 to 1.30) Bronchitis: 1.18 (0.86 to 1.62) Greenspace distance Wheezing: 0.92 (0.715to 1.13) Bronchitis: 1.04 (0.84 to 1.26)	Probably High
Squillacioti, 2020	Cross-sectional	n = 187	Children (10–13 years old) in Turin, Italy	NDVI (greenness) (Landsat; 30 m); Mean NDVI in a 300 m residential buffer	Respiratory symptoms (wheezing, cough)	Air pollutants, namely PM10, NO2 and NO, age, sex, BMI and urinary cotinine levels	Odds ratio of tertile 3 (highest) to tertile 1 (lowest) NDVI (300 m) Bronchitis OR = 0.14 (0.05 to 0.45)	Probably High
Stas, 2021	Case-crossover	*n* = 144	Adults sensitized to Betulaceae pollen in Belgium	Grassland, Garden, Forest cover, Density of allergenic trees (Alnus, Betula and Corylus); Dynamic exposure every 5 s (1 km buffer)	Daily allergy symptom severity score	Birch pollen, air pollutants; subgroup analysis on age, sex, region	Odds ratio for 10% increase in land cover: Garden OR = 0.987 (0.706 to 1.380) Grass OR = 0.655 (0.446 to 0.960) Forest OR = 0.748 (0.521 to 1.074) Alnus OR = 0.625 (0.427 to 0.917) Betula OR = 2.014 (1.162 to 3.490) Corylus OR = 0.707 (0.413 to 1.209)	Probably High
Cavaleiro Rufo, 2021	Population cohort	n = 1050	Children at ages 4 and 7 years. in Porto, Portugal	NDVI; Residential buffers of 100 m, 200 m, 300 m during 2005–2006	Parent-reported asthma/asthma-like symptoms	Sex, maternal history of asthma, household crowding, maternal education, distance to nearest major road and neighbourhood SES.	Odds ratio: NDVI (100 m) (T3: T1): Wheezing - age 7: 0.49 (p > 0.05) Dry cough - age 7: 0.91 (*p* > 0.05)	Probably High

GS = Greenspace; IQR = Interquartile Range; NDVI = Normalised Difference Vegetation Index; OR = Odds Ratios; RR = Relative Risk; SES = Socioeconomic Status; SD = Standard Deviation; SMR = Standardised Mortality Ratio.
* Standardised from reported values.

admissions (21/28 associations were positive), the contribution and importance of different mechanisms is not yet clear. This trend is consistent with research on greenspace and other broad indicators of wellbeing, such as mental health, where multiple potential pathways have been identified, but mechanism-specific evidence is not yet sufficient (Houlden et al., 2018). Although indicators of asthma were the most studied outcome (38 studies), findings were too inconsistent to reach definitive conclusions. Studies of rhinitis and respiratory symptoms did not provide compelling evidence of improved health. The experimental studies demonstrated some improved lung function, but entailed poor characterisation of the greenspace environment; such associations may very likely have been prompted by lower concentrations of ambient air pollutants in lower traffic settings, rather than specifically in urban greenspace.

While we deemed the possibility of residential self-selection not to be necessarily a high source of bias, as indicated in previous studies (Kaczynski and Mowen, 2011; McCormack, 2017; Lu, 2018), it is a pervasive issue in the greenspace literature. Healthier people or those who are more health-conscious, may choose to live in greener areas where there may be, as an example, more opportunities for exercise or lower exposure to air pollution (Cohen-Cline et al., 2015). It is also possible that those with some forms of respiratory condition exacerbated by aeroallergens, for example, might move away from green areas where

Table 9
Study characteristics of the rhinitis studies, ordered by risk of bias and year.

First author, year	Study type	Sample size/# of cases	Study population and setting	Greenspace data/exposure metric	Respiratory health outcome	Confounders/covariates	Main results (95% CI)	Overall risk of bias
Lovasi, 2013	Cohort	n = 492 (5 years) *n* = 427 (7 years)	African American and Dominican children aged <7 years in New York City, USA	Tree canopy from 2001 (LiDAR plus aerial imagery and vector data); % of area within 250 m of address	Rhinitis	Sex, age, ethnicity, maternal asthma, previous birth, other previous pregnancy, Medicaid enrolment, smoking, population density, percent poverty, percent park land, and estimated traffic volume.	Prevalence ratios (or RRs) per 10% increase in neighbourhood tree canopy*: Rhinitis at age 7: 1.52 (0.56 to 4.08)	Probably Low
Gernes et al., 2019	Birth cohort	*n* = 478	Children aged 7 years in Ohio and Kentucky, USA	NDVI greenness Land cover-derived urban greenspace (Tree canopy, grass/shrub coverage); NDVI - Landsat Scene Path at 30 m resolution. Image from June 2010. Urban greenspace: 2.5 m resolution. All metrics use 400 m residential buffers, plus 100 m and 80 m	Allergic rhinitis at age 7 (parent-reported)	Race, sex, environmental tobacco smoke exposure, exposure to traffic-related air pollution, mother's education (7 years), and neighbourhood SES (7 years).	Odds ratio per IQR increase in NDVI or 10% increase in urban greenspace: NDVI (400 m): OR = 0.95 (0.76, 1.20) Urban greenspace: OR = 0.90 (0.69, 1.19)	Probably Low
Dadvand 2014	Cross-sectional	n = 3178	School children aged 9–12 years; Sabadell, Spain	NDVI Vegetation (Landsat), Land use (parks, forests); Mean NDVI 100 m, 250 m, 500 m, 1000 m residential buffers and Living within 300 m of a park or forest	Current allergic rhinoconjunctivitis	SES, type of school, urban vulnerability, age, sex, exposure to environmental tobacco smoke, having older siblings, parental history of asthma	Adjusted ORs for 0.1-unit increase in NDVI (250 m): 0.98 (0.88 to 1.11)* Adjusted ORs for living within 300 m of parks 1.10 (0.90 to 1.35); forests 1.27 (0.94 to 1.70)	Probably High
Fuertes, 2016	Cohort	n = 13,016	Children aged 6–8 and 10–12 years in Australia, Canada, Germany, Netherlands, Sweden	NDVI vegetation at 500 m, 100 m residential buffers	Allergic rhinitis	Parental atopy, older siblings, maternal smoking, SES, group, region, and cohort.	OR per 0.1-unit NDVI*: 6–8 years = 1.00 (0.83 to 1.20); 10–12 years = 0.98 (0.84 to 1.14)	Probably High
Tischer, 2017	Cohort	n = 2472	Children aged 4 years in Asturias, Gipuzkoa, Sabadell and Valencia, Spain	NDVI vegetation (Landsat), Green land use (Urban Atlas); Mean NDVI within 300 m home buffer (average between birth and age 4), Greenspace within 300 m of home	Allergic rhinitis	Sex, maternal education, maternal allergy, breast feeding, pets at home, maternal smoking during pregnancy, second hand smoke, area deprivation, air pollution (NO2), sensitivity analysis with physical activity	ORs (3rd vs 1st tertile) of NDVI and distance (<300 m) to greenspace for all 4 regions combined: NDVI Allergic rhinitis: 0.57 (0.22 to 1.50) Greenspace distance Allergic rhinitis: 0.67 (0.34 to 1.30)	Probably High
Kwon et al., 2019	Ecological	*n* = 423 administrative units	Adults age 20+ years in Seoul, South Korea	NDVI (greenness) (Landsat; 30 m); Mean NDVI level for each district	Allergic rhinitis	Air pollutants (SO2, PM10, O3, NO2, CO), power plants, traffic, age, income, manufacturing employee ratio	Spatial lag model coefficient: NDVI = 0.386 (p = 0.056)	Probably High
Li, 2019	Cross-sectional	n = 5643	Middle school students in Suzhou, China	NDVI (Greenness) (Landsat; 30 m) Parks; Mean NDVI from images in March, June, October, December 2014 at 100 m, 200 m, 500 m, 1000 m residential buffers Distance from home to nearest park	Doctor-diagnosis of rhinitis	Age, sex, environmental tobacco smoke (ETS) at home, parental education, parental history of asthma, air pollution, pets in the home, and dampness and mold	Odds ratio for IQR increase in NDVI or Q4:Q1 distance to a park: NDVI (200 m) Ever rhinitis OR = 0.95 (0.86 to 1.06)	Probably High

Table 9 (*continued*)

First author, year	Study type	Sample size/# of cases	Study population and setting	Greenspace data/exposure metric	Respiratory health outcome	Confounders/covariates	Main results (95% CI)	Overall risk of bias
							Urban parks (Q4:Q1) Ever rhinitis OR = 0.97 (0.76 to 1.24)	
Kim, 2020	Cross-sectional	n = 219,298	Adults in Korea	Forests, parks and reserves, greenness, greenways, and riparian areas. (Korean Statistical Information Service); Green areas (m2) per capita	Allergic rhinitis	Age, sex, marriage, education, monthly income, and job categories + smoking and alcohol + physical activity and self-reported stress + urbanity and body mass index	Odds ratio of Q4:Q1 green area: Physician's diagnosis: OR = 0.94 (0.89 to 0.99)	Probably High
Kuiper, 2020	Cohort	n = 1106 parents n = 1949 children	Parents (exposure) Children (outcome) in Bergen (Norway) and Umea, Uppsala, and Gothenburg (Sweden)	NDVI (Greenness; Landsat); Mean NDVI in summer in 100 m, 300 m, 500 m and 1000 m during 0–18 years of age for parents and 0–10 years of age for offspring.	Hay fever/Allergic rhinitis	Grandparental education, grandparental asthma; parental asthma, offspring's own air pollution/greenness exposures and air pollution/greenness exposures during pregnancy were included as potential mediators	Odds ratio for tertile 3 to tertile 1 of parent's exposure: Hay fever: Mother: OR = 1.57 (0.72 to 3.43) Father: OR = 1.35 (0.44 to 4.19)	Probably High
Markevych, 2020	Cohort	n = 631	Children up to 15 years old in Leipzig, Germany	NDVI (greenness) (Landsat; 30 m), Trees (Stadt Leipzig, Amt für Geoinformation und Amt für Stadtgrün und Gewasser); Mean NDVI, Total number of trees, Number of allergenic trees in 100 m, 300 m, 500 m, and 1000 m around home birth address.	Allergic rhinitis (parent reported of doctor diagnosis)	Age, sex, season of birth, parental atopy and parental education.	Odds ratio for tertile 3 to tertile 1 of birth exposure: NDVI (300 m) OR = 0.77 (0.59 to 1.01) Trees (300 m) OR = 1.53 (1.16 to 2.02) Allergenic trees (300 m) OR = 1.28 (0.97 to 1.87)	Probably High
Cavaleiro Rufo, 2021	Population cohort	n = 1050	Children at ages 4 and 7 years. in Porto, Portugal	NDVI; Residential buffers of 100 m, 200 m, 300 m during 2005–2006	Parent-reported asthma/asthma-like symptoms	Sex, maternal history of asthma, household crowding, maternal education, distance to nearest major road and neighbourhood SES.	Odds ratio: NDVI (100 m) (T3:T1): Rhinitis - age 7: 0.37 ($p < 0.05$)	Probably High
Kuiper, 2021	Matched case-control, cohort	n = 3428	Adults (age 18–40 years) in Norway, Sweden	NDVI (greenness) (Landsat; 30 m); Residential buffer of 300 m (mean value in May, June, July every 5 years from 1984 to 2014)	Rhinitis	O3, NO2, parental education and parental asthma	Odds ratio for 0.1-unit increase in NDVI (300 m) OR = 1.01 (0.92 to 1.11)	Probably High

GS = Greenspace; IQR = Interquartile Range; NDVI = Normalised Difference Vegetation Index; OR = Odds Ratios; RR = Relative Risk; SES = Socioeconomic Status; SD = Standard Deviation; SMR = Standardised Mortality Ratio.

exposures to pollens are higher (Dadvand et al., 2014). On the other hand, reverse-causation might, in some cases, result in the selective migration to green areas of people with established respiratory conditions to avoid more polluted environments (e.g., Pun et al., 2018). Selection bias of this kind may not be diminished by a longitudinal study design (where individuals would continue to select their residential locations over time) and may be relevant for a variety of health outcomes. Moreover, income effects may remain as a potential source of bias even in studies which have ostensibly controlled for SES effects, as dwellings facing green areas are generally more desirable, and hence more expensive, than ones facing busy roads. The direction of bias for this wealth/income effect is likely to favour the selection of healthier populations in greener areas, but the direction and magnitude of bias for the other selection effects largely remain unquantified and may depend on the exposure, population, and health metric under investigation. In addition to the methodological challenges of residential self-selection, exposure levels may also depend on the subject, with the perceived importance of different greenspace characteristics varying across individuals; this phenomenon could cause misclassification of ‘dose’ and lead to challenges of interpretation across studies.

4.8. Strengths and limitations

Our study represents the first systematic review to identify and examine greenspace pathways of effect across broad indicators of respiratory health. Our methods benefitted from the use of an extensive search strategy, which was not likely to have missed relevant and impactful papers; still, there was the potential of the streetlight effect, whereby our search terms and understanding of greenspace may have been constrained by previously established concepts (Whaley et al., 2020). Two papers were not captured initially from the database search strategy, due to addressing biodiversity (i.e., not explicitly including ‘green’ environments) (Liddicoat et al., 2018) and excluding mention of respiratory health in the title or abstract (Maas et al., 2009). Although

Table 10
Study characteristics of the other respiratory health studies, ordered by risk of bias and year.

First author, year	Study type	Sample size/# of cases	Study population and setting	Greenspace data/exposure metric	Respiratory health outcome	Confounders/covariates	Main results (95% CI)	Overall risk of bias
Hoehner, 2013	Cross-sectional	*n* = 8857 (home) *n* = 4734 (work)	Adults aged 18–90 years in Dallas, USA	Parks, vegetation (1 m res NDVI from the National Agriculture Imagery Program 2004); Number of parks within 1600 m buffer; Distance to park with a trail; Average number of park features within 1600 m; Proportion of vegetation (800 m)	Cardiorespiratory fitness (via an exercise test)	Sex, age, marital status, children in home, educational status, smoking status, body mass index, census block group–level percent below 200% poverty, race, and built environment variables.	Regression coefficients (standard error) predicting cardiorespiratory fitness (home greenspace): Proportion of vegetation: 0.423 (0.187) p-value = 0.02 Number of parks: −0.003 (0.008) *p*-value = 0.71 Average number of park features: −0.028 (0.023) p-value = 0.22 Distance to closest park: −0.012 (0.016) p-value = 0.44	Probably Low
Cavalcan-te de Sa, 2016	Experi-mental	*n* = 38	Young, healthy amateur runners in Sao Paolo, Brazil	Running in an urban forest Control: Running on a street	Airway defense markers: nasal mucociliary clearance, pH of exhaled breath condensate (EBC) and number of epithelial and inflammatory cells in nasal lavage fluid (NLF)	Air pollutants, relative humidity, day of the week	Number of subjects with impaired Mucociliary Clearance doubled in the Street group and decreased in the Forest group.	Probably Low
Arbillaga-Etxarri, 2017	Cross-sectional	*n* = 410	COPD patients in Catalonia, Spain	NDVI - Landsat (30 m cell), Proximity to greenspace <300 m; Residential NDVI at 100, 300, 500, 1000 m	Minutes/day of moderate-vigorous physical activity	Age, sex, socio-economic status, smoking, dyspnoea, 6-min walking test and HAD-anxiety.	No quantitative results for GS indicators, but minutes/day MVPA slightly greater in <median greenness and > median proximity to green/blue space (not statistically significant)	Probably Low
Sarkar et al., 2019	Cross-sectional	*n* = 96,779 (*n* = 77,679 in analysis)	Adults aged 39+ years in UK (22 cities of England, Wales, and Scotland)	NDVI (greenness); Mean NDVI in a 500 m residential buffer	COPD prevalence	PM2.5, urbanicity, sociodemographics, lifestyle variables, neighbourhood socioeconomic status, anthropometrics, comorbidities, and haematological biomarkers	OR per IQR increase in NDVI: NDVI (500 m) OR = 0.89 (0.84 to 0.93)	Probably Low
Moshammer, 2019	Experimental	n = 24	Students (age range 21–33) in Vienna	Park ("Augarten", a large park in the centre of Vienna); 1 h walk	Exhaled Nitric Oxide (eNO)	Single exposure models	Increase in eNO after exercise near road compared to park.	Probably Low
Fan, 2020	Cross-sectional	n = 66,752	Adults aged 40+ years in China	NDVI (2010–2014 Jan/Apr/Jun/Oct; Landsat 30 m resolution); Residential buffers of 100, 300, 500, 1000, 2000, 3000 and 5000 m	COPD prevalence	Place of residence, smoke, height, history of tuberculosis, severe pulmonary disease in childhood, biomass or coal in home environment, dust/hazardous chemical gases in workplace, relative humidity and temperature, and PM2.5 concentrations	Odds ratio for IQR increase in NDVI: NDVI (300 m) for urban populations: OR = 1.14 (1.01 to 1.27)	Probably Low
Paciência, 2020	Cross-sectional	*n* = 845	Primary school children in Porto, Portugal	Tree density and dominant tree type (coniferous/	Spirometry - Exhaled Nitric Oxide (NO)	Age, sex, asthma, atopy, parental education level and exposure to tobacco	Standardised regression coefficient for	Probably Low

Table 10 (*continued*)

First author, year	Study type	Sample size/# of cases	Study population and setting	Greenspace data/exposure metric	Respiratory health outcome	Confounders/covariates	Main results (95% CI)	Overall risk of bias
				deciduous) (2015; Copernicus Land Monitoring Service); 500 m buffer around school		smoke at home.	change in NO: Tree cover density Girls: β = -0.01 (−0.02 to 0.001) Boys: β = -0.01 (−0.04 to 0.01) Broadleaves Girls: β = -0.04 (−0.20 to 0.12) Boys: β = -0.14 (−0.49 to 0.22) Coniferous Girls: β = -0.51 (−1.33 to 0.32) Boys: β = −1.16 (−3.09 to 0.76)	
Maas, 2009	Cross-sectional	n = 345,143 individuals	General population, Netherlands	Green land cover), % of greenspace within 1 km and 3 km around home postcode	Prevalence rate of (1) Upper respiratory tract infection, (2) Bronchi(*oli*) tis/pneumonia	Age, sex, SES, urbanicity	Odds Ratio (OR) for 10% increase in greenspace within 1 km: Upper respiratory tract infection: 0.97 (0.96 to 0.98) Bronchi(*oli*) tis/pneumonia: 0.99 (0.97 to 1.00)	Probably High
Bernat, 2016	Ecological	*n* = 8 urban areas	General population in 8 urban areas in Lithuania	Forest coverage, recreational forests, forest remoteness; % (coverage/ remoteness) or ha/1000 inhabitants in urban areas	Acute upper respiratory infections per 1000	Other exposures included, e.g. air pollutants, but independent correlation analysis only	Correlations: Upper respiratory infections: Coverage: r = 0.39 Remoteness: r = −0.26 Recreational: r = −0.24	Probably High
Prist, 2016	Ecological	*n* = 645 municipalities (population ~ 42 million)	General population in Sao Paulo, Brazil	Native vegetation cover; % of vegetation cover and fragmentation (# of patches)	Hantavirus Pulmonary Syndrome (HPS)	HDI, mean annual temperature (°C), total annual precipitation (mm), and rural male population > 14 years old	Graphical results of standardised coefficients from Fig. 3: In Cerrado, slight negative effect of habitat cover and patches on HPS risk, marginal negative effect in Atlantic Forest; all non-significant.	Probably High
Chen, 2017	Cross-sectional	n = 150	Children aged 9–17 years with physician-diagnosed asthma in Chicago, USA	NDVI vegetation (Landsat) - averaged across year; 250 m residential buffer	Airway inflammation, glucocorticoid expression in T-helper cells (relevant to airway inflammation)	SES, season, age, sex, ethnicity, asthma severity, medication use	Regression coefficients predicting asthma outcomes: T-helper cell GR expression: 0.06 (−52.56 to 108.84); FeNO: −0.01 (−168.89 to 145.76)	Probably High
Pun, 2018	Cohort	*n* = 4118	Older adults aged 57–85 years in the US	NDVI vegetation (MODIS - 250 m resolution) (summer); 250 m & 1000 m residential buffers	History of respiratory illness (emphysema, chronic obstructive pulmonary disorder, and asthma)	Age, gender, race/ethnicity, season, region, education attainment, family income, median household income level, current smoking, physical activity, social support, history of illnesses, BMI and physical function, loneliness, roadway distance, urbanicity	History of respiratory disease mediated greenness and stress by −3.80%	Probably High
Li, 2019	Cross-sectional	n = 5643	Middle school students in Suzhou, China	NDVI (Greenness) (Landsat; 30 m), Parks; Mean NDVI from images in March, June,	Doctor-diagnosis of pneumonia	Age, sex, environmental tobacco smoke (ETS) at home, parental education, parental history of asthma, air	Odds ratio for IQR increase in NDVI or Q4:Q1 distance to a park: NDVI (200 m)	Probably High

(continued on next page)

Table 10 (*continued*)

First author, year	Study type	Sample size/# of cases	Study population and setting	Greenspace data/exposure metric	Respiratory health outcome	Confounders/covariates	Main results (95% CI)	Overall risk of bias
				October, December 2014 at 100 m, 200 m, 500 m, 1000 m residential buffers; Distance from home to nearest park		pollution, pets in the home, and dampness and mold	Ever pneumonia OR = 0.95 (0.87 to 1.05) Urban parks (Q4:Q1) Ever pneumonia OR = 0.92 (0.74 to 1.15)	
Squillacioti, 2020	Cross-sectional	n = 187	Children (10–13 years old) in Turin, Italy	NDVI (greenness) (Landsat; 30 m); Mean NDVI in a 300 m residential buffer	Bronchitis	Air pollutants, namely PM10, NO2 and NO, age, sex, BMI and urinary cotinine levels	Odds ratio of tertile 3 (highest) to tertile 1 (lowest) Bronchitis OR = 0.14 (0.05 to 0.45)	Probably High
Lambert, 2020	Cohort	n = 160	Children with a family history of asthma or allergic disease, aged 8 and 14 years in Sydney, Australia	NDVI (greenness) (Landsat; 30 m); Residential buffers at 100 m and 500 m at same seasons of lung function measurement	Exhaled NO	Atopy status, current asthma, daily PM2.5, daily NO2, smoking during pregnancy, maternal asthma and seasonality.	Effect modification by residential greenness: No clinically meaningful effect modification.	Probably High
Russette et al., 2021	Ecological	*n* = 3049 counties	General population in USA	Leaf area index (LAI) (2011–2015; MODIS; 250 m); Mean LAI in county	COVID − 19 mortality	Education, overcrowding, Medicaid (ages 18–64), age 65 and over, race (Black and Native American), physical inactivity, and neigh-bour COVID − 19 mor-tality average	Mortality Rate Ratio (MRR) compared to decile 1 of LAI: MRR of decile 10 (highest LAI) = 0.59 (0.50 to 0.69)	Probably High
Wu, 2021	Cross-sectional	*n* = 993	Adults with respiratory disease (asthma, bronchitis and cough in the past five years) in Shanghai, China	Greenness (NDVI, SAVI, RVI, EVI) (30 m) Tree type; 500 m buffer around community Ratio of evergreen and deciduous to overall green area	Respiratory disease prevalence	individual socio–economic characteristics (age, gender, and BMI) and air pollution around communities (PM2.5, automobile exhaust, building dust, industry exhaust, and garbage smell) as control variables	Logit regression model: NDVI B = -0.789 ($p <$ 0.05) Ratio of evergreen B = 0.011 ($p >$ 0.05) Ratio of deciduous B = 0.025 ($p > 0.05$)	Probably High
Zhang, 2021	Cross-sectional	*n* = 2023	General population in Nanjing, China	Vegetation cover (Google Earth), plant diversity (Flora of China); Vegetation coverage and species richness in residential compounds	Self-reported allergic diseases and respiratory diseases	Gender, age, plant factors, building age	Regression coefficients related to health impairment: "Allergic diseases: Diversity of plants with airborne fibers = −0.065 (*p*-value = 0.683) Diversity of plants with pollen = 0.107 (*p*-value = 0.002) Diversity of overall plants = −0.026 (p-value = 0.029) Veg cover = −0.011 (p-value = 0.032) Respiratory diseases: Diversity of plants with airborne fibers = 0.412 (p-value = 0.015) Diversity of plants with pollen = 0.037 (p-value = 0.303) Diversity of overall plants = −0.007 (p-value = 0.576) Veg cover = −0.011 (p-value = 0.061)"	Probably High
Lambert, 2021	Cohort	n = 2334	Adolescents age 15 years in Germany	NDVI (greenness) (Landsat; 30 m);	Exhaled NO	Area, age, sex, height, weight, asthma	Effect modification by residential	Probably High

Table 10 (*continued*)

First author, year	Study type	Sample size/# of cases	Study population and setting	Greenspace data/exposure metric	Respiratory health outcome	Confounders/covariates	Main results (95% CI)	Overall risk of bias
				Residential buffers at 100 m, 300 m, 500 m, 1000 m, 3000 m at birth and 15 years old		sensitisation, birth factors, early lung infections and indoor second-hand smoke exposure; parental education; parental atopy; seasonally adjusted vitamin D	greenness: Higher exhaled NO in greener areas.	
Moitra et al., 2022	Cross-sectional	$n = 407$	Mild-to-very severe COPD patients in Barcelona, Spain	Green land use (Urban Atlas 2007); Residential distance to blue/green space within 500 m	Health related quality of life (COPD)	Age, education, % predicted of FEV1, modified Medical Research Council (mMRC) score, anxiety, body mass index (BMI) and mean steps/day, and centres. Smoking and physical activity tested as potential confounders.	Regression coefficients for distance to blue/green space (per 100 m): CAT score: $\beta = 0.03$ (0.002 to 0.06) CCQ-score: $\beta = 0.02$ (-0.02 to 0.06)	Probably High

FeNO = Fractional Exhaled Nitric Oxide; GS = Greenspace; NDVI = Normalised Difference Vegetation Index; OR = Odds Ratios; RR = Relative Risk; SES = Socioeconomic Status; SD = Standard Deviation; SMR = Standardised Mortality Ratio.

	Asthma	Respiratory mortality	Lung Function	Symptoms	Hospital Admissions	Rhinitis	Lung Cancer	Other
NDVI/ Greenness	26	16	30	18	12	12	6	14
Green LULC	33	18	5	9	6	8	12	19
Tree cover	8	1	0	5	7	1	2	8
Biodiversity	2	0	0	0	3	0	0	6
Gardens	1	0	0	1	1	0	0	0

Fig. 2. A heat map of the frequencies of different exposure-health associations investigated in the identified studies ($n = 290$).

we implemented a publication year cut-off of 2000, it was not likely that this resulted in the exclusion of any eligible papers, as the earliest identified study in our review was published in 2007. The broad focus of the review constrained the detail into which we could address and explore a given mechanism of specific exposure-health associations. The application and comparability of the risk of bias assessment was hindered by the varied range of methods, exposures, and health outcomes; some study biases may have been more problematic for certain study designs, but were not assigned as such as meaningful contextual information was often omitted (e.g., completion of routine health data, blinding of study personnel) and not easily comparable. Although the main focus of our review was exposure to urban greenspace, several of the studies examined and combined risk estimates representing both urban and rural areas; to be inclusive, we incorporated these studies, though it was not possible to parse out the results pertaining specifically to the urban populations.

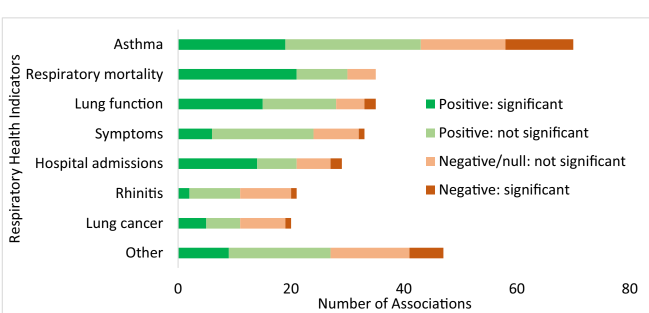

Fig. 3. The number of associations suggesting significant positive (i.e., better health), significant negative (i.e., poorer health), non-significant positive or non-significant negative/null associations for a given health indicator and greenspace exposure ($n = 290$).

4.9. Recommendations for future research

To provide the most value, future observational studies examining health should attempt to isolate specific mechanisms of action through, for example, mediation analyses (James et al., 2016; Vienneau et al., 2017), and focus on exposure-health pathways with inconsistent evidence (e.g., childhood asthma and surrounding land use). The measurement of species presence, and adoption of other more specific metrics of vegetation/green infrastructure, might help explain contrasting findings. Such research can help answer the questions: What are the beneficial/harmful components of different types of greenspace and how can they be magnified/mitigated? Studies of diverse individuals in less studied regions (e.g., low and middle income countries [LMICs]) should be prioritised, complete with subgroup analyses. Longitudinal studies with dynamic greenspace exposure metrics would be useful to explore critical windows (e.g., Cherrie et al., 2018), as well as the use of other methods to address self-selection biases (Mokhtarian and Cao, 2008). Interpretation of experimental studies would be improved with better characterisation of

Table 11
A summary of the quality and strength assessments.

Health outcome	Quality criteria								Overall quality	Strength
	Risk of bias	Indirectness	Inconsistency	Imprecision	Publication bias	Large effect	Dose-response	Confounding		
Respiratory mortality	0	0	0	0	0	0	+1	0	Moderate	Limited
Hospital admissions	−1	0	−1	0	0	0	0	0	Low	Inadequate
Lung cancer	0	0	−1	0	0	0	0	0	Low	Inadequate
Asthma	−1	0	−1	−1	0	0	0	0	Low	Inadequate
Lung function	0	0	−1	−1	0	0	0	0	Low	Inadequate
Respiratory symptoms	0	-1	−1	−1	0	0	0	0	Low	Inadequate
Rhinitis	−1	0	0	−1	0	0	0	0	Low	Inadequate

greenspaces, including natural features, subjective factors of importance (Taylor and Hochuli, 2017), and doses of exposure (e.g., Holt et al., 2019), as well as justification and characterisation of control settings. In addition, further investigation of specific pathways with greenspace (even in the absence of a health outcome) would help crystallise the most efficacious mechanisms and identify other potentially important contextual moderating factors.

4.10. Conformity with published protocol

We adhered to the methods described in the published review protocol though with minor revisions following the peer review process. We expanded the search date end from 31 December 2018 to 3 October 2021 and added an assessment of the strength and quality of studies within each major health outcome. We narrowed the scope of respiratory health outcomes by omitting ICD-10 codes C00-C14: malignant neoplasms of lip, oral cavity.

5. Conclusion

We summarised studies of urban greenspace and respiratory health and the hypothesised pathways of effect. The 108 identified studies included different greenspace exposure metrics, respiratory health outcomes, and research methods. The most compelling evidence for a positive association related to reduced risks of respiratory mortality. The evidence is consistent with, but not conclusive of a causal association, the possible pathways of which may relate to reduced exposures to air pollution, noise and heat, more physically active local populations, reduced stress and improved immune function. The findings for other outcomes were less consistent and included studies reporting negative as well as positive associations between green space and respiratory health (e.g. higher prevalence of asthma in greener areas). The inconsistent and heterogeneous results underscore the potential importance of contextual factors, variations in greenspace metric employed, and the possible bias of subtle selection factors, all of which should be explored further in future research.

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CRediT authorship contribution statement

William Mueller: Conceptualization, Methodology, Writing – original draft. **James Milner:** Conceptualization, Methodology, Supervision, Writing – review & editing. **Miranda Loh:** Conceptualization, Methodology, Supervision, Writing – review & editing. **Sotiris Vardoulakis:**

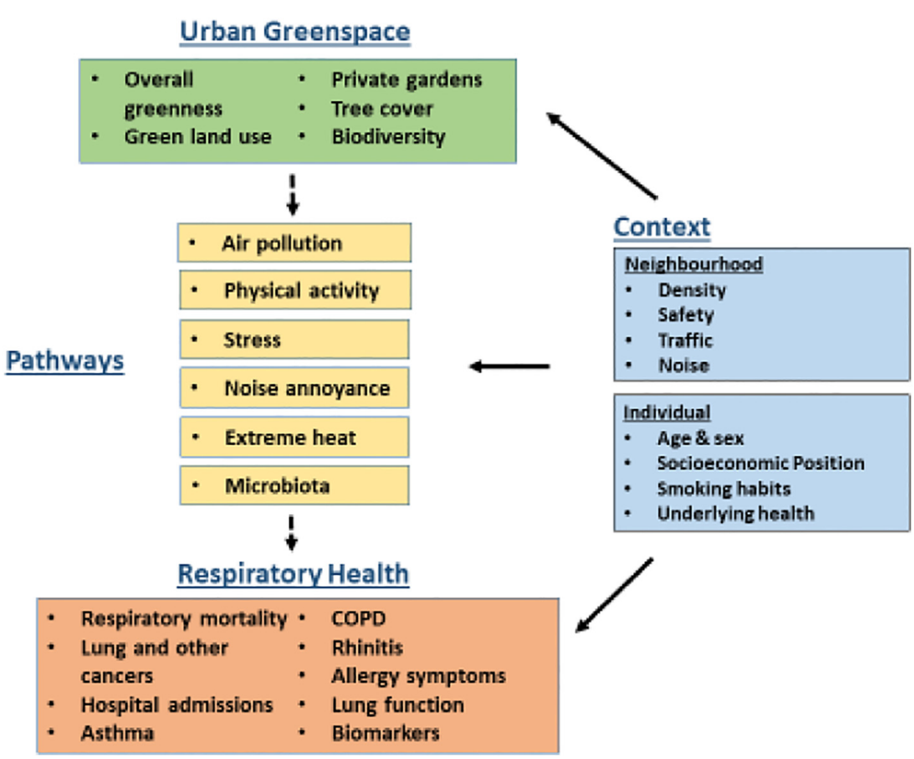

Fig. 4. A diagram of the possible pathways linking urban greenspace and respiratory health with potential neighbourhood and individual modifiers.

Conceptualization, Methodology, Supervision, Writing – review & editing. **Paul Wilkinson:** Conceptualization, Methodology, Supervision, 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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Appendix A. Supplementary data

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