Greenness exposure: beneficial but multidimensional

Ane Johannessen[1], Shanshan Xu[2], Achenyo Peace Abbah[2] and Christer Janson [3]

[1]Department of Global Public Health and Primary Care, University of Bergen, Bergen, Norway. [2]Centre for International Health, Department of Global Public Health and Primary Care, University of Bergen, Bergen, Norway. [3]Department of Medical Sciences, Respiratory, Allergy and Sleep Research, Uppsala University, Uppsala, Sweden.

Corresponding author: Ane Johannessen (ane.johannessen@uib.no)

Shareable abstract (@ERSpublications)
This review of 42 original research papers shows that greenness is mainly a beneficial exposure with protective effects on respiratory health, in particular respiratory mortality, lung cancer incidence, respiratory hospitalisations and lung function. https://bit.ly/43mALMZ

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Abstract

Many studies have shown that greenness has beneficial health effects, particularly on psychological and cardiovascular outcomes. In this narrative review, we provide a synthesis of knowledge regarding greenness exposure and respiratory health. The following outcomes were reviewed: respiratory mortality, lung cancer mortality, lung cancer incidence, respiratory hospitalisations, lung function, COPD, and asthma. We identified 174 articles through a literature search in PubMed, of which 42 were eligible for inclusion in this review. The most common marker for greenness exposure was the normalised difference vegetation index (NDVI), which was used in 29 out of 42 papers. Other markers used were tree canopy cover, landcover/land-use, plant diversity, density of tall trees and subjectively perceived greenness. We found beneficial effects of greenness in most studies regarding respiratory mortality, lung cancer incidence, respiratory hospitalisations and lung function. For lung cancer mortality, asthma and COPD, the effects of greenness were less clear cut. While many aspects of greenness are beneficial, some aspects may be harmful, and greenness may have different health effects in different population subgroups. Future studies of greenness and respiratory diseases should focus on asthma and COPD, on effects in different population subgroups and on disentangling the health effects of the various greenness dimensions.

Educational aims

- To provide an update on the research field of greenness and respiratory health.
- To identify associations between greenness and respiratory outcomes in adults.
- To give an outline of the different dimensions of greenness and how it may affect health.

Introduction

"Greenness" or "green space" can be defined as areas covered by vegetation such as plants, grass, and trees. Greenness can be structured (*e.g.* parks and gardens) or unstructured (*e.g.* forests, grasslands and farms).

It is widely believed that exposure to greenness is good for your health. Although interacting with nature probably always had various beneficial effects, this interaction was not put on the political agenda until industrialisation emerged. Industrialisation led to increased urbanisation, air and noise pollution, and often unhealthy and crowded living conditions for many city dwellers. As a response, the first public parks were designed in the second half of the 19th century. The parks were intended to beautify the increasingly industrial cities in the Western world, but most of all, they were designed to provide urban populations with greenness exposure. With increasing greenness, people should be inspired to engage in relaxation, recreation, physical activity and social gatherings – thereby improving their health and well-being [1].

Although parks were designed with health and well-being in mind as early as the 19th century, associations between greenness exposures and health were not properly investigated through research until quite recently. Research publications within this field started to emerge at the start of the 21st century, with the vast majority of papers being published in the past 5 years. Over this period, however, researchers' interest in greenness and health has veritably surged, and numerous dimensions of health have been investigated in relation to greenness. There is now quite strong consensus that exposure to greenness or green spaces has beneficial effects on mental health, reducing stress and anxiety, and improving sleep quality and physical activity [2]. Greenness has also been quite consistently linked with improved cardiovascular outcomes [2]. Respiratory health has also been investigated in association with greenness, with the evidence being less consistent than for the aforementioned outcomes.

The aim of this narrative review is to shed light on the evidence, to date, regarding greenness exposure and respiratory health. What do we know and what do we not know? Is greenness overall beneficial for respiratory health outcomes, or is greenness beneficial for some outcomes but not others? Is there a difference in the effects of greenness between men and women or between older and younger people? Is all greenness equally related to respiratory health, or is there a difference between structured and unstructured greenness? A review answering these questions will make it easier for clinicians to assess if greenness exposure is something they should be aware of when advising their patients on disease management. It will also help researchers map out fields in need of further studies, and will shed light on how large a role greenness should play in future public health decisions and city planning.

Literature selection

To get an overview of the field, we started the work on this narrative review through the PubMed database. A literature search was carried out on 6 November 2022 with the following search terms: ("greenness" OR "green space") AND ("lung" OR "respiratory"). We did not impose any time limits but excluded non-English language studies. The search resulted in 174 papers for screening. Authors A. Johannessen, S. Xu and A.P. Abbah read through all 174 titles and abstracts independently using Rayyan software [3] and marked all papers for inclusion or exclusion. Results were then compared, and disagreements concerning inclusion and exclusion of studies were resolved by discussion.

The inclusion criteria used in our study were: 1) original research articles; 2) cohort studies, cross-sectional studies, case–control studies, or ecological studies; 3) studies including adult humans; and 4) studies reporting associations between greenness exposure and respiratory health. The exclusion criteria were: 1) coronavirus disease 2019 (COVID-19) outcomes; 2) ineligible effect estimates (lack of association estimates, only descriptive analyses of exposures and outcomes separately); and 3) ineligible greenness exposure assessment (indoor greenness, or climate metrics not convertible to greenness, *e.g.* heat exposure).

As shown in figure 1, 128 papers were excluded after screening titles and abstracts, leaving 46 original research articles. S. Xu and A.P. Abbah proceeded to read them in more detail and extracted key information. Full-text reading led to exclusion of four more original research articles, leaving 42 original research articles in the final selection of papers.

The 42 studies were conducted in 21 different countries, with two multicentre studies accounting for six of those countries. Figure 2 presents the study locations for the included studies.

Exposures

Most of the included research articles measured greenness exposure using the normalised difference vegetation index (NDVI). NDVI is calculated based on satellite images and ranges from −1 to 1, with values close to −1 indicating water, values close to 0 indicating areas without live vegetation, and values close to 1 indicating dense green vegetated areas. Greenness measured with NDVI refers to all vegetation, both structured spaces in parks and gardens, and unstructured spaces such as forests. As many as 29 of the 42 included papers in this review used NDVI as their main greenness definition [4–32]. In the included studies, NDVI was measured at study participants' residential addresses and defined either with circular buffer zones around the addresses (at 100 m, 300 m, 500 m or 1000 m), or with larger neighbourhood/census tract units.

Definitions of greenness in the remaining 13 research articles were tree canopy cover [33, 34], percentage of green space [35–39], or landcover/land-use maps [40–45]. Tree canopy cover refers to areas shaded by trees, more specifically branches and leaves and other vegetation foliage exceeding 5 feet (1.52 m) in height. Green space, landcover and land-use all refer to proportions of land covered by some form of vegetation, but the type of vegetation included in the definitions may vary from study to study.

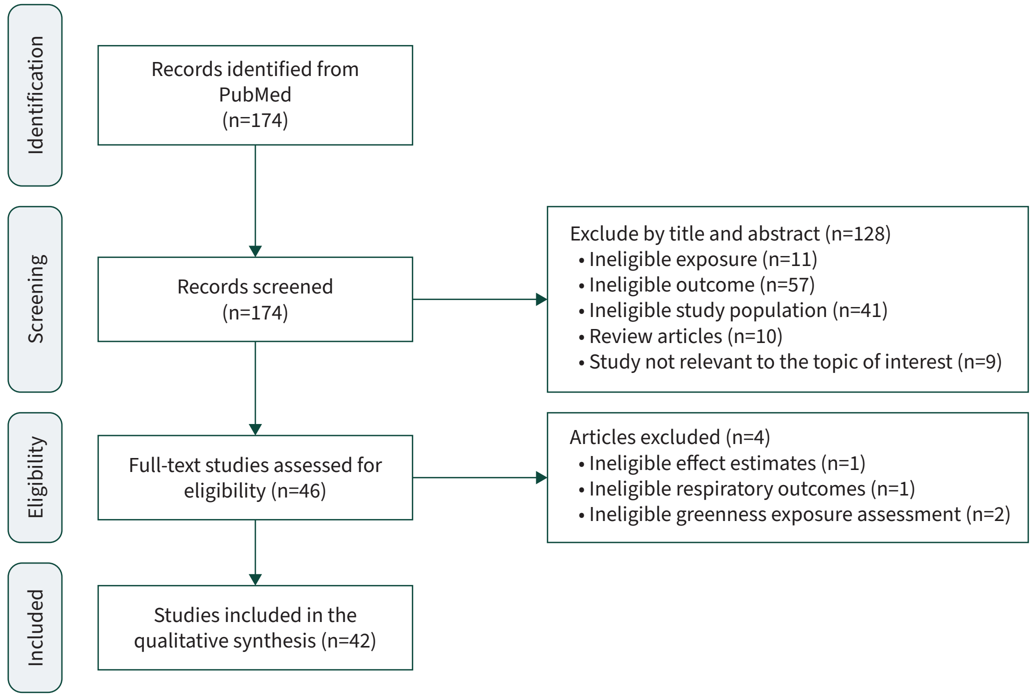

FIGURE 1 Flow chart of study selection process.

In addition, some of the included papers in this review investigated alternative greenness exposure indicators together with NDVI. Such alternative indicators were: 1) plant diversity, calculated based on plant-occurrence data from the Global Biodiversity Information Facility (GBIF), a facility containing over 2 billion geo-coded plant records globally [20]; 2) census tract level proximity to greenspace, defined as public parks, privately held greenspace and canopy cover along roads [33]; 3) the density of tall trees above 3 m (or closely grouped tree crowns where the clustered tree canopies were above 3 m, with one unit

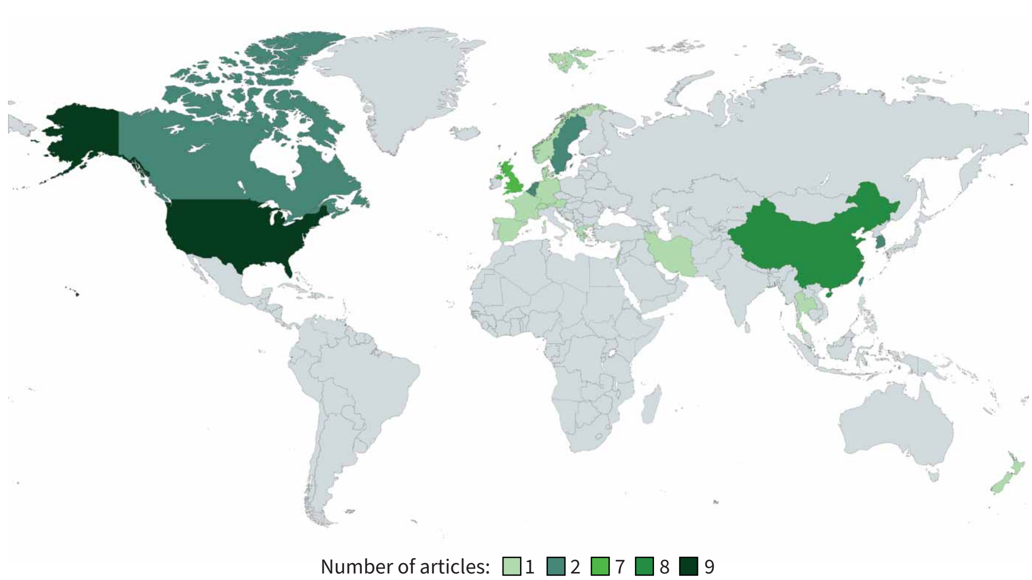

FIGURE 2 Map indicating study locations for the included studies. The USA, China and UK were the countries with most included studies.

increase on the tree density scale representing an increase of 50 trees/clustered tree crowns per km^2), and percentage of gardens calculated from the British Generalised Land Use Database (GLUD) [38]; 4) tree condition, calculated based on the percentage of dead tree tips in the crown of trees with a trunk diameter >2.5 cm at 1.5 m height (condition is then categorised into "excellent", "good", "fair", "poor", "critical/dying" and "dead") [34]; 5) subjectively perceived neighbourhood greenness, calculated from the percentage of household in each census tract reporting very good provision of green spaces in their neighbourhoods in the 2001 Belgian census (based on the question "What do you think of the neighbourhood facilities? The green space" with the three answer categories: "poorly equipped", "normally equipped", and "very well equipped") [4, 11]; and 6) a complex compound of six landscape metrics: percentage of greenspace (defined as tree canopy and grass or shrub cover), mean area of greenspace (with higher values indicating larger mean sizes of greenspace), fragmentation of greenspace (with higher values indicating greenspace area is scattered), greenspace connectedness (with higher values indicating that different parts of greenspaces are connected through paths or similar structures), aggregation of the greenspace pattern (with higher values indicating more aggregation of similar greenspaces together), and complexity of the shape of the greenspace (with higher values indicating more irregular shapes) [46].

Outcomes

Since some studies investigated more than one outcome, the outcomes investigated were higher than the numbers of included scientific articles. In total, the following outcomes were identified: respiratory mortality (19 papers), lung cancer mortality (13 papers), incidence of lung cancer (three papers), hospitalisation due to respiratory causes (four papers), lung function (six papers), COPD (four papers), and asthma (three papers). In the following, a synopsis of greenness results for each of these outcomes is provided.

Greenness and mortality

Respiratory mortality, including lung cancer mortality, was the most investigated outcome in relation to greenness within the field of respiratory outcomes. As many as 25 original research papers included in this review focused on respiratory mortality [6–19, 35, 36, 43, 45, 46] or lung cancer mortality [4–6, 8, 12, 14, 35, 40–45]. Most of the mortality studies investigated greenness in the form of NDVI, with interquartile range (IQR) as the preferred unit of increase in the analyses.

There is a great consensus in existing research that greenness has a protective effect on respiratory mortality. Figure 3 visualises effect estimates for the association of greenness exposure with respiratory and lung cancer mortality in a selection of papers: the 11 included articles that used a Cox proportional hazards model.

Of the 19 papers that focused on respiratory mortality (the nine included in figure 3 as well as 10 more that used effect estimates other than hazard ratios), 14 found a protective association between greenness and mortality, while three found no associations [6, 14, 17]. In the remaining two papers, one found that greenness had a protective effect on respiratory mortality in men but not in women [43], while one did not analyse greenness effects explicitly but instead looked at greenness as a mediator between air pollution and mortality [9].

While greenness has consistent beneficial effects for respiratory mortality, the results regarding lung cancer are not as clear-cut. Of the 13 papers focusing on lung cancer mortality, five reported a protective effect of greenness [4, 5, 8, 35, 45], while eight reported no associations between greenness and lung cancer mortality [6, 12, 14, 40–44].

Greenness and lung cancer

We identified three papers investigating associations between greenness and lung cancer incidence, of which two reported clear beneficial effects of greenness exposure, while one did not observe any associations [26–28]. All three studies were from Asia, with two from China (Shanghai) and one from Taiwan.

In the study from Taiwan, HUANG *et al.* [26] used data from the large Mei Jau (MJ) Health Examination Database with more than 400 000 participants and merged these with data from the Taiwan cancer registry. Greenness was defined as NDVI with a 500 m buffer zone around the participants' residential addresses. The follow-up period was approximately 10 years. The age-standardised incidence rate of lung cancer (International Classification of Diseases, Ninth Revision (ICD-9) code 162, International Classification of Diseases, 10th Revision (ICD-10) codes C33 and C34) was 41 per 100 000 population. Cox regression analysis was performed with adjustment for age, sex, socioeconomic status, smoking and comorbidities. NDVI exposure per 0.1 unit increase had a protective effect on lung cancer incidence with a hazard ratio (HR) of 0.95 (95% CI 0.91–0.99).

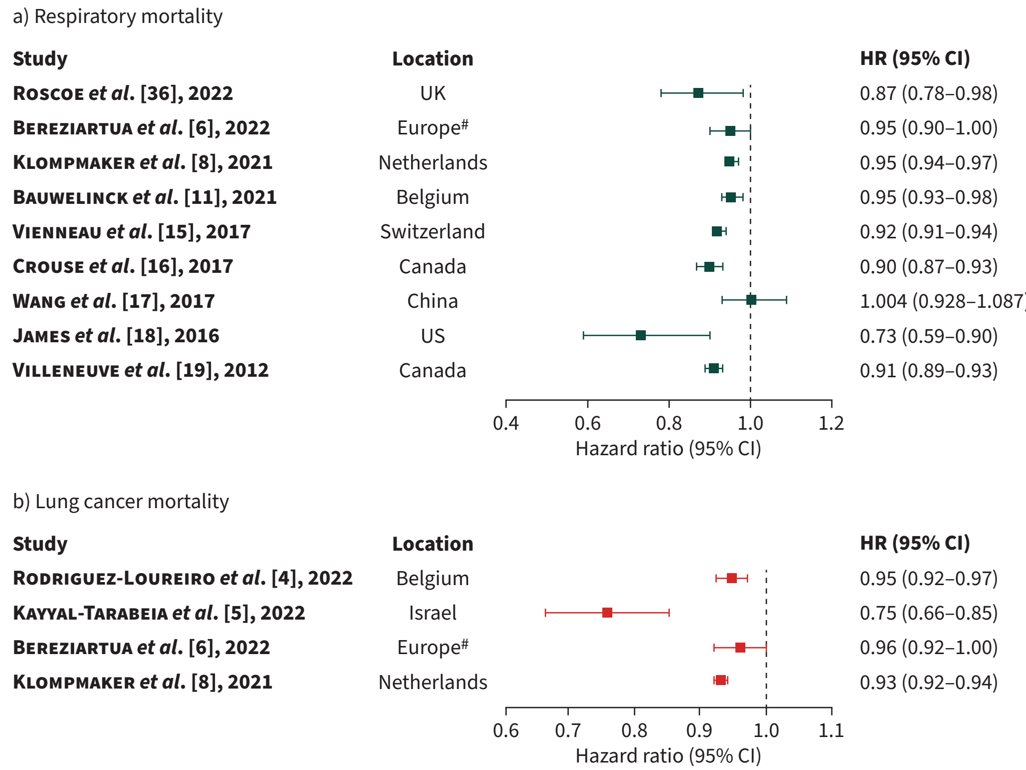

FIGURE 3 Forest plot summarising the effects of exposure to greenness on a) respiratory and b) lung cancer mortality (hazard ratio (HR) with 95% confidence interval (CI)) in a total of 11 included articles using a Cox proportional hazards model in their analysis. #: pooled cohort in Europe, including Sweden, Denmark, the Netherlands, Germany, France and Austria.

In an ecological study by Sun *et al.* [27], 841 neighbourhoods in Shanghai, with a mean area of 0.12 km^2 comprising ∼3.5 million inhabitants, were investigated. Greenness was defined as NDVI with a 1 km resolution and assigned to each neighbourhood. The outcome was lung cancer incidence over 5 years routinely reported by hospitals to the Shanghai Center for Disease Control and Prevention and mapped to neighbourhood units according to participants' residential addresses. Mean NDVI was 0.24, and age-standardised lung cancer incidence was 35 per 10 000 inhabitants. Negative binomial regression was performed, and relative risks were calculated. Model 1 was adjusted for urban form, road traffic and demographic variables, while model 2 was adjusted for housing quality in addition to the variables in model 1. With the adjustments from model 1, a one unit increase in NDVI yielded a relative risk of 0.083 (95% CI 0.034–0.201). With the adjustments from model 2, the effect size decreased slightly but was still significant (relative risk 0.14 (95% CI 0.06–0.33)).

In another study from Shanghai, however, Shao *et al.* [28] did not find any significant associations between greenness exposure defined as NDVI and lung cancer incidence. Their study was a case–control study, including 1461 cases (lung cancer patients) and 954 controls (colorectal cancer patients). NDVI in September and January were averaged to represent both high and low vegetation periods and assigned to each participant's residential address with a 500 m buffer zone. Logistic regression analyses with adjustment for sex, age, smoking and road traffic were performed and resulted in an odds ratio (OR) per unit increase in NDVI of 0.97 (95% CI 0.80–1.18) for the lung cancer patients compared with the controls.

Greenness and respiratory hospitalisation

Of the four papers in this review that focused on greenness and respiratory hospitalisation, one was a cohort study [23], while the other three were ecological studies [24, 34, 38]. Most results indicated a beneficial effect of greenness on respiratory hospitalisations, although some inconsistent findings were also reported.

In a recent nationwide study from the USA, Klompmaker *et al.* [23] created a cohort using data from the Medicare health insurance programme, including all Americans older than 65 years and younger

Americans with disability status. In total, 63 million Americans were followed up from 2000 until the first relevant hospital admission, censoring, death or end of follow-up (total follow-up period 16 years). Greenness was defined in two ways: NDVI and percentage park cover. Cloud-free NDVI was calculated using Google Earth Engine (https://earthengine.google.com/) based on original images from Landsat 7 and 8. Percentage of park cover was calculated from the US Geological Survey Protected Areas Database (PAD-US). This study also calculated the percentage of blue space cover using satellite images from the Joint Research Centre's Global Surface Water Dataset. Exposures and covariates related to socioeconomic status were on an aggregated zip code level, while outcomes, age, sex, and race were on an individual level. Respiratory disease hospitalisation was defined as ICD-9 codes 460 to 519 and ICD-10 codes J00 to J99. Cox-equivalent re-parameterised Poisson analyses were performed for the full cohort and a sub-sample of Americans living in urban areas. NDVI IQR was 0.27. In the full cohort the hazard ratio, per IQR increase in NDVI for respiratory disease hospitalisation, was significant but minimal (HR 0.99 (95% CI 0.98–0.997)), with similar small but protective effects also seen for percentage park cover and percentage blue space cover. In the urban sub-sample, however, greenness was positively associated with respiratory disease hospitalisation (HR 1.02 (95% CI 1.004–1.03)), indicating a small but harmful effect. Park and blue space cover were not associated with respiratory hospitalisation in the urban sub-sample. However, in this sub-sample, park cover did have a beneficial effect on respiratory hospitalisations in zip codes with a low socioeconomic status.

In one of the ecological studies, HEO and BELL [24] analysed 364 US counties using data from the Medicare health insurance programme. The focus of this study was not to assess associations between greenness and hospitalisations *per se*, but to assess whether greenness modified the associations between particulate matter air pollution and hospitalisations. County greenness was defined with NDVI, and daily counts of hospital admissions at the county level were obtained. Analyses were adjusted for aggregated socioeconomic and demographic characteristics. They concluded that greenness decreased the strength of the association between particulate matter pollution and respiratory hospitalisations, particularly in the age group 65–85 years rather than those aged above 85 years.

In another American ecological study, JENNINGS *et al.* [34] defined greenness quite elaborately in four ways: per cent tree canopy, tree density, tree condition and leaf area index. The analysis unit in this paper was census block groups (n=370) in the city of Tampa, in Florida. In logistic regression analyses with adjustment for census block sociodemographic characteristics (income, race, population density and percentage of homeowners), leaf area index had a clearcut beneficial effect on respiratory hospitalisation (OR 0.16 (95% CI 0.06–0.42)) and also higher tree density was associated with slightly lower respiratory hospitalisation rates (OR 0.99 (95% CI 0.99–0.99)). In contrast, the per cent tree canopy cover was not associated with respiratory hospitalisation, and better tree condition actually increased the risk of respiratory hospitalisations (OR 2.13 (95% CI 1.17–3.85)).

Finally, in a British ecological study using "lower-layer super output areas" (LSOAs; with each LSOA covering ∼0.9 km^2 in urban areas) as an analysis unit, ALCOCK *et al.* [38] investigated asthma hospitalisations in relation to the percentage of green space, percentage of gardens, and density of mature trees (more than 3 m tall). Hospitalisation rates were standardised to the 2013 European Standard Population (ESP) according to the age structure of each of the LSOAs, and calculated as number of hospitalisations per 100 000 ESPs. Aggregated LSOA level socioeconomic deprivation and air pollution characteristics were also included in the models, and negative binomial regression analyses were conducted. All three greenness variables were significantly related to a lower risk of asthma hospitalisation after adjustment for confounders. Per 1% increase of greenspace and gardens, the mean reduction of asthma hospitalisations in each LSOA was −3.8 per 100 000 ESPs (95% CI −4.6– −3.0) and −4.3 per 100 000 ESPs (95% CI −5.4– −3.1), respectively, while an increase of 50 tall trees per km^2 reduced asthma hospitalisations in the LSOAs by 9.1 per 100 000 ESPs (95% CI −11.2– −7.1).

Greenness and lung function

Six papers investigated greenness and lung function parameters. They found mainly beneficial health effects where greenness exposure increased lung function, although some inconsistent results were also reported.

In a small Spanish study including 57 participants aged 21–52 years, COLE-HUNTER *et al.* [31] discovered that greenness mediated the harmful effect of air pollution on lung function. NDVI was obtained through Landsat 8 images in mid-April, the time of year with the most vegetation, and calculated with alternative residential buffer zones 100 m, 300 m, and 500 m. In crude mixed-effects model analyses, 10 $\mu g \cdot m^{-3}$ increments of particulate matter with aerodynamic diameter <10 µm decreased forced expiratory volume in 1 s (FEV_1) and forced vital capacity (FVC) with −0.175 L (95% CI −0.353–0.004 L) and −0.291 L (95%

CI −0.486– −0.096 L), respectively. The corresponding estimates after adjusting for NDVI were −0.097 L (95% CI −0.326–0.131) for FEV_1 and −0.219 L (95% CI −0.471–0.033) for FVC. The study, unfortunately, did not report direct effect estimates of greenness on lung function parameters, but the mediating effects pointed to a potential beneficial greenness effect.

Xiao *et al.* [25] also reported a beneficial effect of greenness on lung function in a paper from the Chinese Pulmonary Health (CPH) study. In this large study comprising 50 000 participants, greenness was defined as NDVI with a 500 m buffer zone around the participants' residential addresses. The mean age was 50 years, the mean NDVI was 0.30, and analyses were adjusted for confounders related to air pollution, socioeconomic status, smoking and comorbidities. Greenness had clear beneficial effects on lung function: an IQR increase in NDVI was associated with higher FEV_1 (24.76 mL (95% CI 13.32–36.20)), FVC (16.52 mL (95% CI 3.61–29.44)), and FEV_1/FVC (0.38 higher ratio estimate (95% CI 0.20–0.55)). Stratified analyses indicated that greenness positively affected lung function among people below 65 years of age and women, non-smokers and participants living in rural areas.

In a small study including 39 participants aged 50–64 years living in Hong Kong, Yang *et al.* [29] also reported beneficial effects of greenness exposure on lung function. Greenness was defined as NDVI, based on GPS trackers that the participants wore for 5 weeks. NDVI IQR for the 100 m buffer zone was 0.34, while the mean NDVI was as low as −0.54, indicating close proximity to water for most of the participants. Using generalised linear mixed-effects models, positive associations with NDVI were found for the FEV_1/FVC ratio after adjusting for income, air pollution and physical activity levels. In contrast, no significant associations were observed with regard to FEV_1 or FVC separately.

In a paper from the "Understanding Society: The UK Household Longitudinal Survey" (UKHLS), Chaparro *et al.* [39] investigated associations between socioeconomic deprivation, greenness exposures and various health outcomes, including FEV_1. Greenness was defined as the percentage of green space in 4929 Census Area Statistic (CAS) residence wards, while spirometry was performed individually on 16 347 participants residing in these CAS wards. A CAS ward is a neighbourhood area unit with a mean population of 5518 persons, commonly used when collecting census data. The mean green space in this study was 0.57. Analyses were performed as multilevel models since outcome data were on an individual level, while exposure data was on an aggregated level. After adjusting for neighbourhood income, FEV_1 increased by 0.042 L per percentage increase in green space (95% CI 0.032–0.053 L). Greenness also had a mediating effect on the association between neighbourhood deprivation and lung function in adults in the age range 35–60 years, where more deprivation was associated with less green space, and less green space was associated with worse lung function.

Another study investigating associations between socioeconomic deprivation, greenness and lung function was performed by Humphrey *et al.* [30]. Based on data from the Colorado Home Energy Efficiency and Respiratory Health (CHEER) study, analyses were performed on 263 participants who performed spirometry. Greenness was defined as NDVI within census tract units and was included in latent profile analyses together with air pollution, race, socioeconomic status and crime rates to form four distinct neighbourhood profiles. Of the four profiles, the one with the lowest levels of greenness had the highest levels of air pollution and crime, moderate levels of poverty, and predominantly white and Hispanic residents with higher education. On the other hand, the profile with the highest levels of greenness had the lowest levels of air pollution, crime and poverty and comprised mainly white residents with higher education. Although in generalised estimating equation models, there were no significant associations between the different neighbourhood profiles and lung function, the authors believed they observed a tendency and concluded that low-income populations living in disadvantaged neighbourhoods might have worse lung health than populations with higher income from more advantaged neighbourhoods.

In a paper from the Swedish and Norwegian centres in the RHINESSA study, Nordeide Kuiper *et al.* [32] investigated long-term greenness exposure defined as NDVI from birth onwards and lung function in addition to self-reported asthma outcomes in adulthood. The study included ∼3500 participants in the age range of 18 to 40 years, where a sub-sample of 555 participants also performed spirometry. Residential NDVI was calculated within a 300 m buffer zone around the participants' addresses based on satellite images retrieved from the three most vegetation-rich months in the year (May, June and July). In addition to the 300 m buffer zone, sensitivity analyses were performed using 100 m, 500 m and 1000 m buffers. The exposure time windows under investigation were 0–10 years, 10–18 years, from birth until the time of study participation (lifetime), and separately mean exposure 1 year before participation. Mean NDVI was quite stable across study centres and periods, ranging from 0.53 in Umea to 0.59 in Gothenburg. In logistic regression analyses with adjustment for confounders, each 0.1 unit increase in NDVI increased the risk of both FEV_1 and FVC below the lower limit of normal, particularly when analysed as lifetime exposure. Adjusted odds ratios were 1.74 (95% CI 1.15–2.63) for the lower limit of normal FEV_1 and 1.57 (95% CI 1.00–2.45) for the lower limit of normal FVC.

Greenness and COPD

The four papers with analyses of greenness exposure and COPD showed inconsistent results, with two papers reporting protective effects of greenness on COPD [22, 25] and two papers, on the contrary, reporting greenness as a potential risk factor for COPD [21, 33].

The two papers that concluded that greenness was a potential protective factor for COPD were from the CPH study [25] and the UK Biobank study [22]. Both studies were cross-sectional and included a large number of participants (50 000 and ∼100 000, respectively). They both defined greenness as NDVI in a 500 m circular buffer around the participants' residential addresses. The Chinese study also analysed NDVI in a 1000 m buffer zone. The Chinese study did not provide information on the size of greenness IQR, but the mean NDVI in this study was 0.30. This was higher than in the UK Biobank study, where the mean NDVI was 0.18, and IQR was 0.23.

The age of the participants was quite similar in the two studies. In the CPH study, the mean age was 50 years, while in the UK Biobank study, the mean age was 56 years. Both studies adjusted their analyses for important confounders related to air pollution, socioeconomic status, smoking and comorbidities. In the CPH study, an IQR increase in NDVI was associated with decreased risk of COPD (OR 0.90 (95% CI 0.83–0.97)). Further stratified analyses indicated that the protective effect of greenness on COPD was mainly in women and not in men (OR 0.83 (95% CI 0.73–0.95) *versus* OR 0.97 (0.88–1.07)), and more prominent in persons below rather than above 65 years of age (OR 0.90 (95% CI 0.82–0.99) *versus* OR 0.92 (95% CI 0.79–1.08)). Another interesting result from this study was that greenness decreased the risk of COPD, particularly for persons living in rural areas (OR 0.82 (95% CI 0.69–0.97)) and not in urban areas (OR 0.97 (95% CI 0.87–1.08)).

In the UK Biobank study, the adjusted odds ratio per IQR increase in greenness for COPD was very similar to the results from the CPH study: 0.89 (95% CI 0.84–0.93). The UK Biobank study did not present stratified results with regard to sex and age groups but presented unadjusted results that were very similar to the adjusted results (unadjusted OR per IQR increase in greenness 0.88 (95% CI 0.84–0.92)), indicating that the effect of greenness is a strong independent protective factor for COPD, remaining the same regardless of multivariate adjustments.

The two studies that reported greenness to be associated with increased risk of COPD were a nationwide cross-sectional study from China, reported by Fan *et al*. [21], and an ecological study from the Atlanta area in the USA, reported by Servadio *et al*. [33]. Similar to the two previously mentioned COPD studies, the study by Fan *et al*. [21] also had a large number of participants (67 000), defined greenness as NDVI in a 500 m circular buffer around the residential addresses, and adjusted their analyses for important confounders related to air pollution, socioeconomic status, smoking and comorbidities. This study also conducted sensitivity analyses with alternative NDVI buffer sizes, namely 100 m, 300 m, 1000 m, 2000 m, 3000 m and 5000 m, all with roughly the same results as the 500 m greenness buffer. Greenness IQR was similar to that of the UK Biobank study: 0.22 in the study by Fan *et al*. [21] *versus* 0.23 in the UK Biobank study [22]. However, average greenness levels were much higher in the Fan *et al*. [21] study than in the UK Biobank study and the CPH study: median NDVI 0.52 *versus* means of 0.18 and 0.30, respectively. In the study by Fan *et al*. [21], the odds ratio for COPD for each IQR increase in NDVI (500 m buffer zone) was 1.09 (95% CI 1.01–1.17) after adjusting for confounders, compared with OR 1.19 (95% CI 1.13–1.27) before adjustment.

The ecological study from the US used data from several sources, with both health outcome data and greenness data available at a census tract level. This study by Servadio *et al*. [33] included 169 census tracts, each ∼1 km^2, with 1000–5000 inhabitants. Greenness was defined as tree canopy cover (percentage of the census tract covered by a canopy on both public and private land) and access to greenspace (a metric of land access specifically designated as public parks, privately held greenspace and canopy cover along roadways). Through spatial autocorrelation analysis, the researchers in this study found that census tracts with higher greenness had higher COPD prevalence than census tracts with less greenness, with a parameter estimate of 0.18 for tree canopy and 0.21 for access to greenspace (both p-value <0.05, but no confidence intervals reported).

Greenness and asthma

The picture of greenness and asthma is not clear-cut. Of the three included papers investigating associations between greenness exposure and asthma, two studies reported no association [32, 33]. By contrast, one study reported that greenness exposure might, in fact, both reduce and increase the risk of asthma in adults [20].

In the study by Donovan *et al.* [20], 498 cities from the Centers for Disease Control and Prevention's (CDC) 500 Cities Project were used, comprising 26 367 census tracts. A mixed linear model was conducted, adjusting for race, socioeconomic status, air pollution and proximity to roads. Greenness was defined in two ways: as plant diversity using plant-occurrence data from the GBIF, and as maximum NDVI in each census tract. Interestingly, the authors found that greenness exposure was both protective and harmful: NDVI increased the risk for asthma (coefficient 0.038 (95% CI 0.029–0.048)), while increasing plant diversity had a protective effect on asthma (coefficient −0.053 (95% CI −0.064–−0.042)). The precise unit used in the analyses was not clearly described for either greenness exposure. Still, the tendencies are clear and suggest that exposure intensity and composition are two different entities and that one may have harmful effects while the other may have beneficial effects.

Interestingly, the study by Servadio *et al.* [33] used health outcome data from the same CDC 500 Cities Project as that of Donovan *et al.* [20]. Still, Servadio *et al*. [33] did not find any associations with asthma. One plausible explanation may have been the choice of greenness exposure variables. While Donovan *et al.* [20] investigated NDVI and plant diversity, Servadio *et al*. [33] investigated tree canopy and access to greenness.

In a paper from the Swedish and Norwegian centres in the RHINESSA study, described in more detail in the section on "Greenness and lung function", Nordeide Kuiper *et al.* [32] also investigated long-term greenness exposure in relation to two asthma outcomes: self-reported ever asthma diagnosed by a medical doctor together with the year of diagnosis, and self-reported asthma attacks during the last 12 months [32]. While greenness was associated with lung function in this paper, it was not associated with any of the asthma outcomes in any of the exposure time windows (age 0–10 years, age 10–18 years and lifetime exposure from birth until time of participation) with odds ratios ranging from 0.95 to 1.01 and 95% confidence intervals equally distributed below and above one.

Summary of review results

Mortality caused by respiratory diseases and lung cancer has been extensively studied within the past decade. There is a consensus in the literature today that greenness has a protective effect on respiratory mortality. Still, the picture was much more unclear regarding lung cancer mortality – most papers within that field found no associations between greenness exposure and this outcome. Regarding lung cancer incidence, by contrast, there is a preliminary consensus that greenness has beneficial effects, but more studies are needed. Of the three papers identified in the current review, two found protective effects of greenness on lung cancer incidence, and one found no association. However, this is likely due to the study design: it was a case–control study with lung cancer patients as cases and colorectal cancer patients as controls. One could hypothesise that a more precise picture would be achieved by selecting healthy controls instead of selecting another group of cancer patients as controls.

The four papers investigating greenness exposure and respiratory hospitalisation had very different study designs and a varying focus of interest, yielding heterogeneous results for this review. In one paper, there was a clear result that greenness exposure reduced the risk of respiratory hospitalisation. In contrast, another paper found that this was true only in a subgroup with low socioeconomic status. A third study found that increased greenness exposure had a beneficial effect modification on the association between air pollution and the risk of respiratory hospitalisations, so that the harmful effects of air pollution were reduced if the participants were simultaneously exposed to higher levels of greenness. In the fourth paper, some aspects of greenness (leaf area index and tree density) reduced the risk of respiratory hospitalisation. In contrast, another aspect (better tree condition) was actually a risk factor for respiratory hospitalisation.

One of the six papers focusing on lung function also reported the beneficial mediator effect of greenness on the harmful effect of air pollution and lung health. Greenness exposure increased FEV_1 in two studies and increased FEV_1/FVC in another study, while one study reported particularly beneficial effects on lung function by greenness in areas with low socioeconomic status. The last paper on lung function and greenness included in this review, however, found that greenness was actually a risk factor for both lower limit of normal FEV_1 and FVC.

Regarding COPD, two papers found that greenness exposure reduces the risk, while two papers found that greenness exposure increases the risk. Regarding asthma, two papers found no associations, while one found that increased NDVI elevated the risk of disease but that plant diversity had a protective effect on asthma development.

In what contexts is greenness exposure beneficial?

Potentially, greenness exposure may be beneficial for all respiratory health outcomes. However, we still lack studies to conclude with any certainty for all respiratory outcomes except the mortality outcomes. The results emphasised in the current review render it likely that greenness exposure is a complex exposure where some parts are beneficial. Some elements can, in fact, be harmful to respiratory health. The results described in this review also point to the importance of looking more closely at subgroups in the population because some groups may experience more benefits of greenness than others.

Several potential mechanisms may explain why greenness has a beneficial effect on respiratory health. Green areas in residential vicinity encourage physical activity and social gatherings, and use of greenspace has been shown to reduce stress and improve mental health [47].

Donovan *et al.* [20] found plant diversity to have a positive and protective effect on respiratory health. This would be in line with the hygiene hypothesis and with studies showing that exposure to more diverse vegetation increases the microbiome's diversity. Numerous studies have shown that the microbiome's diversity is associated with a reduced risk of, for example, asthma [48]. Consequently, a plausible hypothesis is that greenness exposure benefits respiratory health through its effect on the human microbiome.

Greenness can reduce air pollution *via* absorption, deposition, and dispersion [22]. Green spaces can also provide ventilation corridors in an urban environment, breaking the air pollution flows.

In what contexts is greenness exposure harmful?

Greenness can be a source of pollen, ozone and other respiratory irritants, for example, volatile organic compounds [23]. In this context, greenness exposure can plausibly be related to allergic sensitivities to pollen which may exacerbate the respiratory disease. This was also supported by one of the included papers in this review, where better tree condition (healthier and fuller green leaves) had a harmful effect on respiratory health [34].

Another potential reason for the harmful effects of greenness is that if there are many tall trees, and wind speed is low, greenness can trap air pollution at ground level if the pollution sources (*e.g.* cars) are below the tree canopy [24].

In addition, some subgroups may experience more harmful effects of greenness than others. For example, urban dwellers will likely be exposed to reduced pathogen levels compared with rural dwellers, with a subsequently lower tolerance to pollen and increased risk of allergy [23].

Why do studies report seemingly conflicting results?

Differences in results between studies are probably due to different methodological designs. We have seen in the current review that definitions of greenness exposure vary quite heavily from study to study, although NDVI is the most commonly used greenness marker. And even in studies where they all use NDVI, this variable varies considerably – from a 100 m buffer zone around the residential address to an entire zip code area as the exposure unit. Greenness exposure may differ substantially from block to block within a zip code area. It will therefore be a rough greenness marker with a low ability to measure an individual's actual exposure levels. In addition, if some aspects of greenness are beneficial while others are harmful, studies using these different aspects of greenness (such as NDVI, plant diversity or tree density) as proxies for overall greenness will undoubtedly come to different conclusions. There will also be important geographical differences regarding greenness exposure, where different areas worldwide will have different vegetation types.

An alternative potentially important explanation for the observed inconsistencies among studies revolves around the differences in outcome definitions. Differences in outcome definitions can be especially relevant regarding asthma and COPD, where epidemiological definitions are looser and more variable compared with harder endpoints such as mortality outcomes, hospitalisation and lung function. Both asthma and COPD can be defined using questionnaires, clinical measurements, and electronic health records – and the definitions are likely to influence the disease rates and analytical results. However, a closer inspection of the included asthma and COPD papers in this review did not support this hypothesis. Of the two papers reporting decreased COPD risk with increasing greenness exposures [22, 25], both defined COPD with objective lung function measurements. The same, however, applied to one of the studies that reported increased COPD risk with increasing greenness exposures [21]. While the second paper reporting a positive association between greenness and COPD defined COPD based on health records on aggregated population levels (census tracts) [33]. Similarly, both the study reporting diverse associations (both negative and positive) between greenness and asthma [20], and one of the studies reporting no associations between greenness and asthma had defined asthma based on health records from census tract levels [33]. While the second study reporting no associations between greenness and asthma defined asthma using self-report questionnaires [32].

Study design, especially when it comes to the length of follow-up time, is very important in understanding the inconsistencies among study results. A longer follow-up time allows for better longitudinal exposure characterisation and a clearer picture of the associations between exposure and outcomes. For example, a study with information on greenness exposure through a 15-year follow-up time will give us a more accurate long-term exposure estimate than a study with information on greenness exposure during a 1-year follow-up time as participants may have recently moved to areas with higher or lower exposure and therefore their average long-term exposure will be lower or higher, respectively, than shown in the study results.

Demographic differences between study populations may also affect the results. For example, elderly people are more likely to have COPD, compared with younger people, and they may also be more prone to moving to greener and wealthier areas in many affluent countries. This could bias association estimates between greenness and COPD prevalence towards spurious positive associations.

Another plausible reason for the inconsistent results among studies revolves around the fact that access to green spaces does not guarantee the actual use of these spaces. The quality and size of the green spaces may matter, as well as demographic characteristics in the study population [39]. Both actual use of the green spaces and interactions between age, gender and socioeconomic status should be considered when looking at associations between greenness and respiratory health outcomes.

Conclusion

This review of 42 original research papers looking at greenness and various respiratory health outcomes shows that greenness is a mainly beneficial exposure with protective effects on respiratory health. Public health policymakers should be aware of this when planning societies for a healthier future. Clinicians should be aware of this when discussing disease management and everyday lifestyle practices with their patients.

In particular, the beneficial effects of greenness apply to respiratory mortality, lung cancer incidence, respiratory hospitalisations and lung function. For lung cancer mortality, the effects of greenness may seem less prominent. For asthma and COPD, we cannot yet conclude with any certainty. It is also important to remember that: 1) greenness is multidimensional – many aspects are beneficial, but some aspects may actually be harmful; and 2) greenness may have different health effects in different population subgroups.

With this in mind, future studies should focus on the following points:
- Disentangling different aspects of greenness.
- Investigating effects of greenness on respiratory health for different subgroups in the population.
- Investigating effects of greenness, particularly on asthma and COPD, where today's body of evidence is too fragile for us to draw conclusions with any certainty.

Key points

- Greenness exposure has beneficial effects in most studies regarding respiratory mortality, lung cancer incidence, respiratory hospitalisations and lung function.
- Both beneficial and harmful effects of greenness exposure have been identified with regards to COPD and asthma.
- The most commonly used marker for greenness exposure in existing literature is the normalised difference vegetation index (NDVI), measured around individuals' residential addresses in circular buffer zones.
- Greenness exposure may be beneficial for respiratory health by promoting physical activity, decreasing stress, reducing air pollution, and increasing the diversity in the human microbiome.

Self-evaluation questions

1. For which respiratory outcomes does greenness exposure have an overall beneficial effect?
   a) Lung function
   b) Respiratory mortality
   c) COPD
   d) Lung cancer incidence
   e) Respiratory hospitalisations
   f) Lung cancer mortality
2. Why may the presence of tall trees make greenness exposure harmful?
   a) Tall trees decrease sun exposure
   b) Tall trees trap air pollution
   c) Tall trees increase ground humidity
3. What does the NDVI scale from −1 to +1 mean?
   a) It describes the intensity of green plants in an area, from −1 referring to yellow leaves and trees with no green leaves to +1 referring to a high intensity of green leaves, typically a large park during the spring.
   b) It describes the degree of all vegetation (structured and unstructured), ranging from water (−1) to intense vegetation (+1).
   c) It describes the degree of man-made greenness (parks and gardens, not unstructured greenness like natural forests) in a city neighbourhood, ranging from −1 (none) to +1 (complete park cover).
4. What are the possible beneficial mechanisms behind the health effects of greenness exposure?
   a) Increased physical activity
   b) Trapped air pollution under tall trees
   c) Air pollution absorption of plant
   d) Reduced sense of stress
   e) Increased social gatherings
   f) Decreased diversity in human microbiome
   g) Increased diversity in human microbiome

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Suggested answers

1. a, b, d and e.
2. b.
3. b.
4. a, c, d, e and g.