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Original article

Green spaces in highly urbanized tracts tied to lower prevalence of chronic respiratory diseases: A nationwide study across levels of urbanicity

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ABSTRACT

Previous studies have found conflicting results between green space and respiratory diseases, possibly due to the use of generalized green space measures and the diverse urbanicity levels in which they were conducted. Few nationwide studies examined how urbanicity modifies the relationship between green spaces and respiratory diseases while considering the geospatial relation between green space and human population, population density, and accessibility.

This study evaluates the relationships between population-weighted forest and open space exposure (inside and outside park), chronic obstructive pulmonary disease (COPD), and asthma in the contiguous United States. The COPD and asthma data were obtained from the Centers for Disease Control and Prevention. The green space exposure within an 800 m buffer was computed using National Land-cover Dataset and WorldPop Global Population Data. The associations were estimated using spatial error models and adjusted for important covariates. We also performed stratified analyses by four urbanicity levels.

Green spaces inside but not outside park were associated with a lower prevalence of COPD and asthma. We found that a 1 m^2 increase in forest inside park was associated with a decrease of 3.57 and 2.97 cases per 100,000 population in COPD and asthma, and a 1 m^2 increase in open space inside park was associated with a decrease of 4.82 and 7.66 cases per 100,000 population in COPD and asthma. A trend of an inverse relationship was observed across urbanicity: the beneficial associations occurred in highly urbanized tracts but not in the three less-urbanized tracts.

Our results provide further evidence that nearby forests and open spaces inside park, particularly in urban areas, were tied to a lower prevalence of respiratory diseases in the US. The beneficial association suggests the necessity of ensuring access to nearby green spaces, especially those in parks, to promote respiratory health.

1. Introduction

Chronic respiratory diseases, commonly chronic obstructive pulmonary disease (COPD) and asthma, contribute significantly to the global disease burden. In 2019, an estimated 212.3 million people suffered from COPD, 3.3 million deaths were due to COPD, and COPD accounted for 74.4 million disability-adjusted life years (DALYs) globally (Safiri et al., 2022). According to the World Health Organization (WHO), asthma affected an estimated 262 million people and caused 455,000 deaths in 2019 (WHO, 2022). In the United States (US), 16 million Americans suffered from COPD. Over 25 million people were affected by asthma, with millions more undiagnosed and untreated (CDC, 2022a).

Chronic respiratory diseases bring substantial economic losses and adversely impact people's quality of life and well-being. In the US, the total cost of all respiratory diseases was $170.8 billion, with asthma having the highest expenditure, followed by COPD (Nurmagambetov, 2023). Asthma costs the US economy more than 80 billion annually, including medical expenses, missed workdays, and pre-mature deaths, and COPD was estimated to cost $49 billion in the US in 2020 (Larsen et al., 2022; Nurmagambetov et al., 2018). Chronic asthma can lead to difficulty in fall asleep and daily fatigue (Van Herck et al., 2018), reduced physical activity (Loponen et al., 2018), and poor work performance (Diette et al., 2000; Sullivan et al., 2018).

COPD includes emphysema and chronic bronchitis that cause airflow

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blockage and breathing difficulties (CDC, 2022b). Asthma is the narrowing of the small airways in the lungs, which causes coughing, wheezing, shortness of breath, and chest tightness (Mims, 2015). The development and exacerbation of COPD and asthma have been attributed to increased airway inflammation (George & Brightling, 2016), immune dysfunction (Bhat et al., 2015; Marshall, 2004), and abnormal respiratory microbiome (Kang et al., 2017; Shukla et al., 2017). Accumulating evidence suggests that contact with green space can enhance immune functioning, lower inflammatory level, and regulate microbial composition (Kuo, 2015; Selway et al., 2020; Wu et al., 2022). Thus, green space may potentially mitigate some of the adverse pathological mechanisms and protect against COPD and asthma.

1.1. Conflicting association between green space and chronic respiratory diseases

Although the risk of developing COPD and asthma is influenced by genetic predisposition and infections at early ages, the risk is also significantly impacted by environmental exposures. Exposure to green space has been found to be negatively associated with COPD and asthma. A systematic review of cohort studies has found a consistent beneficial effect of NDVI on symptoms of asthma and COPD (i.e., wheezing and bronchitis) (Islam et al., 2020). Large-scale cohort studies in Canada, New Zealand, and United Kingdom found that residential green space was associated with lower odds of child asthma, COPD, and respiratory mortality (Crouse et al., 2017; Donovan et al., 2018; Sarkar et al., 2019). A recent review of observational and experimental studies in urban areas found beneficial associations between greenness, tree canopy, parks, forests, and respiratory health in two-thirds of the studies (Mueller et al., 2022). Cross-sectional studies found that higher proportions of eucalypt forests and tree canopy, higher connectedness, and aggregated green space were protective against respiratory disease (Liddicoat et al., 2018; Wang & Tassinary, 2019). Longitudinal studies found grassland and vegetation biodiversity protect against child asthma (Aerts et al., 2020; Donovan et al., 2018).

However, some studies produced conflicting results (Dadvand et al., 2014; Ferrante et al., 2020; Lambert et al., 2017; Sullivan & Thakur, 2020). Studies have found neighborhood greenness linked to a higher prevalence of COPD and asthma (Fan et al., 2020; Andrusaityte et al., 2016), or had a nonsignificant association with respiratory outcomes (Wang et al., 2017). Living in neighborhoods with nearby parks was also found to be associated with higher asthma prevalence (Dadvand et al., 2014). Mixed findings such as these may be attributed to the use of generalized green space measures and diverse contexts.

1.2. Critical knowledge gaps

Below, we identify three critical knowledge gaps in the literature. First, few nationwide studies have examined whether urbanicity modifies the association between different types of green space and COPD and asthma prevalence in the US. Previous studies found that COPD and asthma prevalence were significantly higher among persons living in rural areas than those living in micropolitan or metropolitan areas in the US (Croft et al., 2018; Guo et al., 2021; Raju et al., 2020). The availability and accessibility of green space also differ at the tract level across the urban-rural gradient. Rural areas have substantially greater coverage of green spaces, while urban green spaces are located closer to residents (Wen et al., 2013). Thus, it is reasonable to assume that green space will impact COPD and asthma prevalence differently across urbanicity.

Second, most studies examined the association between green space and chronic respiratory diseases using greenness or total green coverage, which inadequately distinguish the association between different types of green space and chronic respiratory diseases (Lambert et al., 2017; Mueller et al., 2022; Sarkar et al., 2019). However, forests may be more protective against respiratory health than open lawns due to their stronger capacity to improve air quality (Gao et al., 2020; Vieira et al., 2018). Moreover, open lawns typically utilize fertilizers and chemicals, which may trigger asthma (Henneberger et al., 2014). In this regard, the association with respiratory diseases may vary by green space type. In addition, most studies do not directly compare the health effects between green spaces inside park areas and outside park areas (Akpinar et al., 2016; Lu et al., 2018; Markevych et al., 2017; Reid et al., 2017). This is an important knowledge gap because parks are accessible to the public and provide fresh air for exercise and social gatherings (McCormack et al., 2010), suggesting that parks may have greater impacts on respiratory health than private green spaces. Green space outside parks, such as trees along the urban street, may increase air pollutant concentrations (Jeanjean et al., 2017; Vos et al., 2013), thus increasing the risk of respiratory disease (Eguiluz-Gracia et al., 2020; Jeanjean et al., 2017).

Third, these measures equate the total green space within an administrative or buffer boundary to the population's actual exposure, which assumes people have equal exposure to green space over space (Song et al., 2018). They failed to consider the spatial relation and accessibility between green space and human population and population density (Yang et al., 2022; Jiang et al., 2022). These factors significantly impact the health effects of green space (Coombes et al., 2010; Irvine et al., 2013; Sugiyama et al., 2014). Recent studies applying the population-weighted exposure model have shown that green space coverage measures overestimate or underestimate actual human exposure to green space (Song et al.,2021; Chen et al., 2022).

1.3. Research question

To address these critical gaps, we investigated the relationship between various types of green space and COPD and asthma prevalence in the 69,804 tracts in the contiguous United States using population-weighted green space measures across four urbanicity levels. We ask the following two questions:

(1) How does population-weighted green space exposure impact the prevalence of COPD and asthma?
(2) How does population-weighted green space exposure impact the prevalence of COPD and asthma across four levels of urbanicity?

2. Method

We used an ecological, cross-sectional study design at the census tract level. We use tract as the unit of analysis in this study because it is more granular than county, the scale that most previous nationwide studies used (Becker et al., 2022; Heo & Bell, 2019). Census tracts are subdivisions within a county with an optimal population of 4000, and there are approximately 73,666 tracts in the US (Census bureau (2022)). We collected COPD and asthma prevalence data, socio-economic and demographic data, behavioral data, and environmental data at the tract level in the contiguous United States (see definition and data source in Table S1). The green space exposure was estimated in the Google Earth Engine (GEE) platform. The number of tracts for which all variables were available was 69,804.

2.1. Data

2.1.1. COPD and asthma prevalence

Data on COPD and asthma prevalence was retrieved from the PLACES: Local Data for Better Health dataset provided by the Centers for Disease Control and Prevention (CDC), Division of Population Health, Epidemiology and Surveillance Branch. The prevalence of COPD is defined as the number of adults (≥18 years) whom a health professional diagnosed to have a chronic obstructive pulmonary disease, emphysema, or chronic bronchitis per 100,000 population. The prevalence of asthma is defined as the number of adults whom a health professional diagnosed to have asthma per 100,000 population (CDC, 2021) (Fig. 1).

2.1.2. Green space

We applied population-weighted model to estimate green space exposure within an 800 m buffer distance from human settlements as a proxy for residential exposure to green space in GEE. We extracted four natural land covers using the *National Land Cover Database* (NLCD) 2016 Landsat imagery (30 m resolution) that have been found to impact respiratory health in previous literature (Aerts et al. (2020); Antonelli et al., 2022; Fan et al., 2020): open space, deciduous forest, evergreen forest, and mixed forest. Forest areas are dominated by tree cover, and open spaces are planting areas in developed settings (NLCD, 2016). We combined the three types of forest (deciduous, evergreen, and mixed forests) into a single “forest” land cover. Landsat at 30 m is a common though relatively coarse resolution for environmental health studies (Akpinar et al., 2016; Klompmaker et al., 2022). However, this resolution provides a comprehensive classification of land cover for a nationwide study encompassing cities, small towns, and rural areas. While a finer resolution (e.g., 1 m) may capture smaller green spaces in cities and urban settlements that coarser spatial resolutions cannot (Cirino et al., 2022), one study found satellite data of different spatial resolutions did not alter the identified associations between green space metrics and health outcomes (Su et al., 2019).

We used the Environmental Systems Research Institute (ESRI) USA Parks boundary to separate green spaces within parks from green spaces located outside parks, which contains parks in the US at different levels, including national and state parks, county, regional, and local parks (ESRI, 2021). We extracted four green space variables, including open space inside park, open space outside park, forest inside park, and forest outside park. Then, we geolocated the spatial distribution of the US population using the 2019 TIGER census tract shapefile from the Census Bureau and the 2020 WorldPop Dataset (Sorichetta et al., 2015). This dataset provides location and the number of residents in each 100x100m grid (*WorldPop*, 2020). Due to the mismatch of spatial resolution between two datasets, we used the reproject function in GEE to match the 30 m NLCD Landsat imagery to the 100 m spatial resolution of the WorldPop Dataset. The reprojection allowed us to calculate the population-weighted green space exposure within 800 m in each tract using Equation [1] (Chen et al., 2022),

$$FE = \frac{\sum_{i=1}^{N} P_i \times F_i^b}{\sum_{i=1}^{N} P_i} \tag{1}$$

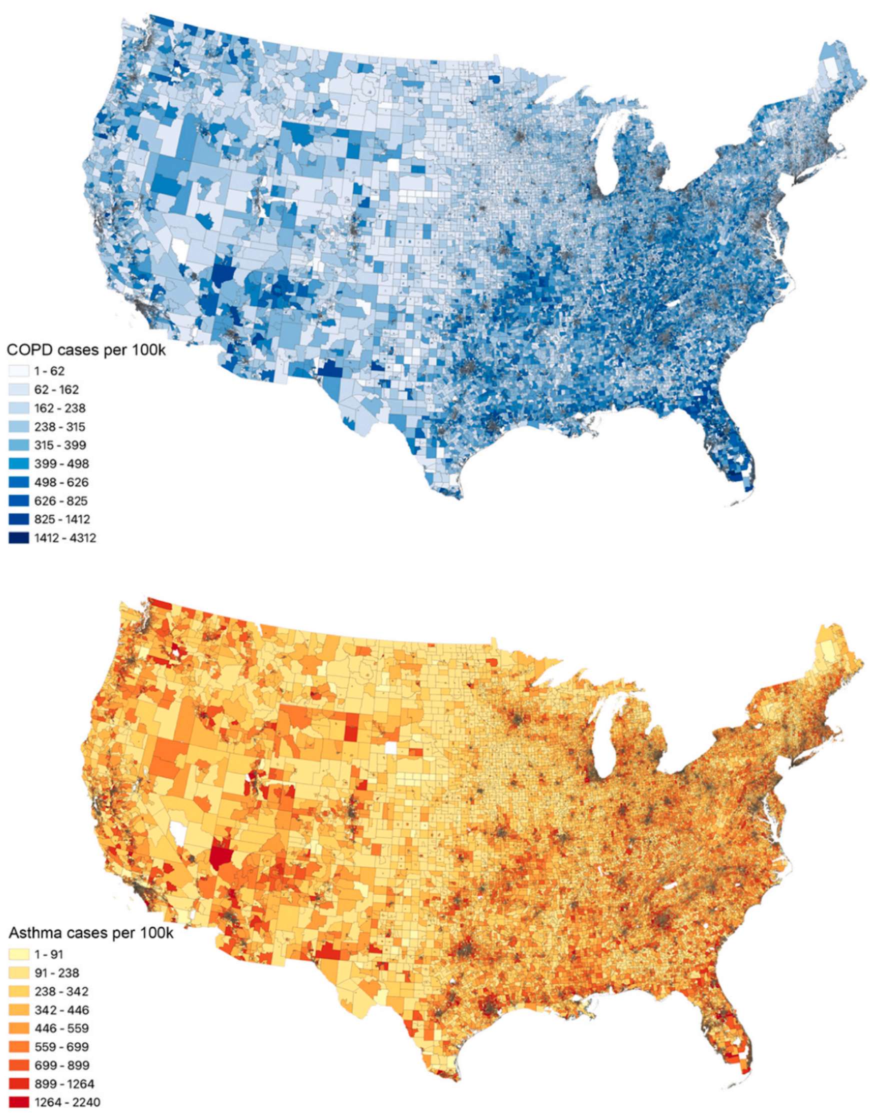

Fig. 1. The prevalence of COPD and asthma (cases per 100,000 population) at tract level in 2019.

where P_i denotes the total number of people in the i^{th} grid, F_i^b represents the green space coverage of the i^{th} grid within a buffer distance of b meters, N represents the total number of grids in a given tract, and FE is the estimated exposure received by the population in the grid they live in and the green space exposure in their neighborhood grids within b meter buffer distance. Greater weighting was given to green space in areas of higher population density. We include grids in the estimation if the centroid of the grid cell is located within the buffer. We selected a buffer distance of 800 m, which includes the acceptable walking distance (0.25 miles or 400 m) in US research and the median walking distance (0.5 miles or 800 m) of US residents (Mueller et al., 2022; Yang & Diez-Roux, 2012).

2.2. Levels of urbanicity

To detect the potential modifying effect of urbanicity, we divided the full dataset into four sub-samples based on the CDC 2010 Rural-Urban Commuting Area (RUCA) Codes, which delineate urbanicity levels based on three types of measures: population density, urbanization, and daily commuting (United States Department of Agriculture (2020)). The classification scheme contains ten primary codes, delineating urbanicity based on the size and direction of commuting flows (See description for each code in Table S2). We grouped all tracts into four subgroups, including highly urbanized tracts (codes 1–3), moderately urbanized tracts (codes 4–6), small towns (codes 7–9), and rural tracts (code 10). Previous studies typically used two levels of urbanicity based on population density or typology schemes and did not provide information to explain the levels (Browning et al., 2022).

2.3. Other covariates

This study included a range of important factors that have been included in previous studies on respiratory diseases, such as socioeconomic and demographic (i.e., income and access to health care) (Eisner et al., 2000; Hossain et al., 2019), behavioral (i.e., smoking and physical inactivity) (Forey et al., 2011; Hylkema et al., 2007; Stapleton et al., 2011), and environmental factors (i.e., air pollution) (Anenberg et al., 2022; Baxi & Phipatanakul, 2010; Guarnieri & Balmes, 2014; Schikowski et al., 2005).

We adjusted the following socioeconomic and demographic factors: population density, median household income, percentage of the urban population, percentage of the population aged 65 and above, percentage of Black, White, and Hispanic population, percentage of the population without a high school diploma, percentage of the population in poverty, percentage of the population unemployed, and percentage of the population with no health insurance. We also controlled for behavioral risk factors, including percentage of the population smoking, percentage of the population binge drinking, percentage of the population physically inactive during leisure time, and percentage of the population with poor sleep.

The adjusted environmental factors include developed intensity and Particular Matter 2.5 ($PM_{2.5}$). We calculated the developed intensity in GEE and collected the $PM_{2.5}$ concentration data from the CDC. By NLCD definition, the low intensity consists of areas with "a mixture of constructed materials (20–49 %) and vegetation" and medium intensity consists of areas with a mixture of constructed materials (50–79 %) and vegetation". Low and medium intensity are most likely areas with single-family housing units. Whereas high intensity refers to "a mixture of constructed materials (80–100 %) and vegetation in areas with high population density", usually include areas such as "apartment complexes, row houses, commercial, and industrial land uses." The definition and data source for all covariates is in Table S1.

2.4. Statistical analysis

This study conducted two sets of analyses to evaluate the associations between green space and COPD and asthma prevalence using negative binomial mixed-effect models and spatial error models. Due to overdispersion, the negative binomial mixed-effect models fit our over-dispersed count data (COPD and asthma prevalence). This model requires count data for the dependent variable, thus, we rounded the prevalence of COPD and asthma to the nearest whole number. The Intraclass Correlation Coefficient was 0.17 for COPD and 0.08 for asthma, indicating that a 17 % and 8 % variation in tract-level COPD and asthma were due to the clustering structure of our data. Thus, we included state as a random effect in our analyses to account for state-level variability. We used Moran's I test to confirm whether spatial autocorrelation exists in our model residuals. The presence of spatial autocorrelation in all our models indicates that associations between green space and the prevalence of respiratory disease may further depend on location. Thus, the results of negative binomial mixed-effect models were not included here (see Table S3-S5).

To address spatial autocorrelation in our non-spatial models, we fitted spatially explicit models to generate more robust estimates of the coefficients. Prior research employed conventional models like linear or multi-level regression could not account for the dependence or autocorrelation of geospatial data and may underestimate error (Anselin (2001)). The spatial error model (SEM) assumes that neighbors' impact occurs at residuals rather than the data structure of variables (Golgher & Voss, 2016). The SEM accounts for spatial dependence by adding a spatial-error parameter (λ) in the model. We used the queen's contiguity for the spatial weight matrix. After that, a variance-covariance matrix based on the spatial weight matrix is used to model the spatial dependence of a location.

$$MWB_i = \beta_0 + \beta_1 GS_{1i} + \dots \beta_m x_{mi} + u_i \quad for \quad i = 1, \dots, n \tag{2}$$

$$u_i = \lambda W_u + \varepsilon_i \quad |\lambda| \quad \leq 1 \tag{3}$$

Equation [2] represents an SEM regression, which includes additional residual term u_i compared to a linear model. MWB_i denotes the prevalence of respiratory disease (COPD and asthma) in tract i, β_0 is the calculated constant, β_1 is the green space coefficient, GS_{1i} denotes the green space exposure of the tract i, and $\beta_m x_{mi}$ represents the contribution of the covariates. The residual term u_i is calculated using Equation [3] with the spatial-error parameter λ (degree of the spatial autocorrelation), the weighted matrix of nearest neighbors W, and the random error ε_i. This term estimates the effects of "noise", or unknown factors that were not included in our models (Yang et al., 2011).

We used the SEM to examine the associations between population-weighted exposure to forest and open space (inside and outside park) within 800 m and the prevalence of COPD and asthma; then, we examined such associations across four levels of urbanicity using separate models. We reported estimate coefficient (β) and significance level (p), model λ, explanatory power (pseudo-R^2), and Akaike Information Criterion (AIC). We also conducted additional sensitivity analyses to confirm the robustness of our results from the SEMs. First, we tested another measure of green space, the ratio of four types of green space, which was calculated as the total coverage of green space over the land area (see results in Table S6). Second, we evaluated the associations using population-weighted green space exposure from 100 m to 1 km buffer distances (see results in Tables S7 & S8). Each explanatory variable was scaled and centered. Variables having a variance inflation factor (VIF) equal to or larger than 4 were removed from our models since they were shown to be multicollinear (O'Brien, 2007). The package 'spdep' was used to run Moran's I test and spatial error models, and package 'lme4' was used to run negative binomial mixed effect models (Bivand and Wong, 2018). We performed all analyses using R v.4.1.3. (R Core Team, 2013).

3. Results

3.1. Descriptive analysis

The characteristics of the 69,804 tracts in the study are presented in Table 1. The average prevalence of COPD was 262 cases per 100,000 population and 147 cases per 100,000 population for asthma in 2019. The average population-weighted exposure within an 800 m buffer distance from the human settlement was 90.24 m^2 for forest inside park, 1103.58 m^2 for forest outside park, 75.88 m^2 for open space inside park, and 1439.75 m^2 for open space outside park at the tract level. Fig. S1 shows the correlation coefficients between all variables. The correlation of forest inside park, forest outside park, open space inside park, open space outside park with COPD prevalence were 0.01 ($p < 0.05$), 0.19 ($p < 0.05$), –0.12 ($p < 0.05$), 0.10 ($p < 0.05$), respectively; correlation with asthma prevalence was –0.05 ($p < 0.05$), 0.03 ($p < 0.05$), –0.07 ($p < 0.05$), 0.09 ($p < 0.05$), respectively.

3.2. Main analyses

3.2.1. Associations between green spaces and COPD and asthma

Table 2 shows the results of SEM that examined the association between green spaces and the prevalence of COPD and asthma. After adjusting for covariates, forest inside park and open space inside park within 800 m were associated with a lower prevalence of COPD and asthma. We found that an increase of 1 m^2 exposure to forest inside park was associated with a decrease of 3.57 and 2.97 cases per 100,000 population in COPD and asthma, respectively; an increase of 1 m^2 exposure to open space inside park was associated with a decrease of 4.82 and 7.66 cases per 100,000 population in COPD and asthma, respectively. In contrast, exposure to forest outside park and open space outside park within 800 m were associated with a higher prevalence of COPD and asthma. We found an increase of 1 m^2 exposure to forest outside park was associated with an increase of 9.96 and 11.03 cases per 100,000 population in COPD and asthma, respectively; an increase of 1 m^2 exposure to open space outside park was associated with an increase of 13.87 and 16.96 cases per 100,000 population in COPD and asthma, respectively.

3.2.2. Effect modification by urbanicity

In Fig. 2 we present the associations between residential exposure to various types of green space (800 m buffer) and prevalence of COPD and asthma stratified by four levels of urbanicity. The associations were significantly modified by urbanicity: the beneficial associations remained significant in highly urbanized tracts and diminished in the three less-urbanized tracts.

In highly urbanized tracts (n = 56,924), we found that an increase of 1 m^2 exposure to forest inside park was associated with a decrease of 5.42 and 5.79 cases per 100,000 population in COPD and asthma, respectively; an increase of 1 m^2 exposure to open space inside park was associated with a decrease of 7.51 and 12.60 cases per 100,000 population in COPD and asthma, respectively. In moderately urbanized tracts (n = 6494) and small towns (n = 3299), green spaces inside parks were insignificant, and green spaces outside parks were associated with higher COPD and asthma prevalence. In rural tracts (n = 3087), forest inside park was insignificant, and other green spaces were associated with higher COPD and asthma prevalence.

4. Discussion

In this nationwide ecological study, we found that forest and open space, especially those inside parks, were associated with a lower prevalence of COPD and asthma; and unexpectedly, those outside parks were associated with a higher prevalence of COPD and asthma. Moreover, the stratified analyses suggest that the beneficial association between green space and respiratory diseases remained in highly urbanized tracts but diminished in the three less-urbanized tracts. The validity of our findings is supported by the consistent results in analyses using different types of green space measures (ratio and popualation-weighted exposure) and different buffer distances (100 m to 1 km). We interpret our findings and discuss potential implications in the following sections.

Table 1
Descriptive statistics for chronic obstructive pulmonary disease, asthma, green space exposure, and all covariates for 69,804 tracts.

Variable Categories	Variables	Min	Max	Mean	SD	Unit
Respiratory diseases	Chronic obstructive pulmonary disease	0.58	4312.22	261.50	132.31	Cases per 100k
	Asthma	0.34	1996.40	147.42	75.71	Cases per100k
Socioeconomic and demographic factors	Population density	0.09	552,750.00	5351.50	120,45.37	Persons per square mile
	Median household income	0.00	250,001.00	66,071.57	33,206.14	USD$
	Urban population	0.00	100.00	69.62	44.04	Percentage
	Population aged 65 and above	0.00	89.37	13.62	7.25	Percentage
	Black non-Hispanic	0.00	100.00	13.54	21.55	Percentage
	White non-Hispanic	0.00	100.00	61.68	29.87	Percentage
	Hispanic	0.00	100.00	16.64	21.52	Percentage
	No high school diploma	0.00	100.00	12.74	10.36	Percentage
	Population with a college degree	0.00	100.00	30.48	19.25	Percentage
	Poverty rate	0.00	100.00	14.75	11.57	Percentage
	Unemployment rate	0.00	100.00	5.79	4.36	Percentage
	Population without insurance	0.00	77.19	8.71	6.87	Percentage
	Median age	0.00	82.80	39.59	7.83	Years
Behavioral factors	Leisure time physical inactivity	9.30	65.60	27.76	8.13	Percentage
	Smoking	3.20	52.10	17.99	5.77	Percentage
	Binge drinking	2.80	42.20	17.60	3.45	Percentage
	Poor sleep	20.20	60.80	36.71	5.22	Percentage
Air pollution	$PM_{2.5}$	3.04	14.87	8.26	1.56	Ug/m^3
Developed intensity	Low built-up intensity	0.00	8558.85	2387.59	1535.94	m^2
	Medium built-up intensity	0.00	8694.00	2109.52	1798.70	m^2
	High built-up intensity	0.00	9560.28	892.92	1385.52	m^2
Green space within 800 m	Forest inside park	0.00	8841.70	90.24	463.43	m^2
	Forest outside park	0.00	9076.38	1103.58	1629.58	m^2
	Open space inside park	0.00	5400.54	75.88	177.18	m^2
	Open space outside park	0.00	7549.21	1439.75	1074.39	m^2

Table 2
Results of spatial error model of all variables and prevalence of COPD and asthma.

Variables		COPD		Asthma	
		Estimate	*p* value	Estimate	*p* value
Socioeconomic and demographic variables	Population density	20.26 ***	<0.0001	37.27 ***	<0.0001
	Median household income	–11.24 ***	<0.0001	5.28 ***	<0.0001
	Urban population	–7.06 ***	<0.0001	8.61 ***	<0.0001
	Population aged 65 and above	15.99 ***	<0.0001	–12.37 ***	<0.0001
	Hispanic	–12.38 ***	<0.0001	7.88 ***	<0.0001
	Black non-Hispanic	–11.39 ***	<0.0001	3.98 *	0.004
	No high school diploma	24.95 ***	<0.0001	1.27	0.407
	Poverty rate	5.56 ***	<0.0001	–6.14 ***	<0.0001
	Unemployment rate	–1.47	0.029	–2.47 *	0.008
	Without health insurance	4.08 ***	<0.0001	-6.53 ***	<0.0001
	Median age	–34.18 ***	<0.0001	–60.85 ***	<0.0001
Behavioral variables	Binge drinking	–30.92 ***	<0.0001	–14.53 ***	<0.0001
Environmental variables	$PM_{2.5}$	–0.78	0.502	–12.36 ***	<0.0001
	Low developed intensity	1.23	0.232	–8.89 ***	<0.0001
	Medium developed intensity	–5.10 ***	<0.0001	8.39 ***	<0.0001
	High developed intensity	–34.46 ***	<0.0001	–52.30 ***	<0.0001
Green space variables	Forest inside park	–3.57 ***	<0.0001	–2.97 *	0.005
	Forest outside park	9.96 ***	<0.0001	11.03 ***	<0.0001
	Open space inside park	–4.82 ***	<0.0001	–7.66 ***	<0.0001
	Open space outside park	13.87 ***	<0.0001	16.96 ***	<0.0001
	Model pseudo-R^2	0.33		0.24	
	Model λ	0.54	<0.05	0.48	<0.05
	Model AIC	882,740		928,340	

Note: the ‘Estimate’ values are the change in cases per 100k population of COPD and asthma associated with each variable; * indicates p < 0.01, ** indicates p < 0.001, *** indicates p < 0.0001.

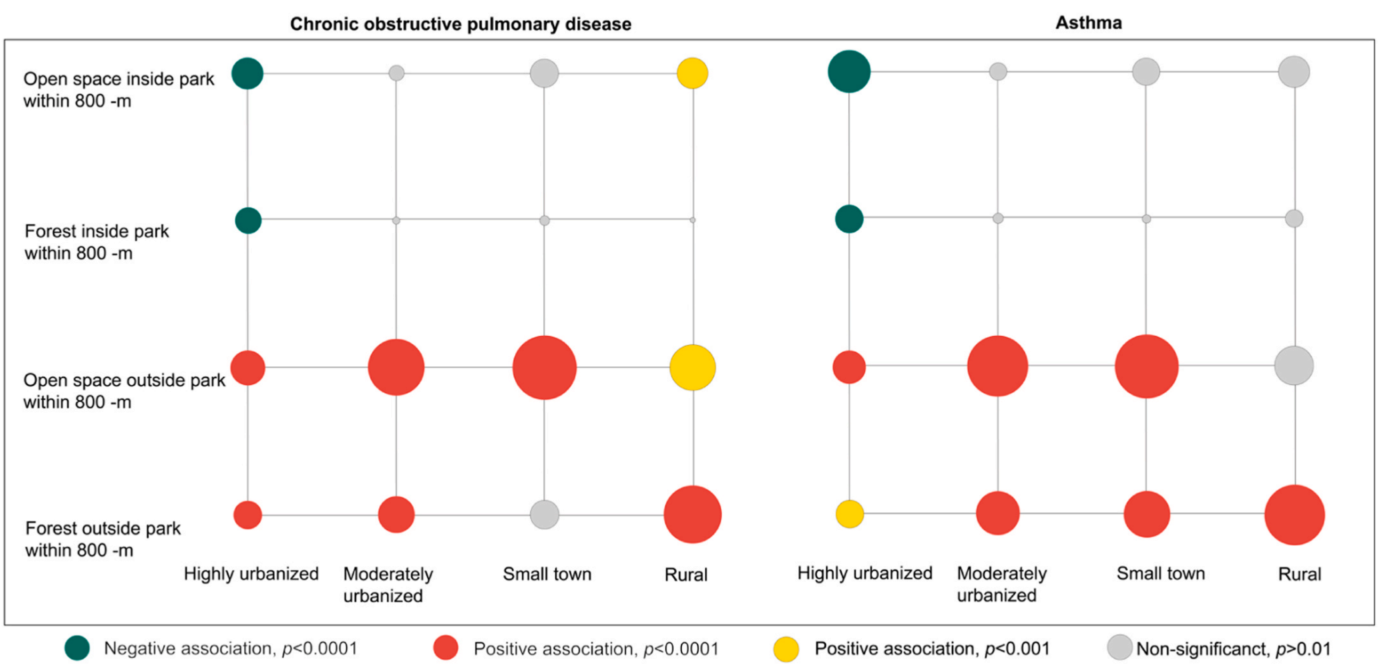

Fig. 2. The beneficial associations of green spaces inside park within walking distance (800 m) remain significant in highly urbanized tracts and diminish in the three less-urbanized tracts. A negative (positive) association means a higher (lower) level of green space is associated with a lower COPD or asthma prevalence. The size of the circles indicates estimate coefficient.

4.1. Interpretation of main findings

4.1.1. Association between green spaces and prevalence of COPD and asthma

Our study first revealed that there were different patterns of health benefits and risks associated with the four different types of green space. Green spaces inside parks, but not outside parks, were associated with a lower prevalence of COPD and asthma, providing important evidence on the impacts of green space by location. The beneficial associations align with earlier findings of green space and respiratory disease outcomes, i. e., more public parks and open space were associated with lower asthma emergency department visits (Douglas et al., 2019; Klompmaker et al., 2022). Although no previous studies have directly compared the effect of green spaces inside and outside parks, the detrimental associations of green space outside parks echo with a study using US Medicare cohort respiratory disease hospitalization data. They found public parks were associated with lower respiratory hospitalization, but green space measures that included green space outside parks were associated with higher respiratory disease hospitalization (Klompmaker et al., 2022). This adverse association is also consistent with other studies that found that residential exposure to forests was associated with a higher risk of respiratory diseases (Parmes et al., 2020; Stas et al., 2021; Cirino et al., 2022).

We explain plausible mechanisms underlying the observed associations and possible reasons for the advantage of green spaces inside park below. The beneficial associations between green space and COPD and asthma prevalence point to green spaces' potential mitigating effect on air pollution, psychological stress and increased exposure to the environmental microbiome. Previous studies found exposure to air pollutants (Li et al., 2016; Zhang et al., 2016), chronic stress (Chen & Miller, 2007; Strzelak et al., 2018; Zuo et al., 2014), and unhealthy microbe composition increased risk of respiratory diseases (Dadvand et al. (2014); Pope et al., 2004; Zhao et al., 2019). There is abundant evidence that green spaces such as forests play a significant role in reducing air pollutants (e.g., particulate matter, NO_2, and ozone) (Nowak et al., 2018; Selmi et al., 2016) and psychological stress (Jiang et al., 2014; Markevych et al., 2017; Yonas et al., 2012). Exposure to green spaces may also impact COPD and asthma by affecting the human nose and respiratory tract microbial composition (Ruokolainen et al., 2017; Selway et al., 2020).

The observed detrimental effect of forest outside park on COPD and asthma prevalence could point to increased exposure to allergic substances. Plants, like birch and hornbeam trees, can emit allergenic pollens into the air, which may activate allergy symptoms (Batra et al., 2022; Guilbert et al., 2018; Idrose et al., 2020). Moreover, experiments in lab and field settings suggest that pollen may bind with fine particles in polluted areas and become concentrated (Motta et al., 2006; Plaza et al., 2020). This suggests that the impacts of green space accessibility on respiratory disease are mixed: while the supply of green space near residents can facilitate physical activity and improve air quality to make neighborhoods healthier, it also can increase the risk of allergies (Cirino et al., 2022; Parmes et al., 2020; Stas et al., 2021). Further, urban forests, especially those not within parks like street trees, may increase air pollution levels in some street canyon configurations (Abhijith et al., 2017; Salmond et al., 2013).

The advantage of green spaces in parks may be attributable to higher usage frequency and longer stays, better maintenance, and better air quality in parks. Parks, as designated places to accommodate recreational uses, are often publicly accessible, well-designed with facilities (i.e., open lawns, lighting, sports field), and well-maintained (Hong et al., 2018; Lee & Maheswaran, 2010; Schipperijn et al., 2013). These characteristics lead to more frequent contact with green space and longer stays (Coombes et al., 2010; Ekkel and de Vries, 2017), therefore reducing the "extinction of experience," which refers to the loss of daily interactions with natural environments (Soga & Gaston, 2016; Soga et al., 2016). A previous study reported that the acceptable walking distance in the US was 0.25 miles (400 m), though people walked longer if the trip was for recreational purposes (Yang & Diez-Roux, 2012). Therefore, within walking distance of 800 m (exceeds 400 m), parks are more likely to be visited than other non-park green spaces.

Moreover, green spaces outside park areas include unmanaged green spaces or vacant lots. Unmanaged green space and vacant lots have been found to evoke a sense of fear, especially when incivilities and litter present, thus discourage people from visiting (Sivak et al., 2021; Sreetheran and van den Bosch, 2014). Green spaces outside park areas also include vegetation along the streets, and they may not be as effective as parks at reducing air pollution exposure.

Although street trees (canopies) provide a comfortable microclimate for physical activities such as walking and cycling (Lu et al., 2018), dense tree canopies close to the roadway may increase the risk of traffic-related air pollution exposure because it may prevent the dispersion of air pollutants, especially when the wind is parallel to the street canyon (Abhijith et al., 2017; Zhang et al., 2021).

4.1.2. *Effect modification of urbanicity*

Few nationwide studies on green space and the prevalence of COPD and asthma have specifically tested for effect modification by urbanicity. We observed a pronounced beneficial association between green space on COPD and asthma prevalence in highly urbanized subgroups but not in moderately urbanized, small towns and rural subgroups. The finding of the urban advantage of green space is consistent with results of previous studies that examined effect modification of urbanicity (Browning et al., 2022; Vienneau et al., 2017; Fuertes et al., 2016); although we detect detrimental association in less-urbanized tracts. A large cohort study (n = 4284,680) tested the modification effect of urbanicity on residential greenness and respiratory mortality in Switzerland and found that protective effects were stronger in the urban (vs. rural) quartile (Vienneau et al., 2017). Another study using data from seven birth cohorts found evidence for stronger beneficial effects in urban settings (Fuertes et al., 2016). Few studies have explained the heterogeneous health effects of green space across different urbanicity levels. We provide a few possible explanations below.

Urban green spaces are more likely to be visited to confer beneficial health effects than green spaces in less-urbanized areas. A recent study found significantly lower particular matter concentrations were recorded in green space than in non-green space (Niu et al., 2022), which implies that physically being in a green space might provide a protective effect. Urban green spaces tend to be publicly accessible and located closer to the residents than rural green space (Wen et al., 2013). Most rural green spaces tend to be natural landscapes that are often scattered and remote, with minimum human effort in their design, facilities, maintenance, and surveillance (Rasidi et al., 2012; Tzoulas & James, 2010; Zuniga-Teran et al., 2019). In addition, a large portion of rural green spaces are privately owned (i.e., farms and private gardens) (United States Department of Agriculture (2022); Brett, 2008), which limits public access and health benefits to the public.

The mitigation effect of green space on harmful exposures may be more significant and ubiquitous in urban areas compared to less-urbanized areas. The higher traffic volume and proximity to roadways in urban areas (Woghiren-Akinnifesi, 2013) increase residents' exposure to concentrated air pollution (Casey et al., 2017; Strosnider et al., 2017). Studies suggest green spaces have a stronger positive effect on air pollution and respiratory diseases in heavy traffic and air-polluted areas (Feng & Astell-Burt, 2017; Zeng et al., 2020). For instance, a study in England found more trees linked to a lower risk of asthma when NO_2 and $PM_{2.5}$ levels were higher (Alcock et al., 2017). Similarly, trees have been found to have a more significant effect in reducing $PM_{2.5}$ concentration in areas with higher ambient $PM_{2.5}$ levels (Chen et al., 2019).

4.2. *Contributions and implications*

To our best knowledge, this is the first nationwide study that examined the modification effect of urbanicity on the tract-level association between various types of green space and respiratory diseases in the US. The major strengths of this study include large geographical scope and population size, diverse environmental heterogeneity, advanced green space exposure assessment and spatial statistics, and adjustment of important covariates. We found that urban but not rural green spaces are tied to a lower risk of respiratory diseases. Unlike most studies that abided by epidemiological research norms, we provided justifications for testing the modification effect of urbanicity. More importantly, we provided plausible mechanistic pathways that drive the differences in the greenspace-respiratory health association across urbanicity, which was lacking in previous studies. Only one review study explained the stronger beneficial effects of green spaces in cities (Browning et al., 2022).

Second, this study compared the impacts of green spaces inside and outside parks on the prevalence of COPD and asthma across urbanicity levels in the contiguous United States. While numerous studies have found green space generally beneficial, these generic findings provided little help to guide policymaking and urban planning. This study moves beyond that generic finding to reveal that urban green spaces, particularly those inside park areas, yielded significant beneficial effects for respiratory diseases. The findings of this study advocate for prioritizing funding for park development in highly urbanized areas, as parks have greater potential to benefit respiratory health by decreasing exposure to air pollution and facilitating physical and social activities. It seems wise to allocate funding to improve rural green space design and accessibility (distance and public accessibility), as many rural green spaces are scattered, remote, and privatized, with limited attention to design. Planners and designers should pay additional attention to street planting design and species selection to avoid increasing air pollution or triggering allergic responses. Reclaiming and reinvigorating vacant green spaces in cities may also be a way to improve respiratory health. As crucial as parks are for respiratory health and other benefits, green spaces outside park areas are likewise valuable. Experimental studies found that vacant lots that were cleaned, landscaped, and well-maintained were associated with better health outcomes for nearby residents (Branas et al., 2011, 2018; Jiang et al., 2018; Sivak et al., 2021). Cities across the United States consist of 16.7 % "vacant land," land that is often overgrown with vegetation and litter (Newman et al., 2016; South et al., 2018). Therefore, urban planning and policies to reclaim and vegetate vacant land may counter the negative association between green space outside park and respiratory health.

The validity of this study is further enhanced by adopting a population-weighted exposure assessment method and controlling for spatial autocorrelation while adjusting for multiple potentially important confounders, such as smoking and physical inactivity. The population-weighted green space exposure measure provides more accurate estimates by considering the geospatial location of green space and the US population and giving greater weighting to areas of larger population density. This new approach attenuates the ecological fallacy to some extent because it does not assume that people are equally exposed to green spaces (Chen et al. (2022)).

4.3. Limitations and future opportunities

We identified limitations of this research, which present opportunities for future studies. First, though a causal association is plausible based on empirical evidence, we identified correlational rather than causal associations due to our ecological study design. The findings based on aggregated tract-level data prevent conclusions to be drawn about individuals. Future studies should use individual-level data or experimental studies to further investigate which types of green space or plant species may be pathogenic for respiratory diseases and the underlying biological pathways. While the effect size of green space variables was not particularly significant, this study's results suggest that green spaces inside park independently and significantly contribute to a lower risk of respiratory disease, even after controlling for a range of covariates. The relatively small effect size may be due to other factors, such as physical activity and air pollution, which may partially explain the beneficial association. Though our study encompasses a large geographical scope and a large demographically heterogeneous population, our results may not be generalizable to populations in Hawaii, Alaska, or other countries.

Second, although we adjusted for a variety of important covariates, such as poverty, smoking, and air pollution, there are other variables that we did not take into account. For instance, we did not take into account medication adherence. Individuals who fail to adhere to asthma treatment may have an increased risk of asthma exacerbations (Engelkes et al., 2015). However, we did control for the percentage of the population without health insurance as a proxy for healthcare availability. We also did not control for occupation. Some occupations are associated with long-term exposure to chemical substances, fumes, and dust, which impact asthma and COPD (Boschetto et al., 2006; Tarlo & Lemiere, 2014). Future studies should account for many other variables that may affect the association between green space and COPD and asthma.

Third, we used a coarse spatial resolution Landsat dataset at 30 m to estimate green space exposure, which provides comprehensive land cover classification but fails to capture smaller green spaces in cities. Future studies could use finer spatial resolution datasets (e.g., sentinel-2 of 10 m and US EPA EnviroAtlas Meter-Scale Urban Land Cover of 1 m) to estimate green space exposure. The population-weighted green space measure provides more accurate estimates by considering how the population might use the green space. However, we did not measure the actual use of these green spaces (Tamosiunas et al., 2014). We did not consider seasonal variations in the prevalence of COPD and asthma and exposure to green space. Acute peaks of aeroallergens in the spring may temporarily increase asthma rates. We focused on different types of green spaces and whether they are located inside or outside park areas in this study. Other studies should focus on the effect of seasonal variations on green space and respiratory disease relationships.

Lastly, we used green space data from 2016 and disease data from 2019. This mismatch between green space exposure and disease data may seem inaccurate. However, urbanization in the United States was slow in the last decade (Mackun et al., 2021), suggesting that land cover, including green land cover, may not change much between 2016 and 2019. It's also worth noting that chronic respiratory diseases usually develop over a long time. Therefore, future research could use green space exposure data even earlier than 2016 to explore the long-term effect of green space on respiratory diseases.

5. Conclusion

This nationwide observational study showed that population-weighted exposure to green spaces inside but not outside parks, in highly urbanized tracts, linked to a lower risk of COPD and asthma. Our findings provided more informative evidence for policymakers and urban planners to consider adding more residential green space, especially parks, in highly urbanized cities; and improve the accessibility, design, and maintenance of rural green space that promotes green space usage. Ensuring residential exposure to green space, particularly green space in parks, may serve as a supportive upstream intervention strategy for improving respiratory health.

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CRediT authorship contribution statement

Yuwen Yang: Conceptualization, Data curation, Methodology, Formal analysis, Validation, Investigation,Writing – Original Draft, Writing – Review & Editing, Visualization, Funding acquisition. **Bin Jiang:** Conceptualization, Methodology, Investigation, Writing – Original Draft, Writing – Review & Editing, Visualization, Supervision, Funding acquisition, Project administration.

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.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.ufug.2023.128149.

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