Where and how to invest in greenspace for optimal health benefits: a systematic review of greenspace morphology and human health relationships

Huaqing Wang, Simin Gholami, Wenyan Xu, Amirhossein Samavatekbatan, Ole Sleipness, Louis G Tassinary

Research on the relationship between greenspace morphology and health is a growing field that informs the spatial design of greenspace to enhance health outcomes. This study reviews the current progress, methodologies, and knowledge gaps in this area. From a database search of 272 940 English articles and 39 053 Chinese articles up to April 18, 2024, we identified 22 and 7 studies on the topic for further evaluation. Predominantly cross-sectional and neighbourhood-scale analyses were conducted using land cover maps ranging from 0·25 to 100 meters in resolution. Six primary characteristics of greenspace morphology have been studied, including size, shape, fragmentation, connectedness, aggregation, and diversity. While associations between greenspace morphology and health outcomes have been observed, both their reliability and generalisability remain suggestive due to ecological study designs and heterogeneity among studies. Future research should prioritise individual-level prospective cohorts and intervention studies. Exploring mechanisms linking greenspace morphology and health, determining optimal map resolution, and distinguishing it from greenness magnitude in statistical analysis is essential. This evidence is crucial for health-promoting greenspace planning and should be routinely integrated into urban epidemiological research.

Lancet Planet Health 2024; 8: e574–87

Department of Landscape Architecture and Environmental Planning, Utah State University, Logan, UT, USA (H Wang PhD, S Gholami MSc, W Xu PhD, A Samavatekbatan MSc, O Sleipness PhD)**; School of Performance, Visualization and Fine Arts, Texas A&M University, College Station, TX, USA** (Prof L G Tassinary PhD JD)

Correspondence to: Huaqing Wang, Department of Landscape Architecture and Environmental Planning, Utah State University, Logan, UT 84322, USA **huaqing.wang@usu.edu**

Introduction

Exposure to greenspace is generally considered to be health beneficial. Experimental studies at the individual level indicate exposure to greenspace contributes to mood and cognitive functions, such as the reduction of stress,[1,2] anxiety,[3] and mental fatigue,[4] and shortened recovery times from surgery.[5] Observational studies, at both individual and population levels, reported that greenspace is associated with reduced risks of mortality and morbidity—ie, mental,[6,7] cardiovascular,[8] and respiratory health.[9] Exposure to greenspace is also associated with physical activity and lower incidents of obesity,[10] diabetes,[11] allergies;[12] and improved immune system function;[13] better pregnancy outcomes;[14] and higher overall quality of life.[15] Additionally, greenspace has been linked to fostering social connections[16,17] and community cohesion.[18]

Studies in this field have primarily focused on assessing the effect of greenspace magnitude or greenness, a construct defined typically as the amount of verdancy or greenspace present.[19] The underlying assumption is that a greater availability of greenspace increases the use of outdoor environments for various activities and mitigates adverse elements, such as air pollution, noise, and heat, which consequently contributes to improved health outcomes.[20] Frequently used metrics for evaluating greenspace magnitude include the percentage of greenspace,[21–23] tree canopy cover,[24–26] normalised difference vegetation index,[27] enhanced vegetation index,[28,29] the number of parks,[30,31] proximity to greenspace,[14,32] and frequency of park visits.[33,34] These studies provide a general understanding that a greener environment is associated with better health. This insight has influenced urban greenspace investment projects leading planners, designers, and policymakers to predominantly focus on increasing vegetated land cover, especially tree canopy cover.

In urban settings, however, the availability of land for greenspace is constrained by the necessity for buildings, infrastructure, and road networks to support daily life. While integrating greenspace is crucial for human wellbeing, it is impractical to convert all available land into green areas. Additionally, it is important to preserve existing large lawns that serve as crucial spaces for physical and social activities, rather than replacing them entirely with initiatives such as widespread tree-planting endeavours solely focused on enhancing the amount of verdancy. Landscape and city planners face considerable challenges in identifying suitable land for greenspace allocation within new community and city planning projects, given the predetermined built densities. Planners typically produce spatial maps to explore alternative land use scenarios. These scenarios inform how the spatial arrangement of urban greenspaces can be modified to improve human health benefits. In cities where vacant lands are either increasingly available or under threat, the results of such research can guide investments for new urban parks.

In this context, a growing field has emerged, which investigates the relationship between greenspace morphology (ie, the spatial arrangement and distribution of greenspaces) and its effect on human health outcomes. Ancient philosophies like Feng Shui from China have emphasised the importance of spatial arrangement and design in physical spaces for thousands of years.[35] Only in the past few decades, however, have scientists started to rigorously test these age-old ideas. Several noteworthy studies illustrate greenspace morphology and its health associations. Census tracts with larger-sized, connected, aggregated, and complex-shaped greenspace morphology are associated with both reduced mortality risk[36] and morbidity risk of non-communicable diseases.[37] These effects hold true even when greenness magnitudes were

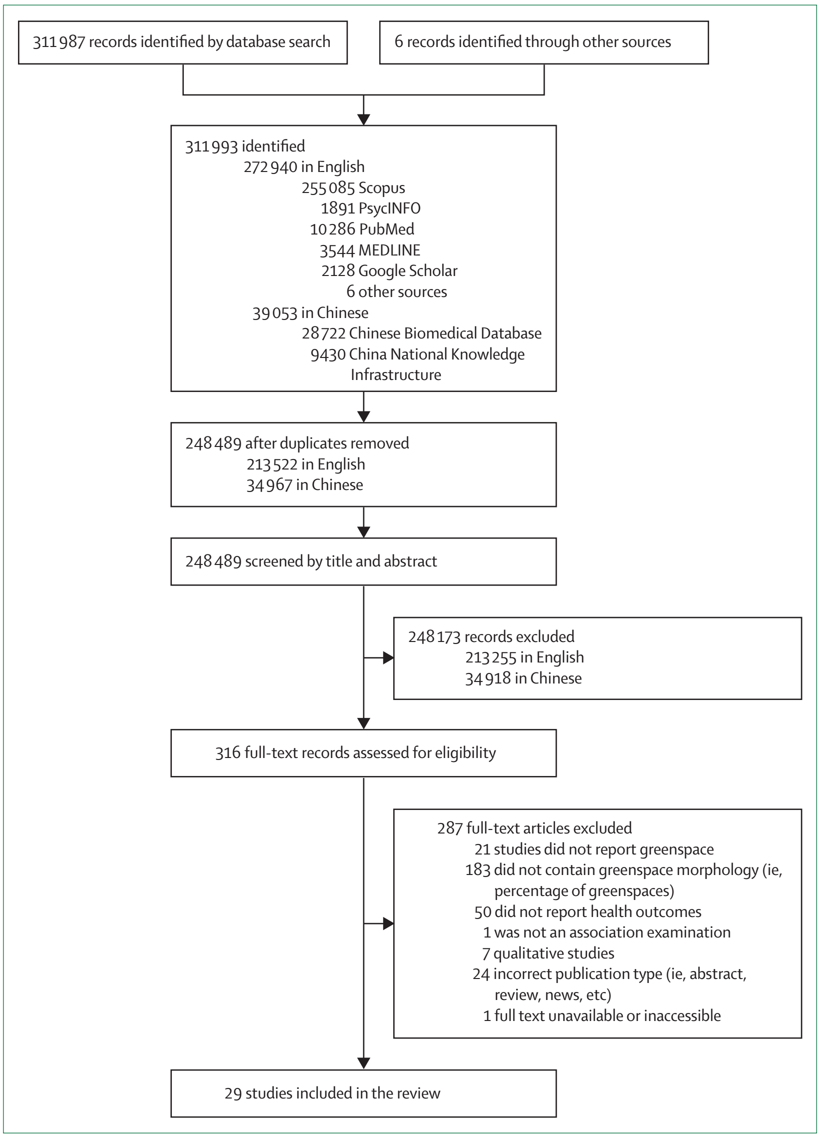

Figure 1: **PRISMA diagram of record retrieval and selection**

See **Online** for appendix

similar. Furthermore, larger parks have been linked to lower levels of chronic illness among older adults.[38] Increased aggregation and connectivity of vegetation-dominated low-intensity developed lands are associated with a reduced risk of death from colon cancer.[39] Conversely, greater distances between shrublands are linked to higher odds of frequent mental distress[40] and a more fragmented greenspace morphology is associated with shorter life expectancy.[41]

For more on **Rayyan** see https://www.rayyan.ai/

Although compelling, it is important to note that these studies were conducted at various spatial scales, used different resolution land cover maps ranging from fine to coarse, used diverse metrics, and explored various health outcomes. Not surprisingly, such varied methodologies have occasionally produced conflicting results. A systematic understanding of the progress made in this field is crucial for informing health-promoting greenspace projects, policy initiatives, and future research endeavours. Analysing the factors that contribute to conflicting conclusions is also essential for establishing a more comprehensive understanding of the topic. To date, we only have a nascent understanding of the underlying mechanisms by which greenspace morphology influences human health. A comprehensive discussion encompassing the current knowledge of these mechanisms, theoretical foundations, and potential future directions will advance our understanding in this field and guide future explorations.

This systematic review concentrates on the nexus between greenspace morphology and human health, a link thus far overlooked in extant literature. Previous reviews have predominantly delved into broad associations between greenspace and health outcomes, encompassing mortality risk,[42–44] obesity,[45] birthweight,[46] and physical wellbeing.[47] However, these reviews have principally focused on the effects of greenspace magnitudes, and studies specifically evaluating greenspace morphology and its effects on human health have been notably absent. Consequently, this study's objectives are to: (1) evaluate the potential health outcomes associated with enhancements in greenspace morphology in the living environment of residents, (2) systematically identify and categorise morphological metrics gleaned from previous investigations, and (3) evaluate the spectrum of variations in study design characteristics. This systematic review explores the potential influences of methodologies, data resolution, spatial scale, and specific metrics on research findings to highlight connections between greenspace morphology and health outcomes.

Methods

We followed the procedures in the PRISMA statement set out by Moher and colleagues (appendix pp 1–3).[48–50] We searched five English databases and three Chinese databases using corresponding Chinese keywords, starting from the very first record in the databases and up to April 18, 2024, for journal articles on greenspace morphology and health relationships. To identify articles, we used three groups of terms to capture greenspace, morphology, and health and a number of specific disease-related keywords (appendix pp 4–10). We also examined the bibliographies of relevant articles and published reviews. Search languages were restricted to English and Chinese.

After deduplication, English article titles and abstracts were reviewed by SG and AS, while WX and HW conducted the same process for Chinese articles. Rayyan, an online platform designed for systematic reviews, facilitated this screening process. Subsequently, full texts of English studies were independently screened by SG, AS, and HW, and Chinese articles screened by WX and HW. The screening was blinded, so the reviewers' decisions were not visible until subsequent discussions.

Later discussions helped minimise ambiguity, resolve conflicts, and clarify further exclusion decisions. To ensure alignment with the emphasis on greenspace morphology and its effects on human health across diverse resident populations, spatial scales, and a wide array of health indicators, a discerning exclusion criterion was applied. We excluded articles that were not human studies, did not explore health outcomes, focused solely on green verdancy without considering greenspace morphology, were not association or causality examinations, were review articles, news, commentaries, abstracts, or policy briefs, were qualitative studies, or had full texts that could not be accessed from databases, university libraries, from the authors, and the publishing journal (appendix pp 11–21).

Data extraction and study quality assessment

Three researchers (SG, AS, and HW) independently extracted data from the included English studies and two investigators (WX and HW) extracted data from the Chinese studies. WX and HW assessed the scientific quality of research independently for all included papers. The following information was obtained from each study according to a predefined plan: title, authors, publication year, study location, sample size, age group, covariates, health outcome assessed, greenspace morphology measures, spatial resolution, spatial analytical unit, spatial scale, and data analysis methods, results, and conclusions. We assessed the scientific quality of the included articles using the Effective Public Health Practice Project (EPHPP) Quality Assessment Tool for Quantitative Studies.[51,52] We chose this tool because it is considered appropriate for observational, cross-sectional, before-and-after studies, and randomised controlled trials, thus aligns well with our selected studies.[51] Additionally, the EPHPP has been extensively used in previous review studies and has documented validity.[53–55] This tool assesses selection bias, study design, confounders, blinding, data collection methods, and withdrawals and dropouts. Each component is rated as either strong, moderate, or weak. Findings were compared for consistency, with disparities addressed with discussions. Data synthesis was performed after data extraction and quality rating. Meta-analysis was not possible due to heterogeneity in methods, greenspace metrics, and health outcomes examined in the studies. Consequently, we conducted a thematic analysis of the included studies.

Results

The initial search identified 311 993 articles, of which 63 504 (20·4%) were duplicates, leaving 248 489 (79·6%) records that were screened by title and abstract for relevance. Of these, 248 173 (99·9%) were excluded, resulting in 316 (0·1%) being considered for full-text review to be assessed for eligibility. 287 (90·8%) of these 316 articles were excluded due to not meeting the inclusion criteria (the reason for each article is detailed in appendix pp 11–21). The remaining 29 (9·2%) articles were included in the final synthesis (figure 1; table).

Although databases were searched from the very first record, the first greenspace morphology and health study was published in 2014, with subsequent increases in the number of studies. Among the 29 identified articles (22 in English and seven in Chinese), 23 (79·3%) are cross-sectional and six (20·7%) are longitudinal studies. Regarding the geographic locations of the studies (panel; table), eight (27·6%) studies were conducted in the USA. 13 (44·8%) studies, including seven in English and six in Chinese, were conducted in mainland China. Five (17·2%) studies were conducted in Taiwan and one (3·4%) study was conducted in the UK[38] and one in Iran.[64] For article quality assessment (figure 2; appendix pp 22–23), two (6·9%) studies were classified as strong, 16 (55·2%) were classified as moderate, and 11 (37·9%) were categorised as weak. The quality of the included articles varied depending on the aspects assessed. For example, 23 (79·3%) of the studies used a cross-sectional study design, which is considered weak for establishing causal inference, and were not suitable for evaluating withdrawals and dropouts. Most of the studies, however, used secondary data from reliable sources covering the entire study area, which resulted in high scores for blinding, data collection methods, and caused selection bias. Approximately one-third of the studies effectively controlled for confounding variables, including sociodemographic, geographical, and other confounders related to examined health outcomes. Unfortunately, most of the Chinese studies only tested correlations without considering confounders, and many others struggled to include known confounders due to data unavailability. Regarding participant age groups, three (10·3%) studies focus on children[56,77,78] and two (6·9%) articles examined older adults.[67,69] 22 (75·9%) studies focused on adult health (table). Six different groups of greenspace morphology characteristics were analysed, including 18 (62·1%) of 29 studies assessing for aggregation, 22 (75·9%) for size, 18 (62·1%) for shape, 17 (58·6%) for fragmentation, 13 (44·8%) for connectedness, and 12 (41·4%) for diversity. Greenspace morphology is associated with mental health, cardiovascular health, respiratory health, liver health, colon health, diabetes, myopia, allergic rhinitis, life satisfaction, life expectancy, frailty, BMI, and physical activity (table; panel).

Common greenspace morphology metrics and data processing information

Figure 3 presents the frequency of metrics that shows statistically significant associations with health. To capture greenspace size, the mean patch area was commonly used in 14 (48·3%) of the 29 studies, followed by the largest patch index in 11 (37·9%) studies. For assessing the shape of greenspaces, the shape index was the

	Country	Sample size (analytical units, n)	Analytical unit of greenspace morphology metrics	Map source for greenspace morphology measures	Map resolution	Study design	Morphological characters examined	Specific metrics analysed (direction of effect)*	Health outcomes	Participants
Kim et al (2014)[56]	USA	61	Half-mile buffer surrounding an individual's home address	Satellite imagery: digital orthophoto quarter quadrangles	1 m	Cross-sectional	Shape, aggregation, and connectedness	Shape index (NS); nearest-neighbour distance (NS); cohesion index (–)	BMI	Children
Shen and Lung (2016)[57]	Taiwan	48	Administrative districts	Land use map: NLCD	50 m	Cross-sectional	Size, aggregation, and fragmentation	Aggregation index (NS); percentage of like adjacencies (NS); patch density (+); largest patch index (–); nearest-neighbour distance (+)	Cardiovascular mortality	Adults
Shen and Lung (2017)[58]	Taiwan	48	Administrative districts	Land use map: national land-use survey	Unknown	Cross-sectional	Size, aggregation, and fragmentation	Aggregation index (NS); percentage of like adjacencies (NS); patch density (+); nearest-neighbour distance (NS); largest patch index (–)	Respiratory mortality	Adults
Tan et al (2018)[59]†	China	57	Subdistrict (Jiedao)	Land use map of Shenzhen City in 2010	Unknown	Ecological study	Aggregation and fragmentation	Splitting index (+); patch density (+)	Pneumonia incidence	Adults
Tsai et al (2018)[40]	USA	276	County	Land cover map: NLCD	30 m	Cross-sectional	Size, shape, aggregation, connectedness, fragmentation, and diversity	Edge contrast index of forest (–); nearest-neighbour distance of shrub (+); cohesion index of shrub (+); mean patch area of shrub (NS); patch density of herbaceous (NS)	Frequent mental distress	Adults
Wang et al (2018)[60]†	China	202	Residents committee	Land use data of Shanghai City in 2011	Unknown	Ecological study	Size and fragmentation	Patch density (+); largest patch index (–)	Incidence of lung cancer	Adults
Wang et al (2018)[61]†	China	139	Residents committee	Greenspace vegetation database surveyed by the authors	Unknown	Ecological study	Size and fragmentation	Patch density (NS); largest patch index (NS)	Incidence of lung cancer	Adults
Mears et al (2019)[62]	UK	345	Lower-layer super-output areas	National Land Use Database	2 m	Cross-sectional	Shape, aggregation, connectedness, fragmentation, and diversity	Shape index (NS); splitting index (+); contiguity index (NS); patch density (NS); Shannon diversity index (NS)	Self-reported general health	Adults
Tsai et al (2019)[41]	USA	55	Community statistical area	Land cover map: classified from National Agriculture Imagery Program satellite imagery in a previous study	1 m, 10 m, 30 m	Cross-sectional	Size, shape, fragmentation, connectedness, and diversity	For 1 m: mean patch area (NS), patch density (NS), edge density (+), edge contrast (NS), nearest-neighbour distance (+); for 10 m: patch density (NS), edge density (+), cohesion index (NS); for 30 m: mean patch area (NS), patch density (NS), edge density (+), cohesion index (NS)	Life expectancy	Unknown
Wang and Tassinary (2019)[36]	USA	369	Census tract	Land cover map: Pennsylvania Spatial Data Access	1 m	Cross-sectional	Size, shape, aggregation, connectedness, and fragmentation	Mean patch area (–); shape index (–); aggregation index (–); cohesion index (–); patch density (+)	All-cause and mortality of heart disease, chronic lower respiratory diseases, and neoplasms	Adults

(Table continues on next page)

	Country	Sample size (analytical units, n)	Analytical unit of greenspace morphology metrics	Map source for greenspace morphology measures	Map resolution	Study design	Morphological characters examined	Specific metrics analysed (direction of effect)*	Health outcomes	Participants
(Continued from previous page)										
Chang et al (2020)[63]	Taiwan	3823 from 349 townships	Townships	Land use map: national land survey database	0·25 m	Longitudinal	Size, aggregation, connectedness, shape, and diversity	Mean patch area (–); contiguity index (–); aggregation index (–); contagion index (–); edge contrast (+); edge density (–); perimeter–area ratio (–)	Schizophrenia incidence	Adults
Dennis et al (2020)[38]	UK	1673	Lower super-output areas	Land cover or use map: integrated landscape map	10 m	Cross-sectional	Size and diversity	Mean patch area (–); Shannon diversity index (–)	Chronic morbidity	Adults
Jaafari et al (2020)[64]	Iran	87	Hexagon (10 km^2 each)	Green area map	10 m	Cross-sectional	Shape, connectedness, and fragmentation	Cohesion index (–); patch density (–); shape index (NS); total edge (+)	Respiratory mortality	Adults
Yeh et al (2020)[65]	Taiwan	37	Administrative districts	Land use map: national land-use survey	30 m	Cross-sectional	Shape, aggregation, and connectedness	Shape index (–); nearest-neighbour distance (+); cohesion index (NS)	Number of ambulatory cares for cardiovascular, mental, and chronic respiratory diseases	Adults
Chang et al (2021)[66]	Taiwan	1 907 776 from 358 townships	Townships	Land use map: national land survey database	0·25 m	Longitudinal	Size, shape, and aggregation	Mean patch area (–); largest patch index (–); mean fractal dimension index (+); perimeter–area ratio (+); proximity index (–); mean similarity index (–)	Incidence of bipolar disorder	Adults
He et al (2021)[67]	China	12 999 from an unknown number of counties	County	Land cover map: derived from advanced land observing satellite research and application project	100 m	Longitudinal	Size and shape	Largest patch index (–); perimeter–area ratio (–)	All-cause mortality	Older adults
Wiese et al (2021)[39]	USA	3949 from an unknown number of census tracts	Census tract	Land cover map: NLCD	30 m	Longitudinal	Connectedness and diversity	Forest contiguity index (–); Shannon diversity index (NS)	Colon cancer survival	Adults
Ha et al (2022)[68]	USA	61	Community	Land cover map: high-resolution land cover	1 m	Cross-sectional	Size, aggregation, and diversity	Mean patch area (NS); nearest-neighbour distance (+); clumpy index (+); Shannon diversity index (NS)	Psychological distress	Adults
He et al (2022)[69]	China	8776 from an unknown number of counties	County	Satellite imagery: advanced land observing satellite	100 m	Longitudinal	Size, shape, and connectedness	Largest patch index (–); shape index (–); cohesion index (–)	Frailty	Older adults
Kong et al (2022)[70]	China	55 441 data of park visitors from 99 urban parks	Urban park	High-resolution remote sensing data	0·5 m	Cross-sectional	Size, shape, fragmentation, and diversity	Mean patch area of forest (+); patch density of park (NS); shape index of park (NS); Shannon diversity index of park (NS)	Positive emotions	Unknown
Xie et al (2022)[71]†	China	228	County	Terra moderate resolution imaging spectroradiometer vegetation indices (MOD13Q1)	250 m	Ecological study	Size, shape, aggregation, fragmentation, and diversity	Mean patch area (–); largest patch index (+ for different regions); shape index (+); aggregation index (+ for different regions); patch density (–); Shannon diversity index (+)	Incidence of lung cancer	Adults

(Table continues on next page)

	Country	Sample size (analytical units, n)	Analytical unit of greenspace morphology metrics	Map source for greenspace morphology measures	Map resolution	Study design	Morphological characters examined	Specific metrics analysed (direction of effect)*	Health outcomes	Participants
(Continued from previous page)										
Leng et al (2023)[72]†	China	228 from residential communities (Xiaoqu)	1000 m buffer surrounding a residential centre	Land cover map: NLCD (Landsat 8.0)	30 m	Ecological study	Size	Mean patch area (NS)	Incidence of cardiovascular diseases	Adults
Shao (2023)[73]†	China	848 students from 18 university campuses	University campus	Land cover map: NLCD (Landsat 8.0)	30 m	Cross-sectional	Shape	Perimeter–area ratio (–)	Poor mental health	College students
Wang et al (2023)[74]†	USA	536 residents from 13 census blocks	Census block	Land cover map: NLCD	30 m	Cross-sectional	Size, aggregation, and diversity	Shannon diversity index (NS); nearest-neighbour distance (+ for different statistical models); mean patch area (+ for different statistical models)	Non-communicable diseases	Adults
Wang et al (2023)[75]	China	773 from 85 urban communities	3 km buffer around the urban communities	The first 10 m resolution global land cover map	10 m	Cross-sectional	Size, shape, aggregation, fragmentation, and diversity	Largest patch index (NS); mean fractal dimension index (NS); shape index (NS); aggregation index (+); patch density (NS); Shannon diversity index (+)	Wellbeing	Adults
Wu and Chen (2023)[76]	China	60	3 km buffer around the centroid of the township*	Global Forest Change 2000–2015 project (version 1.3)	30 m	Cross-sectional	Size, aggregation, fragmentation, and diversity	Largest patch index (NS); percentage of like adjacencies (NS); aggregation index (NS); patch density (–); patch richness (+)	Life satisfaction	Adults
Chen et al (2024)[77]	China	36 867 preschool children	1000 m radius buffers around participants' residences	Finer Resolution Observation and Monitoring of Global Land Cover	10 m	Cross-sectional	Size, shape, aggregation , connectedness, and fragmentation	Aggregation index of forest (–); cohesion index of forest (–); patch density (+); mean patch size (NS); shape index (NS)	Allergic rhinitis	Children age 3–6 years
Wang and Tassinary (2024)[37]	USA	984 Los Angeles, 256 San Antonio, 498 Miami, 241 Seattle, 2101 New York City	Census tract	Satellite imagery: National Agriculture Imagery Program	1 m	Cross-sectional	Size, shape, aggregation, connectedness, and fragmentation	Mean patch area (–); shape index (–); aggregation index (–); cohesion index (–); patch density (+)	Prevalence of poor mental health, heart disease, stroke, diabetes, chronic obstructive pulmonary disease, and lack of leisure time physical activity	Adults
Yang et al (2024)[78]	China	115 350 students from 110 schools	500 m buffer surrounding school campuses	Cloud-free Gaofen-2 satellite data	4 m	Longitudinal	Size, shape, aggregation, connectedness, and fragmentation	Mean patch area (–); largest patch index (–); shape index (NS); proximity index (–); cohesion index (–); patch density (+); aggregation index (–)	Myopia	Students age 6–9 years

+=significantly positive. –=significantly negative. NLCD=National Land Cover Database. NS=not-significant ($p>0.05$). *Township (urban area) in Taiwan is equivalent to the size of a zip-code-level unit in the USA. †Chinese article.

***Table:* Summary of study designs and findings**

common choice in 12 (41·4%) studies. The patch density index was used to capture fragmented distributions of greenspace in 17 (58·6%) of 29 studies, and 11 (64·7%) of these 17 studies reported significant associations with health outcomes. Regarding connectedness, the cohesion index was the most widely adopted metric in ten (58·8%) of 13 studies and eight (80·0%) of these ten studies reported significant associations with health outcomes. The aggregation index was used in ten (58·8%) of 17 studies. Lastly, contrast metrics in three (17·6%) and diversity metrics in eight (47·1%) of 17 studies were used for capturing greenspace diversity. A comprehensive description of each metric identified in this Review is provided in the appendix (pp 24–29). Additionally, some articles presented figures that effectively illustrated differences between some metrics.[67,78,79]

The widely adopted software for calculating greenspace morphology metrics is FragStats, which originated from the landscape ecology field and was developed in 1995. FragStats provides a comprehensive range of landscape metrics for assessing the composition, configuration, and spatial arrangement of different landscape elements.[80] More recently, an R package named landscapemetrics has been introduced, allowing for programming-based computation of a subset of metrics.[81] Additionally, we identified one study from the UK that used the Quantum Geographic Information System plugin LecoS for morphology metrics calculation.[38] Regardless of the software used, all metrics were calculated based on raster maps. These maps were usually sourced from reputable government agencies either derived from image classification of satellite imagery or obtained via surveyed land use maps (table). The literature indicates the use of various map resolutions, including 0·25 m, 0·5 m, 1 m, 2 m, 4 m, 10 m, 30 m, 50 m, 100 m, and 250 m, with four articles not specifying resolution information. The analytical units encompassed individuals, lower super output areas, census tracts, and districts and counties.

Panel: Study characteristics of the 29 selected studies and their frequency

Study characteristics

- Study design: 23 (79%) of 29 cross-sectional studies and six (21%) longitudinal studies
- Study location: eight (28%) in the USA, seven (24%) in China (in English), six (21%) in China (in Chinese), five in (17%) Taiwan, two (7%) in the UK, and one (3%) in Iran
- Health outcomes: nine (31%) for mental health, eight (28%) for respiratory health, five (17%) for cardiovascular health, two (7%) for liver health, one (3%) for colon health, one (3%) for diabetes, one (3%) for myopia, one (3%) for allergic rhinitis, one (3%) for life satisfaction, one (3%) for life expectancy, one (3%) for frailty, one (3%) for BMI, and one (3%) for physical activity
- Data resolution: eight (28%) at 30 m, five (17%) at 10 m, five (17%) at 1 m (n=5), two (7%) at 0·25 m, one (3%) at 0·5 m, one (3%) at 2 m, one (3%) at 4 m, one (3%) at 50 m, two (7%) at 100 m, one (3%) at 250 m, and four (14%) were not available
- Participant characteristics: 21 (72%) with adults age 18 years and older, two (7%) with older adults age 65 year and older, three (10%) with children age younger than 10 years, one (3%) with college students, and two (7%) with unknown age

Greenspace morphology metrics examined

- Aggregation: ten (34%) with aggregation index, eight (28%) with nearest-neighbour distance, three (10%) with percentage of like adjacencies, two (7%) with splitting index, two (7%) with proximity index, one (3%) with clumpy index, one (3%) with contagion index, and one (3%) with mean similarity index
- Connectedness: ten (34%) with cohesion index and three (10%) with contiguity index (n=3)
- Diversity: eight (28%) with Shannon diversity index, three (10%) with edge contrast index, one (3%) with patch richness
- Fragmentation: 17 (59%) with patch density
- Shape: 12 (41%) with shape index, two (7%) with edge density, two (7%) with mean fractal dimension, one (3%) with total edge, and four (14%) with perimeter–area ratio
- Size: 14 (48%) with mean patch area and 11 (38%) with largest patch index

Greenspace connectedness, aggregation, and health

Greenspace spatial connectedness is associated with health. Connectedness reflects whether multiple parks are connected by greenways or are spatially isolated. Ten (34·5%) of 29 studies used the cohesion index.[36,37,40,41,56,64,65,69,77,78] Most studies reported that better connected greenspace morphology was associated with lower mortality and morbidity risk of non-communicable diseases,[36,37,64,65] lower frailty among older adults,[69] lower obesity among children,[56] lower myopia,[78] lower allergic rhinitis,[77] and longer life expectancy.[41] However, one county-level study reported that more connected shrubland was associated with greater rates of frequent mental distress.[40] However, the study only focused on shrubland, excluding all other vegetated land cover considered in the other studies. Two (6·9%) additional studies used the contiguity index to measure connectedness and found that higher greenspace connectedness was related to reductions in schizophrenia cases,[62] and higher forest contiguity was associated with reductions in deaths from colon cancer.[39]

Greenspace spatial aggregation is also associated with health.[36,39–41,56–58,63,68] Aggregation reflects whether parks within a census tract are spatially clustered and compact or disaggregated far apart from each other. From the literature, several different measures reflect aggregation, including the aggregation index, nearest-neighbour distance index, and proximity index. Generally, more aggregated greenspace morphology is associated with lower all-cause and cause-specific mortality risk,[36] reduced morbidity risk of non-communicable diseases,[37] lower diagnoses of schizophrenia,[63] lower mental distress,[40] and better life expectancy.[41] Yet, one study in Chicago, USA, reported increased greenspace distance measured by the nearest-neighbour distance index and clumpy index was associated with higher rates of psychological distress.[68] However, Chicago is an outlier as the most racially segregated major city in the USA.[82] The discernible spatial pattern of this segregation warrants a further separate and in-depth analysis.

For more on **FragStats** see https://fragstats.org/

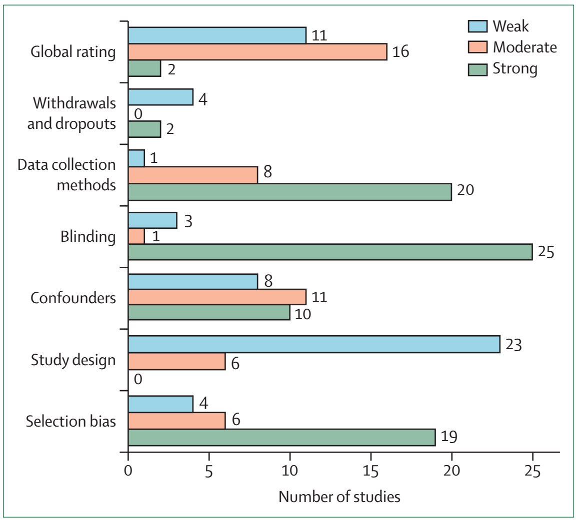

Figure 2: **Results of quality assessment of studies using the Effective Public Health Practice Project quality assessment tool for quantitative studies**

Greenspace size and health

The average greenspace size within an area is associated with health.[36–38,40,41,56,63,66,68] The most widely used measurement for greenspace size is mean patch area. In greenspace studies, when the total areas of greenspaces are comparable, a larger mean patch area value indicates a few large parks in the neighbourhood while a smaller value reflects many small, vegetated land parcels. Larger average sizes were reported to be associated with improved psychological health,[63,66] lower mortality,[36] and lower morbidity risk of non-communicable diseases[37,38] and myopia.[78]

In addition to the average size of greenspaces, studies also examined whether the size of the largest greenspace in a given area affects health.[57,58,67,69] For example, the larger the size (eg, m²) of the biggest park in a census tract, the better the health of residents within the census tract boundary, which is often measured with the largest patch index. Larger-sized parks were associated with lower frailty, decreased mortality risk at the county scale,[58,67,69] and a reduction in cardiovascular disease mortality at the city district scale.[57]

Greenspace shape and health

The shape complexity of greenspace is associated with health.[36,37,40,41,56,64–67,69] Shape complexity measures whether a park reflects a more complex shape including fingers or a goosefoot shape versus more compact shapes, such as perfect circles or rectangles. These spatial characteristics can be captured using the shape index.[36,37,56,64,65,69] More complex shaped greenspaces were associated with reduced numbers of ambulatory care visits for heart, mental, and respiratory diseases;[65] lower mortality risk;[36] lower frailty;[69] and lower morbidity risk of non-communicable diseases.[37] Studies have also measured shape complexity by focusing on the boundaries of greenspace, using two metrics: edge density index and the total edge index. Generally, the longer the boundaries of greenspace, the more complex the shape. Longer edge length is associated with improved mental health,[40] better life expectancy,[41] and lower respiratory mortality.[64] Furthermore, the mean fractal dimension index and perimeter–area ratio index were also used. Both indices are based on the perimeter–area ratio of greenspace. However, when using these two metrics, articles reported conflicting results. One study conducted at the township level with high map resolution (0·25 m) reported decreased values of these two indices, which means decreased shape complexity was associated with lower incidences of bipolar disorders.[66] This decrease of indices suggests that achieving shape complexity at a larger spatial scale might be necessary to attain the associated health benefits. Further studies are necessary to ascertain the influence of scale on greenspace morphology and health associations.

Greenspace fragmentation, diversity, and health

Greenspace fragmentation is the most widely examined metric in the literature[36,37,40,41,57,58,64] and often captured by the patch density index. The index is calculated as the number of greenspaces within a specific area. For example, within a census tract, if there are many green land parcels, they are interpreted as being more fragmented. Most of the studies reported the more fragmented the greenspace morphology, the worse the health outcomes, including all-cause and a range of cause-specific mortality,[36,57,58] morbidity risks from myopia,[78] and non-communicable diseases.[37] Notably, one (3·4%) of 29 studies conducted for Community Statistical Areas, urban areas consisting of one to eight census tracts with populations between 5000 and 20 000, reported no relationship between fragmentation and life expectancy after controlling social demographic variables.[41]

Three (10·3%) of 29 studies also reported a unique metric, the edge contrast index.[40,41,63] This metric captures whether greenspace adjoins similar or contrasting land uses. Higher values indicate that greenspace more likely adjoins highly contrasting urban settings, such as roads or buildings. Greater edge contrast was associated with lower rates of frequent mental distress and schizophrenia.[40,63] However, no association was found for life expectancy.[41] Three (10·3%) studies examined the Shannon diversity index and found that more diverse greenspaces (ie, those containing trees, shrubs, and grasslands) provided better the health benefits.[38,39,68]

Mediating factors between greenspace morphology and health

It has been reported that air pollution and temperature play a mediating role in the relationship between greenspace morphology and cardiovascular diseases.[57] Specifically, PM_{10} (particulate matter less than 10 μm in diameter), $PM_{2·5}$, sulphur dioxide, nitric oxide, carbon monoxide, and annual mean temperature were identified as significant mediators. In another study, $PM_{2·5}$ was highlighted as a mediator between greenspace morphology and a cluster of non-communicable diseases.[37] Additionally, a study suggested that greenspace predicted respiratory mortality by reducing air pollution rather than temperature.[58] Apart from the ecological services provided by greenspace, one study indicated that the lack of leisure time physical activity mediates the relationship between greenspace morphology and non-communicable diseases. Furthermore, this effect was more pronounced than the effect of $PM_{2·5}$, thereby highlighting potential behavioural mechanisms underlying these associations.[37]

Discussion

This systematic review identifies variations in the estimated effects of greenspace morphology on health outcomes across morphology metrics, spatial scale, and data resolution. Generally, greenspaces of larger average sizes, that have more intricate shapes, have improved connectivity, are more aggregated, are less fragmented, and are highly diverse (comprising a mix of trees, shrubs, and grass) in greenspace morphology are linked to better health outcomes. Conflicting results, however, do exist. Furthermore, the evidence from ecological study designs and heterogeneity among the selected studies can only be afforded a modicum of credibility.

Potential mechanisms linking greenspace morphology and health

The morphology metrics in the selected articles were adopted from the field of landscape ecology.[80] The morphology of a landscape, which refers to the spatial arrangement of different land cover types and their configuration, can have a considerable effect on the ecological processes and services that occur within the landscape.[83] Therefore, landscape ecology theorists have developed various metrics to capture landscape morphology, which has enabled empirical study. The ecological services hypothesised to be affected by landscape morphology include reducing air pollution, cooling effect, and water infiltration, which influence human health.[20] Studies have shown that the morphology of greenspace, characterised by increased mean size, connectedness, aggregation, shape complexity, and reduced fragmentation, can effectively reduce air pollution levels. This reduction includes concentrations of PM_{10}, $PM_{2·5}$, nitrogen dioxide, and ozone.[29,84,85] Furthermore, studies indicate that the morphology of the landscape is associated with surface urban heat and temperature.[86–88] We found three studies reporting that air pollution mediates the association between greenspace fragmentation and respiratory mortality and prevalence of non-communicable diseases.[37,57,58] More studies are needed to ascertain the mediating role of other ecological functions provided by greenspace morphology and to verify their effects in other settings.

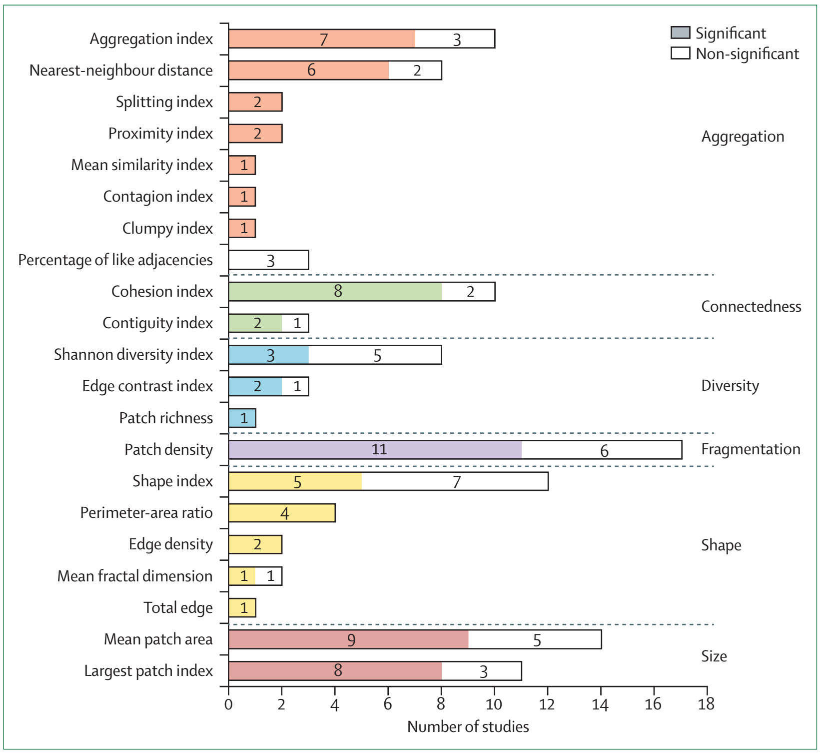

Figure 3: Frequency of greenspace morphology metrics that show statistically significant and non-significant associations with health outcomes
A solid bar represents statistically significant associations, while an uncoloured bar indicates that the metric was examined, but resulted in non-significance.

Studies on greenspace morphology and human health should also consider human behaviour as a potential mediator.[37] Stress reduction theory and attention restoration theory both emphasise that exposure to greenspaces contributes to health. Therefore, increasing the duration, frequency, and intensity of exposure to greenspace might also be beneficial.[37] The duration and frequency of visits to greenspaces were associated with improved mental health,[33] vitality,[89] general health,[90] and cardiovascular health.[33] The intensity of use, such as exercising in greenspaces, has been linked to mental and physical health.[91] Whether the morphology of greenspace might influence the likelihood of residents' exposure to and use of greenspace and therefore contributes to their health, however, needs further exploration. We only noted one study that reported the role of physical activity mediating the relationship between greenspace morphology and the prevalence of non-communicable diseases.[37] Related evidence suggests that linear-shaped parks should increase accessibility compared with parks that have compact shapes[92] and that such accessibility is associated with lowered obesity prevalence.[93] Larger size parks have also been reported to provide broader recreational options compared with small parks and might provide additional benefits.[94,95] Connected parks might also offer greater opportunities for staying longer in a greenspace by walking or biking from one park to the other without leaving the greenspace, therefore contributing to human health.[90] Greenspaces along neighbouring road networks might also increase residents' passive exposure to vegetation on their way to and from work, without requiring individuals to spend extra time deliberately visiting individual parks, thus providing health benefits for busy individuals. Consistent with this hypothesis, visual exposure to greenspace along highways is associated with drivers' mental health.[96] Given the substantial body of literature suggesting such mechanisms, further study is warranted regarding the role of human behaviour in catalysing the positive relationship between greenspace morphology and health.

The importance of considering map resolution and spatial scale

The emergence of conflicting findings regarding the relationship between greenspace fragmentation and health underscores the importance of considering map data resolution in future studies. The choice of resolution can alter the conceptual meanings of real-world measurements. For example, calculating the patch density index (ie, greenspace fragmentation) at a 1 m resolution would be sufficient for capturing individual street trees and the small turf areas in front of houses in a dense residential neighbourhood. However, if the same metric was calculated at 100 m resolution, it would be insufficient for characterising a greenspace that is smaller than 10 000 square meters. At this scale, the resolution would be unsuitable for indicating fragmentation. Instead, the patch density index would become an indicator of the number of large parks within a region. Studies that used a 1 m resolution map reported that when the greenness magnitude is the same, the patch density index positively correlates with mortality risk.[36,58] However, a study based on a 100 m resolution map reported a negative correlation with mortality risk. Although these results might appear inconsistent, when the differing map resolutions are considered, they are consistent because both lower fragmentation and a greater number of large parks are associated with lower mortality risk.[67] Additional evidence for the importance of map resolutions is reflected in a study conducted at 1 m, 10 m, and 30 m resolutions, which reported that the edge density of greenspace was significantly associated with life expectancy at 1 m and 10 m, but not at 30 m.[41] As such, additional studies conducted with differing map resolutions are needed.

Examining the associations in a range of analytical units is also critical for understanding health-promoting characteristics. Within the selected articles, studies reflected various spatial scales, including individual, lower super output area, census tract, district, and county levels. These levels of analysis are of potential relevance for planning initiatives at different scales—ie, for pocket parks, residential small gardens, community parks, and regional parks. However, studies at the city and state levels were notably absent, despite these being crucial spatial scales where landscape and urban planning practices are often implemented. For example, the Olmsted-designed Emerald Necklace in Boston, USA is one of many famous large-scale urban park projects. However, because of the lack of research on the specific health effects of such city-scale greenspace projects, we do not know whether investing in such parks at the city scale is more beneficial than at the neighbourhood scale. As such, further research is urgently needed.

The concern of multicollinearity in modelling

Several studies have incorporated multiple morphological metrics into a single regression model, raising concerns about multicollinearity. Several of these metrics show statistically significant correlations, even though they belong to different categories. Therefore, caution should be exercised when fitting regression models to account for these correlations. For instance, as the average size of greenspaces increase, there is a higher likelihood of increased aggregation. As the average size reaches a specific threshold, greenspaces can become interconnected leading to an increase in the connectedness value. Metrics within the same category, while assessing similar spatial characteristics, exhibit slight differences due to their distinct calculation formulas and focal points. For example, both patch density (fragmentation) and nearest-neighbour distance could reflect a particular level of aggregation. However, the patch density index specifically indicates whether there are numerous small fragments of greenspace (high fragmentation) or a few large greenspaces (low fragmentation). On the other hand, the nearest-neighbour distance focuses more on the spatial proximity of the greenspaces.

Thus, the selection of greenspace morphology metrics during statistical modelling should consider the relationship between metrics to avoid difficulties in interpreting study results. Regression coefficients are typically interpreted to reflect the importance of a variable while holding all other variables constant, or reflect how a change in the independent variable under review would lead to a change in the outcome variable. If the distance between greenspaces and greenspace connectedness indices were put into one regression model, the importance of connectedness might be interpreted as how changes in connectedness influence health when distance between greenspaces is held constant. However, in real-world settings, it is difficult, if not impossible to change the connectedness without influencing the distance between parks. Alternatively, connecting parks with parkways effectively turns isolated parks into one connected park, thereby reducing the distance between them to zero.

The necessity of controlling greenness level

Although we advise against including multiple correlated morphology metrics in one statistical model, it might be beneficial to control greenness levels when investigating the relationship between greenspace morphology and health. This is particularly true when the variance inflation factor indicates minimal collinearity. Isolating the effects of a particular aspect of greenspace morphology from the overall effects of greenness is important. This is because the practical value of morphology study is its ability to identify the ideal spatial arrangement and allocation of greenspace for optimal health benefits, particularly given the restricted capacity to modify the total amount of green. Given the large number of studies reporting the positive value of increased greenspace, greenness magnitude becomes a major confounding factor when exploring the effect of morphology, and therefore should be controlled. Although our detailed analysis reported on 29 articles, only two (6·9%) studies purposefully controlled for the total greenspace area or percentage of greenspace in their analyses.[36,37] More research is needed to further examine the influence of greenspace morphology above and beyond the effects of greenspace magnitude.

Implications for practice and policy

While further research is warranted, the available evidence suggests that health-promoting greenspace practices and policies should consider the potential influence of greenspace morphology, in addition to the magnitude of greenness. Connecting existing parks with green belts along streets might help promote a desired greenspace morphology. Introducing isolated small lawn areas in front of each building, however, might not yield as many benefits as enhancing an already planned or existing large park within a community. In cases where fragmented greenspaces exist, the cost-effective approach of planting trees in gap areas facilitates spatial linkage by providing a substantial tree canopy. Additionally, transforming a large park to create more entry points and border areas has the potential to enhance its accessibility for a larger population. The incorporation of trees, shrubs, and grasslands enhances biodiversity, which is known to be beneficial for ecological health, and this diversity might positively affect human health as well.

Limitations and future research

Several noteworthy limitations are inherent in this field. The literature in this specialised field is predominated by ecological study designs, often conducted at an aggregated population level. The heterogeneity in methodologies, outcomes, and measures restricts the feasibility of a meta-analysis and should be considered in future studies. Furthermore, the suboptimal control of confounding variables and the somewhat modest sample size reduced the studies' statistical significance. We encourage researchers to adopt high-credibility research methodologies, particularly individual-level prospective cohorts and intervention studies, to provide more robust data for causal inference. Studies should report their effect sizes to facilitate meta-analyses. Furthermore, there is considerable potential for future studies to investigate the mediation of human behavioural factors. Examining such associations at varying spatial scales and using diverse map resolutions holds value. Additionally, controlling for the total amount of greenery in such analyses is advisable. Further research could also explore the use of mixed methods to simultaneously examine various metrics, such as those assessing greenspace

Search strategy and selection criteria

We followed the procedures in the PRISMA statement and searched five English databases—Scopus, PsycINFO, PubMed, MEDLINE, and Google Scholar—using English keywords, and three Chinese databases—Chinese Biomedical Database, China National Knowledge Infrastructure, and WanFang Data—using corresponding Chinese keywords, starting from the very first record in the databases and up to April 18, 2024 for journal articles on greenspace morphology and health relationships. To identify articles, we used three groups of terms to capture greenspace, morphology, and health. Greenspace terms included: "landscape" OR "recreation" OR "green*" OR "park*" OR "forest*" OR "garden" OR "vegetation*" OR "nature" OR "natural" OR "NDVI" OR "normalized difference vegetation index" OR "tree*" OR "grass*" OR "shrub*" OR "woodland" OR "wild". Morphology search terms included: "morphology" OR "typology" OR "shape" OR "spatial*" OR "structure" OR "distribution" OR "pattern" OR "character*" OR "connect*" OR "fragment*" OR "size*". Health-related keywords included "mortalit*" OR "life expentanc*" OR "death" OR "obes*" OR "overweight*" OR "BMI*" OR "adipos*" OR "cardiovascular*" OR "acute MI" OR "myocardial infarction*" OR "cardiac" OR "heart" OR "coronary syndrome*" OR "cardiometabolic" OR "hypertension" OR "blood pressure" OR "stroke" OR "cholesterol" OR "dyslipidemia" OR "atherosclerosis" OR "arrhythmia*" OR "peripheral artery" OR "venous thromboembolism" OR "neurological" OR "neuro*" OR "neoplasm*" OR "carcinoma" OR "cancer*" OR "diabet*" OR "insulin" OR "asthma*" OR "wheez*" OR "lung" OR "spirometry" OR "allerg*" OR "atopic dermatitis" OR "respirat*" OR "COPD" OR "chronic obstructive pulmonary disease" OR "pulmonary" OR "chronic bronchitis" OR "emphysema" OR "birth*" OR "weight*" OR "birthweight*" OR "pregnan*" OR "maternal" OR "reproductive outcome*" OR "preeclampsia" OR "diabetes" OR "spontaneous abortion" OR "pregnancy" OR "infant" OR "physical" OR "chronic*" OR "*morbidit*" OR "self-reported" OR "perceived" OR "hospital*" OR "hospitaliz*" OR "admiss*" OR "readmiss*" OR "hospital stay" OR "prevalence" OR "disease" OR "life expectancy" OR "life-expectancy" OR "quality of life" OR "well-being" OR "wellbeing" OR "physical fitness" OR "health status" OR "functional status" OR "mobility" OR "lifestyle*" OR "health" OR "myopia" OR "disorder" OR "mental" OR "emotion*" OR "psychological" OR "cogniti*" OR "stress" OR "depressi*" OR "anxiety" OR "mood" OR "bipolar" OR "schizophrenia" OR "post-traumatic" OR "PTSD" OR "psychiatric" OR "obsessive-compulsive" OR "OCD" OR "eating*" OR "sleep" OR "immunological" OR "immune" OR "kidney" OR "breath*" OR "cough*" OR "life satisfaction" OR "happiness" OR "Alzheimer" OR "Parkinson" OR "Vascular" OR "incidence" OR "morbidity" and a considerable number of specific disease-related keywords (appendix pp 4–10). We also examined the bibliographies of relevant articles and published reviews. Search languages were restricted to English and Chinese. Inclusion and exclusion criteria aligned with the emphasis on greenspace morphology and its effect on human health across diverse resident populations, spatial scales, and a wide array of health indicators, in English or Chinese. Exclusion criteria were: non-human studies; studies not exploring health outcomes; those that lack a focus on greenspace morphology; studies not an association or causality examination; review articles; news, commentaries, abstracts, or policy briefs; qualitative studies; and papers with no full text available.

morphology and quality. Moreover, investigating the health effects of brownfield sites and the morphology of blue spaces could also prove valuable beyond the study of urban greenery.

Our Review comes with a few limitations. We acknowledge that our exclusion of qualitative literature might have resulted in the omission of relevant data, a limitation inherent in our approach. Our focus on peer-reviewed journals rather than grey literature might have also led to the oversight of important publications. Additionally, our review was confined to works published in English and Chinese, potentially limiting its scope in capturing the entirety of global research output. Although the EPHPP quality-assessment method enabled us to identify weak study designs and inadequate control of confounding variables, revealing a general lack of robust evidence in the field, it might not be entirely suitable for evaluating withdrawals and dropouts in cross-sectional studies. Future review efforts might benefit from conducting separate assessments tailored to different study designs, provided a sufficient volume of literature supports such differentiation.

Conclusion

In summary, the prevailing literature in this domain consistently reported that greenspace morphology is associated with improved health outcomes and that this correlation is evident across various geographic scales. The current literature, however, is composed predominantly of observational studies using an ecological study design, with notable heterogeneity among research findings. Consequently, the current level of certainty of this data is deemed as low. To bolster causal inference, future research endeavours should prioritise individual-level prospective cohorts and intervention studies. Furthermore, incorporating mediation analyses should reveal the variables that influence the intricate relationships between greenspace morphology and health. Future research initiatives should also consider factors including map resolution, scale, control for confounders, and greenness levels in their analyses. These factors will enhance understanding of the complex relationships between greenspace morphology and health.

Contributors

HW conceptualised the study. SG and AS conducted the literature search for English databases. SG, AS, and HW conducted the literature screening and data extraction for English databases. WX and HW contributed to the literature search, screening, and data extraction for Chinese literature. HW and LGT interpreted the findings. HW and SG drafted the initial manuscript. HW and WX contributed to its revision. HW, LGT, and OS reviewed and edited the manuscript. HW verified the data. HW and WX accessed the raw data from Chinese databases. HW, SG, and AS accessed raw data from English databases. HW had final responsibility for the decision to submit for publication.

Declaration of interests

The authors declare no competing interests.

Acknowledgments

We thank Daniella Hirschfeld and Daniel Jost for their comments on the initial draft of this article.

References

1 Parsons R, Tassinary LG, Ulrich RS, Hebl MR, Grossman-Alexander M. The view from the road: implications for stress recovery and immunization. *J Environ Psychol* 1998; **18:** 113–40.
2 Ulrich RS, Simons RF, Losito BD, Fiorito E, Miles MA, Zelson M. Stress recovery during exposure to natural and urban environments. *J Environ Psychol* 1991; **11:** 201–30.
3 Jiang B, Wang H, Larsen L, Bao F, Li Z, Pryor M. Quality of sweatshop factory outdoor environments matters for workers' stress and anxiety: a participatory smartphone-photography survey. *J Environ Psychol* 2019; **65:** 101336.
4 Li D, Sullivan WC. Impact of views to school landscapes on recovery from stress and mental fatigue. *Landsc Urban Plan* 2016; **148:** 149–58.
5 Ulrich RS. View through a window may influence recovery from surgery. *Science* 1984; **224:** 420–21.
6 Wang H, Li D. Emergency department visits for mental disorders and the built environment: residential greenspace and historical redlining. *Landsc Urban Plan* 2023; **230:** 104568.
7 Collins RM, Spake R, Brown KA, Ogutu BO, Smith D, Eigenbrod F. A systematic map of research exploring the effect of greenspace on mental health. *Landsc Urban Plan* 2020; **201:** 103823.
8 Liu X-X, Ma X-L, Huang W-Z, et al. Green space and cardiovascular disease: a systematic review with meta-analysis. *Environ Pollut* 2022; **301:** 118990.
9 Mueller W, Milner J, Loh M, Vardoulakis S, Wilkinson P. Exposure to urban greenspace and pathways to respiratory health: an exploratory systematic review. *Sci Total Environ* 2022; **829:** 154447.
10 Coombes E, Jones AP, Hillsdon M. The relationship of physical activity and overweight to objectively measured green space accessibility and use. *Soc Sci Med* 2010; **70:** 816–22.
11 Bodicoat DH, O'Donovan G, Dalton AM, et al. The association between neighbourhood greenspace and type 2 diabetes in a large cross-sectional study. *BMJ Open* 2014; **4:** e006076.
12 Stas M, Aerts R, Hendrickx M, et al. Exposure to green space and pollen allergy symptom severity: a case-crossover study in Belgium. *Sci Total Environ* 2021; **781:** 146682.
13 Rook GA. Regulation of the immune system by biodiversity from the natural environment: an ecosystem service essential to health. *Proc Natl Acad Sci USA* 2013; **110:** 18360–67.
14 Grazuleviciene R, Danileviciute A, Dedele A, et al. Surrounding greenness, proximity to city parks and pregnancy outcomes in Kaunas cohort study. *Int J Hyg Environ Health* 2015; **218:** 358–65.
15 Barile JP, Kuperminc GP, Thompson WW. Resident characteristics and neighborhood environments on health-related quality of life and stress. *J Community Psychol* 2017; **45:** 1011–25.
16 Maas J, Van Dillen SM, Verheij RA, Groenewegen PP. Social contacts as a possible mechanism behind the relation between green space and health. *Health Place* 2009; **15:** 586–95.
17 Kemperman A, Timmermans H. Green spaces in the direct living environment and social contacts of the aging population. *Landsc Urban Plan* 2014; **129:** 44–54.
18 Dinnie E, Brown KM, Morris S. Community, cooperation and conflict: negotiating the social well-being benefits of urban greenspace experiences. *Landsc Urban Plan* 2013; **112:** 1–9.
19 James P, Banay RF, Hart JE, Laden F. A review of the health benefits of greenness. *Curr Epidemiol Rep* 2015; **2:** 131–42.
20 Markevych I, Schoierer J, Hartig T, et al. Exploring pathways linking greenspace to health: theoretical and methodological guidance. *Environ Res* 2017; **158:** 301–17.
21 Mitchell R, Popham F. Greenspace, urbanity and health: relationships in England. *J Epidemiol Community Health* 2007; **61:** 681–83.
22 Maas J, Verheij RA, Groenewegen PP, De Vries S, Spreeuwenberg P. Green space, urbanity, and health: how strong is the relation? *J Epidemiol Community Health* 2006; **60:** 587–92.
23 van den Berg AE, Maas J, Verheij RA, Groenewegen PP. Green space as a buffer between stressful life events and health. *Soc Sci Med* 2010; **70:** 1203–10.
24 Astell-Burt T, Feng X. Urban green space, tree canopy and prevention of cardiometabolic diseases: a multilevel longitudinal study of 46 786 Australians. *Int J Epidemiol* 2020; **49:** 926–33.

25 Graham DA, Vanos JK, Kenny NA, Brown RD. The relationship between neighbourhood tree canopy cover and heat-related ambulance calls during extreme heat events in Toronto, Canada. *Urban For Urban Green* 2016; **20:** 180–86.

26 Ulmer JM, Wolf KL, Backman DR, et al. Multiple health benefits of urban tree canopy: the mounting evidence for a green prescription. *Health Place* 2016; **42:** 54–62.

27 Dzhambov A, Hartig T, Markevych I, Tilov B, Dimitrova D. Urban residential greenspace and mental health in youth: different approaches to testing multiple pathways yield different conclusions. *Environ Res* 2018; **160:** 47–59.

28 Hu Y, Chen Y, Liu S, et al. Residential greenspace and childhood asthma: an intra-city study. *Sci Total Environ* 2023; **857:** 159792.

29 Chen L, Jia Y, Guo Y, et al. Residential greenness associated with decreased risk of metabolic- dysfunction-associated fatty liver disease: evidence from a large population-based epidemiological study. *Ecotoxicol Environ Saf* 2023; **249:** 114338.

30 Veitch J, Abbott G, Kaczynski AT, Wilhelm Stanis SA, Besenyi GM, Lamb KE. Park availability and physical activity, TV time, and overweight and obesity among women: findings from Australia and the United States. *Health Place* 2016; **38:** 96–102.

31 Grobman WA, Crenshaw EG, Marsh DJ, et al. Associations of the neighborhood built environment with gestational weight gain. *Am J Perinatol* 2023; **40:** 638–45.

32 Moran MR, Rodríguez DA, Cortinez-O'ryan A, Miranda JJ. Is self-reported park proximity associated with perceived social disorder? Findings from eleven cities in Latin America. *Landsc Urban Plan* 2022; **219:** 104320.

33 Grilli G, Mohan G, Curtis J. Public park attributes, park visits, and associated health status. *Landsc Urban Plan* 2020; **199:** 103814.

34 Yigitcanlar T, Kamruzzaman M, Teimouri R, et al. Association between park visits and mental health in a developing country context: the case of Tabriz, Iran. *Landsc Urban Plan* 2020; **199:** 103805.

35 Hong S-K, Song I-J, Wu J. Fengshui theory in urban landscape planning. *Urban Ecosyst* 2007; **10:** 221–37.

36 Wang H, Tassinary LG. Effects of greenspace morphology on mortality at the neighbourhood level: a cross-sectional ecological study. *Lancet Planet Health* 2019; **3:** e460–68.

37 Wang H, Tassinary LG. Association between greenspace morphology and prevalence of non-communicable diseases mediated by air pollution and physical activity. *Landsc Urban Plan* 2024; **242:** 104934.

38 Dennis M, Cook PA, James P, Wheater CP, Lindley SJ. Relationships between health outcomes in older populations and urban green infrastructure size, quality and proximity. *BMC Public Health* 2020; **20:** 626.

39 Wiese D, Stroup AM, Maiti A, et al. Measuring neighborhood landscapes: associations between a neighborhood's landscape characteristics and colon cancer survival. *Int J Environ Res Public Health* 2021; **18:** 4728.

40 Tsai W-L, McHale MR, Jennings V, et al. Relationships between characteristics of urban green land cover and mental health in U.S. metropolitan areas. *Int J Environ Res Public Health* 2018; **15:** 340.

41 Tsai W-L, Leung Y-F, McHale MR, Floyd MF, Reich BJ. Relationships between urban green land cover and human health at different spatial resolutions. *Urban Ecosyst* 2019; **22:** 315–24.

42 Twohig-Bennett C, Jones A. The health benefits of the great outdoors: a systematic review and meta-analysis of greenspace exposure and health outcomes. *Environ Res* 2018; **166:** 628–37.

43 Rojas-Rueda D, Nieuwenhuijsen MJ, Gascon M, Perez-Leon D, Mudu P. Green spaces and mortality: a systematic review and meta-analysis of cohort studies. *Lancet Planet Health* 2019; **3:** e469–77.

44 Gascon M, Triguero-Mas M, Martínez D, et al. Residential green spaces and mortality: a systematic review. *Environ Int* 2016; **86:** 60–67.

45 Lachowycz K, Jones AP. Greenspace and obesity: a systematic review of the evidence. *Obes Rev* 2011; **12:** e183–89.

46 Dzhambov AM, Browning MHEM, Markevych I, Hartig T, Lercher P. Analytical approaches to testing pathways linking greenspace to health: a scoping review of the empirical literature. *Environ Res* 2020; **186:** 109613.

47 Thompson Coon J, Boddy K, Stein K, Whear R, Barton J, Depledge MH. Does participating in physical activity in outdoor natural environments have a greater effect on physical and mental wellbeing than physical activity indoors? A systematic review. *Environ Sci Technol* 2011; **45:** 1761–72.

48 Moher D, Shamseer L, Clarke M, et al. Preferred reporting items for systematic review and meta-analysis protocols (PRISMA-P) 2015 statement. *Syst Rev* 2015; **4:** 1.

49 Liberati A, Altman DG, Tetzlaff J, et al. The PRISMA statement for reporting systematic reviews and meta-analyses of studies that evaluate health care interventions: explanation and elaboration. *Ann Intern Med* 2009; **151:** W65–94.

50 Page MJ, McKenzie JE, Bossuyt PM, et al. The PRISMA 2020 statement: an updated guideline for reporting systematic reviews. *Int J Surg* 2021; **88:** 105906.

51 Armijo-Olivo S, Stiles CR, Hagen NA, Biondo PD, Cummings GG. Assessment of study quality for systematic reviews: a comparison of the Cochrane Collaboration Risk of Bias Tool and the Effective Public Health Practice Project quality assessment tool: methodological research. *J Eval Clin Pract* 2012; **18:** 12–18.

52 Thomas BH, Ciliska D, Dobbins M, et al. A process for systematically reviewing the literature: providing the research evidence for public health nursing interventions. *Worldviews Evid Based Nurs* 2004; **1:** 176–84.

53 Barlow P, Sanap R, Garde A, Winters LA, Mabhala MA, Thow A-M. Reassessing the health impacts of trade and investment agreements: a systematic review of quantitative studies, 2016–20. *Lancet Planet Health* 2022; **6:** e431–38.

54 Villa-González E, Barranco-Ruiz Y, Evenson KR, Chillón P. Systematic review of interventions for promoting active school transport. *Prev Med* 2018; **111:** 115–34.

55 Ward SA, Bélanger MF, Donovan D, Carrier N. Relationship between eating behaviors and physical activity of preschoolers and their peers: a systematic review. *Int J Behav Nutr Phys Act* 2016; **13:** 50.

56 Kim J-H, Lee C, Olvara NE, Ellis CD. The role of landscape spatial patterns on obesity in Hispanic children residing in inner-city neighborhoods. *J Phys Act Health* 2014; **11:** 1449–57.

57 Shen Y-S, Lung S-CC. Can green structure reduce the mortality of cardiovascular diseases? *Sci Total Environ* 2016; **566–567:** 1159–67.

58 Shen Y-S, Lung S-CC. Mediation pathways and effects of green structures on respiratory mortality via reducing air pollution. *Sci Rep* 2017; **7:** 42854.

59 Tan B, Wu S, Su, S, Weng M. Spatial association of urban public green space supply and residents' health. *Urban Architecture* 2018; **24:** 57–61.

60 Wang L, Jiang X, Sun W, Zhao X, Tang J. Impact of urban built environment on respiratory health and its planning strategy: a case study of a district in Shanghai. *City Planning Rev* 2018; **6:** 15–22.

61 Wang L, Liao S, Wang M. The impact of spatial factors of urban green space on respiratory health: a case of a central district in Shanghai. *Urban Architecture* 2018; **9:** 10–14.

62 Mears M, Brindley P, Jorgensen A, Ersoy E, Maheswaran R. Greenspace spatial characteristics and human health in an urban environment: an epidemiological study using landscape metrics in Sheffield, UK. *Ecological Indicators* 2019; **106:** 105464.

63 Chang H-T, Wu C-D, Wang J-D, Chen P-S, Wang Y-J, Su H-J. Green space structures and schizophrenia incidence in Taiwan: is there an association? *Environ Res Lett* 2020; **15:** 094058.

64 Jaafari S, Shabani AA, Moeinaddini M, Danehkar A, Sakieh Y. Applying landscape metrics and structural equation modeling to predict the effect of urban green space on air pollution and respiratory mortality in Tehran. *Environ Monit Assess* 2020; **192:** 412.

65 Yeh C-T, Cheng Y-Y, Liu T-Y. Spatial characteristics of urban green spaces and human health: an exploratory analysis of canonical correlation. *Int J Environ Res Public Health* 2020; **17:** 3227.

66 Chang H-T, Wu C-D, Wang J-D, Chen P-S, Su H-J. Residential green space structures are associated with a lower risk of bipolar disorder: a nationwide population-based study in Taiwan. *Environ Pollut* 2021; **283:** 115864.

67 He Q, Liu L, Chang H-T, Wu C-D, Ji JS. Residential green space structures and mortality in an elderly prospective longitudinal cohort in China. *Environ Res Lett* 2021; **16:** 094003.

68 Ha J, Kim HJ, With KA. Urban green space alone is not enough: a landscape analysis linking the spatial distribution of urban green space to mental health in the city of Chicago. *Landsc Urban Plan* 2022; **218:** 104309.

69 He Q, Chang H-T, Wu C, Ji JS. Association between residential greenspace structures and frailty in a cohort of older Chinese adults. *Commun Med* 2022; **2:** 1–7.

70 Kong L, Liu Z, Pan X, Wang Y, Guo X, Wu J. How do different types and landscape attributes of urban parks affect visitors' positive emotions? *Landsc Urban Plan* 2022; **226:** 104482.

71 Xie B, Chen Y, Pang Z, Lin T, Wang L. Layout optimization of ecological spaces in territorial spatial planning toward respiratory health. *Urban Planning Forum* 2022; **5:** 67–73.

72 Leng H, Xu S, Yuan Q. Impact of community green spaces on cardiovascular health: a case study of Chang'an district, Xi'an City. *Landscape Architecture* 2023; **30:** 33–39.

73 Shao Z, Ying J, Wu X. Pathways link green space to college students' mental health in campus by configurational analysis. *Zhejiang Forestry Tech* 2023; **43:** 98–106.

74 Wang Y, Wang X, Yin H. Design thinking of community green space planning model from the perspective of health benefits. *Urban Environment Design* 2023; **1:** 365–72.

75 Wang X, Ouyang L, Lin J, et al. Spatial patterns of urban green-blue spaces and residents' well-being: the mediating effect of neighborhood social cohesion. *Land* 2023; **12:** 1454.

76 Wu L, Chen C. Does pattern matter? Exploring the pathways and effects of urban green space on promoting life satisfaction through reducing air pollution. *Urban For Urban Green* 2023; **82:** 127890.

77 Chen H, Meng X, Yu Y, et al. Greenness and its composition and configuration in association with allergic rhinitis in preschool children. *Environ Res* 2024; **251:** 118627.

78 Yang Y, Liao H, Zhao L, et al. Green space morphology and school myopia in China. *JAMA Ophthalmol* 2024; **142:** 115–22.

79 Wang H, Tassinary LG, Newman GD. Developing the health effect assessment of landscape (HEAL) tool: assessing the health effects of community greenspace morphology design on non-communicable diseases. *Landsc Urban Plan* 2024; **244:** 104990.

80 McGarigal K, Marks BJ. FRAGSTATS: spatial pattern analysis program for quantifying landscape structure. *Gen Tech Rep PNW-GTR-351 Portland US Dep Agric For Serv Pac Northwest Res Stn 122 P* 1995; 351.

81 Hesselbarth MHK, Sciaini M, With KA, Wiegand K, Nowosad J. landscapemetrics: an open-source R tool to calculate landscape metrics. *Ecography* 2019; **42:** 1648–57.

82 Lee M-A. Neighborhood residential segregation and mental health: a multilevel analysis on Hispanic Americans in Chicago. *Soc Sci Med* 2009; **68:** 1975–84.

83 Turner MG. Landscape ecology: what is the state of the science? *Annu Rev Ecol Evol Syst* 2005; **36:** 319–44.

84 Cai L, Zhuang M, Ren Y. Spatiotemporal characteristics of NO_2, $PM_{2.5}$ and O_3 in a coastal region of southeastern China and their removal by green spaces. *Int J Environ Health Res* 2022; **32:** 1–17.

85 Lei Y, Duan Y, He D, et al. Effects of urban greenspace patterns on particulate matter pollution in metropolitan Zhengzhou in Henan, China. *Atmosphere* 2018; **9:** 199.

86 Connors JP, Galletti CS, Chow WT. Landscape configuration and urban heat island effects: assessing the relationship between landscape characteristics and land surface temperature in Phoenix, Arizona. *Landsc Ecol* 2013; **28:** 271–83.

87 Li J, Sun R, Liu T, Xie W, Chen L. Prediction models of urban heat island based on landscape patterns and anthropogenic heat dynamics. *Landsc Ecol* 2021; **36:** 1801–15.

88 Li W, Cao Q, Lang K, Wu J. Linking potential heat source and sink to urban heat island: heterogeneous effects of landscape pattern on land surface temperature. *Sci Total Environ* 2017; **586:** 457–65.

89 van den Berg M, van Poppel M, van Kamp I, et al. Visiting green space is associated with mental health and vitality: a cross-sectional study in four European cities. *Health Place* 2016; **38:** 8–15.

90 White MP, Alcock I, Grellier J, et al. Spending at least 120 minutes a week in nature is associated with good health and wellbeing. *Sci Rep* 2019; **9:** 1–11.

91 Pretty J, Peacock J, Sellens M, Griffin M. The mental and physical health outcomes of green exercise. *Int J Environ Health Res* 2005; **15:** 319–37.

92 Ngom R, Gosselin P, Blais C. Reduction of disparities in access to green spaces: their geographic insertion and recreational functions matter. *Appl Geogr* 2016; **66:** 35–51.

93 Mylona EK, Shehadeh F, Fleury E, Kalligeros M, Mylonakis E. Neighborhood-level analysis on the impact of accessibility to fast food and open green spaces on the prevalence of obesity. *Am J Med* 2020; **133:** 340–46.e1.

94 Sugiyama T, Francis J, Middleton NJ, Owen N, Giles-Corti B. Associations between recreational walking and attractiveness, size, and proximity of neighborhood open spaces. *Am J Public Health* 2010; **100:** 1752–57.

95 Epstein LH, Raja S, Gold SS, Paluch RA, Pak Y, Roemmich JN. Reducing sedentary behavior: the relationship between park area and the physical activity of youth. *Psychol Sci* 2006; **17:** 654–59.

96 Jiang B, He J, Chen J, Larsen L, Wang H. Perceived green at speed: a simulated driving experiment raises new questions for attention restoration theory and stress reduction theory. *Environ Behav* 2021; **53:** 296–335.