Review

# Greenspace and human health: An umbrella review

**Bo-Yi Yang,[1,11] Tianyu Zhao,[2,11] Li-Xin Hu,[1,11] Matthew H.E.M. Browning,[3] Joachim Heinrich,[4] Shyamali C. Dharmage,[5] Bin Jalaludin,[6] Luke D. Knibbs,[7] Xiao-Xuan Liu,[1] Ya-Na Luo,[1] Peter James,[8] Shanshan Li,[9] Wen-Zhong Huang,[1] Gongbo Chen,[1] Xiao-Wen Zeng,[1] Li-Wen Hu,[1] Yunjiang Yu,[10,*] and Guang-Hui Dong[1,*]**

*Correspondence: yuyunjiang@scies.org (Y.Y.); donggh5@mail.sysu.edu.cn (G.-H.D.)

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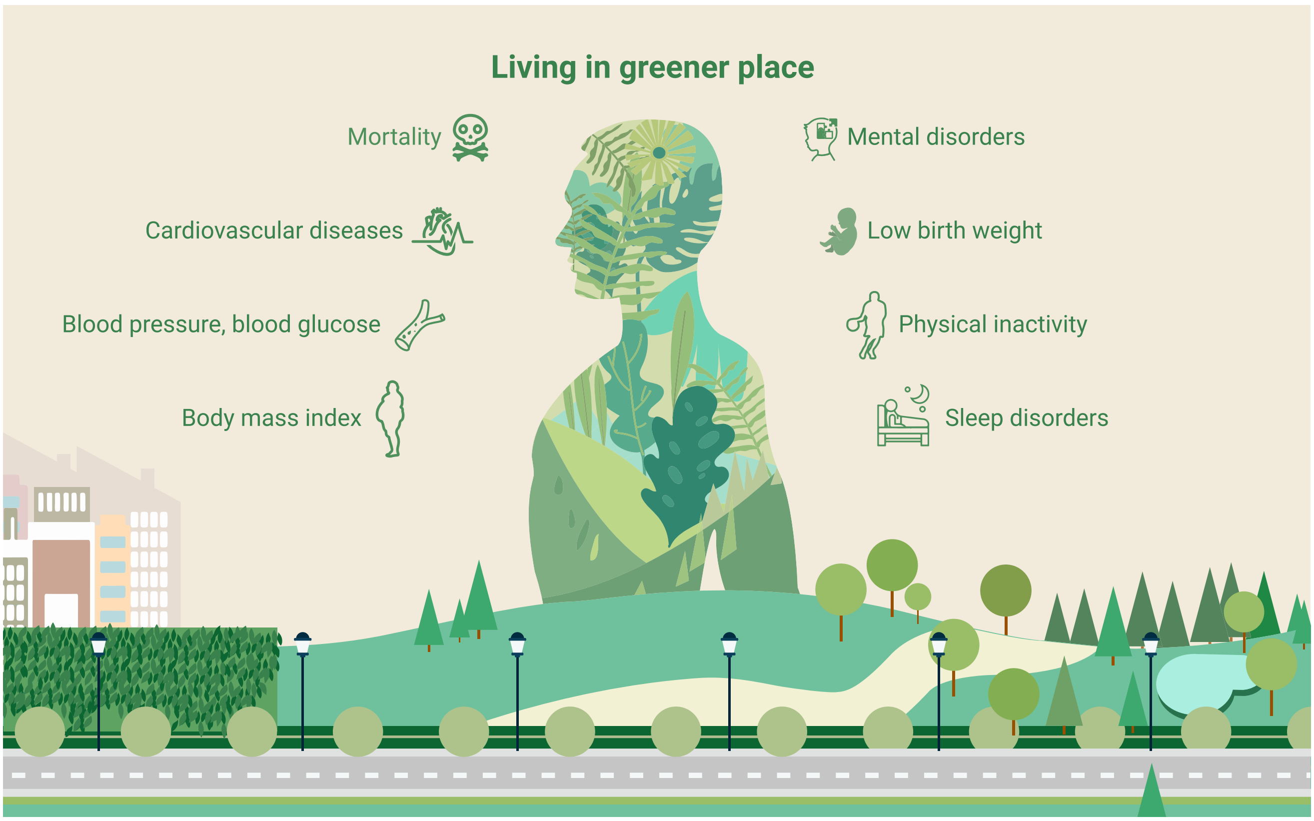
## Graphical abstract




## Public summary


- The evidence concerning greenspace and health outcomes remains unclear
- We performed an umbrella review of 40 systematic reviews on greenspace and health
- Greenspace exposure was estimated with various objective and subjective parameters
- Greenspace was beneficially associated with several aspects of human health

# Greenspace and human health: An umbrella review

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[1]Guangdong Provincial Engineering Technology Research Center of Environmental and Health risk Assessment, Department of Occupational and Environmental Health, School of Public Health, Sun Yat-sen University, Guangzhou 510080, China

[2]Institute and Clinic for Occupational, Social and Environmental Medicine, LMU University Hospital Munich, Comprehensive Pneumology Center (CPC) Munich, member, German Center for Lung Research (DZL), Munich 80036, Germany; Institute of Epidemiology, Helmholtz Zentrum München - German Research Center for Environmental Health, 85764 Neuherberg, Germany

[3]Department of Park, Recreation, and Tourism Management, Clemson University, Clemson, SC 29634, USA

[4]Institute and Clinic for Occupational, Social and Environmental Medicine, LMU University Hospital Munich, Comprehensive Pneumology Center (CPC) Munich, member, German Center for Lung Research (DZL), Munich 80036, Germany; Allergy and Lung Health Unit, Melbourne School of Population and Global Health, The University of Melbourne, Melbourne, VIC 3010, Australia

[5]Allergy and Lung Health Unit, Centre for Epidemiology and Biostatistics, School of Population and Global Health, The University of Melbourne, Melbourne, VIC 3010, Australia

[6]Centre for Air Quality and Health Research and Evaluation, Glebe NSW 2037, Australia; Population Health, South Western Sydney Local Health District, Liverpool NSW 2170, Ingham Institute for Applied Medical Research, Liverpool, NSW 2170, Australia; School of Public Health and Community Medicine, The University of New South Wales, Kensington, NSW 2052, Australia

[7]School of Public Health, The University of Sydney, NSW 2006, Australia

[8]Department of Population Medicine, Harvard Medical School and Harvard Pilgrim Health Care Institute, Boston, MA; Department of Environmental Health, Harvard T.H. Chan School of Public Health, Boston, MA 02215, USA

[9]Climate, Air Quality Research Unit, School of Public Health and Preventive Medicine, Monash University, Melbourne, VIC 3004, Australia

[10]State Environmental Protection Key Laboratory of Environmental Pollution Health Risk Assessment, South China Institute of Environmental Sciences, Ministry of Environmental Protection, Guangzhou 510080, China

[11]These authors contributed equally

*Correspondence: yuyunjiang@scies.org (Y.Y.); donggh5@mail.sysu.edu.cn (G.-H.D.)

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**Multiple systematic reviews on greenspace and health outcomes exist, but the overall evidence base remains unclear. Therefore, we performed an umbrella review to collect and appraise all relevant systematic reviews of epidemiological studies on greenness exposure and health. We searched PubMed, Embase, and Web of Science from inception to June 28, 2021, and screened references of relevant articles. Systematic reviews with or without meta-analyses of epidemiological studies that examined the associations of greenness with any health outcome were included. Two independent investigators performed study selection and data extraction. We also evaluated the methodological quality of the included systematic reviews using the "Assessing the Methodological Quality of Systematic Reviews 2" checklist. A total of 40 systematic reviews and meta-analyses were included, of which most were cross-sectional studies conducted in high-income countries. Greenspace exposure was estimated with various objective and subjective parameters. Beneficial associations of greenspace with all-cause and stroke-specific mortality, CVD morbidity, cardiometabolic factors, mental health, low birth weight, physical activity, sleep quality, and urban crime were observed. No consistent associations between greenspace and other health outcomes (e.g., cancers) were observed. Most of the included systematic reviews and meta-analyses had one or more limitations in methodology. Our findings provide supportive evidence regarding the beneficial effects of greenspace exposure on some aspects of human health. However, the credibility of such evidence was compromised by methodological limitations. Better performed systematic reviews and meta-analyses as well as longitudinal designed primary studies are needed to validate this conclusion.**

**Keywords:** greenspace; vegetation; human health; umbrella review; systematic review

## INTRODUCTION

Our planet has experienced a rapid urbanization during the last century. Now about 50% of the global population lives in urban areas,[1] and by 2050 it is estimated that this proportion will be over 65%.[1] In addition to polluted water, soil, and air, urbanization poses a big challenge in providing sufficient access to areas with vegetation (hereon referred to as greenspace).[2,3] This is of great concern to public health, since exposure to greenspace may bring many health benefits.[4] The underlying mechanisms include encouraging physical activity, reducing environmental hazards (e.g., air pollution, noise, and air temperature), mitigating mental stress and inattention, improving social interaction, and enriching microbial diversity.[5,6]

Many epidemiological studies have been performed, particularly in high-income countries, to evaluate the associations between greenspace and a range of health outcomes, such as cardiovascular diseases (CVDs),[7] birth outcomes,[8] mental health,[9,10] allergic diseases,[11] and blood biomarkers.[4] As a response to the increasing literature in the field, a number of systematic reviews and meta-analyses have been performed to synthesize this literature. Evidence for associations between environmental exposures and health outcomes are hierarchical (Figure 1); primary studies exist along a continuum with preclinical studies being lower on the hierarchy and randomized controlled trials (RCTs) being higher on the hierarchy.[12] Secondary studies, including reviews and meta-analyses, exist even higher than RCTs on the evidence hierarchy and might have less chance for bias and error. However, with the rapid increase in primary studies on greenspace and health outcomes, the number of reviews and meta-analyses are also accumulating. For example, between 2014 and 2020, there have been seven published systematic reviews and meta-analyses on maternal greenness exposure and birth weight alone.[8,13–17] Such rapid updates make keeping up with the systematic reviews difficult for researchers, healthcare practitioners, and policy makers. In addition, many of the systematic reviews and meta-analyses focus on a single disease or one kind of similar health endpoints. Since greenspace exposure is proposed to be linked to numerous health effects,[5] the

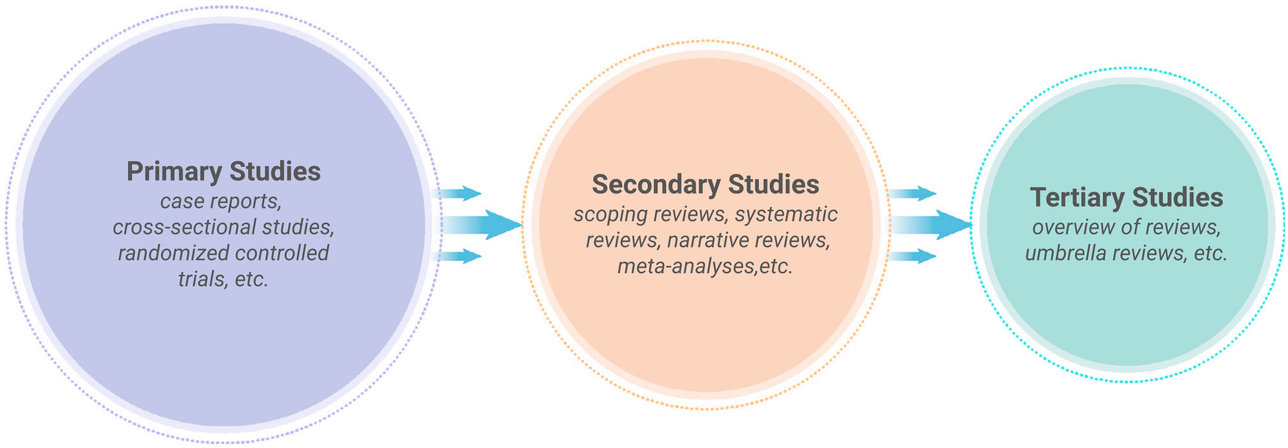


**Figure 1. Hierarchy of study designs and estimated number of studies on greenness exposure and health at each level** Increasingly higher levels (shown here as smaller circles) represent less chance for bias and error, adapted from Biondi-Zoccai.[12] Estimated numbers are derived from past reviews[18,19] and the results of the current review.

overall picture on greenspace and these health effects thus remains unclear from those systematic reviews and meta-analyses.

A tertiary-level study (an umbrella review), systematically collects and evaluates previously published secondary-level systematic reviews and meta-analyses on a research topic to generate even more robust evidence than its constituent parts (i.e., individual systematic reviews and meta-analyses).[12] We are aware of only one prior systematic effort to review previous reviews and meta-analyses concerning nature environment and health outcomes.[18] There has been a notable rise in the number of both primary- and secondary-level articles on greenspace and health since August 2016, when the former effort concluded its retrieval of articles.[19] Therefore, in this updated umbrella review, we summarize and appraise all relevant systematic reviews and meta-analyses of epidemiological studies concerning greenspace exposure and any human health outcome through June 2021, in order to provide researchers and healthcare professionals in this field with a more comprehensive and higher quality of evidence on the health effects of greenspace exposure.

## RESULTS

### Systematic review retrieval

As shown in Figure 2, the initial search identified 3,917 records. After removing duplicates, the titles and abstracts of 3,125 systematic reviews were assessed and 3,073 articles were removed following title and abstract screening. A total of 52 articles underwent a full-text review. Of these, six were further excluded due to irrelevance to the topic or with other focuses, five more articles were excluded because they duplicated other included articles, and one was removed since it was a conference abstract. Finally, 40 systematic reviews were included in the umbrella review.[4,7–9,11,20–54]

### Characteristics of systematic reviews included in the umbrella review

Our umbrella review included 9 systematic reviews with meta-analyses[4,7,8,11,20,32,33,37,47] and 31 without meta-analyses. These articles were published between 2010 and 2021, and 29 (approximately 73%) were published since 2019 (Table 1). The number of databases used for keyword searches ranged from 1 to 19. The number of primary studies included in the systematic reviews ranged from 7 to 201. Most of the primary studies included were cross-sectional, followed by experimental/intervention studies, cohort studies, and ecological studies. Study populations across all age groups (i.e., from infant to the elderly) were covered, and mostly resided in higher-income countries in North America or Europe. Only a small number of primary studies were conducted in lower- and middle-income countries like China.

### Greenspace exposure measures

Greenspace exposures were evaluated using a number of metrics, including objective parameters, such as the normalized difference vegetation index (NDVI), percentage of greenspace in a certain area, distance to the nearest greenspace, number of parks in an area, act of walking or running or gardening in a natural environment, or viewing simulations of natural environments. Subjective parameters were also presented and included self-reported exposure, perceived access to greenspace through window views, and reported visitation to natural settings for outdoor activities.

### Health outcomes

Over 100 health outcomes were investigated with greenspace exposures, including mortality, CVDs, pregnancy outcomes, mental health, general health, allergic diseases, and blood biomarkers. These health outcomes were measured using various methods, including doctor diagnoses, questionnaires, records from hospitals or other health-related departments, self-reported health status, and laboratory tests.

### Methodological quality

Many of the included systematic reviews failed to meet the seven critical domains of the "Assessing the Methodological Quality of Systematic Reviews 2" (AMSTAR2) checklist (Table 2). Four systematic reviews (10%) provided a list of excluded studies and justified the exclusions. Fifteen (38%) developed an *a priori* protocol for the review. Twenty-eight (70%) accounted for the risk of bias in the primary studies when discussing the results of the systematic reviews. Twenty-eight (70%) assessed the risk of bias in the primary studies. Finally, 37 (93%) performed a comprehensive literature search. The remaining two critical domains related to meta-analysis were hard to evaluate since most of the included systematic reviews did not perform a meta-analysis.

Many of the included studies also failed to meet at least one of the nine, non-critical domains of the AMSTAR2 checklist (Table 2). None of the systematic reviews reported the sources of funding for the primary studies. Fifteen (38%) included the components of the PECO. Fourteen (39%) performed data extraction in duplicates. Twenty-nine (73%) performed study selection in duplicates. The other non-critical domains were met by most of the included systematic reviews.

### Associations between greenspace exposure and health outcomes

Table 1 summarizes the detailed information on the associations between greenspace exposure and health outcomes in each of the included systematic reviews.

***Mortality.*** A few systematic reviews have examined all-cause or non-accidental mortality and greenspace exposure. One example was a systematic review and meta-analysis of nine longitudinal cohort studies that showed

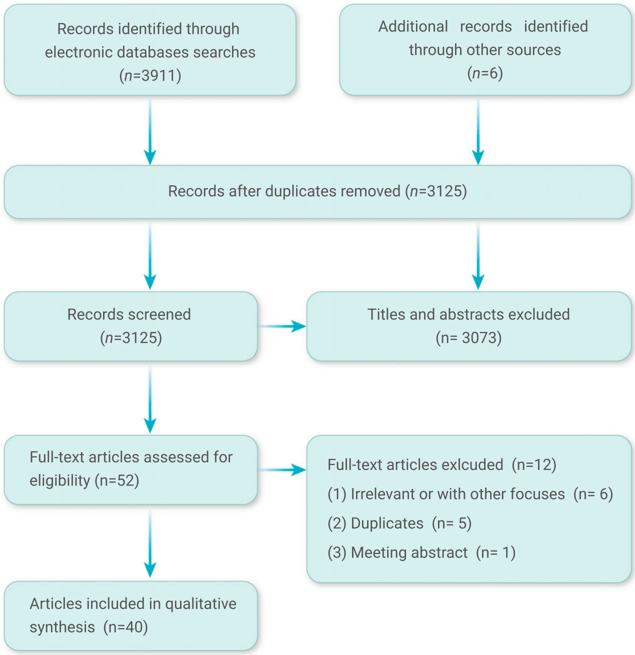


**Figure 2. Flow chart of study selection process**

that a 0.1-unit increase in greenness within 500 m of the home was associated with a 4% decrease in all-cause mortality.[37] Another systematic review and meta-analysis limited to elderly populations found that higher greenness levels reduced odds of both all-cause mortality and stroke-related mortality. No significant associations were found for CVD-related mortality and ischemic heart disease-related mortality.[7] Primary studies have also investigated greenspace and other cause-specific mortality rates, such as respiratory diseases, but the number of these studies was too low and the results were too mixed to draw conclusions.[7]

***Cardiovascular and metabolic health.*** Cardiovascular health was one of the most widely studied outcomes in the included systematic reviews. In a systematic review by Yuan et al.,[7] eight studies investigated associations of greenspace exposure and total CVD risk. Among them, seven showed beneficial associations. Less consistent evidence was reported for other CVD outcomes, including stroke, myocardial infarction, and coronary heart disease.[4,7,23] Greenspace was also linked to preclinical cardiometabolic factors. Our research group's recent systematic review and meta-analysis found that greater NDVI was associated with lower odds of being overweight or obese.[47] Another systematic review with meta-analysis showed that people who lived in areas with little greenspace had higher odds of having diabetes compared with people who lived in areas with abundant greenspace.[4] Similar beneficial associations were found between greenspace and heart rate, diastolic blood pressure, and high-density lipoprotein cholesterol.[4,39] However, no significant associations were observed for systolic blood pressure, total cholesterol, low-density lipoprotein cholesterol, and glycosylated hemoglobin.[4,45]

***Mental health and behavioral issues.*** The effects of greenspace exposure on mental and behavioral diseases have been widely evaluated, although studies have differed substantially in study population composition, greenspace assessment, outcome assessment, and study design. Four systematic reviews with overlap but mutually different primary studies concluded that greenness exposure was associated with improved cognition, including cognitive development, attention, and dementia across the life course.[22,23,39,51] Another systematic review of 57 studies found that built environments lacking greenspace predicted depressive moods across age groups.[27] Two systematic reviews, summarizing 52 observational studies[28] and 38 nature experiments,[31] respectively, concluded that urban greenspace levels (or greenspace intervention) were positively associated with mental well-being. Two more systematic reviews reported that engaging with gardens or wildland recreation had the potential to improve mental health.[34,46] In a systematic review of 12 studies, Shuda et al. found that walking in natural settings, hearing natural sounds, or viewing a simulated nature environment was associated with reduced physiologic and perceived stress levels.[38] Mygind et al. summarized 26 experimental studies and found that seated relaxation and walking in natural environments might be associated with improved acute psychophysiological stress response.[33] Similar results were found in studies restricted to children and adolescents; 2 systematic reviews of 14 and 45 studies, respectively, showed beneficial associations between greenspace exposure and stress, mood, depressive symptoms, emotional well-being, mental health and behavior, and psychological distress in children and adolescents.[9,52] Another systematic review found that higher levels of exposure to residential greenness may potentially increase prosocial behavior among children and adolescents.[42] Two systematic reviews by Bowler et al.[20] and Roberts et al.[32] found that spending time in natural environments during walking, running, or wilderness backpacking among other outdoor activities was associated with reduced levels of anger, anxiety, and depression as well as increased levels of attention. In contrast, another systematic review reported that there was insufficient evidence showing outdoor and indoor greenspace around school campuses impacted students' well-being.[44]

***Birth outcomes.*** Numerous systematic reviews have synthesized the evidence regarding maternal greenspace exposure and birth outcomes.[4,8,23,40,49] The latest and the most comprehensive was performed by Hu et al.[8] In that systematic review with meta-analysis, the authors found that higher residential greenness levels were generally associated with higher birth weight and lower odds of low birth weight. More specifically, a 0.1-unit increase in greenness within 100 m of the home was associated with a 15.22-g increase in birth weight and a 13% lowered odds of low birth weight. No significant associations between greenness and preterm birth or small gestational age were observed. The authors evaluated the credibility of the pooled evidence and concluded that the associations above had "moderate" certainty.

***Allergic endpoints.*** Lambert et al. [11] published the first systematic review and meta-analysis of studies on residential greenness and allergic respiratory diseases in children and adolescents. Neither asthma nor allergic rhinitis were associated with greenness exposure. Hartley et al.[48] performed an updated systematic review by synthesizing literatures that were published after Lambert and colleagues' review, and also found a null association. In addition, Lambert et al.[25] summarized 11 cohort studies on residential greenness and atopic sensitization and found that 4 of these studies reported protective effects, 2 reported deleterious effects, and 5 reported null effects. The diversity of these findings makes it difficult to draw a conclusion on the association between greenspace and allergic diseases.

***Physical activity.*** Since greenspace is usually hypothesized to benefit human health by encouraging physical activity, a large number of studies have explored this topic. A systematic review by Lambert et al.[36] included four studies on neighborhood greenspace levels and outdoor play among children and adolescents. Three showed more outdoor play time with higher neighborhood greenspace levels. Another systematic review by Thomsen et al.[46] included 34 studies on physical activity that were mainly performed in adults and reported that wildland recreation had the potential of improving physical activity levels. In addition, de Keijzer et al.[39] reviewed 17 studies on physical activity, which were conducted in middle- and older-aged populations, and found that approximately two-thirds of the primary studies observed beneficial associations between residential greenness and physical activity.

***Other health outcomes.*** Effects of greenspace on other health aspects have also been investigated. For instance, a systematic review of 13 studies reported that greenspace exposure was associated with reduced odds of short sleep and/or poor sleep quality.[41] A systematic review of 29 studies summarized greenspace exposure and cancers, but the evidence was limited and mixed.[53] Another systematic review of 45 studies concluded that the presence of parks and other types of greenspace may reduce urban crime.[29]

**Table 1.** Characteristics of included systematic reviews on greenspace and health with or without meta-analyses (N = 40)

| Author(Year) | Included Studies | Exposure(s) | Outcome(s) | Finding(s) |
| --- | --- | --- | --- | --- |
| Bowler et al.[20] | 25 studies (24 articles) including 13 crossover trials, 7 randomized controlled trials (RCTs), and 5 observational studies | Exposure group: walking or running in the natural environment, wilderness backpacking, gardening, passive/sedentary activities, or a mixture of activities Control group: outdoor built and non-green environment or indoor environment | Emotions (e.g., revitalization, anger, anxiety), attention, cardiovascular outcomes (e.g., blood pressure or pulse) hormone levels (salivary, urinary cortisol, amylase, and adrenaline), immune function, physical activity, motor performance, cerebral brain activity, engagement, memory recall, and sleep | Compared to a built environment, short-term exposure to natural environments was associated with better emotional states and attention (effect sizes ranged from 0.35 to 0.76), but not with other health outcomes. |
| van den Berg et al.[21] | 40 studies (32 articles) including 34 cross-sectional studies and 6 longitudinal studies | Percentage of greenspace within a certain distance or radius around the residence, percentage of greenspace, greenspace percentage at the city level and county level, NDVI, and tree canopy coverage, distance to the nearest greenspace, number of different recreational or green qualities within a certain distance, and subjective measures of greenspace/naturalness | Perceived general health, perceived mental health, and all-cause mortality | There was evidence for positive associations between the quantity of greenspace and perceived mental health and all-cause mortality; there was moderate evidence for positive associations between greenspace and perceived general health. Despite these findings, the evidence was not convincing due to the lack of high-quality studies. Gender, age, and SES may modify the association between greenness and health, but the strength and direction of these effect modifiers is unclear. |
| de Keijzer et al.[22] | 13 studies including 3 cohort studies, 2 ecological studies, and 8 cross-sectional studies | Percentage of greenspace and park area, greenness surrounding schools, homes, and commuting route between the two (using NDVI or tree counts) as well as ratings of greenness, self-reported or surveyed views of greenspace through the windows, and reporting of settings visited during activities | Cognitive development, cognitive function, cognitive decline or impairment, distraction and concentration problems, symptoms of inattention, measures of school performance, and dementia incidence | There was inadequate but suggestive evidence for a positive association between long-term greenspace exposure and cognitive functioning over the life course. |
| Kondo et al.[23] | 68 studies including 14 with between-subjects designs, 3 case-control or case crossover studies, 9 quasi-experimental studies, 1 RCT, 30 longitudinal cohort studies, and 21 with within-subjects designs | Greenspace in residential area (e.g., NDVI, proximity to parks), greenspace in activity spaces (e.g., presence or absence of greenspace or park space), nature walk or run, greening intervention (e.g., neighborhood-level greenspace improvements, cleaned-and greened vacant lots), nature leisure experience, and residential relocation | Behavior (e.g., behavioral problems, smoking), birth outcomes (e.g., birth weight, preterm birth, small for gestational age), prostate cancer, cardiovascular diseases (e.g., autonomic function, blood pressure, CVD risk, dyslipidemia, etc.), metabolic (obesity, cortisol, diabetes, etc.), mortality, mental health (e.g., anger, anxiety, anxious, attention, etc.), violence-aggression, and respiratory diseases | There were positive associations between urban greenspace and attention, mood, and physical activity, as well as negative associations between greenspace and mortality, short-term cardiovascular markers and violence. No consistent associations were observed for the remaining outcomes. |
| Lambert et al.[11] | 15 studies (11 articles) including 11 cohort studies, 1 cross-sectional studies, and 3 ecological studies | NDVI and street tree density | Asthma and allergic rhinitis | There was no significant association between residential greenness and asthma. |
| Houlden et al.[28] | 52 studies including 6 longitudinal studies, 4 uncontrolled studies, 37 cross-sectional surveys | Amount of local-area greenspace, greenspace types, visits to greenspace, views of greenspace, greenspace accessibility, and subjective connectedness to nature | Mental wellbeing | There was adequate evidence for protective associations between local greenspace and life satisfaction but between local greenspace and personal flourishing. Evidence for associations between visits to greenspace, accessibility, types of greenspace, views of greenspace, and connectedness to nature were insufficient. |

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**Table 1.** *Continued*

| Author(Year) | Included Studies | Exposure(s) | Outcome(s) | Finding(s) |
|---|---|---|---|---|
| Lambert et al.[25] | 5 papers including 11 different cohort studies | NDVI, proportion of tree canopy, land cover databases, and combination of high-resolution light detection and ranging (LiDAR), color infrared aerial imagery, and ancillary vector data. | Atopic sensitization | Protective effects of greenspace were r eported in four cohorts; deleterious effects were reported in two cohorts; no significant associations were reported in another five cohorts. |
| Rautio et al.[27] | 57 studies (11 on greenspace) including 43 cross-sectional studies and 14 longitudinal studies | Proportion of green area, presence of park, distance to parks, and proportion of greenspace, among others | Depressive mood | Built environments lacking greenspaces were related to depressive mood although the results were mixed. |
| Schulz et al.[24] | 18 studies (4 on greenspace) including 14 cross-sectional studies and 4 longitudinal studies | Naturally or human-built areas (e.g., parks, forest, garden, and cemeteries) covered with grass, trees, shrubs, or other vegetation | Overall health, acute respiratory illness, chronic/allergic disease | Greenspace tended to be associated with acute respiratory symptoms but not with chronic respiratory conditions. |
| Twohig-Bennett and Jones[4] | 143 studies including 103 observational and 40 interventional studies | Neighborhood greenspace (e.g., residential greenspace, street greenery, and tree canopy), greenspace-based interventions, proximity to large greenspace, comparisons between a green environment with an urban or indoor environment, and viewing trees through window, among others | Almost 100 outcomes including cardiovascular diseases (e.g., cardiovascular mortality, blood pressure, heart rate, and incidence of angina and myocardial infarction), pregnancy outcomes, self-reported health, mortality (e.g., all-cause, respiratory and intentional self-harm), and diabetes as well as various blood biomarkers (e.g., HDL-C, LDL-C, FBG, etc.) | Greenspace exposure was beneficially associated with a wide range of health outcomes including salivary cortisol, heart rate, diastolic blood pressure, high-density lipoprotein cholesterol, heart rate variability, preterm birth, type 2 diabetes, all-cause mortality, small size for gestational age, cardiovascular mortality, self-reported health, stroke, hypertension, dyslipidemia, asthma, and coronary heart diseases. Non-pooled studies showed health-denoting associations for neurological and cancer-related outcomes as well as respiratory mortality. |
| Vanaken and Danckaerts[26] | 21 studies including 12 cross-sectional studies, 7 longitudinal studies, and 2 ecological studies | Land use data, NDVI, subjective measures like time spent in greenspaces evaluated using questionnaires, and distance to nearest greenspace | Emotional and behavioral difficulties, mental well-being, and neurocognitive development | There was a beneficial association between greenspace exposure and emotional and behavioral problem. There was limited evidence in support of a beneficial association between greenspace exposure and mental well-being and depressive symptoms. The current evidence suggested that physical activity, air pollution and social interaction mediated these associations. |
| Browning and Rigolon[35] | 13 studies including 12 observational studies and 1 experimental study | NDVI, tree canopy cover, and green view | Academic performance | Approximately two-thirds of the reviewed studies showed non-significant associations between greenspace and academic performance, and the other studies reported mixed associations. |
| Shepley et al.[29] | 45 papers, all of which were ecological studies | Parks, community gardens/greening, vegetated streets and walkways, tree and ground cover, and undeveloped or partially developed green areas | Murder, assault and theft. | Presence of parks and other greenspaces reduced urban crime. |

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Review

**Table 1.** *Continued*

| Author(Year) | Included Studies | Exposure(s) | Outcome(s) | Finding(s) |
|---|---|---|---|---|
| Hunter et al.[31] | 38 studies, of which were experiments or quasi-experiments with controlled pre-post designs (n = 21), uncontrolled pre-post design (n = 6) or controlled post-design (n = 8) | Park-based urban greenspace interventions, greenways/trails, urban greening, and greening interventions | Health and wellbeing | There was strong evidence for park-based and greenway/trail interventions on park use and physical activity for greened vacant lots on health and wellbeing (e.g., reduction in stress) and social outcomes (e.g., reduction in crime, increased perception of safety); there was also sufficient evidence for urban street trees increasing biodiversity. |
| Jo et al.[30] | 37 articles, all of which were experiments | Real life nature stimuli like green plants, flower, and/or wooden materials; exposure to images of natural elements like slides, photos, videos of forests and/or urban park landscapes | Brain activity and autonomic nervous activity | Viewing natural scenery and visual contact with flowers, green plants, and wooden materials had positive effects on cerebral and autonomic nervous activities compared with control groups. |
| Lakhani et al.[34] | 18 studies | Green care farm, forest therapy, gardens, and outdoor adventure programs | Psychological, emotional and social health domains | Engaging with gardens and gardening favorably impacted the emotional and social health of people with dementia. |
| Lambert et al.[36] | 18 studies (4 studies on greenspace) including 14 cross-sectional studies, 2 longitudinal studies, and 2 studies with a combination of longitudinal and cross-sectional designs | Neighborhood greenness | Time spent in outdoor play | Neighborhood greenness was a predictor of more time spent in outdoor play (one longitudinal reported reverse association). |
| Mygind et al.[33] | 26 studies (11 in the meta-analysis) including 3 experimental studies, 16 experimental within-subject randomized crossover trials, 3 quasi-experimental studies within-subject design, and 4 quasi-experimental with controlled before-and-after studies | Seated relaxation or walking in natural environments over the course of 10 min to 8 weeks | Psychophysiological outcomes including serum and salivary cortisol, heart rate variability, salivary amylase, adrenaline, noradrenaline and dopamine as well as cortisol awakening response | Seated relaxation and walking in natural environments enhanced heart rate variability more than the same activities in control conditions. Associations between nature exposure and cortisol were mixed. |
| Roberts et al.[32] | 33 studies including 16 randomized crossover studies, 5 non-randomized crossover studies, 3 2×2 factorial design studies, 6 randomized parallel group study, 1 parallel group study, and 2 single group crossover studies | Spending 10 to 90 min in natural environments | Depression | A small effect was found for a reduction in depressive moods following exposure to nature environments (effect sizes ranged from -2.30 to 0.84). |
| de Keijzer et al.[39] | 59 studies including 44 cross-sectional studies, 4 longitudinal studies, and 1 ecological study | Residential exposure to greenspace including NDVI, proportion of greenspace in a certain area, distance to the nearest greenspace, and tree canopy, among others | Mental health, cognitive function, physical capability, morbidity, cardiometabolic risk factors, and perceived wellbeing | There was limited evidence for protective associations between greenspace and morbidity, mental health, cognitive function, physical capability, cardiometabolic risk, and perceived wellbeing. |
| Hartley et al.[48] | 7 studies including 4 cross-sectional studies and 3 cohort studies | NDVI and land cover, among others | Asthma | No significant association between greenness and children asthma was found. |

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**Table 1.** *Continued*

| Author(Year) | Included Studies | Exposure(s) | Outcome(s) | Finding(s) |
|---|---|---|---|---|
| Hu et al.[8] | 29 studies including 22 cross-sectional studies, 6 cohort studies, and 1 case-control study | NDVI, tree cover, distance to greenspaces, residential surrounding greenspace, visual access to greenspace, and time spent in greenspaces | Birth weight, small gestational age, preterm birth, low birth weight, gestational age, etc. | An increase in residential greenness was generally associated with higher birth weight and lower odds of low birth weight. No associations were found between residential greenness and preterm birth and small gestational age. |
| Islam et al.[49] | 23 studies including 10 cohort studies, 11 cross-sectional studies, and 2 studies without a study design explained | NDVI, distance to greenspace, and street tree density, among others. | Perinatal health (e.g., birth weight, gestational age, atopic dermatitis), physical activity, respiratory health (e.g., asthmatic symptoms, wheezing) and psychological health (e.g., memory, attentiveness, emotional well-being, etc.) | An increase in greenspace was associated with increased birth weight, decreased risk for low birth weight, increased levels of physical activity, lower risk of obesity, and inattentiveness. Associations between greenspace and respiratory diseases were mixed. |
| Kim et al.[55] | 27 studies including 14 cross-sectional studies, 5 quasi-experimental studies, 5 randomized controlled trials, and 1 crossover trial, 1 cohort study, and 1 longitudinal study | NDVI, walking in forests, and gardening activities, among others | Physiological benefits, psychological benefits, social health, perceived general health, and physical activity | Greenspace was improved physiological and psychological indicators as health as well as expanded the social networks of older people. |
| Luo et al.[47] | 57 studies (67 analyses) including 46 cross-sectional studies and 11 cohort studies | Residential proximity to greenspaces, NDVI, proportion of greenspace, and number of parks in a certain area, among others | Weight status (e.g., body mass index or BMI, waist circumference, overweight, obesity, etc.) | More than half of the reviewed studies reported beneficial associations between greenspace and overweight/obesity; meta-analyses showed that NDVI, but not other metrics, was associated with lower odds of overweight/obesity. |
| Mmako et al.[43] | 19 studies including 12 qualitative studies, 4 quantitative studies, and 3 mixed-methods studies | Attending to plants and animals, nature inspired crafts, exercise and social interaction, and walking outdoors | Engaging in meaningful activities, empowerment, positive risk taking and reinforcing identity | Greenspace may enable an active and meaningful community-life, despite cognitive decline. |
| Putra et al.[42] | 15 studies including 6 cross-sectional studies, 6 experiments, and 3 longitudinal studies | NDVI, percentage of greenspace, residential proximity to greenspace, land cover map, and Google Street View, among others | Prosocial behavior | Exposure to greenspace may potentially increase prosocial behavior among children and adolescents but the volume and quality of evidence was not yet sufficient to draw conclusions on causality. |
| Rojas-Rueda et al.[37] | 9 studies all of which were cohort studies | NDVI | All-cause mortality | Increased residential greenness was associated with decreases in all-cause mortality. |
| Rugel and Brauer[40] | 51 studies (12 on greenspace) including 25 prospective cohort studies, 6 ecological studies, 10 cross-sectional studies, 4 retrospective cohort studies, 2 case-control studies, one case-crossover, 1 individual-level time series study, 1 ecological time-series study, and 1 study integrating both ecological and cross-sectional data | NDVI, gardening, number of greenspaces, and access to greenspace, among others | Diabetes, term birthweight, respiratory diseases, infantile atopic dermatitis, mortality, acute ischemic stroke, CVD, asthma and mortality | There was limited evidence for direct associations between natural environments exposure and chronic respiratory diseases and adverse reproductive outcomes; there was evidence that associations between natural environments and COPD were partially explained by adverse effects of traffic-related air pollution. |

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**Table 1.** *Continued*

| Author(Year) | Included Studies | Exposure(s) | Outcome(s) | Finding(s) |
|---|---|---|---|---|
| Shin et al.[41] | 13 studies including 7 cross-sectional studies, 5 intervention studies, 2 randomized controlled trials, and 1 case report | NDVI, tree canopy, land cover, natural amenity index, neighborhood access to park or forest, and window facing to greenspace from home, among others | Sleep | Higher greenspace exposure was associated with a reduced risk for short sleep and poor sleep quality. |
| Shuda et al.[38] | 12 studies including 8 cross-sectional studies and 4 RCTs | Walking in a natural setting, nature sounds, and viewing a color/sound tape of natural environment, among others | Perceived stress and physiologic stress | There was an inverse relationship between nature exposure and various physiologic and perceived stress. |
| Thomsen et al.[46] | 113 studies, of which 74% used quantitative data, 18% used qualitative data, and 8% used a mixed-methods approach | Wildland recreation activities like hiking, camping, and paddling sports | Physical activity, cardiovascular health, muscle strength/bone, mass endurance, obesity, blood pressure, respiratory health, flexibility, sleep quality, self-esteem, emotional well-being, perceived stress/anxiety, family friend functioning, coping with illness/disorder, quality of life, hopelessness/depression, flourishing/happiness/joy, youth behavioral/emotional, and mindfulness | Wildland recreation has the potential to improve physical and mental health, including physical activity, self-esteem, and perceived stress. |
| van den Bogerd et al.[44] | 37 studies including 18 experimental and intervention studies and 19 cross-sectional or cohort studies | Campus greenspace | Students' well-being, academic outcomes, and outcomes related to the pathways of mitigation, restoration, and instoration | There was limited evidence for the effects of nature in the study environment on students' well-being, academic outcomes, or outcomes related to the possible underlying pathways. |
| Wolf et al.[45] | 201 studies including 56 experimental studies, 26 natural/quasi-experimental studies, 11 longitudinal studies, 69 cross-sectional studies, 24 modelling studies, and 14 time-series studies | Experience or visit to forest or woodland, canopy cover, individual trees, clusters of trees, associated measures like pollen, moss, and tree loss to emerald ash borer; viewing images/tapes of trees, forest/woodland/land cover, experiencing trees in a park, and view of trees/forest through a window | Psychological and cognitive outcomes like mental acuity, stress; physiological measures such as heart rate, cortisol, and glucose levels; self-reported symptoms of illness and allergies; modelling of human health impacts related to heat and air quality; actual air quality, hospitalization and medical records, medication usage, neurological measures, etc. | Greenspace can reduce environmental hazards levels like air pollution, ultraviolet radiation, heat exposure, and pollen; greenspace can also restore capacities like attention restoration, mental health, stress reduction, and clinical outcomes; greenspace can build capacities including birth outcomes, active living, and healthy weight status. |
| Yuan et al.[7] | 22 studies (8 in the meta-analysis) including 18 cohort studies and 4 cross-sectional studies | NDVI, walkable greenspaces near the residence, urban greenspace visits, and number or size of parks in a certain area, among others | Mortality and cardiovascular outcomes | Most studies showed reductions in the risk of all-cause mortality and total cardiovascular disease with increased in residential greenness. |
| Zhang et al.[9,19] | 14 studies including 10 cross-sectional studies, 3 controlled experiments, and 1 longitudinal study | NDVI, percentage of greenspace for a certain area, and views to greenspace, among others | Mental well-being | There were beneficial associations between greenspace exposure and reduced stress, positive mood, less depressive symptoms, better emotional well-being, improved mental health and behavior, and decreased psychological distress in adolescents. |
| Andersen et al.[54] | 20 human studies with pre-post study design | Forest bathing | Pro- or anti-inflammatory cytokines in serum, numbers and percentages of immune cell subsets and expression of cytotoxic mediators, and cytotoxic NK cell activity | There exist positive effects of nature exposure on immunological health parameters, such as anti-inflammatory, anti-allergic, anti-asthmatic effects, or increased natural killers cell activity. |

(*Continued on next page*)

Table 1. *Continued*

| Author(Year) | Included Studies | Exposure(s) | Outcome(s) | Finding(s) |
|---|---|---|---|---|
| Davis et al.[52] | 45 studies including 36 cross-sectional studies, six longitudinal studies, two pseudo-experimental studies, and one case-control study | NDVI, proportion of nature environment, distance to nearest nature environment, reported amount or quality of greenness, time spent in nature environment | Academic achievement, emotional and behavioral functioning, well-being, social functioning, cognitive skills, prevalence of doctor diagnosed disorders | There was sufficient evidence for NDVI and emotional and behavioral well-being, but the evidence for other comparisons were limited. |
| Li et al.[51] | 29 studies including 24 longitudinal studies and 5 cross-sectional studies | Lifelong exposure to NDVI, land cover/land use class, access to public greenspace, access to private greenspace, tree cover, urbanicity, self-reported frequency, self-reported duration, quality of public space audit, self-reported quality | Incidence of mental disorders, psychiatric symptoms, emotions, behavioral problems, cognitive function, and subjective well-being | Early-life nature exposure was generally beneficially associated with five domains of mental health including incidence of mental disorders, psychiatric symptoms and emotions, conduct problems in children, cognitive function, and subjective well-being, although inconsistencies were also reported. |
| Porcherie et al.[53] | 29 studies including 19 cross-sectional studies, 4 cohort studies, 2 case-control studies, two qualitative studies, one quasi experimental studies, and one systematic review and meta-analysis | Playgrounds or recreational areas, and coverage or distance to natural space, NDVI, census unit, and proportion of land cover | Lung cancer, bladder cancer, breast cancer, skin cancer, larynx cancer, non-specific cancer mortality, non-specific carcinogenic risk, and prostate cancer. | Evidence concerning greenspace and cancer risk is limited and mixed. |

A handful of studies have also explored school greenspace and students' academic performance, but a systematic review by Browning and Rigolon reported that the evidence was insufficient to support a link between them. Jo et al.[30] concluded that visual contact with flowers, green plants, and wooden materials had more positive effects on cerebral and autonomic nervous activities than viewing built environments without these natural elements. A systematic review of 20 human studies also reported that there exist positive effects of nature exposure on immunological health parameters.[54] Effects of greenspace on hormones and brain activity have been evaluated, but the effects were based on too few studies and participants to draw conclusions.[20]

## DISCUSSION

### Key findings

This umbrella review included a total of 40 systematic reviews (9 with meta-analyses and 31 without meta-analyses) and the vast majority of them were published since 2019. The primary studies included in these systematic reviews and meta-analyses had investigated more than 100 health outcomes and covered populations across the lifespan; however, they were mostly cross-sectional and carried out in high-income countries. Greenness exposures were evaluated using both objective and subjective parameters but varied greatly across studies. Overall, we observed that exposure to greenspace was beneficially associated with all-cause and stroke-specific mortality, total CVD morbidity, cardiometabolic factors, mental disorders, low birth weight, and physical inactivity. We also observed that greenspace exposure was beneficially associated with sleep problems, urban crime rate, and immunological health parameters in the singular review articles that studied each of these respective outcomes. In contrast, exposure to greenspace was not associated with stroke, coronary heart disease, preterm birth, small gestational age, asthma, and allergic rhinitis in the included systematic reviews. Evidence for other health outcomes, including cancer, respiratory-specific mortality, and hormone levels, was limited and not conclusive. AMSTAR2 evaluations indicated that most of the included systematic reviews and meta-analyses had one or more limitations in their methodology, which may have comprised the credibility of the pooled evidence.

### Potential mechanisms underlying greenspace and health

Several mechanisms have been proposed to explain the beneficial health effects of greenspace. First, physical activity is a well-documented protective factor for health, and living close to greener areas may encourage people to engage in physical activity more often and/or more vigorously.[56] Three of the included systematic reviews provided support for this mechanism by concluding that greenspace exposure was positively associated with physical activity levels.[23,31,49] Further, Vanaken and Danckaerts reported that physical activity mediated the beneficial associations between greenspace exposure and emotional and behavioral problems.[26] Second, greenspace can mitigate environmental hazards, such as air pollution, noise, and air temperature,[5] which are well-documented environmental risk factors for a range of health outcomes.[57–59] Dzhambov and colleagues[60] carried out a scoping review of studies testing pathways linking greenspace to health and found that 43 studies explored the mediating role of air pollution, 11 explored the mediating role of noise, and 5 explored the mediating role of heat. Significant mediating effects were found in about half of these studies.[60] Stanhope et al. has recently suggested that attention should also be placed on the potential of greenspace to mitigate artificial light at night and its downstream health impacts.[61–63] Third, *stress reduction theory*[64] and *attention restoration theory*[65] propose that greenspace provides the opportunity to restore attention, alleviate stress, and improve relaxation. Each of these are closely related to numerous health benefits.[5] Consistent with this, several systematic reviews included in this

**Table 2.** Methodological quality of included systematic reviews on green space and health with or without meta-analyses (N = 40)

| | **AMSTAR 2 items** | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Author (year)** | **I** | **II*** | **III** | **IV*** | **V** | **VI** | **VII*** | **VIII** | **IX*** | **X** | **XI*** | **XII** | **XIII*** | **XIV** | **XV*** | **XVI** |
| Bowler et al.[20] | N | P | Y | P | Y | N | P | Y | N | N | Y | Y | Y | Y | Y | Y |
| van den Berg et al.[21] | N | N | Y | P | Y | Y | N | Y | P | N | N/A | N/A | Y | Y | N/A | N |
| de Keijzer et al.[22] | N | N | Y | P | N | N | P | Y | Y | N | N/A | N/A | Y | Y | N/A | Y |
| Kondo et al.[23] | N | N | Y | P | Y | N | N | Y | N | N | N/A | N/A | N | N | N/A | Y |
| Lambert et al.[11] | N | N | Y | P | Y | Y | P | Y | Y | N | Y | Y | Y | Y | N | Y |
| Houlden et al.[28] | Y | P | Y | P | Y | N | N | Y | Y | N | N/A | N/A | Y | Y | N/A | Y |
| Lambert et al.[25] | Y | N | Y | P | Y | Y | P | Y | Y | N | N/A | N/A | Y | Y | N/A | Y |
| Rautio et al.[27] | N | N | Y | P | Y | Y | N | Y | P | N | N/A | N/A | Y | Y | N/A | N |
| Schulz et al.[24] | N | N | Y | P | N | N | N | Y | P | N | N/A | N/A | Y | Y | N/A | Y |
| Twohig-Bennett and Jones[4] | Y | P | Y | P | Y | N | N | Y | Y | N | Y | Y | Y | Y | N | Y |
| Vanaken and Danckaerts[26] | N | N | Y | P | N | N | N | Y | N | N | N/A | N/A | N | N | N/A | Y |
| Browning and Rigolon[35] | N | N | N | P | Y | Y | N | P | P | N | N/A | N/A | Y | N | N/A | Y |
| Hunter et al.[31] | Y | P | Y | P | Y | Y | N | Y | P | N | N/A | N/A | Y | Y | N/A | Y |
| Jo et al.[30] | N | N | Y | N | N | N | N | P | N | N | N/A | N/A | N | N | N/A | Y |
| Lakhani et al.[34] | Y | P | Y | P | N | N | N | P | P | N | N/A | N/A | Y | N | N/A | Y |
| Lambert et al.[36] | Y | P | Y | P | Y | Y | N | Y | N | N | N/A | N/A | Y | Y | N/A | Y |
| Mygind et al.[33] | Y | P | Y | P | Y | N | N | Y | Y | N | Y | Y | Y | Y | N | Y |
| Roberts et al.[32] | Y | P | Y | P | Y | Y | N | Y | P | N | Y | Y | Y | Y | Y | Y |
| Rojas-Rueda et al.[37] | Y | P | Y | N | Y | Y | N | Y | P | N | Y | Y | Y | Y | N | Y |
| Shepley et al.[29] | N | N | Y | P | Y | Y | N | P | N | N | N/A | N/A | N | N | N/A | Y |
| de Keijzer et al.[39] | N | N | Y | Y | Y | N | N | Y | Y | N | N/A | N/A | Y | Y | N/A | Y |
| Hartley et al.[48] | N | N | Y | P | N | N | N | N | N | N | N/A | N/A | N | N | N/A | N |
| Hu et al.[8] | Y | N | Y | P | Y | Y | N | Y | Y | N | Y | Y | Y | Y | Y | Y |
| Islam et al.[49] | N | N | Y | Y | Y | N | N | P | N | N | N/A | N/A | N | N | N/A | Y |
| Kim et al. (2020) | N | N | Y | Y | Y | N | N | P | N | N | N/A | N/A | N | N | N/A | N |
| Luo et al.[47] | N | N | Y | Y | Y | Y | N | Y | Y | N | Y | Y | Y | Y | Y | Y |
| Mmako et al.[43] | N | N | Y | Y | N | N | N | P | Y | N | N/A | N/A | N | N | N/A | Y |
| Putra et al.[42] | N | N | Y | Y | Y | Y | N | Y | Y | N | N/A | N/A | N | N | N/A | Y |
| Rugel and Brauer[40] | Y | P | Y | Y | N | N | N | Y | Y | N | N/A | N/A | Y | Y | N/A | Y |
| Shin et al.[41] | N | N | Y | P | Y | N | N | Y | Y | N | N/A | N/A | Y | N | N/A | Y |
| Shuda et al.[38] | N | N | Y | P | N | N | N | P | Y | N | N/A | N/A | Y | Y | N/A | Y |
| Thomsen et al.[46] | N | P | Y | N | N | N | N | Y | N | N | N/A | N/A | N | N | N/A | N |
| van den Bogerd et al.[44] | Y | Y | Y | P | Y | N | N | Y | Y | N | N/A | N/A | Y | Y | N/A | Y |
| Wolf et al.[45] | N | N | Y | Y | Y | N | N | P | Y | N | N/A | N/A | Y | N | N/A | Y |
| Yuan et al.[7] | Y | Y | Y | Y | Y | Y | N | Y | P | N | Y | Y | Y | Y | Y | Y |
| Zhang et al.[9,19] | Y | Y | Y | Y | Y | N | N | Y | N | N | N/A | N/A | Y | Y | N/A | Y |
| Andersen et al.[54] | N | N | Y | Y | N | N | N | Y | Y | N | N/A | N/A | Y | N | N/A | Y |
| Davis et al.[52] | N | N | Y | Y | Y | Y | N | Y | N | N | N/A | N/A | N | Y | N/A | Y |
| Li et al.[51] | N | N | Y | Y | Y | Y | N | Y | Y | N | N/A | N/A | Y | Y | N/A | Y |
| Porcherie et al.[53] | Y | Y | Y | Y | Y | Y | N | Y | N | N | N/A | N/A | N | Y | N/A | Y |

N, no; Y, yes; P, partly; N/A, not applicable since no meta-analysis was conducted.
*Critical domains.

umbrella review concluded that greenspace exposure does have beneficial effects on mental health.[21,23,45,46] Finally, exposure to greenspaces may increase microbial diversity and alter human microbiota composition,[63,66] which further leads to positive effects in human health.[6,67] We did not identify any reviews on greenspace exposure, microbial diversity, and human health. Despite the above possible hypotheses, the exact mechanisms underlying greenspace and health are complex and remain unclear, which are thus urgently needed to be uncovered by future mechanistic studies.

### Strengths and limitations

This umbrella review has some strengths. First, this is the most comprehensive "tertiary-level" article that summarizes and assesses the evidence on greenspace and human health using a pooled sample of systematic reviews and meta-analyses, which otherwise would be difficult to be obtained from individual primary studies or isolated systematic review. These tertiary-level studies are higher on the hierarchy of evidence than other study designs, including primary- and secondary-level studies. Second, we applied a comprehensive search of three international databases to identify relevant systematic reviews, and study selection and data extraction were carried out by two independent authors. The Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines were rigorously followed, and we assessed the methodological quality of the included articles with the AMSTAR2 checklist. This provided an objective appraisal for the current evidence, identified gaps and limitations of the existing literature, and could give some hints and guidance for future systematic reviews. However, during the AMSTAR 2 appraisal process, we observed that the methodological quality of the included systematic reviews and meta-analyses should be critically reevaluated.[68] Most systematic reviews only performed narrative evidence synthesis rather than quantitative meta-analyses. Meta-analysis may provide more precise effect estimates of greenspace exposure than individual studies, which are of significance for policy makers, practitioners, and researchers in this field to take targeted strategies to improve greenness levels, perform greenness intervention, evaluate current evidence, and improve such studies in future. The underuse of meta-analytical pooling thus has hindered the reporting of quantitative effect estimates, appraisal of the robustness of the effect estimates, and detection of publication bias. However, a meta-analysis is not an option in systematic reviews when there is high methodological or statistical heterogeneity as well as limited study numbers. Also, nine of ten systematic reviews did not fully account for the primary studies they excluded; exclusions were relatively invisible and might have caused exclusion (or inclusion) bias. More than half of the reviews did not report an *a priori* well-developed protocol, which might have increased the risk of sampling bias, selection bias, and within-study bias. Another 60% did not extract data and 30% did not select studies in duplicate, which challenged the accuracy of the extracted data and the eligibility of studies for inclusion. The sources of funding for the primary studies were not reported in all the included systematic reviews. Components of PECO were absent from more than half of the included systematic reviews, and the risk of bias was not assessed in several of the included systematic reviews. These flaws might have reduced the quality of synthesized evidence and reporting standardization. Finally, our umbrella review could only synthesize the associations of greenspace with health outcomes in the published systematic reviews, and thus we might have missed or underestimated associations not covered in these systematic reviews (e.g., latest original high-quality studies that may be neglected).

In addition, interpretation of findings from this umbrella review was also limited by the primary studies included in the systematic reviews. The cross-sectional design of most of the primary studies precludes us from establishing a causal link between greenspace exposure and health outcomes. Second, the short follow-up period in experimental/intervention studies has limited the ability to evaluate long-term effects of greenspace exposure.[31] An ideal greenspace exposure metric would include different dimensions, such as quality, quantity, use of greenspace, physical access, visual/auditory access, biodiversity, and composition.[22] However, most of the primary studies evaluated only one or two dimensions of greenspace exposure, which is far from a comprehensive assessment. Among the objective parameters, vegetation indexes derived from satellite images (e.g., NDVI, soil adjusted vegetation index, and enhanced vegetation index) within various buffers were commonly used, but these indexes are limited in differentiating specific vegetation types and species.[5,69] Furthermore, health outcome assessment was heterogeneous between studies. Questionnaires and self/parental reports were commonly used but doctor-diagnosed outcomes were rarely used. Most studies to date were also from European countries and North America. The generalizability of the current evidence to other geographical areas is limited, although the bodies of literature from China and some other Global South countries is mounting. Finally, in addition to only a few health outcomes (e.g., all-cause mortality and overweight/obesity) that were widely explored, evidences concerning most of the studied health outcomes were based on a small number of studies.

### Concluding remarks and future perspectives

The current evidence shows protective effects of greenspace exposure on aspects of cardiovascular health, mental health, low birth weight, mortality, physical activity, sleep quality, urban crime, and immunity function. The effects of exposure on other health outcomes are limited or inconclusive. However, this evidence is drawn largely from cross-sectional studies with high levels of heterogeneity and higher-income countries. Better designed primary studies are needed to validate the association between greenspace and health. Particularly needed are longitudinal or intervention study designs to test for cause-and-effect; accurate and dynamic greenness exposure assessments to account for dimensions beyond the presence/absence of greenness; non-linear relationships between greenspace and health; study populations outside of higher-income countries to lower- and middle-income countries; "gold standard" health outcome measures and full adjustment for confounding factors; improved results reporting, such as providing numerical estimates and describing bias concerns; and mediation analyses to explore underlying mechanisms. In addition, future systematic reviews should strictly follow standard guidelines to improve their methodological quality, including comprehensive literature search, accurate literature selection and data extraction, assessments of both study quality and risk of bias, use of appropriate statistical method (particularly for meta-analysis), and detailed results reporting.

## METHODS

We performed this umbrella review following the PRISMA reporting guideline (Table S1 in the supplemental information).[70]

### Literature search and selection criteria

We systematically searched three international electronic databases—PubMed, Embase, and Web of Science—from database inception to June 28, 2020, to identify peer-reviewed systematic reviews with or without meta-analyses of studies concerning greenspace exposure and any human health outcome. Our search strategy used a combination of search terms related to greenspace (i.e., "green space," "greenspace," "greenness," "greenery," "normalized difference vegetation index," "soil adjusted vegetation index," "enhanced vegetation index," "vegetation," and "leaf area index") and systematic review and meta-analysis (i.e., "systematic review" OR "meta-analysis") (a detailed search strategy is shown in Table S2). We also manually screened the reference lists of the retrieved systematic reviews and meta-analyses to identify additional relevant records.

All records identified were downloaded into a reference manager (Noteexpress 3.2., Aegean Software, Beijing, China). Duplicates were deleted using the innate function of the software, and the remaining records were screened for eligibility by two independent authors (B.-Y.Y. and L.-X.H.). We deleted irrelevant articles from the remaining records by reading first the titles and then the article abstracts. Last, we evaluated the full text of the articles for eligibility. Any discrepancies during the process were resolved by a discussion with a third author (T.Y.Z.). We developed the inclusion criteria based on the overall PECO framework: (1) *population*—studies of human populations regardless of age, sex, race, geographical region, and health status; (2) *exposure*—studies of greenspace exposure, including residential greenspace (evaluated using vegetation index, proportion of greenspace, proximity to greenspace, or number of greenspaces in a certain area, etc.), doing activities (e.g., running or walking in a nature environment as well as gardening), and viewing simulations of greenspaces or landscapes with leafy green vegetation; (3) *comparator*—studies comparing health effects between individuals exposed to different greenspace levels; and (4) *outcome*—studies investigating any health outcome(s), such as diseases, conditions, symptoms, mortality, and behaviors.[71] In addition, we did not apply any restriction in study design for the primary studies included in systematic reviews and meta-analyses.

We excluded primary studies, non-human studies, and conference abstracts. We also excluded articles published in languages other than English. For duplicate articles on the same topic, we included only those published most recently, included most primary studies, or had the highest methodological quality. For articles investigating multiple or partially overlapping health outcomes, we included all the articles but focused only on the one(s) in results reporting and interpreting.

### Data extraction

Two authors (B.-Y.Y. and L.-X.H.) independently performed data extraction, and discrepancies were resolved by discussion with a third author (T.Y.Z.). For each eligible systematic review, the following information was extracted: authors, publication year, type of study (i.e., systematic review with meta-analysis versus systematic review without meta-analysis), literature search results (i.e., number of databases and date of literature search), main findings, and characteristics of the included primary studies, including study design(s), age ranges, sample sizes, greenspace assessment methods, and health outcome(s).

### Methodological quality assessment

Two authors (B.-Y.Y. and T.Y.Z.) assessed the methodological quality of the included systematic reviews and meta-analyses using the AMSTAR2″ checklist.[68] Any discrepancy was discussed with a third author (L.-X.H.). The AMSTAR2 checklist contains 16 items that include questions related to (1) the use of the PECO framework as study question or inclusion criteria, (2) *a priori* protocol for the review, (3) the selection criteria for the study design, (4) the comprehensiveness of the literature search strategy, (5) the number of authors performing the literature selection, (6) the number of authors performing the data extraction, (7) the reporting of the characteristics of the excluded studies, (8) the reporting of the characteristics of the included studies, (9) the risk of bias assessment for the included studies, (10) the reporting of the sources of funding in the included studies, (11) the use of appropriate statistical methods for any meta-analyses reported, (12) the impact of risk of bias in the included studies on the pooled results, (13) the explanation for the risk of bias in the included studies and its impact on the results of the review, (14) the explanation for the heterogeneity in the review, (15) the investigation of publication bias, and (16) the reporting of conflicts of interest in the review. Of these, items 2, 4, 7, 9, 11, 13, and 15 were identified as critical domains and the remaining were considered non-critical domains by the authors checklists. We chose not to use the AMSTAR2 checklist to rate the overall quality of each systematic review because we observed in the initial article search that many of the included reviews did not perform meta-analyses, which are closely related to two critical domains (items 11 and 15) and one non-critical domain (item 12) of the AMSTAR2 checklist.

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## AUTHOR CONTRIBUTIONS

B.-Y.Y., G.-H.D., and Y.Y. had full access to all of the study data and take responsibility for the integrity of the data and the accuracy of the data analysis. B.-Y.Y., T.Z., and L.-X.H. drafted the manuscript. T.Z., L.-X.H., and B.-Y.Y. performed literature search, study selection, and data extraction. J.H., S.C.D., B.J., L.D.K., X.-X.L., Y.-N.L., P.J., S.L., W.-Z.H., G.C., X.-W.Z., and L.-W.H. revised the manuscript and interpreted the results. B.-Y.Y., Y.Y., and G.-H.D. conceived, designed, and supervised the study and revised the manuscript. All authors contributed to the critical reading of, and commented on, the manuscript, helped to interpret the data, and approved the final manuscript.

## DECLARATION OF INTERESTS

The authors declare no competing interests.

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## SUPPLEMENTAL INFORMATION

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