Credibility of the evidence on green space and human health: an overview of meta-analyses using evidence grading approaches

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Summary

Background Green space is an important part of the human living environment, with many epidemiological studies estimating its impact on human health. However, no study has quantitatively assessed the credibility of the existing evidence, impeding their translations into policy decisions and hindering researchers from identifying new research gaps. This overview aims to evaluate and rank such evidence credibility.

Methods Following the PRISMA guideline, we systematically searched PubMed, Web of Science, and Embase databases for systematic reviews with meta-analyses concerning green spaces and health outcomes published up to January 15, 2024. We categorized the credibility of meta-analytical evidence from interventional studies into four levels (i.e., high, moderate, low, and very low) using the Grading of Recommendation, Assessment, Development and Evaluations framework, based on five domains including risk of bias, inconsistency, indirectness, imprecision, and publication bias. Further, we recalculated all the meta-analyses from observational studies and classified evidence into five levels (i.e., convincing, highly suggestive, suggestive, weak, and non-significant) by considering stringent thresholds for *P*-values, sample size, robustness, heterogeneity, and testing for biases.

Findings In total, 154 meta-analysed associations (interventional = 44, observational = 110) between green spaces and health outcomes were graded. Among meta-analyses from interventional studies, zero, four (wellbeing, systolic blood pressure, negative affect, and positive affect), 20, and 20 associations between green spaces and health outcomes were

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graded as high, moderate, low, and very low credibility evidence, respectively. Among meta-analyses from observational studies, one (cardiovascular disease mortality), four (prevalence/incidence of diabetes mellitus, preterm birth, and small for gestational age infant, and all-cause mortality), 12, 22, and 71 associations were categorized as convincing, highly suggestive, suggestive, weak, and non-significant evidence, respectively.

Interpretation The current evidence largely confirms beneficial associations between green spaces and human health. However, only a small subset of these associations can be deemed to have a high or convincing credibility. Hence, future better designed primary studies and meta-analyses are still needed to provide higher quality evidence for informing health promotion strategies.

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Research in context

Evidence before this study

A comprehensive search of three electronic databases (PubMed, Web of Science, and Embase) was performed to identify relevant systematic reviews with meta-analyses exploring the association between green space exposure and human health up to January 15, 2024. Our search strategy employed a combination of terms related to green space (i.e., "green space," "greenspace," "greenness," "greenery," "normalized difference vegetation index," "soil adjusted vegetation index," "enhanced vegetation index," "vegetation," "leaf area index," "park," and "natural environment") and overview of meta-analyses (i.e., "overview" and "umbrella review"). We found only one prior umbrella review on green spaces and health, which just included reviews up to June 28, 2021. The prior umbrella review largely confirmed the overall beneficial association between green spaces and health, but it did not quantitatively grade the credibility of the pooled evidence.

Added value of this study

In this study, we provide a comprehensive assessment of the credibility of existing systematic reviews with meta-analyses investigating the associations between green spaces and human health. Our study shows that only a limited number of the associations can be graded as high-credibility evidence. Our findings contribute to the field by providing a rigorous evaluation of the evidence landscape. High-credibility evidence can be used to aid policymakers and health professionals in developing green space-based strategies to improve human health. Meanwhile, low-credibility evidence can be used to help researchers in the green spaces and health field to find research gaps.

Implications of all the available evidence

The existing body of evidence predominantly supports the beneficial associations between green spaces and human health. However, it is crucial to acknowledge that only a fraction of these associations can be considered to have high or convincing credibility and have certain translational and practical values for making policy decisions and health promotion strategies. Most of the associations on green spaces and health have weak credibility and thus need to be further validated in future studies.

Introduction

The global urban population has experienced significant growth in recent decades, leading to various environmental challenges, including the reduction of access to natural environments.[1] Within urban areas, green spaces such as parks, forests, roadside trees, and gardens play a critical role in human health through multiple pathways. These pathways include reducing stress, restoring attention, enhancing social contact, promoting outdoor physical activity, mitigating urban-related environmental hazards (e.g., air pollution, heat island effect, and noise), as well as enriching microbial diversity.[2–4] As a result, investigating the potential impact of exposure to green space on human health has garnered considerable attention from researchers worldwide.[3]

A growing body of epidemiological research has investigated the association between exposure to green spaces and various health outcomes,[3] and most have been summarized by many systematic reviews with or without meta-analyses.[5] However, the credibility of the pooled evidence from these systematic reviews remains unclear because they have not undergone objective and quantitative evaluation. Recently, our research group has performed an umbrella review to summarize the existing systematic reviews and meta-analyses, which included 40 reviews up to June 28, 2021. However, we did not perform a credibility assessment, and thus reviews with high credibility still mixed up with those with low credibility.[3] Such lack of credibility assessment hinders the translation of evidence regarding green spaces and health into policy decisions (e.g., urban green space planning) and health promotion strategies (e.g., encouraging frequent visits to green spaces) and limits the researchers in this field to find new research gaps.

Therefore, we graded the credibility of the meta-analysed evidence from interventional studies using the Grading of Recommendation, Assessment, Development and Evaluations (GRADE) framework[6,7] and those from observational studies using an established framework.[7,8] We also assessed the methodological quality of the existing systematic reviews with meta-analyses using the Methodological Quality of Systematic Reviews 2 [AMSTAR2] checklist.[9]

Methods

The overview was conducted following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines (Details are shown in Supplementary Table S1).[10] Two authors (YX and SF) independently selected the studies for inclusion, assessed methodological quality, extracted data, and graded evidence. Any discrepancies were resolved following discussions with a third author (BY).

Literature search

We comprehensively searched three electronic databases—PubMed, Web of Science (all databases), and Embase—to identify relevant systematic reviews with meta-analyses exploring the association between green spaces and human health published in English. The search included articles published from databases inception (PubMed: January 1, 1946; Web of Science: January 1, 1900; Embase: January 1, 1974) up to January 15, 2024, and the detailed search strategies are presented in Supplementary Table S2. Furthermore, citation searching was conducted for all included relevant studies.

Inclusion and exclusion criteria

The inclusion criteria for the study were established based on the Population, Exposure, Comparator, Outcomes, and Study (PECOS) framework.[11] Briefly, systematic reviews with meta-analyses concerning green spaces and human health human were included. Detailed descriptions on the inclusion criteria are shown in Supplementary Table S3. We excluded primary articles, non-human studies, narrative reviews, and systematic reviews without meta-analysis from our current review. Additionally, reviews with incomplete data and meta-analyses based on fewer than three primary studies were also excluded.[12]

Data extraction

For each eligible meta-analysis, we extracted the following information: authors, publication year, countries, sample sizes, green space assessments, health outcomes, primary study designs, key findings, and point effect estimates with corresponding 95% confidence intervals (CI) of the primary studies included in the meta-analysis.

The World Health Organization (WHO)-Europe recommended a minimum of one hectare of green space within 300 m from residential areas.[13] In addition, the neighbourhood was defined as a distance within 500 m from a residence.[14] Therefore, when multiple buffers were used to assess green space exposure in a meta-analysis, we primarily selected effect estimates corresponding to 300 m and 500 m buffers as main results. If estimates with the two buffers were not available, we used the effect estimates the studies provided (e.g., estimates corresponding to 200 m, 1000 m, and mixed multiple buffers). In addition, if two or more meta-analyses focused on the same exposure-outcome association, then the meta-analysis with the highest methodological quality according to the Methodological Quality of Systematic Reviews 2 (AMSTAR2) checklist (Supplementary Table S4) was included (the AMSTAR2 classified the methodological quality into four levels: high, moderate, low, and critically low levels [Supplementary Table S5]),[9,15] and the remaining repeated one(s) was excluded.

Grading the credibility of evidence

For meta-analyses of interventional studies, we evaluated the credibility of the evidence using the GRADE framework, which classifies evidence as high, moderate, low, and very low credibility.[6,7] As recommended by GRADE, level of evidence was determined by five domains, namely, risk of bias (RoB), inconsistency, indirectness, imprecision, publication bias (Supplementary Methods). The level of evidence was initially started with the highest quality, and then downgraded if some domain(s) were not or partly met. For example, a meta-analysis assessing gardening intervention and wellbeing mixed clinical and non-clinical populations, which failed to meet the indirectness domain, and its credibility was thus graded as moderate.[16] In another meta-analysis evaluating exposure to natural environment and salivary cortisol, which failed to meet three domains (i.e., mixed populations and intervention strategies, had less than 50% primary studies with low ROB, and had publication bias), and thus the evidence was graded as having very low credibility.[17]

Since the GRADE framework was primarily developed for assessing the evidence from interventional studies,[18] we thus graded the credibility of the evidence from observational studies using established framework (detailed protocols are shown in Supplementary Methods)proposed by Solmi et al. and Brabaharan et al. in previous umbrella reviews.[7,8] The established framework included eight items, according to which the evidence was classified into five levels: convincing, highly suggestive, suggestive, weak, and nonsignificant (Table 1). For instance, a meta-analysis assessing residential greenness and cardiovascular disease mortality was graded as convincing evidence because it met all eight items (Table 1).[19] In another meta-analysis evaluating NDVI and low birth weight, the *P*-value of the pooled estimate was greater than 10^{-3}, which failed to meet the items of higher-level credibility (i.e., suggestive) and was graded as having weak credibility.[20]

Whenever possible, we extracted necessary data (e.g., *P*-value for meta-analyses, I^2 statistic, sample size, and publication bias) directly from the meta-analyses of observational studies to quantitatively classify the generated evidence against eight items of the grading criteria. If the meta-analysis did not provide the needed data, we either recalculated the meta-analysis (detailed calculations are shown in Supplementary Methods) or contacted the corresponding author for detailed information (only one out of five authors responded). When the required information on item(s) was unobtainable or could not be recalculated, we conservatively considered the item(s) as not meeting the criteria. All statistical analyses were conducted using R software (version 4.2.0).

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Evidence	Criteria
I: Strong	$P < 10^{-6}$[a]; >1000 participants; $P < 0.05$ of largest study in meta-analysis; $I^2 < 50\%$; No small study effect[b]; Prediction interval excludes null value; No excess significance bias[c]; Survive 10% credibility ceiling[d];
II: Highly suggestive	$P < 10^{-6}$[a]; >1000 participants; $P < 0.05$ of largest study in meta-analysis;
III: Suggestive	$P < 10^{-3}$[a]; >1000 participants;
IV: Weak	$P < 0.05$[a];
V: Nonsignificant	$P > 0.05$[a];

[a]*P*-value of meta-analysis. [b]*P*-value from Egger's regression asymmetry test ($P > 0.1$). [c]$P > 0.1$ of excess significance test. [d]With a ceiling of 10%, no meta-analyses gave an I^2 estimate larger than 50% and changed statistically significant result.

***Table 1:* Grading criteria.**

Results
Systematic review retrieval
Initially, our literature search yielded 40,441 records. After removing duplicates by NoteExpress (n = 9199), excluding records by screening the titles and abstracts (n = 31,140), we conducted a full-text screening of 102 systematic reviews. The full-text screening excluded 51 systematic reviews without meta-analysis. The remaining systematic reviews included 261 meta-analyses, which were further assessed for methodological quality according to the AMSTAR2 checklist. After this assessment, we further excluded 71 meta-analyses that had repeated exposure-outcome associations but lower methodological quality (Supplementary Tables S6 and S7). Further, 36 meta-analyses were excluded due to pooling estimates from fewer than three primary studies. Ultimately, 34 systematic reviews incorporating 154 unique meta-analytical results were evaluated for the credibility of evidence (Fig. 1), of which 44 were meta-analyses of interventional studies[16,17,21–28] and 110 were meta-analyses of observational studies (Fig. 1).[19,20,29–50]

Characteristics of the included meta-analyses
The number of primary studies included in the included meta-analyses varied from three (with a minimum

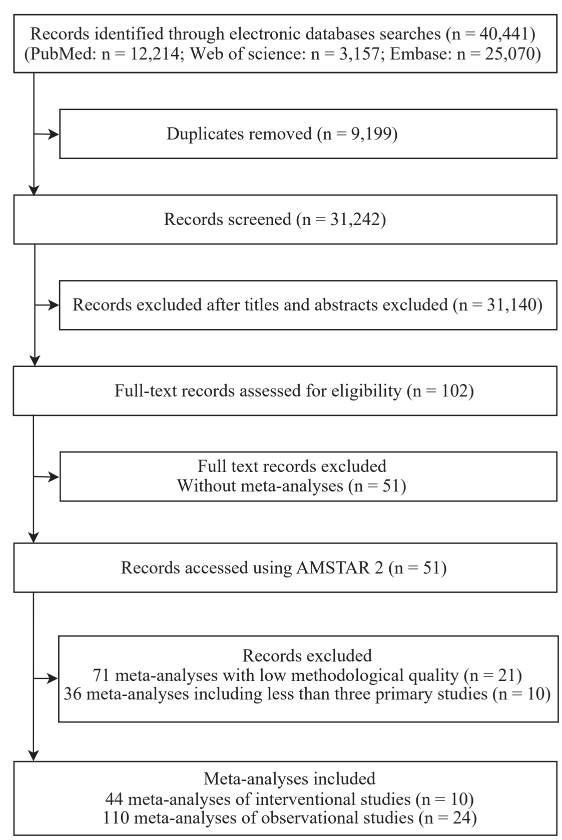

***Fig. 1:* The flow diagram for eligible meta-analysis.** "n" represents number of articles.

threshold of three studies for inclusion) to 45 (Table 2). Among the 44 meta-analyses of interventional studies, 59.1% were derived from randomized control studies only, and 40.9% were from mixed randomized and non-randomized studies. Among the 110 meta-analyses of observational studies, 60 (53.9%) were derived from cross-sectional studies, 40 (35.7%) from cohort studies, and ten (9.1%) from ecological and case–control studies. Green spaces were most frequently assessed through comparisons between green and non-green areas (44.6%), followed by NDVI (33.8%), mixed indicators (20.0%; for example, green space assessed as gardening and mixed activities in green spaces), and percentage of green space (1.5%). The study populations represented a wide range of ages from neonates to the elderly. Geographically, the majority of these populations resided in high-income countries (i.e., countries in North America and Europe), followed by middle-income countries (i.e., countries in South America and Asia). The quality assessment using AMSTAR 2 checklist revealed that 29% and 71% of the systematic reviews were categorized as low quality and critically low quality, respectively (Supplementary Table S6).

Credibility of the evidence from meta-analyses of interventional studies

Based on the GRADE framework, zero, four, 20, and 20 meta-analytical associations of interventional studies were graded as high, moderate, low, and very low credibility evidence, respectively (Table 3; Fig. 2; Supplementary Table S8). Nine, 18, 39, 38, and 29 of the meta-analytical associations were downgraded due to imprecision, inconsistency, high RoB, indirectness, and publication bias, respectively. Further details on each grade of the evidence are presented below.

High-level evidence

None of the 44 meta-analytical associations was categorized as having high-level credibility.

Moderate-level evidence

The associations of green spaces with wellbeing, systolic blood pressure (SBP), negative affect, and positive affect were graded as moderate (Table 3). Specifically, gardening and natural-based intervention could improve wellbeing (pooled standard mean difference [SMD] = 0.37, 95% CI: (0.01–0.73)[16] and decrease negative affect (SMD = –0.52, 95% CI: –0.77 to –0.26),[27] but had no significant effects on positive affect and SBP.[22]

Low-level evidence

A total of 20 associations were graded as low evidence (Table 3). Green space-based interventions (i.e., a specific activity or mixed activities in green spaces including gardening, viewing, walking, and sitting) significantly reduced negative affect, anger, and depression with estimated SMDs ranging from –0.34 to –0.64, significantly increased positive affect, wellbeing, heart rate variability (HRV), attention, and sadness with estimated SMDs ranging from 0.49 to 0.61 and Hedges' g from 0.31 to 0.36, but showed no association with health-related quality of life, anxiety, stress, DBP, serum and salivary cortisol, tranquillity, and energy scores.[16,21–23,25,26,28] In addition, activities in natural environment were associated with decreased pulse rate (mean difference [MD] = –4.03) compared to those in built environment.[17] Individuals exposed to nature showed better self-regulation compared to those exposed to non-nature spaces (Cohen's d = 0.15).[27]

Very low-level evidence

Twenty associations between green spaces and health outcomes were graded as very low, which are detailed in Table 3. Briefly, 13 (65%) of these associations investigated the effects of activities in natural environments on negative affect, self-reported stress, and psychological assessments using semantic differential method, total mood disturbance, restoration outcome scale, and state-strait anxiety inventory, of shinrin-yoku (forest bathing) on anger, anxiety, and depression, and of gardening intervention on depression.[16,17,22,24,28] Five (25%) of the associations investigated the effects of seated relaxation or activities in natural environments on DBP, SBP, heart rate, and HRV.[17,25] Two (10%) of the associations investigated the effects of seated relaxation or activities in natural environments on salivary cortisol.[17,25]

Credibility of the evidence from meta-analyses of observational studies

According to the established framework, only one meta-analytical association fulfilled all the criteria, thereby receiving a strong grade in terms of evidence credibility (Table 4; Fig. 2; Supplementary Table S9). Four, 12, and 22 meta-analytical associations were graded as highly suggestive, suggestive, and weak evidence, respectively Finally, 71 meta-analytical associations were graded as nonsignificant due to the associations did not reach statistical significance. Further details on each grade of the evidence are provided below.

Convincing evidence

The associations of green spaces with cardiovascular disease mortality were graded as strong evidence (Table 4). Specifically, participants residing in areas with green space levels (measured as the percentage of green space in an area or NDVI) at the third quartile (Q3) had a 4% decreased risk of cardiovascular disease mortality (relative risk [RR] = 0.96, 95% CI: 0.94–0.97) compared to those at the first quartile (Q1).[19]

Highly suggestive evidence

The associations between green space exposures and four outcomes (i.e., prevalence/incidence of diabetes mellitus, preterm birth, and small for gestational age

Author	Year	Primary studies	Exposure	Outcome	Findings
Squillacioti et al.[49]	2024	Six studies including two cohort studies and four cross-sectional studies	NDVI	Asthma	No overall significant association was observed between the NDVI assessed within 500-m buffers
Ahmer et al.[47]	2023	31 studies including 26 cross-sectional studies, three cohort studies, one case control study, and one quasi experimental study	NDVI	Birth weight, LBW, PTB, and SGA	Residential green spaces are positively associated with increased birth weight and lower odds of low birth weight, preterm births and SGA deliveries
Tang et al.[50]	2023	35 studies including 10 cross-sectional studies, 18 cohort studies, 4 ecological studies, and 3 case–control studies	NDVI	Incidence/prevalence of asthma, AR, COPD, and lung cancer, mortality of COPD and lung cancer	Increments in NDVI were significantly related to lower rates of asthma incidence, lung cancer incidence, and COPD mortality risk
Li et al. (a)[48]	2023	14 cohort studies	NDVI (multiple buffers)	Cancer incidence, prostate cancer incidence, lung cancer incidence, breast cancer incidence, cancer mortality, lung cancer mortality, colorectal cancer incidence, bladder cancer incidence, and skin cancer incidence	Greenspace exposure measured as NDVI reduces lung cancer and prostate cancer mortality, as well as prostate, lung, and breast cancer incidence
Li et al. (b)[33]	2023	There were 27 longitudinal studies, seven cross-sectional studies, four ecological studies, four case–control studies, and two time-series studies	NDVI (multiple buffers)	Cerebrovascular diseases, neurodegenerative diseases, stroke mortality, Parkinson's disease incidence, and stroke prevalence/ incidence	There existed significant and inverse relationships between the risk of nervous system disease mortality and incidence/prevalence and greenness levels
Liu et al.[34]	2023	18 cross-sectional studies	NDVI and the proportion of green space	Depression and anxiety	Higher green space exposure might be beneficial for depression and anxiety disorders
Wang et al.[40]	2023	48 studies including 19 cohort or longitudinal studies, 18 cross-sectional studies, seven ecological studies, and four case–control studies	NDVI	Allergic diseases including ever asthma, current asthma, AR, allergic rhino conjunctivitis, atopic dermatitis, and food allergy	Exposure to a greener environment at birth reduces the risk of asthma and AR in childhood, and higher greenness exposure decreased odds of current asthma in children
Briggs et al.[16]	2022	12 RCTs	Gardening intervention vs. non-gardening activities	Depression, anxiety, stress and health-related quality of life wellbeing	Gardening related interventions may increase wellbeing and reduce symptoms of depression
Meo et al.[36]	2022	16 studies including three cross-sectional, two longitudinal, and 11 cohort studies	Per interquartile range NDVI (multiple buffers)	Prevalence and mortality of type II diabetes mellitus	An interquartile range higher NDVI significantly decreased the prevalence and mortality of type II diabetes mellitus
Song et al.[26]	2022	24 RCTs consisted of 10 parallel studies and 14 crossover studies	Green space settings vs. non-green space settings	Fatigue, tension, confusion, vigour, depression, and anger from POMS; negative affect and positive affect from PANAS	Compared to non-green space situations, green space exposure was related to decreased negative feelings, increased pleasant emotions, and lower physiological indicators
Zhao et al.[45]	2022	38 articles (52 analysis) including 27 cross-sectional designs, 10 cohort studies, and one case–control study	NDVI, the proportion of greenspace, distance to greenspace	Systolic blood pressure, diastolic blood pressure, and hypertension	Higher NDVI was significantly associated with lower levels of systolic blood pressure and diastolic blood pressure, and higher proportion of greenspaces was associated with lower odds of hypertension
Kelley et al.[23]	2022	Four pre-post matched groups studies	Physical activity in natural outdoor environment vs. indoors	Wellbeing	Physical activity in the natural outdoor environment was associated with higher wellbeing, but limited in superior benefits to that engaged indoors
Sakhvidi et al.[43]	2022	18 studies including six prospective and retrospective cohorts, four case–control, and eight cross-sectional studies	NDVI-300 m	Breast, lung, prostate, skin, all-site cancer, brain, mouth and throat incidence, and all-site cancers mortality	Greenspace could be a potential risk factor for skin cancer, but for the other cancers, the results were non-conclusive
Zagnoli et al.[42]	2022	12 studies including four cross-sectional studies, one case–control study, five cohort studies, one including both cross-sectional and cohort design study, and one ecological study	NDVI, land use/cover	Dementia, Alzheimer's disease and cognitive impairment	A slight inverse association between dementia and greenness at intermediate exposure levels, but not at high levels
Coventry et al.[22]	2021	50 studies including 16 RCTs, 18 controlled studies, and 16 uncontrolled before and after studies	Activities in outdoor green spaces vs. non-nature spaces	Physical health and/or mental health symptoms	Nature-based interventions were effective for improving depressive mood, reducing anxiety, improving positive affect, and reducing negative affect

(Table 2 continues on next page)

Author	Year	Primary studies	Exposure	Outcome	Findings
(Continued from previous page)					
Hu et al.[20]	2021	29 studies including 22 cross-sectional design, six cohort, and one case–control study	NDVI	Birth weight, preterm birth, SGA, LBW	An increase in NDVI was generally associated with higher birth weight and lower odds of LBW
Jia et al.[29]	2021	21 studies including four cohort studies and 17 cross-sectional studies	Access to green space	Children's BMI z-score, children's BMI, and risk of overweight/obesity	More access to green space was associated with lower BMI and weight status among children
Mygind et al.[25]	2021	26 studies including 16 experimental studies and seven quasi-experimental studies	Activities in natural environments vs. urban environments	HRV, serum and salivary cortisol, and salivary cortisol	Seated relaxing and walking in natural environments enhanced HRV more than the same activities in urban environments, but the associations were inconsistent for cortisol concentrations
Qiu et al.[37]	2021	33 studies including 18 cross-sectional studies, 11 cohort studies, and four case studies	NDVI (multiple buffers)	Allergic, respiration, LBW, CVD, obesity, mental health, and blood pressure	High-level residential greenness significantly decreased respiratory disease, LBW, CVD, obesity, mental disorders, and blood pressure
Yao et al.[17]	2021	31 studies including 20 randomized crossover studies, five nonrandomized crossover studies, three randomized parallel group studies, two factorial studies and one single-group crossover study	Exposure to the natural environment vs. built/urban environment	POMS, total mood disturbance, PANAS, state-trait anxiety inventory, semantic differential method, restorative outcome scale, SBP, DBP, HR, HRV, salivary cortisol	Increased natural exposure was associated with decreased levels of salivary cortisol, state-of anxiety, self-reported stress, SBP, DBP, HRV and increased odds of restorative outcomes
Zhao et al.[46]	2021	Eight studies including four cohort, two case–control and two cross-sectional studies	Residential greenness (measured as NDVI, percentage of greenspace, availability of green environment [in $km^2/10^5$ people], and the distance to nearest greenspace)	Cognitive impairment/dementia	Exposure to more greenness was protective for cognitive impairment and dementia
Kua et al.[30]	2021	20 studies including seven longitudinal cohort studies and 13 cross-sectional studies	NDVI	All-cause mortality	Increased levels of greenness exposure were associated with a significant decrease in all-cause mortality
Yao et al. (a)[28]	2021	20 studies including 12 mixed factorial studies, six between-subject studies and two within-subject studies	Exposure to the natural environment vs. built environment	Positive and negative affect	Exposure to the natural environment could increase positive affect and decrease negative affect
Yuan et al.[41]	2021	Eight cohort studies	NDVI	Respiratory disease mortality, all-cause mortality, stroke mortality, CVD mortality, IHD mortality	Greater greenness exposure was associated with a reduced risk of all-cause mortality and stroke mortality in older individuals
Kotera et al.[24]	2020	20 studies including eight non-randomized trials and 12 randomized controlled trials	Shinrin-yoku (forest bathing) and nature therapy	Depression, anger, and anxiety	Shinrin-yoku was effective for reducing negative mental health symptoms, particularly anxiety
Lee et al.[32]	2020	21 studies including 7 cohort studies and 13 cross-sectional studies	NDVI	Term birth weight, birth weight, LBW, very low birth weight, SGA, and preterm delivery	Greater greenness levels were positively associated with birthweight and inversely associated with odds of LBW, SGA, and preterm delivery
Luo et al.[35]	2020	57 articles (67 analyses) including 46 cross-sectional studies and 11 cohort studies	NDVI, proximity to green spaces, proportion of greenspace, and number of parks	Overweight/obesity	Greater NDVI levels were associated with lower odds of overweight/obesity
Zhan et al.[44]	2020	36 studies including 14 cohort studies, two case–control studies, 19 cross-sectional studies, and one ecological study	NDVI, percentage of tree canopy, proximity to green spaces, green space percentage, and distance to nearest green spaces	Birth weight, LBW, SGA, PTB, gestational age and head circumference, and gestational diabetes mellitus	Compared mothers at the lowest greenness levels, those at the higher greenness levels had increased birth weight and head circumference levels as well as reduced odds of LBW, SGA, and mental disorders
Kunpeuk et al.[31]	2020	19 articles including 14 cross-sectional studies, four quasi-experimental studies and one case–control study	Gardeners vs. non-gardeners	BMI	Gardening was significantly associated with lower BMI levels
Weeland et al.[27]	2019	31 studies including 16 (Quasi-) experimental studies and 15 Correlational studies	Correlational studies: residential greenness vs. green-based activities (Quasi-)Experimental studies: exposure to nature vs. not exposure to nature	Self-regulation including cognitive, affective, and behavioural self-regulation	More exposure to nature was associated with better self-regulation both in correlational studies and experimental studies

(Table 2 continues on next page)

Author	Year	Primary studies	Exposure	Outcome	Findings
(Continued from previous page)					
Twohig-Bennett et al.[39]	2018	142 studies including 40 interventional studies and 102 observational studies (including 35 cohort studies, 69 cross-sectional studies, and 18 ecological studies)	Greenspace (assessed as neighbourhood greenspace, greenspace-based interventions, proximity to a large greenspace and comparing green environment with an urban or indoor environment)	Gestational age, PTB, SGA, DBP, SBP, CVD mortality, all-cause mortality, HR, coronary heart disease, HRV, stroke, type II diabetes, high density lipoprotein cholesterol, low density lipoprotein cholesterol, haemoglobin A1C, fasting blood glucose, total cholesterol, triglycerides, dyslipidaemia, salivary cortisol, asthma, and self-reported health	Increased greenspace exposure was associated with decreased levels salivary cortisol, HR, DBP, high density lipoprotein cholesterol, low frequency HRV, PTB, type II diabetes, all-cause mortality, SGA, cardiovascular mortality, stroke incidence, hypertension, dyslipidaemia, asthma, coronary heart disease, and bad self-reported health, as well as increased high frequency HRV
Sadoine et al.[38]	2018	11 observational studies	NDVI	Malaria risk	NDVI was not found to be significantly associated with malaria
Gascon et al.[19]	2016	12 articles including seven ecological design studies, three cohort studies, and two cross-sectional studies	Residential greenness (measured as the percentage of green space in an area or as NDVI)	CVD mortality, lung cancer mortality, and all-cause mortality	Higher residential greenness levels were associated with reduced risk of CVD
Bowler et al.[21]	2010	24 articles including 13 crossover trials, five observational studies, and seven comparison groups	Before vs. after activity in natural environments; natural vs. synthetic environment	Sadness, attention, anger, fatigue, energy, anxiety, tranquillity, systolic blood pressure, diastolic blood pressure, and cortisol concentrations	Exposure to natural environment was associated with reduced odds of anxiety, attention, and sadness

Abbreviation: NDVI, normalized difference vegetation index; AR, allergic rhinitis; RCTs, randomized controlled trials; POMS, The Profile of Mood States; PANAS, Positive and Negative Affect Schedule; CVD, cardiovascular disease; IHD, ischemic heart disease; COPD, chronic obstructive pulmonary disease; SGA, small for gestational age infant; LBW, low birth weight; BMI, body mass index; HRV, heart rate variability; SBP, systolic blood pressure; DBP, diastolic blood pressure; HR, heart rate; PTB, preterm birth.

Table 2: **Characteristics of the included systematic reviews with meta-analyses on green spaces and health (n = 34).**

infants, and all-cause mortality) were graded as highly suggestive evidence (Table 4). Specifically, a 0.1 unit increase in NDVI (multiple buffers) was associated with 1% (95% CI: 0%–3%) reduced odds of preterm birth.[20] Participants at the highest quartile or quintile of green space (assessed as neighbourhood green space, green space-based interventions, proximity to a large green space, or comparing a green environment with an urban or indoor environment) were associated with 19% (95% CI: 14%–24%) decreased odds of small for gestational age infants compared to those at the lowest quartile or quintile of green space levels.[39] Additionally, an interquartile range (IQR) increase in NDVI (multiple buffers) was associated with a 12% (95% CI: 11%–14%) decreased odds of prevalent diabetes mellitus.[36] Moreover, individuals with residential green space levels (measured as the percentage of green space in an area or as NDVI) at the third quartile had 8% (95% CI: 3%–13%) decreased odds of all-cause mortality compared to those at the first quartile.[19]

Suggestive evidence

The associations between green space exposures and 12 health outcomes were graded as suggestive evidence (Table 4). Specifically, a 0.1 unit increase in NDVI was associated with 22.41 g and 0.003 g increase in birth weight (500 m buffer) and term birth weight (multiple buffers), as well as 2%, 12%, 38%, 11%, and 5% reduced odds of neurodegenerative diseases mortality (multiple buffers), obesity (multiple buffers), gestational diabetes mellitus (>300 m buffer), cardiovascular disease (multiple buffers), and respiratory diseases (multiple buffers), respectively.[32,33,35,37,44] Each IQR increase in NDVI (multiple buffers) was associated with 8% reduced odds of diabetes mellitus specific death.[36] Compared with individuals living in lower green space levels (built-up environments or mixed green space metrics), those living in higher green space levels had 12% increased odds of good self-reported health as well as 13% and 28% reduced odds of preterm birth and type II diabetes prevalence, respectively.[39] Additionally, a 10% increase in the percentage of green space was associated with 4% reduced odds of depression.[34]

Weak evidence

The associations between green space and 22 health outcomes were graded as weak evidence, which are detailed in Table 4. Of these weak associations, the most frequently studied outcomes were cardiovascular disorders (36.4%, including stroke, hypertension, DBP, SBP, heart rate, pulse rate, and heart rate variability),[39,45,48] followed by birth outcomes (27.3%, including birth weight, LBW and SGA),[20,47] mortality (13.6%, including all-cause mortality, cancer mortality, and lung cancer mortality),[39,48] and other outcomes (22.7%, depressive symptom, asthma, overweight/obesity, cognitive impairment/dementia, and salivary cortisol).[29,34,39,46,50] The green spaces were mainly measured using NDVI, followed by mixed green space indicators.

Non-significant associations

The evidence for 71 green space–health associations from observational studies were classified as non-significant. A detailed list of these associations can be found in Supplementary Table S10. Among these studied health outcomes, the majority were birth

Author (year)	Intervention	Control	Outcome	Metric	Effect estimates (95% CI)	Grade	Q
Briggs et al. (2022)[16]	Gardening intervention	Non-gardening activities	Wellbeing	SMD	0.37 (0.01, 0.73)	Moderate	CL
Coventry et al. (2021)[22]	Nature-based interventions	Non-natural activities	SBP	SMD	0.06 (−0.20, 0.33)	Moderate	CL
Coventry et al. (2021)[22]	Nature-based interventions	Non-natural activities	Negative affect	SMD	−0.52 (−0.77, −0.26)	Moderate	CL
Coventry et al. (2021)[22]	Nature-based interventions	Non-natural activities	Positive affect	SMD	0.95 (0.59, 1.31)	Moderate	CL
Briggs et al. (2022)[16]	Gardening intervention	Non-gardening activities	Health-related quality of life	SMD	0.06 (−0.45, 0.34)	Low	CL
Briggs et al. (2022)[16]	Gardening intervention	Non-gardening activities	Anxiety	SMD	−0.42 (−1.00, 0.16)	Low	CL
Briggs et al. (2022)[16]	Gardening intervention	Non-gardening activities	Stress	SMD	−0.17 (−0.68, 0.35)	Low	CL
Song et al. (2022)[26]	Green space settings	Non-green space settings	Negative affect	SMD	−0.34 (−0.61, −0.07)	Low	L
Song et al. (2022)[26]	Green space settings	Non-green space settings	Positive affect	SMD	0.57 (0.27, 0.86)	Low	L
Song et al. (2022)[26]	Green space settings	Non-green space settings	Anger	SMD	−0.48 (−0.70, −0.26)	Low	L
Song et al. (2022)[26]	Green space settings	Non-green space settings	Depression	SMD	−0.50 (−0.82, −0.18)	Low	L
Kelley et al. (2022)[23]	Outdoor nature activities	Indoor activities	Wellbeing	SMD	0.49 (0.33, 0.66)	Low	CL
Coventry et al. (2021)[22]	Nature-based interventions	Non-natural activities	DBP	SMD	−0.09 (−0.92, 0.74)	Low	CL
Coventry et al. (2021)[22]	Nature-based interventions	Non-natural activities	Depressive mood	SMD	−0.64 (−1.05, −0.23)	Low	CL
Mygind et al. (2021)[25]	Walking in natural environments	Walking in non-natural environments	HRV	Hedges' g	0.31 (0.06, 0.55)	Low	CL
Mygind et al. (2021)[25]	Walking in natural environments	Walking in non-natural environments	Serum and salivary cortisol	Hedges' g	−0.27 (−0.85, 0.30)	Low	CL
Yao et al. (2021a)[28]	Exposure to natural environment	Exposure to built environment	Positive affect	SMD	0.61 (0.41, 0.81)	Low	L
Yao et al. (2021b)[17]	Exposure to natural environment	Exposure to built environment	Pulse rate	MD	−4.03 (−4.91, −3.15)	Low	CL
Weeland et al.[27]	Exposure to nature actively	Exposure to nature passively	Self-regulation	Cohen's d	0.15 (0.08, 0.22)	Low	CL
Bowler et al. (2010)[21]	Activities in natural environments	Activities in synthetic environments	Attention	Hedges' g	0.32 (0.06, 0.58)	Low	CL
Bowler et al. (2010)[21]	Activities in natural environments	Activities in synthetic environments	Tranquillity	Hedges' g	0.39 (−0.08, 0.86)	Low	CL
Bowler et al. (2010)[21]	Activities in natural environments	Activities in synthetic environments	Sadness	Hedges' g	0.36 (0.08, 0.63)	Low	CL
Bowler et al. (2010)[21]	Activities in natural environments	Activities in synthetic environments	Energy scores	Hedges' g	0.28 (−0.01, 0.57)	Low	CL
Bowler et al. (2010)[21]	Activities in natural environments	Activities in synthetic environments	Anxiety	Hedges' g	0.12 (−0.34, 0.58)	Low	CL
Briggs et al. (2022)[16]	Gardening intervention	Non-gardening activities	Depression	SMD	−0.43 (−0.79, −0.06)	Very low	CL
Kotera et al. (2022)[24]	Shinrin-yoku and nature therapy	No intervention	Anger	Hedges' g	−1.63 (−3.25, −0.01)	Very low	CL
Kotera et al. (2022)[24]	Shinrin-yoku and nature therapy	No intervention	Anxiety	Hedges' g	−1.83 (−3.07, −0.58)	Very low	CL
Kotera et al. (2022)[24]	Shinrin-yoku and nature therapy	No intervention	Depression	Hedges' g	−2.54 (−3.56, −1.52)	Very low	CL
Coventry et al. (2021)[22]	Nature-based interventions	Non-natural activities	Anxiety	SMD	−0.94 (−1.87, −0.01)	Very low	CL
Mygind et al. (2021)[25]	Seated in natural environment	Seated in non-natural environment	HRV	Hedges' g	0.51 (−0.01, 1.03)	Very low	CL
Mygind et al. (2021)[25]	Seated in natural environment	Seated in non-natural environment	Salivary cortisol	Hedges' g	−0.72 (−1.19, −0.25)	Very low	CL
Yao et al. (2021a)[28]	Exposure to natural environment	Exposure to built environment	Negative affect	SMD	−0.47 (−0.71, −0.24)	Very low	L
Yao et al. (2021b)[17]	Exposure to natural environment	Exposure to built environment	Restoration outcome scale	MD	4.82 (−1.87, 11.51)	Very low	CL
Yao et al. (2021b)[17]	Exposure to natural environment	Exposure to built environment	Salivary cortisol	MD	−0.06 (−0.08, −0.04)	Very low	CL
Yao et al. (2021b)[17]	Exposure to natural environment	Exposure to built environment	DBP	MD	−3.17 (−6.01, −0.33)	Very low	CL
Yao et al. (2021b)[17]	Exposure to natural environment	Exposure to built environment	SBP	MD	−3.82 (−6.77, −0.86)	Very low	CL
Yao et al. (2021b)[17]	Exposure to natural environment	Exposure to built environment	SDM-refreshed	MD	16.05 (12.95, 19.15)	Very low	CL
Yao et al. (2021b)[17]	Exposure to natural environment	Exposure to built environment	Total mood disturbance	MD	−6.42 (−12.2, −0.63)	Very low	CL
Yao et al. (2021b)[17]	Exposure to natural environment	Exposure to built environment	State-trait anxiety inventory	MD	−12.48 (−26.61, 1.66)	Very low	CL
Yao et al. (2021b)[17]	Exposure to natural environment	Exposure to built environment	HRV	MD	−0.29 (−0.41, −0.18)	Very low	CL
Yao et al. (2021b)[17]	Exposure to natural environment	Exposure to built environment	Self-reported stress	MD	−0.33 (−0.78, 0.13)	Very low	CL
Yao et al. (2021b)[17]	Exposure to natural environment	Exposure to built environment	Heart rate (bpm)	MD	−3.81 (−4.80, −2.81)	Very low	CL
Yao et al. (2021b)[17]	Exposure to natural environment	Exposure to built environment	SDM-soothed	MD	3.66 (3.23, 4.08)	Very low	CL
Yao et al. (2021b)[17]	Exposure to natural environment	Exposure to built environment	SDM-comfortable	MD	4.34 (3.61, 5.08)	Very low	CL

Abbreviation: CI, confidence interval; Q, quality measured with AMSTAR 2; L, low; CL, critically low; SBP, systolic blood pressure; HRV, heart rate variability; DBP diastolic blood pressure; SMD, standard mean difference; MD, mean difference.

Table 3: **Credibility of the evidence from meta-analyses of interventional studies linking green space and health outcomes (n = 44).**

outcomes, followed by cardiovascular disorders, and metabolic indicators (note: with different green space metrics). The measurement of green spaces was primarily based on NDVI, followed by mixed green space indicators, proportion of green space, and proximity to green spaces.

Discussion

Following a comprehensive literature search and selection, our study rated the credibility of evidence of 154 meta-analyses that synthesized primary studies concerning green spaces and human health outcomes. Green spaces were primarily assessed through

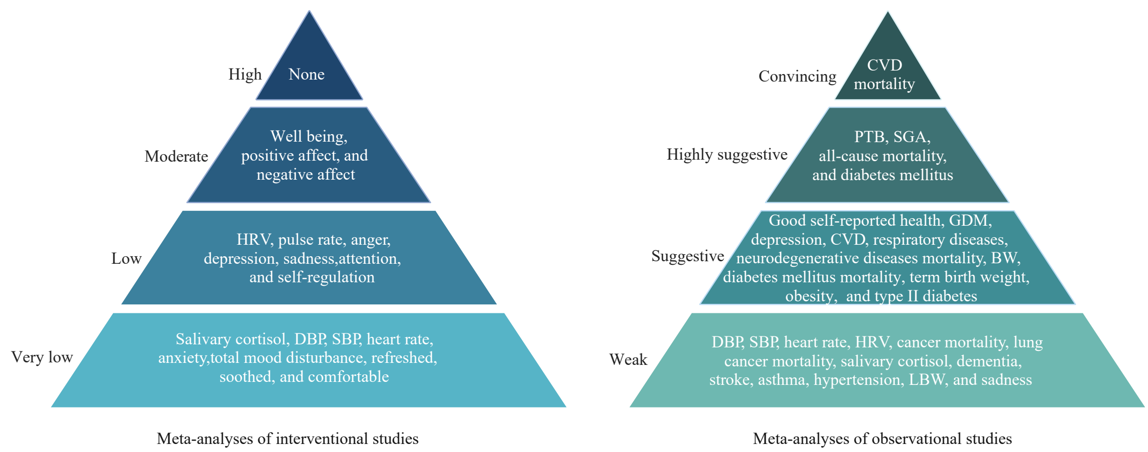

***Fig. 2:* Pyramid of evidence credibility on green spaces and human health.** Abbreviation: HRV, heart rate variability; DBP, diastolic blood pressure; SBP, systolic blood pressure; CVD, cardiovascular disease; PTB, preterm birth; SGA, small for gestational age; BW, birth weight; GDM, gestational diabetes mellitus; LBW, low birth weight.

comparisons between green and non-green areas and using NDVI as a surrogate for surrounding greenness. Meta-analytical evidence from both interventional and observational studies showed that only a small part of the associations between green spaces and health outcomes were graded as high-credibility evidence, which mainly estimated cardiovascular outcomes, birth outcomes, mental health, and mortality. The majority of our meta-analytical evidence was just graded as low credibility, which needs to be validated by more future studies.

We estimated that none of the meta-analysed evidence from interventional studies could be graded as high-level, indicating that in the future more high-quality primary studies and meta-analyses should be performed to explore and pool the interventional effects of green space on health. Meta-analytical associations of green space intervention with mental health and blood pressure were graded as moderate-level evidence, which was evidence-downgraded by indirectness sourced from mixed green space interventions. However, such effects are likely to closely reflect the true effects of green space on the health outcomes and indicate that green spaces-based interventions may be used to improve mental health and blood pressure.

We also estimated that the associations of green space interventions with 20 and 18 health outcomes (mainly mental health outcomes and cardiovascular indicators) were categorized as low and very low-level evidence, respectively. The main reasons for downgrading the evidence included mixed green spaces-based interventions (i.e., walking, sitting, viewing, and gardening in green space were mixed), high RoB in primary interventional studies, inadequate sample size, heterogeneity between studies, and publication bias. The confidence of such evidence was limited and might be significantly different from the true effects. Thus, when interpreting and applying such low and very low evidence, great caution should be exercised, and more better-designed studies with larger sample sizes and appropriate green space exposure are necessary to strengthen the evidence.

Regarding the meta-analytical evidence from observational studies, the associations of green spaces with cardiovascular disease mortality can be classified as convincing evidence, suggesting such evidence have relatively high translational and practical values. However, considering the limited ability of observational studies in inferring causality, the potential effects of green spaces on reducing cardiovascular disease mortality still need to be established by future studies, particularly in terms of utilizing intervention-based approaches.

The meta-analytical associations from observational studies for green spaces in relation to decreased obesity, preterm birth, small for gestational age, and all-cause mortality were supported by highly suggestive evidence, indicating certain confidence in these associations. However, there were concerns about a high risk of publication bias, between-study heterogeneity, and chance findings when interpreting and applying this relatively less robust evidence. The associations between green space and 12 health outcomes were graded as suggestive evidence. This was primarily due to larger *P*-values for meta-analyses ($P > 10^{-6}$) and non-significant *P*-values for the largest primary study included in the meta-analysis. A *P*-value smaller than 10^{-6} is considered a threshold to substantially reduce false positive findings.[51–53] Therefore, this evidence still carries a high risk of chance findings and publication bias. Moreover, 22 meta-analytical associations between green space and health outcomes were supported by weak evidence. The

Author (year)	Exposure	Exposure contrast	Outcome	Metric	Effect estimates (95% CI)	Class of evidence	Q
Gascon et al. (2016)[19]	Residential greenness (a)[a]	Q1 vs. Q3	Cardiovascular disease mortality	RR	0.96 (0.94, 0.97)	Convincing	CL
Meo et al. (2022)[36]	NDVI (multiple buffers)	Per IQR increase	Prevalence of diabetes mellitus	OR	0.88 (0.86,0.89)	Highly suggestive	CL
Hu et al. (2021)[20]	NDVI-500 m	Per 0.1 increase	Preterm birth	OR	0.99 (0.97, 1.00)	Highly suggestive	CL
Twohig-Bennett et al. (2018)[39]	Greenspace[b]	Q1 vs. Q3/Q4	Small for gestational age	OR	0.81 (0.76, 0.86)	Highly suggestive	CL
Gascon et al. (2016)[19]	Residential greenness (a)[a]	Q1 vs. Q3	All-cause mortality	RR	0.92 (0.87, 0.97)	Highly suggestive	CL
Li et al. (2023a)[33]	NDVI (multiple buffers)	Per 0.1 increase	Neurodegenerative diseases mortality	RR	0.98 (0.98, 0.99)	Suggestive	CL
Liu et al. (2023)[34]	Percentage of greenspace	Per 10% increase	Depression	OR	0.96 (0.95, 0.98)	Suggestive	L
Meo et al. (2022)[36]	NDVI (multiple buffers)	Per IQR increase	Mortality of diabetes mellitus	OR	0.92 (0.90, 0.93)	Suggestive	CL
Qiu et al. (2021)[37]	NDVI (multiple buffers)	Per 0.1 increase	Cardiovascular disease	OR	0.89 (0.86, 0.91)	Suggestive	CL
Qiu et al. (2021)[37]	NDVI (multiple buffers)	Per 0.1 increase	Respiratory diseases	OR	0.95 (0.92, 0.98)	Suggestive	CL
Luo et al. (2020)[35]	NDVI (multiple buffers)	Per 0.1 increase	Overweight/obesity	OR	0.88 (0.84, 0.91)	Suggestive	CL
Lee et al. (2020)[32]	NDVI (multiple buffers)	Per 0.1 increase	Term birth weight	SMD	0.003 (0.002, 0.004)	Suggestive	CL
Zhan et al. (2020)[44]	NDVI (>300 m)	Per 0.1 increase	Gestational diabetes mellitus	OR	0.62 (0.49, 0.78)	Suggestive	CL
Zhan et al. (2020)[44]	NDVI-500 m	Per 0.1 increase	BW	β	22.41 (11.01, 33.82)	Suggestive	CL
Twohig-Bennett et al. (2018)[39]	Greenspace[b]	Q1 vs. Q3/Q4	Preterm birth	OR	0.87 (0.80, 0.94)	Suggestive	CL
Twohig-Bennett et al. (2018)[39]	Greenspace[b]	Q1 vs. Q3/Q4	Type II diabetes prevalence	OR	0.72 (0.61, 0.85)	Suggestive	CL
Twohig-Bennett et al. (2018)[39]	Greenspace[b]	Q1 vs. Q3/Q4	Good self-reported health	OR	1.12 (1.05, 1.19)	Suggestive	CL
Ahmer et al. (2023)[47]	NDVI -250/300 m	Per 0.1 increase	BW	β	8.95 (1.63, 16.27)	Weak	L
Ahmer et al. (2023)[47]	NDVI -250/300 m	Per 0.1 increase	LBW	OR	0.97 (0.96, 0.98)	Weak	L
Li et al. (2023a)[48]	NDVI (multiple buffers)	Per 0.1 increase	Cancer mortality	HR	0.96 (0.95, 0.98)	Weak	L
Li et al. (2023a)[48]	NDVI (multiple buffers)	Per 0.1 increase	Lung cancer mortality	HR	0.97 (0.95, 0.98)	Weak	L
Li et al. (2023b)[33]	NDVI (multiple buffers)	Per 0.1 increase	Stroke prevalence/incidence	RR	0.98 (0.97, 0.99)	Weak	CL
Liu et al. (2023)[34]	NDVI (selected the most significant effect value)	Per 0.1 increase	Depressive symptoms	OR	0.93 (0.89, 0.98)	Weak	L
Tang et al. (2023)[50]	NDVI-300 m	Per 0.1 increase	Asthma incidence/prevalence	RR	0.92 (0.86, 0.98)	Weak	L
Zhao et al. (2022)[45]	NDVI-250/300 m	Per 0.1 increase	Blood pressure levels/hypertension	OR	0.98 (0.97, 0.99)	Weak	L
Zhao et al. (2022)[45]	NDVI-500 m	Per 0.1 increase	Blood pressure levels/hypertension	OR	0.94 (0.93, 0.95)	Weak	L
Zhao et al. (2022)[45]	NDVI-500 m	Per 0.1 increase	DBP	β	−0.32 (−0.57, −0.07)	Weak	L
Zhao et al. (2022)[45]	NDVI-500 m	Per 0.1 increase	SBP	β	−0.77 (−1.23, −0.32)	Weak	L
Hu et al. (2021)[20]	NDVI-500 m	high vs. low	BW	β	15.69 (4.94, 26.45)	Weak	CL
Hu et al. (2021)[20]	NDVI-500 m	Per 0.1 increase	LBW	OR	0.90 (0.83, 0.99)	Weak	CL
Hu et al. (2021)[20]	NDVI-300 m	high vs. low	LBW	OR	0.83 (0.69, 0.99)	Weak	CL
Hu et al. (2021)[20]	NDVI-300 m	Per 0.1 increase	Small for gestational age	OR	0.78 (0.61, 0.99)	Weak	CL
Jia et al. (2021)[29]	Green space access[c]	high vs. low	Overweight/obesity	OR	0.91 (0.88, 0.95)	Weak	CL
Zhao et al. (2021)[46]	Residential greenness (b)[d]	high vs. low	Cognitive impairment/dementia	OR	0.97 (0.95, 1.00)	Weak	L
Twohig-Bennett et al. (2018)[39]	Greenspace[b]	Q1 vs. Q3/Q4	DBP	MD	−1.97 (−3.45, −0.49)	Weak	CL
Twohig-Bennett et al. (2018)[39]	Greenspace[b]	Q1 vs. Q3/Q4	Heart rate	MD	−2.57 (−4.30, −0.83)	Weak	CL
Twohig-Bennett et al. (2018)[39]	Greenspace[b]	Q1 vs. Q3/Q4	HRV	MD	−0.06 (−0.08, −0.03)	Weak	CL
Twohig-Bennett et al. (2018)[39]	Greenspace[b]	Q1 vs. Q3/Q4	All-cause mortality	OR	0.69 (0.55, 0.87)	Weak	CL
Twohig-Bennett et al. (2018)[39]	Greenspace[b]	Q1 vs. Q3/Q4	Salivary cortisol	MD	−0.05 (−0.07, −0.04)	Weak	CL

[a]Residential greenness measured as the percentage of green space in an area or as NDVI. [b]Mixed green space metrics including neighbourhood green space, green space-based interventions, proximity to a large green space, or comparing a green environment with an urban or indoor environment. [c]Green space access including presence of green space, number of green spaces, density of green spaces and distance to the nearest green spaces. [d]Residential greenness measured as NDVI, percentage of green-space, availability of green environment (km^2/105 people), and the distance to nearest greenspace. CI, confidence interval; NDVI, normalized difference vegetation index; BW, birth weight; MD, mean difference; Q, quality measured with AMSTAR 2; Q1, the first quartile/tertile; Q3, the third quartile; Q4, the fourth quintile; L, low; CL, critically low; RR, risk/rate ratio; IQR, interquartile range; OR, odds ratio; LBW, low birth weight; HRV, heart rate variability; SMD, standard mean difference; POMS, profile of mood states; DBP, diastolic blood pressure; SBP, systolic blood pressure; SDM, semantic differential method.

Table 4: **Evidence from meta-analyses of observational studies linking green spaces and health outcomes supported by convincing, highly suggestive, suggestive, or weak credibility (n = 39).**

main reasons for this downgrade included the limited sample size and high *P*-values for meta-analyses.

The remaining 71 observational meta-analyses showed non-significant results. However, it is worth mentioning that while these null associations may be genuine, they could also be influenced by factors such as poor data quality, large heterogeneity in settings, populations, methodologies, and small sample sizes that may lead to null findings in meta-analyses. Therefore, similar tool(s) should also be developed to evaluate the robustness of non-significant associations from observational studies, and primary studies may also be needed to validate these findings. A strength of our overview is that we quantitatively graded the credibility of epidemiological evidence regarding the association between green spaces and various human health outcomes. In particular, apart from adopting the AMSTAR 2 criteria to evaluate the methodological quality of the included systematic reviews, we also used the GRADE/established framework to rank the credibility of the evidence. Thus, compared to the prior umbrella review that only used the AMSTAR 2 criteria, our current study provided a more robust and reliable synthesis of the evidence on greenspace and health, which would be more useful for health professionals, policymakers, and researchers. In addition, although most of our meta-analysed associations had low credibility, we still identified some evidence with high-credibility that green spaces were beneficially associated with cardiovascular outcomes, birth outcomes, mental health, and mortality. The high-credibility evidence, on one side, provides additional insight into the development of these health outcomes, indicating green space exposure might be an aetiology of these disorders. On the other side, the high-credibility evidence would be useful for healthcare professionals and urban planners to develop individual- and population-level interventions to mitigate the burden of cardiovascular-specific deaths. For instance, healthcare professionals can suggest people increase green space visits to prevent or treat these disorders. Urban planners can develop greening strategy to increase people's availability of green spaces.

Our study also had several limitations. First, for some meta-analyses, the number of studies for publication bias test and excess significance test was limited (i.e., less than recommended 10 studies for Egger's test and five studies for the excess significance test),[18,19] which might have compromised the precision of our evidence grading. Second, part of the data (e.g., study quality and RoB of primary studies) that we used to grade the credibility of evidence were directly extracted from meta-analyses, thus information bias and misclassification errors are possible in our evidence grading process. Third, the estimated health effects of green spaces varied depending on the specific green space metrics adopted (e.g., the association between preterm birth and NDVI-500 m was graded as highly suggestive, but the association between preterm birth and mixed greenspace quartile/quintile comparison was graded as suggestive). The discrepancies superficially seemed confusing, but it also reflects the fact that different green space metrics characterize different functions of green space, which may have different effects on human health. Thus, interpretations of our findings can only be limited to the specific green space metric(s), and future studies should comprehensively assess green spaces using multiple metrics. Fourth, the study was not registered in PROSPERO, an international platform designed to enhance transparency, reduce selective reporting, and minimize the risk of duplicated reviews. Nonetheless, we performed this study strictly following the PRISMA guideline, provided detailed descriptions of study procedures, and systematically searched several databases to make sure our overview was not duplicated with prior ones. Fifth, we only included reviews published in English, thus the risk of language bias is possible. Sixth, we did not estimate the effect modification of factors like socioeconomic status on the health effects of green spaces. Thus, we could not identify participants who may benefit more from green space exposures. This is because only a small part of the existing systematic reviews reported effect modification of these potential modifiers, and the number of studies in most subgroups was limited. In addition, we did not estimate the effect modification of geographical regions. Since green space characteristics (e.g., shape, size, tree species) differ across geographical regions and thus their health effects may be different. However, only two of the existing meta-analyses conducted location-stratified analyses, and the majority of the primary studies included in these reviews were carried out in Europe and North America. Thus, primary studies and systematic reviews are still warranted to estimate such effect modifications in the future. Finally, the credibility of the non-significant meta-analysed associations from observational studies was classified, but it was not actually assessed due to the lack of available grading tools or criteria.

In summary, a significant number of studies have been synthesized in meta-analyses to examine the association between urban green space and health, revealing evidence for beneficial associations. However, only a small number of these studies can be ranked as having convincing credibility due to various factors including high RoB, indirectness, publication bias, between-study heterogeneity, and chance findings. Our study findings hold relevance for informing the development of urban plan policies and public health initiatives. To further establish and improve the evidence base regarding green space and human health, better designed primary studies and meta-analyses that specifically address these limitations are warranted.

Contributors

BY and YX researched the data, performed the analyses, and wrote the manuscript. YX and SF contributed to the study design, selection of included studies, extraction of data, assessment of the methodological quality, verification of the underlying data, and grading the credibility of evidence. BY, YZ, JL, LH, HQ, GZ, Joachim, TZ, ZL, LL, AX, John, ZZ, YZ, SSL, XZ, GD, and PD equally conceived the research, provided overall supervision, and reviewed and edited the manuscript. All authors reviewed and provided feedback on the manuscript and approved the final version. BY is the guarantor of this work and, as such, had full access to all the data in the study and takes responsibility for the integrity of the data and the accuracy of the data analysis.

Data sharing statement

The data that supported the findings of this study are available from the corresponding author (BY) upon reasonable request.

Declaration of interests

We declare no competing interests.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at https://doi.org/10.1016/j.ebiom.2024.105261.

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