Journal of Environmental Psychology 112 (2026) 103087

Contents lists available at ScienceDirect

Journal of Environmental Psychology

journal homepage: www.sciencedirect.com/journal/journal-of-environmental-psychology

Unpacking the heterogeneity: A global meta-analysis and multidimensional framework for urban green space and mental health

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ARTICLE INFO

Keywords:
One health
Urban green space
Mental health
Meta-analysis
Spatiotemporal coupling

ABSTRACT

Urban green spaces (UGS) are increasingly recognized as vital for mental health within the One Health framework. However, evidence regarding their psychological benefits remains inconsistent across different regions and methodologies. Adhering to PRISMA guidelines, this study presents a comprehensive global meta-analysis and systematic review of 45 quantitative studies published between 2020 and 2025, covering over 3.85 million participants from over 20 countries. Using a random-effects model, we identify a robust positive association between UGS exposure and mental health (*pooled* $r \approx 0.263, p < 0.001$). Notably, the analysis reveals significant heterogeneity driven by urban morphology, highlighting a density-dependent paradox. High-density Asian metropolises exhibit a strong protective effect ($r = 0.319$), acting as urban oases, whereas sprawling North American contexts show a much weaker association ($r = 0.059$), suggesting a saturation point where marginal returns diminish. Furthermore, indicators of visual perception ($r = 0.578$) show significantly stronger associations than objective quantity metrics ($r = 0.228$). Further pathway analysis reveals that mental health benefits are mediated hierarchically, primarily through psychological pathways, followed by physiological and social mechanisms. To address the limitations of static metrics and current methodological inconsistencies, we propose a unified Spatiotemporal Coupling framework. This approach integrates standardized structural, functional, and experiential exposure metrics with dynamic mental health assessments to advance our global understanding of how urban nature fosters psychological resilience.

1. Introduction

As global urbanization accelerates, cities face increasing population density and spatial congestion. While this expansion drives economic growth, it also creates significant social and environmental challenges, including traffic congestion, air pollution, and a notable scarcity of public green space. Emerging evidence suggests these environmental shifts exact a quantifiable toll on mental health. Large-scale longitudinal studies indicate that individuals with minimal exposure to green space during childhood have an up to 55% higher risk of developing psychiatric disorders compared to those with high exposure (Engemann et al., 2019). Consequently, optimizing urban green systems has shifted from being merely an aesthetic consideration to a critical imperative for improving urban living environments and resident well-being.

Mental health disorders are increasingly recognized as a major global public health challenge. Under the World Health Organization's One Health framework, the connection between human populations and their environment is fundamental to addressing these health crises. This relationship is supported by foundational theories such as Attention Restoration Theory (ART) and Stress Reduction Theory (SRT). ART posits that natural environments facilitate recovery from directed attention fatigue through four interrelated qualities: (1) being away

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https://doi.org/10.1016/j.jenvp.2026.103087
Received 23 November 2025; Received in revised form 24 May 2026; Accepted 24 May 2026
Available online 25 May 2026
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(providing a psychological distance from stressors), (2) extent (offering an immersive and coherent environmental structure), (3) fascination (the capacity to capture attention effortlessly), and (4) compatibility (the alignment between environmental features and individual goals) (Kaplan, 1995), while SRT emphasizes the rapid physiological reduction of stress triggered by non-threatening natural settings (Ulrich, 1984). While these mechanisms provide the foundational pathways through which urban green spaces influence mental health, their restorative efficacy is critically contingent upon contextual determinants, most notably perceived safety. Rather than acting as a parallel mechanism of restoration, perceived safety functions as a fundamental boundary condition—if an environment is perceived as unsafe, the cognitive and physiological pathways delineated by ART and SRT are effectively inhibited (Xu et al., 2021).

Globally, approximately one in eight individuals suffers from mental disorders, now a leading cause of disease burden in high-income countries (White et al., 2021). Mental disorders have been identified as a leading cause of ill health and disability worldwide (WHO, 2017). Urban residents appear disproportionately vulnerable, with meta-analyses showing a significantly higher risk of anxiety and mood disorders compared to rural populations (Peen et al., 2010). The decoupling of humans from nature—driven by rapid urbanization—is identified as a key driver of this trend (White et al., 2021). As noted by Coldwell and Evans (2018), urban dwellers face a difficult combination of intense social competition, eroding social support networks, and sensory overload from the built environment, all of which threaten mental resilience.

A robust body of empirical literature indicates that living in greener environments or maintaining frequent contact with nature is positively associated with mental health and subjective well-being. Residents in greener neighborhoods typically exhibit a lower prevalence of depression, higher life satisfaction, and better perceived quality of life (Zhang et al., 2024; Zheng et al., 2024; Zhou et al., 2022). Longitudinal evidence reinforces these findings (Araújo et al., 2024). For instance, an analysis of over 400,000 participants from the UK Biobank revealed that individuals in high-vegetation surroundings had a 14%-16% lower risk of developing depression and anxiety (Wang et al., 2024). Moreover, greener areas correlate with lower psychiatric medication prescription rates, suggesting that greenery exerts protective effects at the community level (Wang et al., 2024; Xian et al., 2024).

Despite methodological diversity, a general consensus exists: urban green space (UGS) benefits residents' mental health. Multiple systematic reviews and meta-analyses support this view. Gascon et al. (2015) found that higher exposure to greenery was associated with lower risks of depression and anxiety and higher levels of subjective well-being. Specifically, Liu et al. (2023) reported that every 10% increase in residential greenness was associated with a 3.7% reduction in depression risk. Furthermore, short-term exposure to natural environments has been shown to improve mood and reduce depressive feelings (Roberts et al., 2019). Cross-national surveys corroborate these findings: among 18 countries, people living in greener neighborhoods or closer to coastlines reported higher life satisfaction. Notably, the impact of green space tends to be stronger for positive mental health indicators (e.g., happiness, positive affect) than for reducing negative mental illness symptoms (White et al., 2021), highlighting the need to carefully select outcome indicators when evaluating the psychological effects of green space.

However, despite this broad consensus, the empirical landscape remains inconsistent. The strength of the association varies considerably across cities and populations, with some studies reporting non-significant or even null effects. These inconsistencies likely stem from systematic heterogeneity in three key dimensions:

(1) Theoretical divergence. Studies differ substantially in the pathways they emphasize. A large proportion of the literature has focused narrowly on green space quantity, often overlooking how these spaces are used or the social functions they support. This quantity-oriented perspective risks neglecting whether green spaces possess the spatial and experiential qualities necessary to promote health. Consequently, studies that ignore use frequency, perceived quality, or social affordances may systematically underestimate total effects (Araújo et al., 2024; White et al., 2021). A comprehensive re-evaluation of these mechanisms—integrating restorative, social, and experiential pathways—is therefore critical.

(2) Methodological variations. Differences in research designs pose a challenge. While cross-sectional studies often identify strong associations, they are susceptible to confounding bias. More rigorous longitudinal or experimental designs tend to yield more conservative estimates. For instance, while some cross-sectional studies found substantial benefits for residents in high-greenness areas, longitudinal follow-ups with strict control for covariates often showed attenuated effects (Gonzales-Inca et al., 2022). This suggests that more stringent methods produce more conservative estimates, and findings must be interpreted in light of the evidential level.

(3) Undefined nature attributes and metric inconsistency. A major source of variability lies in how exposure and outcome are operationalized (Xian et al., 2024). Exposure metrics range from objective remote-sensing indicators (e.g., NDVI) to subjective assessments of perceived quality. Many studies relying on quantity-based indicators fail to specify the spatial configuration, landscape features, or environmental qualities necessary for psychological restoration, perceived safety, and social interaction. As articulated by Bratman et al. (2019), environments with similar levels of aggregated greenness may differ substantially in their impact depending on whether they possess specific health-promoting spatial and landscape attributes.

While prior reviews have established a foundational link between green space and mental health (e.g., Gascon et al., 2015; Liu et al., 2019), significant knowledge gaps remain. First, existing reviews largely predate the surge of post-2020 research and fail to capture recent shifts in urban living patterns and exposure definitions. Second, most previous syntheses have focused on establishing whether an effect exists, but have insufficiently explored why effects vary across global contexts. Specifically, few studies have systematically compared the differential impacts of objective quantity versus perceived quality within a unified framework, or quantitatively dissected the sources of heterogeneity driven by diverse urban forms.

To bridge these gaps, this study conducts a systematic review and global meta-analysis synthesizing evidence from 2020 to 2025. We aim to: (1) elucidate the potential theoretical pathways—physiological, psychological, and social—through which green space confers mental health benefits; (2) critically evaluate the heterogeneity introduced by differing research designs and exposure metrics; and (3) quantitatively integrate empirical data to estimate pooled effects and identify key sources of global variation. This review aspires to not only deepen the theoretical understanding of the nature-health nexus but also provide a scientifically grounded evidence base for urban planning and public health policy.

2. Methods

2.1. Literature search and selection for meta-analysis

In this study, UGS is defined as vegetated areas within administrative city boundaries that serve critical functions, including ecological maintenance, landscape beautification, and recreation. This comprehensive definition covers both formal managed spaces (e.g., urban parks, gardens, street trees) and informal green spaces (e.g., vacant lots, spontaneous vegetation on roadside verges, and brownfields).

Mental health is operationalized to encompass the spectrum of psychological well-being and distress in the general population. This

includes positive dimensions, such as subjective well-being and life satisfaction, as well as negative dimensions, such as anxiety, depressive symptoms, and stress. To minimize confounding effects from heavy medication or institutionalization, we excluded severe psychiatric or psychotic disorders (e.g., schizophrenia, bipolar disorder with psychotic features, or organic mental disorders) that typically require clinical intervention beyond environmental exposure alone. In the included empirical studies, these outcomes correspond to scores derived from validated psychological scales (e.g., PHQ-9, GAD-7), questionnaires, or physiological indicators.

Adhering to the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines, we conducted a comprehensive literature search for journal articles published between January 1, 2020 and March 1, 2025 (search cutoff date: March 19, 2025). This timeframe was selected to capture the most recent empirical evidence following substantial changes in urban living patterns and green-space exposure assessment methods, particularly in the post–COVID-19 context. Since foundational theories and earlier findings have been summarized in previous reviews, this study focuses on updating and synthesizing contemporary evidence.

We queried three primary databases: China National Knowledge Infrastructure (CNKI), Web of Science, and PubMed. For Web of Science, we searched the topic field; for PubMed, we searched the Title/Abstract fields. Rather than universally applying truncation symbols, we explicitly listed relevant synonyms to balance sensitivity and specificity. Detailed search strategies and the number of records retrieved from each database are presented in Table 1.

The review protocol was registered with the International Prospective Register of Systematic Reviews (PROSPERO) (Registration number: CRD420261309103). To ensure methodological rigor and transparency, the review question, search strategy, and eligibility criteria were explicitly guided by the PECOS (Population, Exposure, Comparator, Outcome, Study design) framework.

The initial search yielded 3775 records (179 from CNKI, 802 from PubMed, and 2794 from Web of Science). After removing 652 duplicates, 3123 unique articles remained. Guided by the PECOS framework, the selection process was conducted systematically through a rigorous double-screening procedure.

The screening was executed in two distinct stages. In the first stage (title and abstract screening), records were screened for broad relevance, excluding studies clearly unrelated to the topic (e.g., toxicology, non-human subjects), qualitative-only research, or non-empirical articles such as reviews and editorials. This process resulted in 594 potentially eligible records. In the second stage (full-text review), the remaining articles underwent a detailed assessment based on strict eligibility criteria. Studies were excluded if they lacked quantitative exposure data (e.g., no distinct green space metric), validated mental health outcomes, or sufficient statistical data for meta-analysis.

Table 1
Database and search query.

Database	Search Strategy	Results
CNKI	(‘城市绿色空间’ OR ‘城市绿地’ OR ‘植被覆盖率’ OR ‘绿视率’ OR ‘NDVI’) AND (‘心理健康’ OR ‘抑郁’ OR ‘焦虑’ OR ‘压力’ OR ‘生活满意度’ OR ‘情绪’)	179 records
Web of Science	TS = (“green space” OR “urban green space” OR “vegetation cover” OR “NDVI” OR “green view” OR “green space exposure”) AND TS = (“mental health” OR “psychological health” OR “depression” OR “anxiety” OR “stress” OR “well-being” OR “life satisfaction” OR “mood”) AND TS = (“city” OR “urban” OR “residents” OR “students” OR “elderly” OR “population")	2794 records
PubMed	(“green space” OR “urban green space” OR “vegetation cover” OR “NDVI” OR “green view” OR “green space exposure”) AND (“mental health” OR “psychological health” OR “depression” OR “anxiety” OR “stress” OR “well-being” OR “life satisfaction” OR “mood”) AND (“city” OR “urban” OR “residents” OR “students” OR “elderly” OR “population")	802 records

Study quality was assessed using the Newcastle-Ottawa Scale (NOS) adapted for cross-sectional studies (see Supplementary Table S3 for specific scoring rules). Studies with a total score of less than 6 (out of 10) were defined as low-quality (high risk of bias) and were rigorously excluded ($n = 18$) to ensure the robustness of the synthesis. This exclusion criterion specifically targeted studies that failed to control for critical confounders, such as socioeconomic status, or relied on non-validated measures. Ultimately, 45 studies were retained for the systematic review. Due to multiple outcomes reported in some studies, these contributed 72 independent effect sizes for the meta-analysis. The complete selection process is illustrated in the PRISMA flow diagram (see Fig. 1).

Eligible studies meet the following criteria: (1) they examined general populations or individuals with subclinical concerns (e.g., mild depression or anxiety) rather than patients with severe clinical psychiatric diagnoses; (2) they employed at least one quantitative measure of green-space exposure, such as the Normalized Difference Vegetation Index (NDVI), Green View Index (GVI), green-space coverage, or self-reported exposure frequency. Notably, regarding these measurements, many of the included studies relied on aggregate objective metrics (such as NDVI or generic land-cover data) to mathematically combine both formal managed spaces and informal green spaces (e.g., vacant lots) into a single exposure variable, without explicitly distinguishing between the two categories in their analyses; and (3) they assessed validated mental-health outcomes, including depression, anxiety, psychological distress, subjective well-being, or quality of life. We excluded studies with incomplete statistical data or missing specific environmental or psychological variables. Regarding sample size, studies with fewer than 50 participants were excluded to ensure adequate statistical power and mitigate small-study effects. To verify that this criterion did not systematically bias the overall estimates, a sensitivity analysis was conducted by re-incorporating these small-sample studies. Regarding study design, eligible literature was restricted to real-world observational studies (including cross-sectional and longitudinal designs) and quasi-experimental studies. To ensure high ecological validity and to strictly assess authentic, everyday exposure to urban environments, fully controlled laboratory interventions and virtual reality (VR)-based experiments were explicitly excluded. This restriction ensures that the synthesized evidence reflects actual population-level interactions with urban green spaces.

We systematically extracted data using a standardized coding protocol. Key elements included author details, publication year, study location, sample characteristics, study design, mental health instruments, and definitions of green space exposure. Exposure variables covered satellite-derived greenness indices (e.g., NDVI), street-view greenness (e.g., GVI), percentage of green land cover, proximity to green areas, per-capita park area, and self-reported usage frequency. Studies lacking sufficient quantitative details to calculate an effect size were excluded. The final dataset comprised 45 studies, contributing 72 independent effect size estimates, providing a robust basis for meta-analysis. We evaluated publication bias using funnel plots and Egger's regression tests (R package metafor, version 4.5.1). Because Egger's test indicated potential asymmetry ($t = 4.29, p < 0.001$), we applied the trim-and-fill method to estimate missing studies and adjust the pooled effect size accordingly.

2.2. Data synthesis and statistical analysis

Following the literature screening, key variables were systematically extracted, including study region, population characteristics, green space metrics (e.g., NDVI, EVI, GVI, accessibility, visitation frequency), and mental health outcomes (e.g., PHQ-9, CES-D, WHO-5). Reported associations—primarily standardized regression coefficients (β), correlation coefficients (r), Odds Ratios (OR), and Relative Risks (RR) —were

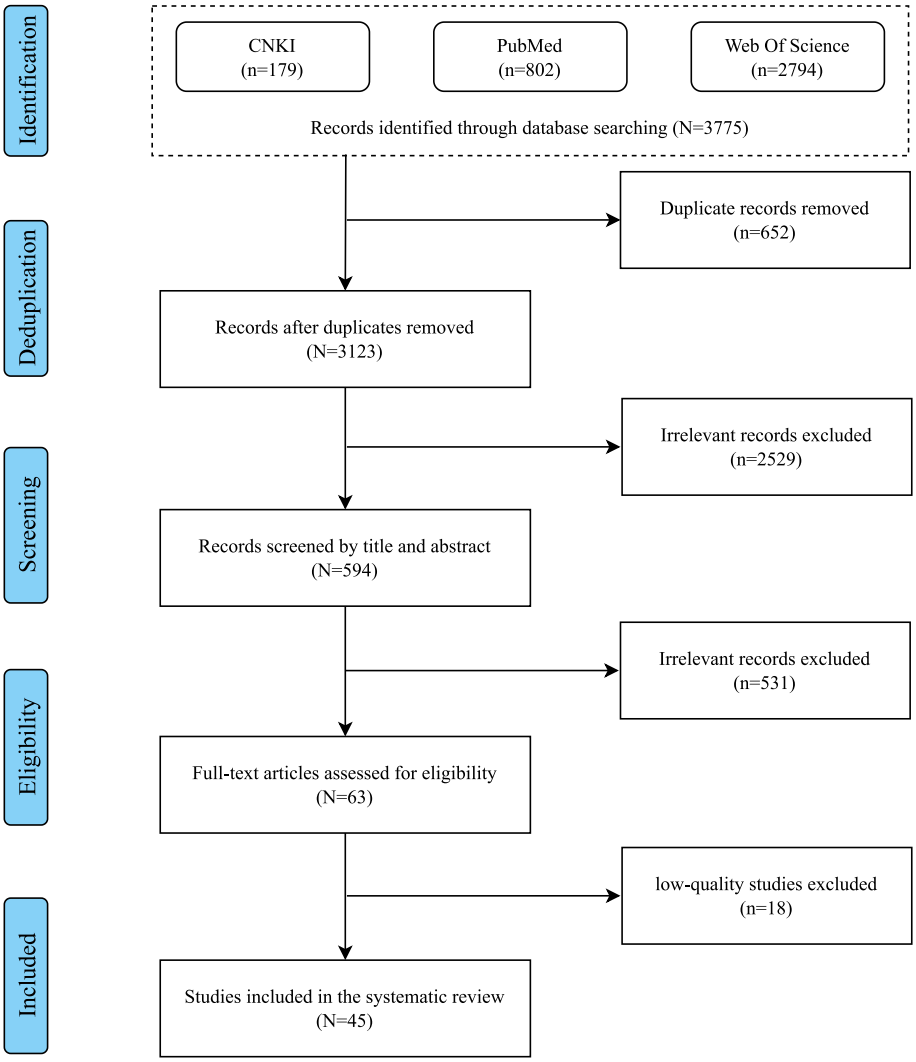


Fig. 1. The PRISMA flow diagram.

recorded along with their standard errors or confidence intervals.

To ensure comparability across studies employing diverse metrics, we selected the Pearson correlation coefficient (r) as the common effect size for this meta-analysis. We standardized these estimates using a transformation process. For studies reporting Odds Ratios, we first converted them to Standardized Mean Differences (Cohen's d) using the formula derived by (Chinn, 2000):

$$d = \frac{\ln(OR)}{1.814}$$

Subsequently, d was converted to r following the method established by (Borenstein et al., 2021).

$$r = \frac{d}{\sqrt{d^2 + 4}}$$

To ensure methodological rigor, Relative Risks (RR) were not converted using this direct OR pathway, as doing so can overestimate effect sizes for non-rare outcomes. Instead, we employed a two-step procedure: RR was first transformed into OR using the reported or assumed baseline incidence rate (p_0) of the outcome, applying the standard epidemiological formula:

$$OR = \frac{RR \times (1 - p_0)}{1 - RR \times p_0}$$

Once converted to OR, the values followed the aforementioned transformation into Cohen's d and finally to r.

For studies reporting standardized regression coefficients (β), we adopted a conditional transformation protocol established by Peterson and Brown (2005) to ensure statistical validity. Coefficients falling within the theoretical range of a correlation ($|\beta| \leq 1$) were treated as reliable, direct approximations of Pearson's r, as they represent stable partial correlations. Conversely, instances where coefficients exceeded unity ($|\beta| > 1$)—which typically signal artifacts of severe multicollinearity or variance inflation among predictors rather than true bivariate relationships—cannot be mathematically equated to a correlation. To address these inflated estimates, we applied a projection transformation to constrain them within the valid $[-1, 1]$ bounds prior to imputation, utilizing the formula:

$$r = \frac{\beta}{\sqrt{\beta^2 + 4}}$$

This ensured all effect sizes remained within the valid boundary of $[-1, 1]$. We harmonized directionality so that positive r values consistently represented beneficial mental health outcomes (e.g., reduced depression scores or increased well-being). Prior to synthesis, all r coefficients were converted to Fisher's z scale to ensure a normal distribution and stabilize variance; meta-analyses were performed on the z scores, and the final pooled estimates were back-transformed to r for interpretation. This standardized dataset formed the empirical basis for subsequent quantitative analyses.

2.2.1. Exposure domain analysis and quantitative synthesis

We quantified the strength of the association between green space and mental health using the harmonized Pearson's correlation coefficients (r). Instead of assuming a strictly monotonic dose–response relationship, we focused on estimating the average linear association across the compiled studies, acknowledging that the underlying relationship may exhibit non-linear or threshold effects in specific local contexts.

In parallel, to illustrate the tangible magnitude of these effects in their original measurement units, we systematically extracted representative quantitative estimates (e.g., percentage risk reduction, score changes per unit increase) from primary studies. These original estimates were tabulated to provide concrete examples of the impact of distinct exposure domains—specifically distinguishing between objective ecological metrics (e.g., NDVI) and street-level perception data (e.g., GVI)—establishing the empirical foundation for interpreting the practical significance of the meta-analytic results.

2.2.2. Subgroup analysis

To investigate the sources of heterogeneity and scrutinize how contextual factors modulate the green space and mental health relationship, we conducted stratified subgroup analyses using random-effects models.

First, to capture the influence of urban morphology and cultural context, studies were stratified by geographic region (Asia, Europe, North America, Oceania, and South America). Second, green space indicators were categorized into four distinct exposure domains: (1) Objective ecological metrics (e.g., NDVI, green coverage); (2) Visual perception indicators (e.g., Green View Index and street greening rate, both of which are specifically derived from street-level panoramic imagery to calculate the proportion of visible green pixels, serving as direct proxies for human eye-level exposure); (3) Behavioral usage indicators (e.g., visitation frequency); and (4) Subjective perception indicators (e.g., satisfaction with greenery). Random-effects models were employed in R to estimate the pooled Pearson's correlation coefficients (r) and 95% confidence intervals (CIs) for each subgroup. Forest plots were generated to visualize the relative effect magnitudes and consistency across these stratified domains.

2.2.3. Pathway categorization

To elucidate the mechanisms linking green space to mental health, we adopted the Cognitive-Limbic-Motor (CLM) framework to categorize and interpret the reported associations. Instead of conducting a separate meta-analysis on sparse physiological mediators, we mapped the exposure-outcome associations into three neuroscientific domains: (1) the Cognitive domain, linked to attention restoration (theorized for objective greenness); (2) the Limbic domain, encompassing emotional regulation and stress reduction (linked to visual/subjective perception); and (3) the Motor domain, involving physical activity (linked to behavioral usage). Outcomes within each domain were analyzed using random-effects meta-analysis (REML method) to compute pooled effect sizes (r). This classification facilitates a comparative assessment of how urban nature influences mental well-being through distinct neural and behavioral pathways.

3. Results

3.1. Study characteristics and robustness analysis

The systematic review identified 45 eligible studies contributing 72 independent effect size estimates, encompassing a cumulative sample of over 3.85 million participants across more than 20 countries. Geographically, the evidence is global but unevenly distributed, with a concentration of research in East Asia, Europe, and North America, while data from Africa and South America remain sparse.

Using a random-effects model, we found a statistically significant positive association between UGS exposure and mental health outcomes. The pooled correlation coefficient was moderate to strong ($r = 0.263$, 95% $CI: 0.213$ *to* $0.311, p < 0.001$). However, we observed substantial heterogeneity ($Q = 49,311, df = 71, p < 0.001$; $I^2 = 99.99\%$), indicating that the magnitude of this benefit depends highly on contextual moderators and measurement approaches.

Regarding publication bias, Egger's regression test indicated potential asymmetry ($t = 4.29, p = 0.001$). To investigate this, we applied the Trim-and-Fill method, which imputed 28 missing studies and resulted in a notably attenuated adjusted effect size. However, this instability likely reflects the high heterogeneity ($I^2 > 99\%$) caused by combining disparate exposure metrics rather than a systematic bias across the entire field. Notably, when we stratified by exposure domain, the Trim-and-Fill analysis for the Visual Perception subgroup imputed zero missing studies ($k = 0$). This suggests that the core association between perceived greenness and mental health remains inherently robust and not driven by the selective publication of positive results.

3.2. Representative dose-dependent associations

Our meta-analysis confirmed a robust positive association between urban green space and mental health across the included studies (*pooled* $r = 0.263, p < 0.001$). However, this aggregated statistic can obscure the tangible impacts observed in real-world settings. To illustrate the practical magnitude of these benefits, Table 2 summarizes representative quantitative findings extracted from primary studies, categorized by specific exposure metrics.

(1) Objective ecological metrics. Satellite-derived indices, such as NDVI and EVI, provide a baseline measure of protection. Our subgroup analysis indicates a moderate and statistically significant correlation for these objective metrics ($r = 0.228$, 95% $CI: 0.175$ *to* 0.279). Beyond the pooled estimate, individual studies offer precise risk assessments. For instance, an interquartile range (IQR) increase in objective greenness is associated with a 5%-12% reduction in the risk of depression (Bakhtsiyarava et al., 2024; Di et al., 2020). This protective effect appears even more pronounced for severe outcomes; higher NDVI levels have been linked to an approximate 40% decrease in suicide mortality risk (Mendoza et al., 2023), suggesting that dense vegetation may act as a critical buffer against extreme psychological distress (Helbich et al., 2020). Furthermore, alongside total greenness quantity, objective spatial accessibility serves as another vital dimension of ecological supply. Evidence shows a clear distance-decay effect: for every 100 m increase in distance from a resident's home to the nearest green space, mental well-being scores (e.g., WHO-5) diminish by approximately 0.49 points (Noordzij et al., 2020). This underscores that convenient physical access is a prerequisite for realizing the potential benefits of green infrastructure.

(2) Visual perception indicators. Beyond broad satellite coverage, the greenery actually visible at eye level exerts a substantially stronger influence on mental health. Consistent with our subgroup analysis finding that visual indicators yielded the highest pooled effect size ($r = 0.578$, 95% $CI: 0.410$ *to* 0.708), primary studies in Table 2 highlight profound improvements in daily well-being. For instance, Bai et al. (2024) observed that higher GVI scores were linked to a 0.656-point reduction in psychological distress, reaffirming that the human-scale visual experience is paramount for psychological restoration.

(3) Behavioral usage indicators. Active engagement with nature—measured by the frequency and duration of visits—exhibits consistent cumulative associations with mental health. Although the pooled correlation for behavioral indicators is moderate ($r = 0.205$, 95% $CI: 0.121$ *to* 0.286) compared to

Table 2
Representative quantitative associations between urban green space and mental health, categorized by exposure domains.

Exposure Domain	Green space exposure indicator (dose)	Mental health indicators	Dosage units and ranges	Dose-response relationship (The change in response for each unit increase in dose)	Data Source and Description
Objective Ecological Metrics	Normalized Difference Vegetation Index (NDVI)	Depression (CESD-SF)	Dimensionless (in units of IQR variation)	Risk ↓ 8.7%	MODIS data (Bakhtsiyarava et al., 2024; Di et al., 2020; Fossa et al., 2024)
		Depression prevalence rate (CIDI-SF)		Rate ↓ 9%	
		Depression (PHQ-2)		Score ↓ by 0.024 pts	
		Depression score (CFPS)		Score ↓ 0.143 pts	Remote sensing image (Liao and Du, 2022; Liu et al., 2024; Scaioli et al., 2023)
		Depression in Middle School Students (PHQ-9)		Rate ↓ 10.2%	
		Mental health issues (HBSC-SCL)		Rate ↓ 29%	
		Suicide mortality rate		Rate ↓ 40%	Landsat image (Liu et al., 2022; Mendoza et al., 2023; Wang et al., 2021; Yue et al., 2022)
		Life satisfaction (WAVE survey)		Score ↑0.75 pts	
		Subjective Well-Being (WHO-5)		Score ↑ 0.69 pts	
		Subjective Well-being (SWPB Scale)		Score ↑ 0.200 pts	
		Subjective Well-Being (WHO-5)		Score ↑ 0.26 pts	GlobeLand30 (White et al., 2021)
	Enhanced Vegetation Index (EVI)	Depression (PHQ-2)		Score ↓ 0.022 pts	MODIS data (Di et al., 2020)
		Anxiety (GAD-2)		Score ↓ 0.028 pts	
	Green space coverage rate/Greening percentage	Mental health score (Center for Epidemiologic Studies Depression Scale)	Percentage (%)	Score ↑ 0.049 pts	Remote sensing image data (Krols et al., 2022; Zhou et al., 2022; Zuo et al., 2024)
		Stress Relief (DASS-21)		Score ↑ 0.796 pts	
		Depression relief (DASS-21)		Score ↑ 0.795 pts	
		Depressive symptoms (CESD-10)		Rate ↓ 27%	
		Subjective Well-Being (SWLS)		Score ↑ 0.44 pts	Street view map data (Han and Leng, 2022)
	Green space area	Mental health issues (GHQ-12)	Hectare/Square meter	Rate ↓ 2.7%	Landsat image (Zijlema et al., 2024)
		Mental health issues (CFPS)		Score ↓ 0.04 pts	Remote sensing image (Zhang et al., 2020)
Objective Ecological Metrics	The distance to the nearest green space	Subjective Well-Being (WHO-5)	100m	Score ↓ 0.494 pts	Bestand Bodemgebruik dataset (Noordzij et al., 2020)
Visual Perception Indicators	Green View Index (GVI)	Mental health issues (Mental Health Rating Scale)	Dimensionless (in units of IQR variation)	Score ↓ 0.656 pts	Street View Images (Bai et al., 2024; Wang et al., 2021; Zhang et al., 2021)
		Mental health score (GHQ-12)		Rate ↑ 7.2%	
	Street greening rate	Subjective Well-Being (WHO-5)	Percentage (%)	Score ↑ 0.59 pts	
Behavioral Usage Indicators	Total activity volume/ frequency of use	Lower levels of well-being (PSS-10 scale)	Times/Week	Rate ↓ 40.7%	Questionnaire survey (Jeong et al., 2023; Nie et al., 2024; Wu et al., 2024)
		Mental health level (SF-12 Health Survey Short Form)		Score ↑ 0.182 pts	
		Psychological distress (K6)		Rate ↓ 3.0%	
Subjective Perception Indicators	Nature Connectedness	Depression Risk	Points	Rate ↓ 1.0%	White et al. (2021)

Note: NDVI = Normalized Difference Vegetation Index (range: −1 to 1); EVI = Enhanced Vegetation Index; GVI = Green View Index. Arrows (↑/↓) indicate direction of effect (improvement or risk reduction). All relationships shown were statistically significant ($p < 0.05$) in the source studies. (a) Objective ecological metrics in this table encompass both macro-scale vegetation indices (e.g., NDVI via satellite) and human-scale physical attributes. The latter includes spatial accessibility (e.g., distance to green space) and pixel-based greening percentages derived from street-view imagery. Although derived from street-level photos, indicators like "street greening rate" are classified as objective metrics here because they quantify the physical volume of biomass rather than subjective psychological perceptions. (b) While visual and objective indicators correlate strongly with mental health, current metrics (e.g., GVI, greening rate) primarily measure the volume of visible greenery. Their association with "visual complexity" or "plant-type biodiversity" remains an interpretive inference grounded in theoretical models (e.g., CLM) rather than a conclusion directly demonstrated by the raw pixel-count data.

visual metrics, likely due to the physical effort required for visitation, specific interventions demonstrate high individual value. Table 2 highlights that increasing visitation frequency can significantly mitigate mental health risks; for instance, Jeong et al. (2023) reported that each additional weekly visit reduced the risk of low well-being by ~40.7%. Similarly, extending the duration of outdoor activity is linked to a steady increase in mental health scores. However, demographic sensitivity exists: while university students may experience substantial mood lifts from a single additional walk, population-wide statistics show more moderate gains per visit, suggesting that interventions should be tailored to group-specific responsiveness (Arnberger et al., 2024; Gong et al., 2023; Kodali et al., 2023).

(4) Subjective perception indicators. Subjective evaluations—such as nature connectedness and satisfaction with neighborhood greenery—serve as meaningful predictors of well-being, yielding a moderate pooled correlation of $r = 0.258$ (95% CI : −0.068 *to* 0.535). Although the wide confidence interval reflects

substantial individual variability in psychological response, primary evidence highlights its qualitative significance. For instance, a one-point increase in nature connectedness correlates with a 1% reduction in depression risk (White et al., 2021). Furthermore, recent studies highlight that perceived quality (e.g., aesthetics, safety) often exerts a stronger influence on happiness than mere quantity, particularly among disadvantaged groups (Nguyen et al., 2021; Rigolon et al., 2018). This implies that psychological benefits stem not only from the physical presence of nature but also from the emotional and cognitive resonance it evokes (Wicks et al., 2023; Yang et al., 2025).

3.3. Heterogeneity and subgroup analyses

Given the substantial socioeconomic and cultural diversity across study locations, we stratified the 45 included studies ($N_{studies}$ = 45, yielding 72 distinct effect sizes) by geographic region to investigate how local context modulates the green space and mental health relationship. The analysis covered Asia, Europe, Oceania, and North America, with limited data available for South America (k = 3) and none for Africa. This stratification uncovers a profound regional heterogeneity (Fig. 2), revealing that the magnitude of mental health benefits is not uniform but is sensitive to differences in urban density and measurement modalities.

Asia contributed the largest share of evidence (k = 46) and revealed a robust positive association (r = 0.319). This finding challenges the assumption that high urban density necessarily negates ecological benefits. Instead, our results support an oasis effect: in high-density Asian metropolises dominated by gray infrastructure, the relative scarcity of green space appears to amplify its psychological utility (He et al., 2022). A small patch of greenery in a concrete environment may serve as a critical refuge, offering a more profound restorative escape than in less dense contexts. Additionally, high heterogeneity (I^2 = 99.98%) persisted, likely driven by the diversity of measurement tools; recent Asian studies increasingly utilized visual metrics (e.g., GVI), which capture users' eye-level experience. These metrics demonstrate stronger explanatory power than satellite imagery, likely contributing to the higher effect sizes observed in this region (Lu et al., 2021; Yoo et al., 2024).

European studies (k = 13) demonstrated a moderate and stable association (r = 0.178), positioning them between the extremes of Asia and North America. The relative stability suggests a balance between supply and demand characteristic of many European cities. In these contexts, mature urban planning often ensures that objective green provision aligns reasonably well with actual accessibility and usability, avoiding both the acute scarcity often found in Asia megacities and the sprawl-induced saturation typical of North America (Pelgrims et al., 2021).

In stark contrast, results from North America (k = 6) revealed the weakest association among all regions (r = 0.059). This aligns with the concept of saturation in the context of urban sprawl. In cities characterized by low-density expansion and high baseline greenness (e.g., private lawns and abundant roadside vegetation), the mere quantity of vegetation (captured by NDVI) reaches a saturation point where additional biomass yields diminishing marginal returns for mental health (Vegaraju and Amiri, 2024). Similarly, Oceania (k = 4, r = 0.312) showed a strong association, suggesting that the benefits in this region remain highly impactful.

Synthesizing these patterns reveals that mental health benefits do not follow a linear dose-response relationship globally. Instead, they appear to follow the law of diminishing marginal utility: green space exerts the most powerful protective effects in environments where it is scarcest (Asia), while in environments with high baseline greenery (North America), quantity becomes less relevant, and benefits are likely contingent on specific quality and active usage rather than availability.

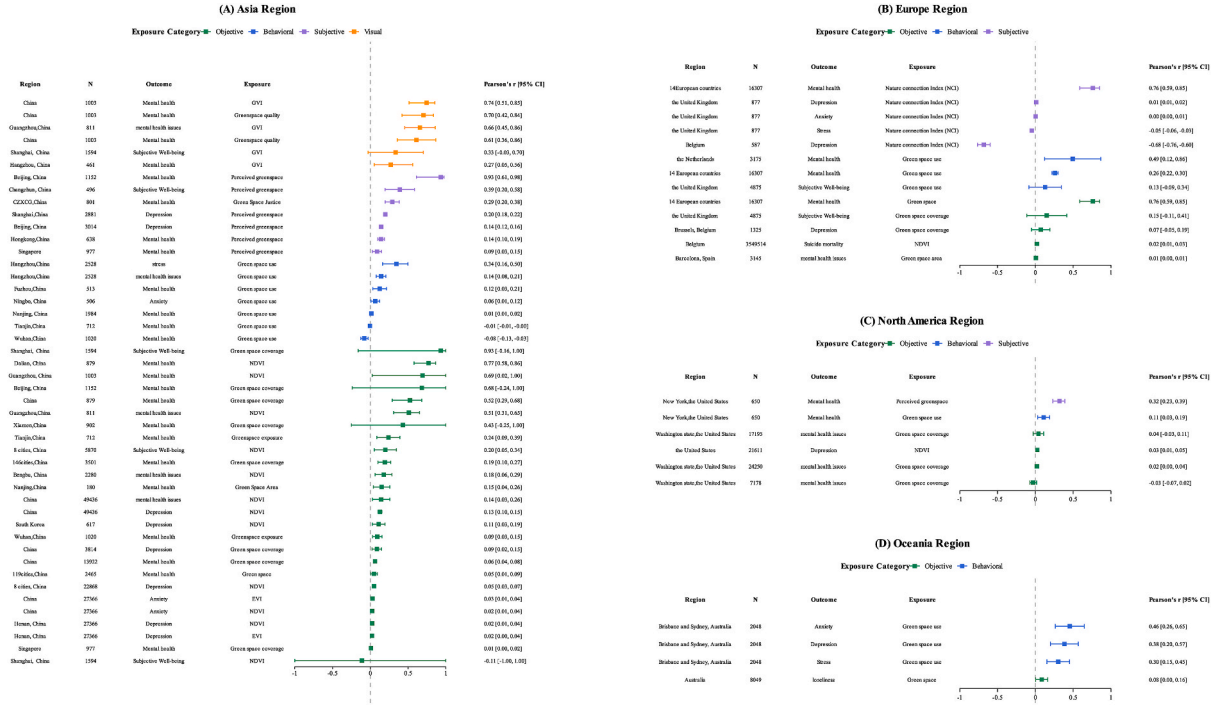


Fig. 2. Forest plots of the associations between green space exposure and mental health outcomes. Studies are grouped by geographic regions and categorized into four exposure domains. Each horizontal line represents the effect size (Pearson's r) and 95% confidence interval (CI) for an individual study, while the squares represent the pooled effect sizes for each subgroup. Colors indicate distinct exposure domains: Green (Objective Ecological metrics), Orange (Visual Perception), Blue (Behavioral Usage), and Purple (Subjective Perception). (A) Subgroup meta-analysis of urban green space and mental health in Asia ($N_{studies}$ = 30, k = 46). (B) Subgroup meta-analysis in Europe ($N_{studies}$ = 8, k = 13). (C) Subgroup meta-analysis in North America ($N_{studies}$ = 4, k = 6). (D) Subgroup meta-analysis in Oceania ($N_{studies}$ = 2, k = 4) (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

3.4. Mechanistic pathways

To move beyond simple correlation and explore the mechanisms driving these associations, we synthesized evidence across three synergistic domains: psychological, physiological, and social (see Fig. 3). The results demonstrate that UGS enhances mental health through all three pathways, though their relative strengths vary significantly, revealing a hierarchy of influence.

The Psychological Pathway emerged as the primary mediator, characterized by a significant internal divergence. Within this domain, direct visual immersion (e.g., eye-level GVI) exhibits the most robust association with well-being ($r = 0.578$), highlighting the immediate restorative power of naturalistic complexity. In contrast, subjective cognitive evaluations (e.g., nature connectedness) show a more moderate correlation ($r = 0.258$), suggesting that while cognitive bonds are important, they may not drive psychological resilience as potently as direct sensory input.

The physiological ($r = 0.228$) and social ($r = 0.205$) pathways followed, exhibiting significant effects that function as long-term buffers. Interestingly, a divergence emerged in outcome sensitivity: while the psychological pathway (particularly the visual sub-dimension) strongly drives positive well-being, the physiological pathway—acting through stress reduction and HPA axis regulation—appears to play a more distinct role in mitigating negative clinical symptoms such as depression severity.

4. Discussion

This meta-analysis confirms a robust and generally positive association between UGS and mental health globally. However, the profound heterogeneity observed in our results reveals that this relationship is far from uniform. Rather than dismissing this variability as mere statistical noise, we interpret it as a crucial signal—one that highlights systemic challenges in how the current literature conceptualizes, measures, and contextualizes human-nature interactions. The following sections systematically unpack these discrepancies, transitioning from an analysis of specific exposure metrics and spatial characteristics to a critical evaluation of underlying theoretical mechanisms and methodological blind spots. Ultimately, this discussion lays the groundwork for a unified, multidimensional research paradigm.

4.1. Decoding the sources of heterogeneity: metrics, characteristics, and psychological endpoints

While our meta-analysis confirms a robust overall benefit of urban green spaces on mental health, the profound heterogeneity observed (as detailed in Section 3) demands deeper theoretical scrutiny. Rather than dismissing this variance as mere statistical noise, we interpret it as a reflection of the complex, multidimensional nature of human-environment interactions. To unpack this complexity, this section systematically decodes the sources of heterogeneity across three critical dimensions: the methodological divergence in how green space exposure is measured, the physical and social characteristics that define spatial quality, and the varying sensitivities of different psychological etiologies to natural interventions.

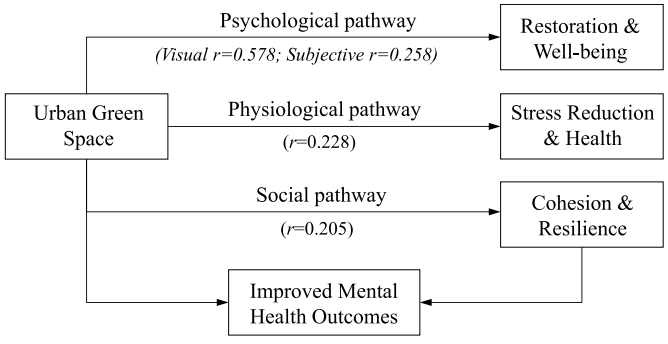


Fig. 3. Hierarchical mechanistic pathways linking urban green space to mental health. The diagram illustrates the three synergistic pathways identified via meta-path analysis. The values represent the pooled Pearson's correlation coefficients (r) derived from the random-effects meta-analysis.

4.1.1. The indicator paradox: Disparities between visual immersion and objective supply

As highlighted by the statistical gaps in our Results section, green space is not a monolithic exposure; different metrics capture distinct dimensions of the human–nature interaction. A clear functional hierarchy emerges among the assessed categories of green space metrics. Direct visual indicators (representing sensory experience, e.g., eye-level GVI; $r = 0.578$) significantly outperformed both objective ecological metrics (representing environmental supply, e.g., NDVI; $r = 0.228$) and subjective evaluations (representing cognitive experience, e.g., Nature Connectedness Index; $r = 0.258$). The approximately 2.5-fold difference in effect size specifically between visual sensory input and objective supply underscores a critical distinction: mere physical availability does not automatically translate to psychological benefit. While objective metrics like NDVI provide a necessary baseline for ecological supply, they inherently fail to capture the restorative quality of a space (e.g., an area might have high canopy cover but lack safe, accessible sightlines).

Theoretical frameworks such as the CLM and ART help explain this functional differentiation. Our finding aligns with the "quality imperative" (White et al., 2021) and CLM, which posits that trees and forests act as archetypal elements that trigger deep attention restoration (Olszewska-Guizzo et al., 2018). In contrast, while large open lawns captured by satellite data may offer open views and high NDVI scores, they often lack the sense of refuge essential for stress reduction, especially in noisy urban environments (Lohr and Pearson-Mims, 2006).

Consequently, we hypothesize that the superior performance of visual indicators relates to their ability to capture immersive, eye-level naturalistic exposure. However, it is crucial to acknowledge that current visual metrics (e.g., GVI) primarily quantify the sheer volume of visible green pixels, rather than directly measuring specific plant-type composition or structural complexity. Therefore, the assertion that biodiverse urban forests directly drive these psychological benefits remains a theoretical inference grounded in CLM, rather than an empirical conclusion directly demonstrated by our current pixel-based data. This implies that future studies utilizing advanced computer vision to explicitly measure ecological complexity are necessary to validate whether optimizing vegetation structure truly maximizes public health dividends.

4.1.2. Landscape characteristics, social modulation, and environmental justice

The superior performance of visual metrics naturally raises the question of what specific features within the visual field drive these psychological benefits. Beyond broad indicators, the specific characteristics of green spaces (such as biodiversity, maintenance, amenities) can strongly moderate mental health outcomes, although empirical quantification of these factors remains limited (Gong et al., 2024; Ma and Wu, 2025).

Recent findings in neuropsychology suggest that mental health outcomes are highly sensitive to specific landscape components. According to the Contemplative Landscape Model, elements such as long-distance views, layered vegetation, and the presence of old-growth trees can induce a state of restful alertness characterized by increased alpha brainwave activity (Olszewska-Guizzo et al., 2018). This neurobiological resonance helps explain why visual metrics exhibit stronger associations than objective biomass; whereas a flat, manicured lawn offers limited visual fascination, a naturalistic forest structure provides the complexity necessary for deep attention restoration.

Beyond structural elements, cultural and social affordances significantly influence outcomes. In Asian contexts, pavilions and fitness squares facilitate social interaction among older adults, boosting mental health via social cohesion (Zheng et al., 2024). Conversely, in Western contexts, community gardens often alleviate loneliness by fostering a sense of purpose (Kardan et al., 2015; Spano et al., 2023). Crucially, however, the potential of these structural and social characteristics can only be realized under conditions of equitable access. Safety and maintenance act as the primary gatekeepers to realizing these benefits. For instance, Cheng et al. (2021) found that socioeconomically disadvantaged populations had 42% lower access to high-quality green spaces, resulting in psychological health gains that were approximately 19% lower compared to affluent groups. This stark disparity underscores a critical issue of environmental justice (Twohig-Bennett and Jones, 2018): simply providing green spaces is insufficient if vulnerable communities cannot safely or comfortably engage with them.

4.1.3. Etiological and temporal divergences in mental health endpoints

Just as environmental exposure varies in structural quality and social equity, the human psychological response is equally multidimensional. Our synthesis reveals that the sensitivity of mental health to green exposure varies significantly across different outcome dimensions, such as subjective well-being and life satisfaction. Regarding negative indicators, it effectively mitigates depression and psychological distress, whereas the association with anxiety appears comparatively weaker and less consistent.

This distinction likely stems from the differing etiologies of these conditions. Depression and rumination are highly responsive to the restorative and contemplative qualities of nature (aligning with ART and CLM). In contrast, anxiety is often driven by acute physiological arousal or immediate social stressors that may override environmental buffering. Furthermore, our findings suggest a temporal divergence: short-term, micro-restorative exposures can rapidly elevate transient mood, whereas influencing clinical outcomes like depression likely requires long-term, cumulative exposure. In summary, while enhancing the quality of green space is paramount for promoting positive well-being, maintaining a sufficient quantity of residential greenery remains essential for reducing population-level risks of clinical depression. Understanding these nuanced outcome differences naturally sets the stage for unraveling the specific psychological, physiological, and social mechanisms that drive them.

4.2. Disentangling the psychological, physiological, and social pathways

As conceptualized in our mechanistic framework (Fig. 3), green space engagement translates into mental well-being through three synergistic, hierarchically structured pathways.

4.2.1. Psychological pathway

The psychological pathway serves as a primary mechanism through which green space engagement translates into mental well-being benefits. This mechanism is primarily anchored in ART, though it intimately interacts with SRT. ART posits that the complex yet effortless stimuli found in nature—often termed “soft fascination"—allow the mind to recover from the fatigue of directed attention required by modern urban life (Hunter et al., 2019). This shift replenishes depleted cognitive resources, leading to measurable improvements in concentration, working memory and reductions in impulsivity (Kaplan, 1995).

Beyond this restorative function, active psychological engagement plays a crucial role (Wan et al., 2020). The construct of nature connectedness acts as a powerful mediator; individuals with a strong emotional bond to nature tend to exhibit healthier coping mechanisms, reduced rumination, and a greater sense of life purpose (Martin et al., 2020; White et al., 2021). Furthermore, empirical studies using ecological momentary assessment confirm that even brief exposures, such as a short walk or viewing greenery can yield immediate improvements in mood ((Shanahan et al., 2019).

Crucially, this pathway helps explain the observed “oasis effect” in our Asian subgroup analysis. In high-density environments, the visual contrast of green space acts as a profound psychological refuge. Regarding the structural complexity of landscapes, this aligns with the hypothesis that the benefit is fundamentally a function of experiential quality. While current visual metrics broadly capture immersive exposure, future research is needed to empirically verify how the brain perceives the specific structural complexity and biodiversity of nature, rather than simply the physical presence of biomass.

4.2.2. Physiological pathway

Working in tandem with cognitive restoration, the physiological pathway operates by directly dampening the body's stress response, a process grounded in SRT. Unlike the cognitive focus of ART, SRT emphasizes immediate autonomic responses to nature, which the evolutionary brain interprets as safety (Ulrich, 1984). Empirical evidence included in our synthesis confirms that exposure to green environments effectively regulates the hypothalamic-pituitary-adrenal (HPA) axis, resulting in lowered salivary cortisol levels, reduced heart rate variability, and improved sleep quality (Yamashita et al., 2021).

Additionally, green spaces provide functional benefits by physically buffering environmental stressors. They reduce urban heat, dampen noise, and filter air pollution. This pathway is likely the driver behind the significant reduction in clinical depression risks noted previously, as chronic physiological stress is a known precursor to psychiatric pathology (Xiao et al., 2021).

4.2.3. Social pathway

The social pathway constitutes the third fundamental mechanism, showing a positive, though relatively weaker, aggregated effect ($r = 0.205$). This mechanism centers on the ability of green spaces to facilitate social interaction, thereby increasing perceived social support and community cohesion (Astell-Burt et al., 2022; Pasanen et al., 2023). By acting as neutral public venues, parks and communal gardens reduce isolation, particularly among vulnerable populations such as the elderly and those living alone, effectively mitigating feelings of loneliness.

However, the efficacy of this pathway depends critically on the usability and safety of the space. Cheng et al. (2021) consistently show that social benefits only materialize in areas perceived as safe, well-maintained, and equipped with appropriate amenities (e.g., seating, play areas) that encourage lingering and interaction. Importantly, this dependency likely explains the weaker association observed in our North American subgroup ($r = 0.059$); unlike public parks that foster interaction, the private lawns typical of suburban sprawl often isolate residents rather than bringing them together. Therefore, realizing the full potential of the social pathway requires planners to move beyond passive provision and actively design spaces that encourage equitable access and community engagement (Lin et al., 2023; Zhang et al., 2022).

4.3. Methodological challenges and blind spots in current research

Having established the synergistic mechanisms driving the nature-health nexus, it is imperative to critically evaluate how current research methodologies often fail to fully capture this complexity.

4.3.1. The challenge of defining exposure

A primary source of heterogeneity lies in the inconsistent definition of exposure. As noted in previous methodological reviews, the lack of a standardized classification for UGS limits cross-study comparability (Markevych et al., 2017). Current literature varies significantly, ranging from objective metrics—such as NDVI—to subjective assessments of quality.

For instance, while a high NDVI value indicates vegetation density, it captures neither safety nor aesthetics. A dense tree canopy might be

ecologically rich, but if it is inaccessible or perceived as unsafe, its mental health benefits may remain unrealized. This limitation is clearly demonstrated by our North America subgroup findings ($r = 0.059$), where high baseline greenery (typical of urban sprawl) failed to translate into significant mental health benefits, contrasting sharply with the strong effects of visual/subjective metrics globally. Without distinguishing between the mere physical presence of green space and the functional experience of it, researchers risk underestimating the complexity of how urban nature influences mental well-being.

4.3.2. Divergence in mental health endpoints

A further challenge in interpreting existing evidence is the inconsistent way mental health is defined and measured. Mental health is often treated as a single entity, yet it encompasses a broad spectrum ranging from positive well-being (e.g., life satisfaction, happiness) to clinical pathology (e.g., depression, anxiety).

Our analysis indicates that these dimensions respond differently to environmental exposure. As highlighted by White et al. (2021), green space tends to have a stronger, more immediate impact on positive affective states than on the reduction of chronic clinical symptoms. Improving mood may occur after a brief walk, whereas mitigating a disorder like depression likely requires sustained, cumulative exposure over time. By combining these distinct endpoints or using non-standardized scales, current research risks obscuring the specific mechanisms through which green space operates. Future scholarship must adopt a more granular approach, clearly specifying whether the intended outcome is the promotion of psychological resilience or the treatment of psychiatric disorders, as these goals may require different environmental interventions.

4.3.3. Contextual heterogeneity and the equity gap

Beyond measurement issues, the generalization of findings is heavily influenced by differences in urban morphology. Our stratification reveals a density-dependent relationship that contradicts the assumption that high-density living necessarily negates the benefits of nature.

We observed the strongest associations in Asia ($r = 0.539$) and the weakest in North America ($r = 0.097$). This discrepancy suggests that the mental health benefits of green space follow the law of diminishing marginal utility. In the sprawling, car-dependent landscapes common in North America, green space is often abundant (high quantity) but lacks distinctiveness, leading to a saturation point where the additional greenery yields negligible marginal benefits. Conversely, in the dense, vertical cities of Asia, green space is a scarce resource. This scarcity creates a powerful "oasis effect", where even small pockets of accessible nature provide disproportionate psychological relief from the intense built infrastructure. Thus, urban density does not negate nature's benefits; rather, it amplifies the psychological value of every square meter of green space, provided it is high-quality and accessible.

Furthermore, the average effects reported in many studies likely mask profound inequalities. Vulnerable populations—including the elderly, children, and low-income residents—often face a compounding challenge: they are exposed to higher environmental stressors while having the least access to high-quality green infrastructure (Twohig-Bennett and Jones, 2018). Existing research frequently fails to stratify results by socioeconomic status, thereby overlooking potential environmental justice issues (Dong et al., 2024). A more nuanced understanding requires investigating not just if green space works, but for whom it works, and under what conditions.

4.3.4. Moving from correlation to causality

Finally, a critical barrier to establishing causality is the field's heavy reliance on cross-sectional designs. While associations are well-documented, the direction of the relationship often remains ambiguous. It is plausible that individuals with better mental health or higher socioeconomic status choose to live in greener neighborhoods, introducing significant self-selection bias.

Although longitudinal cohorts and quasi-experimental designs are emerging, they remain rare compared to the volume of cross-sectional snapshots. Moreover, there is a scarcity of rigorous mediation analyses that quantitatively test the theoretical pathways, such as social cohesion, physical activity, or stress reduction. Without robustly modeling these mechanisms, our understanding remains descriptive rather than explanatory. To advance from observation to intervention, future research must prioritize longitudinal designs and natural experiments that can isolate the specific contribution of green space to mental health trajectories, independent of confounding lifestyle and socioeconomic factors. Ultimately, these methodological gaps underscore the urgent need for a unified research paradigm.

4.4. Limitations

Despite the breadth of this synthesis, several limitations must be acknowledged. First, the literature is geographically imbalanced. The vast majority of studies are situated in the Global North and high-income East Asian metropolises, with a critical scarcity of data from Africa, South America, and Southeast Asia. This limits our ability to generalize findings to rapidly urbanizing contexts in middle- and low-income countries.

Second, while our analysis highlights profound regional differences in urban morphology—ranging from vertical, hyper-dense Asian hubs to car-dependent North American suburbs—the coarse resolution of the primary data limits our capacity to account for micro-scale design nuances (e.g., specific plant composition, street furniture) across these varied contexts.

Third, there is a critical methodological limitation regarding green space typologies. While our conceptual definition of UGS encompasses both formal managed spaces (e.g., parks) and informal green spaces (e.g., vacant lots, brownfields), the reliance on aggregate objective metrics (such as NDVI) in many primary studies mathematically combines these into a single "greenness" variable. This obscures the fact that informal spaces—often lacking maintenance and restorative amenities—may trigger feelings of neglect and diminish perceived safety, thereby inhibiting restorative mechanisms like ART and SRT. The inability to isolate these informal spaces in current literature limits a more nuanced understanding of their specific mental health effects.

Finally, as much of the evidence remains observational, we cannot definitively establish causality. Future research should leverage the multidimensional framework proposed to explore these regional contingencies through longitudinal and quasi-experimental designs.

5. Toward a unified research framework on spatiotemporal coupling of ecology and health

Despite extensive documentation linking UGS to mental health, our analysis highlights that the evidence remains fractured due to heterogeneity in exposure metrics, outcome definitions and study design. Variations in how greenness is defined—whether as a static satellite image or a perceived street-level experience—contribute significantly to the variance in reported effect sizes. Yet, the consistent positive associations identified in our meta-analysis, alongside the emergence of multi-pathway mechanisms, suggest a robust underlying signal.

To advance beyond these limitations, we propose a shift from a static, pathway-centric view to a dynamic, interaction-centric paradigm. While foundational work by Markevych et al. (2017) has successfully categorized the "why" of nature's benefits, existing research often overlooks the "how" and "when" of real-time exposure. To address this gap, we introduce a multidimensional Spatiotemporal Coupling framework (see Fig. 4) to guide future inquiry toward a standardized and context-sensitive approach.

We conceptualize environmental assessment not as a single metric, but as a stratified stream comprising three distinct layers. (1) Structural Exposure layer encompasses relatively static, spatially explicit

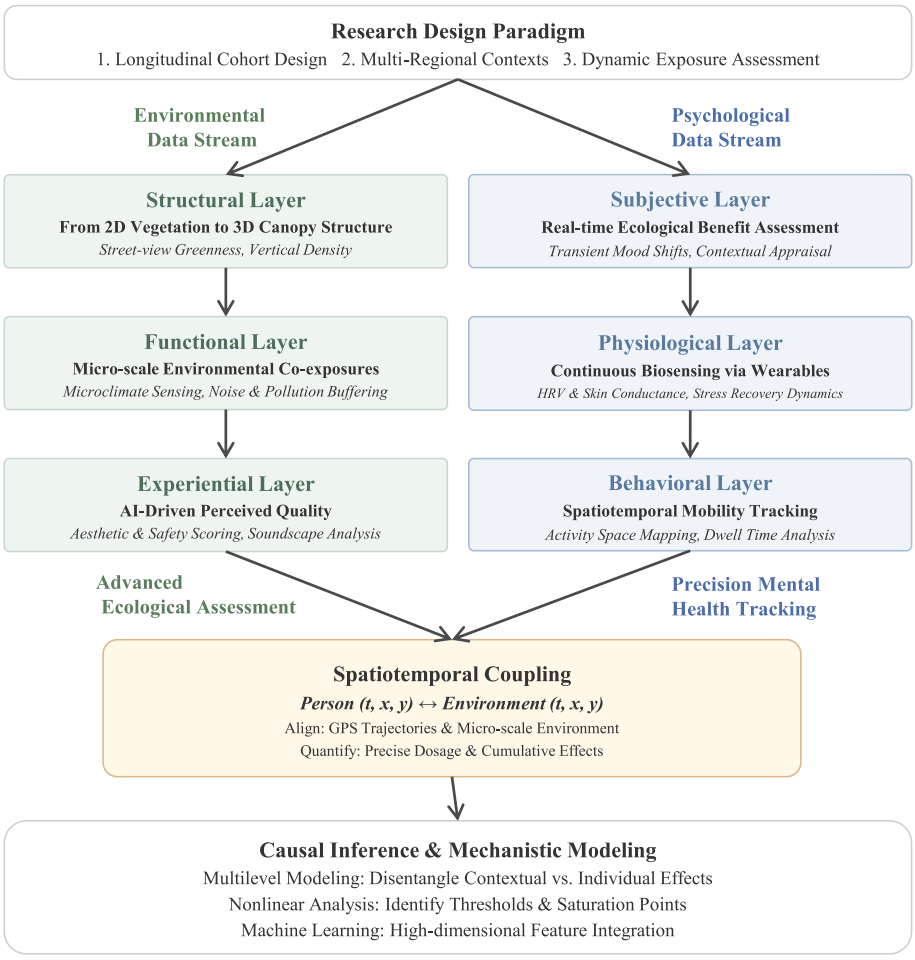


Fig. 4. A multidimensional framework for assessing environmental exposure, psychological responses, and their spatiotemporal coupling.

characteristics such as satellite-derived vegetation indices (NDVI, EVI) and land-cover data. While these indicators provide essential data on the physical availability of green infrastructure, they are often limited by coarse spatial resolution and a lack of user-centric perspective. (2) Functional Exposure layer addresses the environmental context that modulates the usability of green space. It integrates co-exposures such as urban heat, air pollution, and noise levels—factors that directly influence physiological stress and thermal comfort. These variables are critical confounders that remain inconsistently measured in current literature. (3) Experiential Exposure represents the most granular layer, focusing on the human-scale perception of quality. This includes aesthetic appraisal, perceived safety, soundscapes, and the actual time spent in green environments. To capture this, we advocate a hybrid approach. Established scoring systems like the Contemplative Landscape Model provide theoretically grounded assessments of neuro-restorative features. Complementing these, emerging AI-driven methodologies (e.g., computer vision applied to street-view imagery) allow for scaling these perceptual metrics across vast urban areas, synthesizing expert validity with algorithmic scalability.

Parallel to the environmental stream, mental health assessment is organized into three complementary domains to overcome the limitations of relying solely on self-reports. Subjective Indicators, such as validated scales for depression (e.g., PHQ-9) and well-being (e.g., WHO-5), remain the standard for assessing general psychological states. However, these measures are susceptible to recall bias and often lack temporal precision. Physiological Indicators offer objective validation of stress and affective responses. Metrics like heart rate variability, skin conductance, and sleep quality capture the body's immediate biological reaction to environmental stimuli, providing a high-resolution window into the SRT mechanism, especially when monitored via wearable technology. Behavioral Indicators ground psychological states in physical action. Derived from GPS trajectories, accelerometry, and activity diaries, these metrics quantify the "dose" of nature interaction—measuring not just where people live, but how they move, the intensity of their physical activity, and their frequency of engagement with green spaces.

The defining innovation of this framework is the Spatiotemporal Coupling component, which bridges the environmental and psychological streams. Rather than treating exposure as a static attribute of a residential address, this model aligns person-based states with environmental conditions at matched temporal and spatial scales—conceptually expressed as $Person_{(t,x,y)} \leftrightarrow Environment_{(t,x,y)}$. By mapping dynamic exposure along an individual's actual daily activity space, researchers can reduce exposure misclassification and dissect specific "dosage" effects. This alignment allows for the analysis of lagged and cumulative effects, clarifying which specific aspects of green space (e.g., a quiet park vs. a shady street) matter most at specific times and for specific populations.

To fully exploit this high-dimensional data, the framework necessitates a shift in analytical strategy. Future studies must move beyond cross-sectional associations to employ designs that support causal inference, such as longitudinal cohorts and natural experiments surrounding urban interventions (Xie et al., 2022; Xie and Tan, 2024). Analytically, we advocate for the use of nonlinear and dose-response models to identify potential thresholds or saturation points in the benefits of greenery. Multilevel models are essential for handling the

hierarchical structure of data (individuals nested within neighborhoods), while spatial analysis can reveal clustering patterns and environmental inequities. Finally, machine learning techniques offer a promising avenue for extracting features from complex, high-dimensional datasets, provided they remain theoretically interpretable.

By integrating these components, the framework provides a unifying structure that addresses the One Health perspective. It emphasizes that progress depends on the synchronized measurement and integrative analysis of ecological and psychological data. Ultimately, this framework serves as a flexible guide to facilitate more comparable, cumulative, and policy-relevant research, ensuring that urban planning decisions are grounded in a deep understanding of how specific environmental features foster population mental health.

6. Conclusion

Our comprehensive analysis reaffirms that UGS are not merely aesthetic amenities but vital components of healthy, resilient cities, providing substantial, albeit context-dependent, dividends for residents' mental well-being. The evidence synthesized from over 3.8 million participants globally indicates a consistent association whereby individuals living in greener environments or engaging frequently with nature report significantly lower levels of distress and higher life satisfaction. However, this relationship is contingent upon the interplay between the quality, accessibility, and safety of the green-space provision, as well as the socioeconomic context of the population.

Crucially, our findings underscore that the "quantity" of green space alone is insufficient to guarantee health outcomes. The experiential quality, aesthetic appeal, and functional maintenance of these spaces are decisive factors. However, because current visual metrics (e.g., GVI) primarily quantify the overall volume of visible greenery rather than plant-type composition, asserting that these benefits stem specifically from biodiversity remains an interpretive inference. Decoding the exact roles of structural complexity will require future empirical studies utilizing advanced computer vision. Furthermore, this qualitative distinction is particularly salient for environmental justice: benefits cannot be realized if vulnerable communities lack safe and equitable access to high-quality—not just abundant—green infrastructure. Therefore, urban planning must transition from a " one-size-fits-all " approach to context-sensitive strategies that prioritize the specific needs and usage patterns of local demographics.

Ultimately, by adopting the multidimensional "Spatiotemporal Coupling" framework proposed in this study, the scientific community can bridge current methodological fractures and move toward a more causal, evidence-based understanding of nature-health interactions. For policymakers, the implication is compelling: strategic investment in high-quality urban greenery is an investment in public health. As cities confront the dual challenges of densification and rising mental health disorders, integrating nature into the urban fabric offers a scalable, resilient solution to support the emotional and psychological flourishing of future urban generations.

CRediT authorship contribution statement

Menghan Guo: Writing – original draft, Visualization, Software, Methodology, Data curation, Conceptualization. **Gengyuan Liu:** Writing – review & editing, Writing – original draft, Validation, Supervision, Project administration, Methodology, Funding acquisition, Conceptualization. **Zhaomao Huo:** Software, Data curation. **Weicen Chang:** Resources, Data curation. **Dan Zhang:** Validation, Methodology. **Jiahua Li:** Data curation. **Xinzhao Dai:** Resources, Investigation. **Alessandra Romano:** Writing – review & editing, Resources. **Francesco Gonella:** Writing – review & editing, Validation.

Acknowledgements

This study is supported by the Jing-Jin-Ji Regional Integrated Environmental Improvement-National Science and Technology Major Project (No. 2026ZD1217803), the Key Projects of National Natural Science Foundation of China (No. 52430003) and the Major Science and Technology Innovation Demonstration Project of Inner Mongolia Autonomous Region (No. 2025ZDSF0010).

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jenvp.2026.103087.

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