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A generalized relationship between dose of greenspace exposure behaviours and mental health responses

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ABSTRACT

Greenspace exposure is a low-cost strategy for improving mental health, yet practical dose benchmarks for exposure behaviours remain unclear. We synthesized 92,430 studies (1980–2025) in a comprehensive meta-analysis. Because data were limited for accessibility, the main analyses focused on frequency and duration of greenspace exposure. For both dimensions, the best-fitting relationship was a generalized sigmoid dose–response curve: mental health benefits increased rapidly at lower doses and then approached a plateau. Both frequency and duration were significantly associated with mental health responses. Estimated Dose Benchmarks (EDBs) were: one visit per week and 1 h per week for EDB50 (satisfactory effect); four visits and 4 h per week for EDB90 (good effect); and six visits and 8 h per week for EDB99 (excellent effect). These benchmarks correspond to 50%, 90%, and 99% of the estimated maximum response, respectively. This might be one of the earliest studies to identify and rationalize a generalized sigmoid dose–response curve linking greenspace exposure behaviours to mental health benefits. These findings advance theory, guide future research, and offer practical targets to help citizens worldwide adopt a healthier lifestyle.

1. Introduction

1.1. Background

Urban residents worldwide face rising levels of mental distress and illness, such as stress, anxiety, depression, and persistent negative mood. At the same time, cities have become denser and less green. By 2050, about 70% of the world's population (5.6 billion) will live in cities (Nations, 2024). Urban hardscapes have expanded more than fivefold over recent decades (Angel et al., 2011), which puts the quantity and quality of greenspaces – urban environments that are mainly covered by vegetation - under pressure (Gao & O'Neill, 2020; Haaland & van Den Bosch, 2015; Liu et al., 2014; Pauchard et al., 2006; Wang et al., 2025). Meanwhile, city residents are at greater risk of depression, anxiety, and stress (Oh et al., 2021). Globally, over 550 million people are affected by depression and anxiety disorders, which rise over 15% over the past decade (WHO, 2022). These disorders are major contributors to disability, chronic diseases, and economic costs (Ferrari et al., 2013; Organization, 2019; Shanahan et al., 2016). These statistics highlight the urgent need to promote the greenspace exposure as an effective approach for more comprehensive mental health strategies.

A large body of research links greenspace exposure to improved mental health (Hartig et al., 2014; Jiang, He, et al., 2021). Yet critical questions remain. The dose-response relationship between multifaceted greenspace exposure, including how much greenspace people are exposed to (intensity), how long they spend in greenspaces (duration),

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and how often they visit greenspaces (frequency) and corresponding mental health benefits is limited and fragmented (Cox et al., 2018; Dye, 2008; Jiang et al., 2015, 2019). Current evidence does not provide clear guidance on optimal doses either (Cox et al., 2017). Also, past work often assumed a simple linear association, which overlooked the potential curvilinear patterns.

An emerging view suggests a more comprehensive understanding: the mental health benefits of greenspace exposure may follow a curvilinear pattern, with diminishing marginal effects at higher doses (Bressane et al., 2024; Cox et al., 2018; Jiang et al., 2015, 2025; Shanahan et al., 2015). This raises a practical question: how can we identify and apply this pattern into actionable advice for daily life?

It is time to synthesize and interpret findings from previous studies. By doing so, we can achieve a deeper theoretical understanding of the dose-response relationship and provide more precise recommendations that help urban residents adjust everyday behaviours to improve their mental health.

1.2. Existing dose of greenspace exposure studies: A non-linear trend

Theoretical and empirical work on greenspace exposure and mental health provides a strong foundation for this study. The dose of nature framework highlights four dimensions of exposure: intensity, frequency, duration, and accessibility. The empirical evidence collectively reveals the potential of a non-linear association between exposure and mental health, and diminishing marginal benefits at higher doses. Further, a series of circumstantial theoretical models in the related fields can shed light on proposing possible patterns of dose-response curves for this study.

1.2.1. Theoretical base: the dose of nature framework

Our study builds on the dose-of-nature framework in environmental psychology. This framework adapts the dose-response modelling from health and pharmacological studies, with supporting empirical evidence from environmental psychology to quantify non-linear associations between multiple nature exposure dimensions and mental health outcomes (e.g., Jiang et al., 2014; Jiang et al., 2015; Jiang, Shen, et al., 2021; Shanahan et al., 2015; Shanahan et al., 2016). Its full name is the “dose-response relationship between nature exposure and mental health response,” and it comprises three core concepts: (1) nature exposure, (2) mental health response, (3) dose-response curve pattern.

The current framework acknowledges the difficulty of identifying clear dose-response curves. Heterogeneity exists in how nature exposure and mental health responses are defined and measured (Hartig et al., 2014; Markevych et al., 2017). Despite this complexity, meta-analysis remains a valuable tool for synthesizing fragmented evidence and translating it into practical guidance for design, policy, and daily behaviour. So, in this study, we narrow down and specify each core concept to reduce heterogeneity, while retaining a clear focus on environmental psychology and ensuring sufficient data for analysis. To build a solid theoretical foundation for the meta-analysis, this section describes the original definitions of the core concepts within the dose-of-nature framework, and the refined definitions we adopt.

First, nature exposure has been defined in various ways across health science and ecology. To integrate knowledge across these fields and provide a general measure of "nature dose," the dose-of-nature framework specifies three components: the intensity of exposure (how much), the frequency of exposure (how often), and the duration of exposure (how long) (Jiang et al., 2015; Shanahan et al., 2016). Intensity measures the quantity of nature elements, such as the Normalized Difference Vegetation Index (NDVI), tree cover density, or the percentage of eye-level greenery. Frequency measures how many times a person visits a nature element within a given period. Duration measures how long a person remains exposed to that element. Our study adds a fourth component: accessibility (how far).

Second, the classic environmental psychology theories like Stress Reduction Theory and Attention Restoration Theory define mental health response as the measurable change in a person's psychological state following nature exposure (Kaplan, 1995; Ulrich et al., 1991). Based on the theories, the dose-of-nature framework studied diverse mental health responses, including stress, attention restoration, depression, anxiety, mood, and cognition function (Jiang et al., 2014, 2015; Jiang, Shen, et al., 2021; Pretty et al., 2005; Shanahan et al., 2015, 2016). The results reported clear curvilinear relationships between green exposures and mental health responses. Our study adopts the same definition as the dose-of-nature framework for mental health response.

Third, the dose–response curve pattern is a crucial concept because its shape reveals how mental health responds to low, moderate, and high dose exposure. These critical thresholds offer guidance for daily behaviour, urban planning, and future research. Jiang and colleagues (2014, 2015) proposed and identified validity of several specific curve types, including linear, power, and inverted-U patterns. Shanahan and colleagues (2015) suggested two general curve patterns. The first pattern is a rapid increase in health effects followed by a plateau or decline, and the second is a gradual increase in improvement in health followed by a plateau or decline. Since our study aim to use the meta-analysis to identify the general dose-response pattern, we synthesize the curve types proposed by Jiang and Shanahan, and test three major non-linear models: power, inverted-U, and sigmoid. We explain the theoretical basis, definition, and thresholds of each pattern in Section 1.2.2.

1.2.2. Circumstantial dose-response curve patterns

The dose-of-nature framework provides three candidate curve patterns: power pattern, inverted-U pattern, and sigmoid pattern (see Fig. 1). The power and inverted-U patterns are classic curvilinear models in environmental psychology. The sigmoid pattern is widely used for the dose-response modelling in health studies and pharmacology (Davis & Svendsgaard, 1990; Stevens & Marks, 1999; Yerkes & Dodson, 1908). It is critical to understand how each candidate pattern describes the curve shape, defines the key thresholds, and applies to our study.

a. **The power pattern.** The power pattern derives from a foundational principle in psychology: the Steven's Power Law. It is a monotonic curve describing how perceived intensity changes as a power function of stimulus magnitude (Stevens, 1957). The curve shape depends on the exponent (n): it is compressive and decelerating when $n < 1$, linear when $n = 1$, and expansive when $n > 1$. Unlike the inverted-U or sigmoid patterns, the power pattern only decelerates, and it has neither an upper plateau nor a subsequent decline. In other words, the mental health response rises gradually at low exposure, followed by a deceleration with no peak or downturn. In recent years, this pattern has been used to describe the relationship between varies levels of intensity of environmental stimuli and related mental health responses.
b. **The inverted-U pattern.** Both Yerkes-Dodson Law and Hormesis Theory in the field of environmental psychology describe an inverted-U relationship between environmental exposure and mental health (Cook & Calabrese, 2006; Yerkes & Dodson, 1908). The inverted-U (quadratic) pattern is a non-monotonic curve: mental health benefits rise when dose increases, reach a peak at optimal dose, then decline with further exposure (Jiang et al., 2025). The optimal threshold is the most critical feature of this pattern. It demonstrates that a moderate dose may offer the greatest benefit and a lower or higher dose may lead to weaker or even adverse effects (Davis & Svendsgaard, 1990; Stevens & Marks, 1980). This law highlights how the moderate stimulation of the environmental features may optimize mental health outcomes like health and well-being, creativity, or productivity, whereas extreme doses may impair those outcomes (Yerkes & Dodson, 1908).
c. **The sigmoid pattern.** This pattern is widely used for dose-response modelling in public health and pharmacology research and practice.

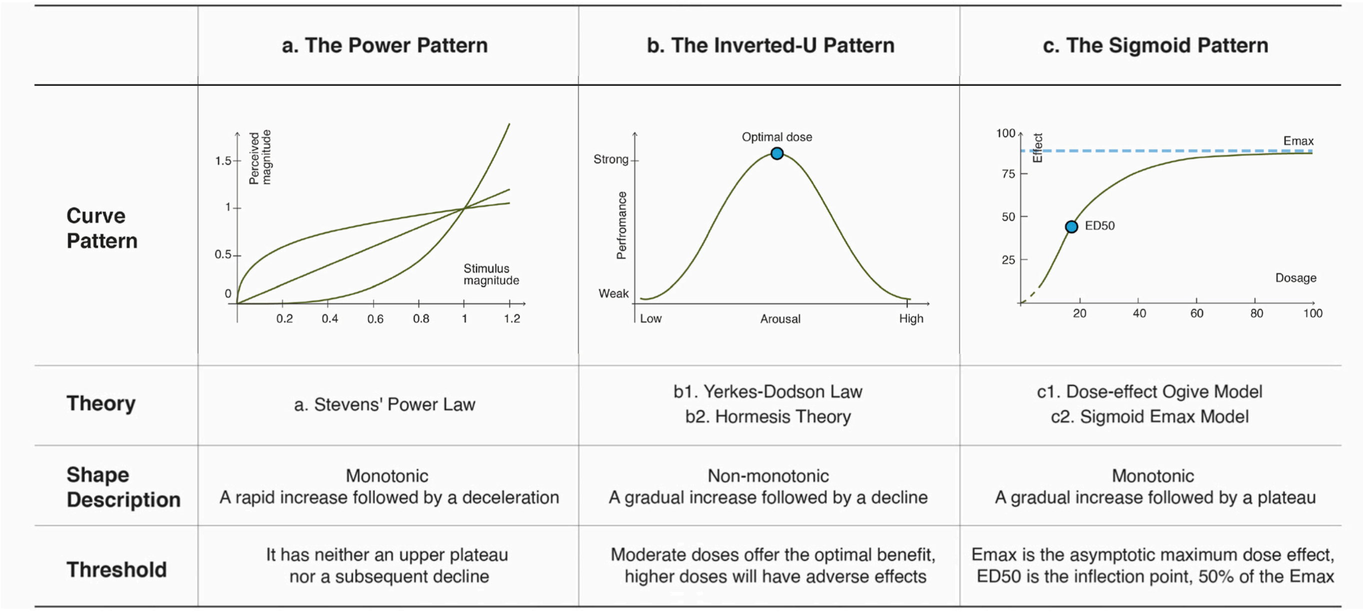

Fig. 1. Three types of circumstantial dose-response curve patterns with the supporting theories, curve shape descriptions, and the key thresholds. (a) Power pattern; (b) Inverted-U pattern; (c) Sigmoid pattern.

Bliss (1934) introduced the sigmoid dose–effect ("ogive") relationship linking dosage to the probability of an effect. Later studies confirmed the sigmoid Emax model relating drug concentration to effect, and pointed out the decreased effect for a prolonged drug exposure (Bliss, 1934; Goutelle et al., 2008; Holford & Sheiner, 1981). The sigmoid pattern is a monotonic curve ending with a plateau, and it has three distinctive phases: a lag phase at low doses, then a steep acceleration at intermediate doses, and then an upper plateau at high doses with diminishing returns (Goutelle et al., 2008; Holford & Sheiner, 1981). The sigmoid model generates two critical threshold values. Emax is the asymptotic maximum dose effect, representing the upper limit of the achievable effect. ED50 marks the inflection point and it represents the dose that achieves 50% of the maximum effect (Emax). ED90 and ED99 represent near-maximum and optimal benefits, respectively (Holford & Sheiner, 1981).

1.2.3. *Empirical evidence: non-linear patterns of multifaced greenspace exposure*

This body of work established a clear framework but did not offer a systematic test of the full curvilinear pattern of each greenspace exposure component. An increasing body of empirical work provided evidence from the specific nature exposure or health response perspective: They reported non-linear links between the frequency, duration, and accessibility of greenspace exposure and mental health outcomes. Many studies revealed a curvilinear dose-response pattern with diminishing marginal benefits at higher doses (Frumkin et al., 2017; Hunter & Askarinejad, 2015; Hunter et al., 2019; Shanahan et al., 2015).

Frequency of greenspace exposure. Frequent visits to greenspaces are associated with lower depression, anxiety, and stress, and with more positive mood (Lin et al., 2023; Yigitcanlar et al., 2020). Several studies suggest a curve pattern that rises quickly at low doses and then reaches a plateau or declines beyond a threshold (Cox et al., 2018; White et al., 2021). For example, studies report an immediate effect after one or two visits per week. Cox et al. (2017) found that even one visit per week can be significantly associated with a notably lower depression. Other studies observed the lowest levels of psychological distress, anxiety, and depression at about four to five visits per week, with only small additional gains at higher frequencies (Bressane et al., 2024; Hong et al., 2019).

Duration of greenspace exposure. Duration shows a similar non-linear pattern: increase with a plateau or decline (Cox et al., 2018; Hong et al., 2019). The rate of mental health improvement can change over very short time periods. Barton and Pretty (2010) identified a curvilinear dose-response pattern to describe the green exercise duration and mental health effects. The association revealed large benefits from short duration (10 min) in green space, with diminishing but still positive returns for longer exposure per week (3-5 h) (Barton & Pretty, 2010). Hazer et al. (2018)reported that 1 h of greenspace exposure per week was associated with a significant reduction in perceived stress (Hazer et al., 2018). Reported duration thresholds for near-plateau mental health responses range from brief sessions (10-30 min) to several accumulated hours. Many studies identified 30 to 90 min per week as a practical threshold for the near-plateau mental health responses (Bressane et al., 2024; Lin et al., 2023; Shanahan et al., 2016). Lower depression has been reported to associate with at least 5 h of greenspace exposure per week (Cox et al., 2017; Zhang et al., 2022), while broader mental health benefits may plateau at approximately 200–300 min per week, with little additional benefit beyond 300 min per week (Barton & Pretty, 2010; Lin et al., 2023; White et al., 2019).

Greenspace exposure accessibility. Accessibility also significantly relates to mental health, often with a quadratic association that shows diminishing returns as travel time increases. Many studies report an optimal walking distance of 15–20 min, consistent with the widely cited "20-min park theory" (Xie et al., 2022). The theory identified a threshold of "a 20-min walking distance from a quality public greenspace to home, " the optimal accessibility that balances the mental health benefits and the practical constraints of daily life (Giles-Corti et al., 2016; Xie et al., 2022). Nutsford et al. (2013) found that improved accessibility to usable urban greenspace was associated with fewer mental health disorders (Nutsford et al., 2013). White et al. (2021) reported significant associations for walking buffers of 900 to 1,500m (White et al., 2021), and Yang et al. (2023) found positive effects of accessibility on mental health that weakened as buffer sizes increased (Yang et al., 2023).

1.3. *Research gaps and questions*

Theory and empirical findings point to curvilinear associations between the frequency, duration, and accessibility of greenspace exposure and mental health. Yet key questions remain unresolved. We identify three gaps and their corresponding research questions to conduct the systematic investigation.

Research gap 1: Limited study of multifaceted greenspace exposure. Many studies examine intensity of greenspace exposure and show clear links to mental health. Fewer studies assess frequency, duration, and accessibility systematically or analyze thresholds in depth (Barton & Pretty, 2010; Duku et al., 2023; Hunter et al., 2019). More importantly, current studies also use diverse contexts and outcome measures, which makes synthesis difficult. Policymakers and professionals need evidence on how often people should visit and how long they should stay to achieve measurable mental health gains. Therefore, it is critical to conduct a meta-analysis to integrate the fragments into a clear body of knowledge.

Research gap 2: Lack of identified non-linear curve pattern. Most studies investigating the mental health impacts of greenspace exposure used a single threshold, which may lead to inconsistent, linear, or generalized findings (Hunter et al., 2019). Such approaches often overlook how duration, frequency, and accessibility shape outcomes across the full dose range, including diminishing returns or possible reversals at very high doses (Frank et al., 2019). Even when non-linear models are considered, studies rarely specify whether the curve follows a power, inverted-U, or sigmoid pattern. A synthesis is now timely.

Research gap 3: Lack of unified thresholds and evidence on diminishing marginal effects. Little is known about the optimal dose thresholds for the impacts of frequency, duration, and accessibility of

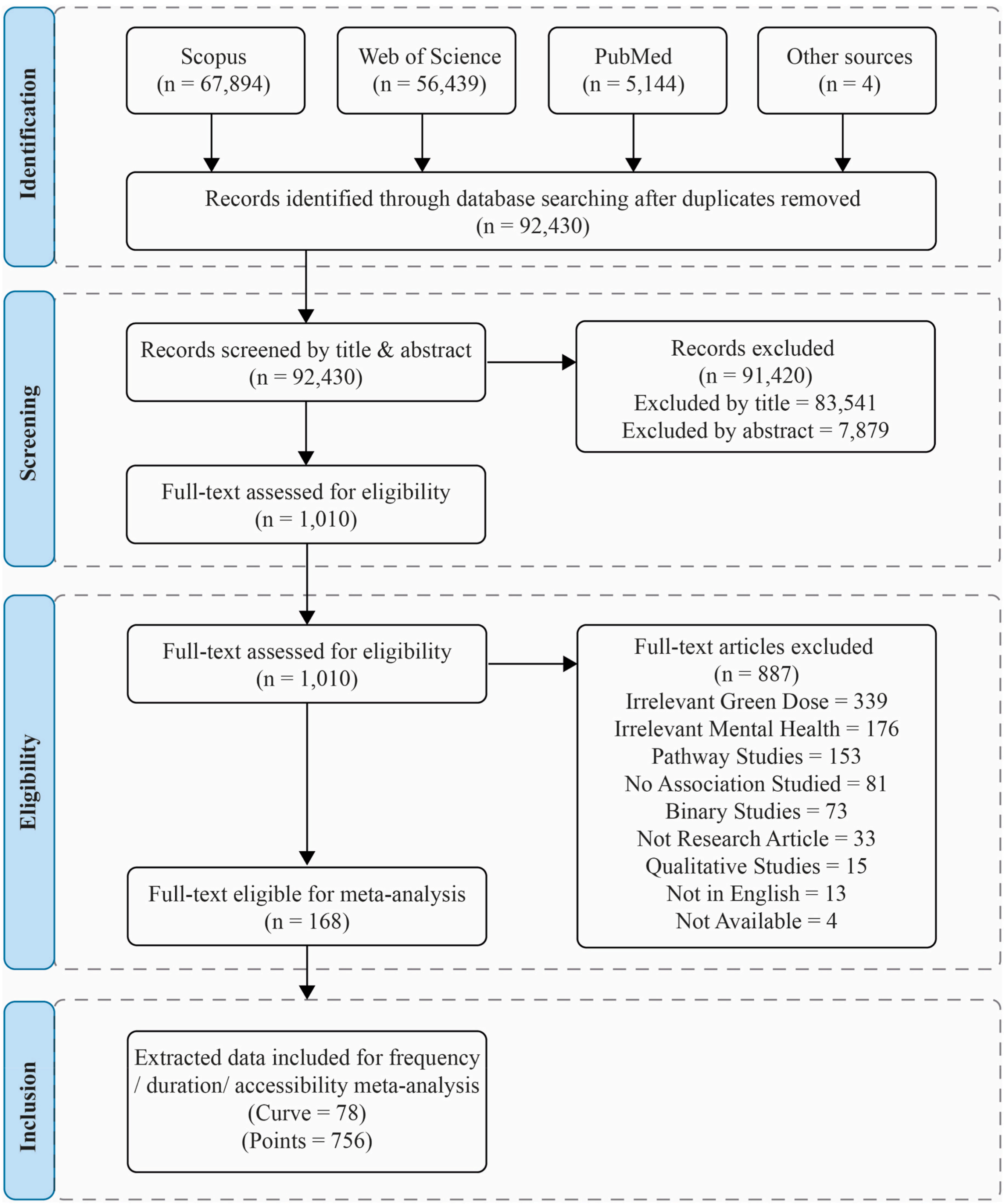

Fig. 2. Preferred Reporting Items for Systematic Reviews and Meta-analyses (PRISMA) process and results.

the greenspace exposure on mental health. Current studies reported diverse outcomes from the immediate effect of a brief exposure to the accumulated effect of a long-time exposure. Without clearer guidance on optimal doses, it is hard to design evidence-based strategies for urban green environments (Jiang et al., 2014, 2015; Shanahan et al., 2016).

To address these gaps, we want to answer the following questions: which curve shape best describes the dose–response relationship for each exposure dimension—frequency, duration, and accessibility—and mental health outcomes? Do we observe clear diminishing marginal effects at higher doses or prolonged exposure? What are the optimal threshold values of the identified dose-response curves? How can these thresholds inform practical guidance that helps residents adjust everyday behaviours to maximize mental health benefits?

By clarifying dose–response patterns and thresholds across exposure types, the results can offer actionable insights for the design and development of urban green spaces that are not only accessible and ecologically sustainable but also optimized for mental health benefits.

2. Methods

Our study designed three steps to answer the research questions. First, we conducted a systematic review spanning last forty-five years (1980-2025) to identify all studies on the greenspace exposure behaviours and mental health responses to collect data. Second, we extracted and standardized all the selected dose-response curves to unify the ranges and measurements. Third, we performed the meta-analysis of the standardized curves with the curve refitting of linear, power, inverted-U, and sigmoid functions to identify the best-fitted dose-response patterns and the optimal thresholds. We uploaded all our collected data to the public repository. The link can be found in the data availability statement.

2.1. Data collection

We followed the Preferred Reporting Items for Systematic Reviews and Meta-analyses (PRISMA) procedure to collect all published studies on the multifaceted greenspace exposure and mental health responses (Fig. 2). Our study belongs to a larger research project examining dose–response relationships between greenspace exposure and mental health. The first paper in this project focused on the intensity dimension (Anonymous et al., 2025). Our study is the second part of the project that focused on the frequency, duration, and accessibility of the greenspace exposure. The PRISMA procedure involved identification, screening, eligibility, and inclusion. six professional researchers participated in the PRISMA review process: three independently filtered the titles, keywords, abstracts, and full texts for each record, and three other investigators were involved when disagreements appeared.

2.1.1. Systematic literature review

Identification. The three databases we used are Web of Science Core Collection (Sep. 1st, 1980- August. 25th, 2025), Elsevier's Scopus database (Mar. 1st, 1985- August. 25th, 2025), and PubMed (Oct. 5th, 2004- August. 25th, 2025). The time range of the literature review was set between the earliest available study in each database to the date we finished the statistical analysis. The search syntax can be found in Appendix A. Our search strategy was intentionally broad to maximize sensitivity and capture the diverse terminology studying the relationship between greenspace and mental health. The Boolean operator "OR" was used within each topic group (greenspace terms and mental health terms), and "AND" was used between groups. We supplemented the database search with citation tracking of included studies to identify any missed records. We collected 92,430 studies during identification process after the exclusion of duplicated studies.

Screening & Eligibility. Six researchers first screened the studies by title and abstract, and then assessed the eligibility according to the five criteria with full text. Including (I) explored associations between the multifaceted exposure of green spaces and mental health responses; (II) assessed dose of green spaces exposure with objective metrics (e.g., number of visits to the green spaces, duration of green exposure, distance travelled to the nearest green space); (III) measured the mental health responses with objective metrics (e.g., brain waves (EEG), skin conductance levels (SCL), salivary cortisol) or subjective metrics (e.g., self-reported mental health); (IV) had quantitatively measured relationships between green space exposure and mental responses without using a binary or pathway study design, and provided data for meta-analysis; (V) written in English. We included studies with both statistically significant and not statistically significant, negative, or positive results. Fig. 2 shows the results of the systematic review. Studies were excluded for reasons detailed in Fig. 2 and Appendix B. The most common exclusion reasons were: irrelevant greenspace exposure variables (38.22%), irrelevant mental health variables (19.84%), and pathway studies without extractable quantitative data (17.25%).

In all, we identified 78 dose-response curves with 756 data points between greenspace exposure (duration/frequency/accessibility) and mental health responses for the meta-analysis for our study.

2.1.2. Quality assessment and bias check

We developed an evaluation framework that integrates two validated tools frequently employed in environmental psychology: the Risk of Bias in Non-randomized Studies (ROBINS-E) and the Effective Public Health Practice Project Quality Assessment Tool (EPHPP) (Higgins et al., 2024; Thomas et al., 2004). ROBINS-E is recommended by the Cochrane Collaboration for assessing bias in non-randomized studies of health effects of exposures, and has been applied in environmental health systematic reviews. EPHPP has been validated for use with diverse quantitative study designs and is widely employed in public health and built environment research (Armijo-Olivo et al., 2012; Rigolon et al., 2018). ROBINS-E evaluates seven domains of bias relevant to observational exposure studies: confounding, selection of participants, classification of exposures, deviations from intended exposures, missing data, measurement of outcomes, and selection of reported results. EPHPP assesses six components: selection bias, study design, confounders, blinding, data collection methods, and withdrawals (Higgins et al., 2024; Thomas et al., 2004).

Based on these two tools and previous systematic reviews in environmental psychology, our evaluation framework adopted four critical domains and the evaluation criteria relevant to greenspace-mental health associations: study design, exposure assessment, outcome assessment, and confounding assessment (see Appendix H1 for detailed criteria). For example, the rating criteria of study design involved the study type, scale of analysis, geographic scale of green space, and study time range. Two investigators independently rated each study based on the evaluation criteria, and a third investigator validated the scores. We applied a four-point scale ranging from low risk (4) to high risk (1). Appendix H1 provided detailed descriptions for each score in every domain. Domain scores were aggregated to generate final quality metrics, expressed as percentages of maximum attainable points. We classified studies into five quality tiers based on the percentage of maximum attainable quality points, following classification thresholds established in previous environmental health reviews (Armijo-Olivo et al., 2012; Rigolon et al., 2018): Excellent (>81%), Good (60-80%), Fair (40-60%), Poor (20-40%), and Very Poor (<20%).

We documented the final risk of bias results in Appendix H2. The analysis revealed that 96.3% of duration studies were classified as good or excellent, and 84.6% of frequency studies were classified as good or excellent. All studies, regardless of quality rating, were retained in the primary analysis. Studies rated below 'Good' (i.e., Fair or Poor) were then excluded in a sensitivity analysis to test the robustness of the main findings. The sensitivity analysis showed that the sigmoid curve pattern and threshold values remained consistent when restricted to studies of Good or Excellent quality, with minimal changes in AIC, BIC, and adjusted R^2 (see detailed model comparison results in Appendix H3).

2.2. Data extraction and standardization

2.2.1. Curve data extraction

We developed a codebook for data collection (Appendix C). Using the 78 selected dose-response curves, three independent investigators extracted the relevant information of the dose-response curve refitting. Any discordance in data extraction was resolved through discussion with a fourth investigator. The information included curve ID, citation, publication year, location, study design (cohort experiment, cross-sectional, mixed-method, ecological longitudinal), mental health type, mental health scale (DASS-21, MHS-14, etc.), mental health range, greenspace exposure type (duration, frequency, accessibility), greenspace exposure description, exposure time unit (by day, by week, by year), greenspace exposure audit methods, optimal dose, quality check, and other notes. Data from each reported studies were compiled into a common data table for meta-statistical analysis (Appendix E1, F1, G1). We excluded papers that cannot provide data for the meta-analysis, while all statistically significant/not statistically significant and positive/negative results were retained.

2.2.2. Curve data standardization

We applied standardization methodologies to minimize heterogeneity issues in both greenspace exposure and mental health response measurements. For greenspace exposure standardization, we unified the greenspace exposure time and the audit methods within each individual type (frequency, duration, accessibility). For mental health responses, variables included the representative responses: depression, anxiety, stress, mood, general mental health, etc., which utilized similar self-reported measurement scales. The primary objective was to standardize the mental health score range.

Standardization of greenspace exposure (duration, frequency, accessibility). Within the selected curves, 100% of the frequency, duration, and accessibility measurements were the self-reported questionnaire data. 67% of the frequency and duration measurements documented the exposure time frame by week, while the remaining 33% varied from per visit, from a month to a year. Detailed measurement of the exposure time and audit methods can be found in Appendix E1. To standardize quantitative measurement for meta-analysis, we converted all the frequency and duration data to a weekly basis. We chose weekly frequency and duration because longer time frames like a month or year are less accurate and harder to apply for practical implications. Also, the detailed audit of curves that were measured by month or year are still based on weeks (e.g., 2–3 days a week, weekly, daily, once a week) (See details for Appendix E1 & F1). To standardize, monthly totals were divided by 4.33 and annual totals by 52. This introduces an assumption when the original study did not define a weekly exposure period, which we acknowledge as a measurement heterogeneity. Finally, the frequency of green space visits was standardized to times per week, ranging from 0 to 7 times; for duration, we standardized to total time spent per week ranging from 0 to 10 h.

Standardization of mental health responses. Within the selected studies, 87.5% of the mental health measurements were derived from self-reported survey data. The questionnaires used were well-acknowledged and validated in previous studies. Only one study applied a biomarker (salivary cortisol) for the mental health responses, and two studies used a single question to evaluate the mental health responses. Detailed distributions of the mental health measurement methods can be found in Appendix D1. To avoid the unequal contribution bias, we applied mean normalization of the mental health values with a common range of 0 to 1, where 0 indicates the worst mental health response and 1 indicates the best mental health response.

2.3. Meta-analysis: dose-response curve refitting

Finally, we used R studio 10.2 to refit the dose-response curves based on the standardised curve dataset. To minimize the heterogeneity issue, we first refitted curves of greenspace exposure (duration, frequency, accessibility) with specific mental health responses (depression, anxiety, stress, mood, etc.) separately. Then, we refitted the greenspace exposure with all the mental health responses combined to compare the general patterns (Fig. 3). The general refitted results were in the result section, and the detailed refitted results with specific mental health responses were in the Appendix I1-I2. The refitting process involved four steps. The first two steps represent and predict the dose-response relationship, and the last two steps identifies the final best-fitting curve pattern.

Step 1 is the scatter plot of all data points on a two-dimensional plane.

Step 2 applied non-parametric Generalized additive model (GAM) to identify the actual relationship between dependent and independent variables. The pattern of fitted GAM curve and the effective degrees of freedom (EDF) value help predict the pattern with the best fit (linear, power, inverted-U, or Sigmoid). An EDF of 1 indicates a linear relationship, and EDF of 2 suggests a power or inverted-U relationship, while an EDF around 3 suggests Sigmoid curves.

$$g(E(Y)) = \beta_0 + f_1(x_1) + f_2(x_2) + \cdots + f_m(x_m)$$

Step 3 applied the linear (M1), power (M2), quadratic (M3), and sigmoid (M4) functions to refit alternative curves to the standardised combined data, measuring p-value.

$$M1 : f(x) = ax + b$$

$$M2 : \log_b(b^x) = x$$

$$M3 : f(x) = ax^2 + bx + c$$

$$M4 : f(x) = L / (1 + \exp(-k(x - x_0)))$$

Step 4 compares AIC (Akaike information criterion), BIC (Bayesian information criterion) and adjusted R^2 to compare model fit.

3. Results

3.1. Descriptive statistics

Two major characteristics of the existing dose-response curves between multifaceted green exposure and mental health responses can be observed from descriptive statistics: 1/the rapidly growing trend of the curvilinear studies; 2/the collected data are representative, with only minor heterogeneity concerns.

First, there is a clear increasing trend of the studies demonstrating the curvilinear association between multifaceted greenspace exposure and mental health. 78.2% of the selected curves were published within the recent five years (Appendix D2).

Second, after the data extraction and standardization, the refitting curves did not exhibit significant heterogeneity (Appendix D3). The percentages of frequency, duration, and accessibility curves, and percentages of the mental health responses showed minimal variances. In terms of mental health responses, 85.9% of the selected curves focused on the major representative mental issues, including depression, anxiety, stress, and mood. Also, the scales applied to measuring the mental health responses are highly representative and standardized. 52.4% of the depression, anxiety, and stress applied the same DASS-21 Depression, Anxiety, and Stress Scale to measure. Also, within the collected curve data, 71.8% reported curvilinear results. Another critical characteristic observed in the collected curves was the description of "greenspace" in the context of "greenspace exposure." 91% of the collected frequency, duration, and accessibility curves defined green space as "urban/public green spaces."

In all, we collected 78 curves and 756 points. For the frequency of

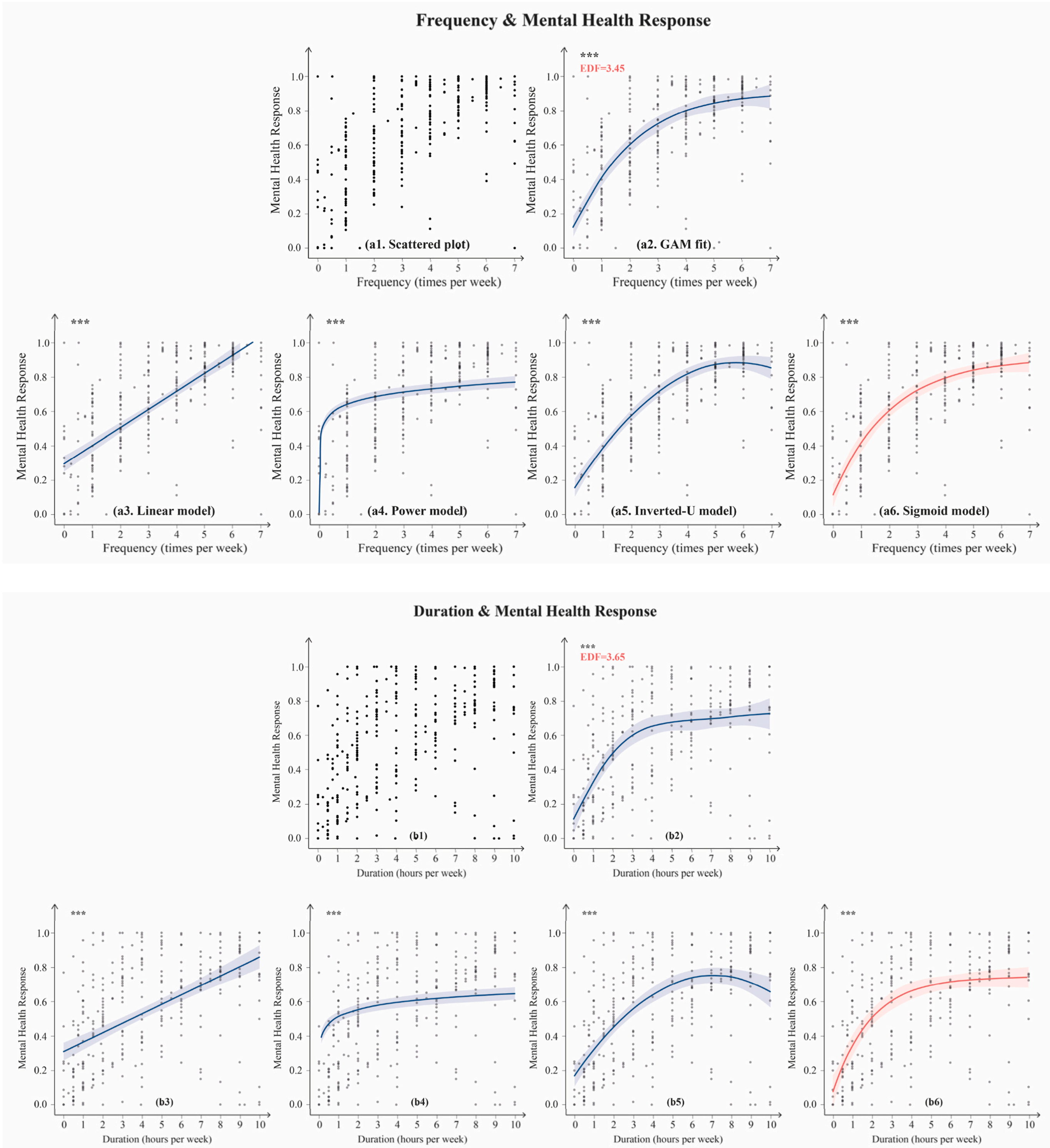

Fig. 3. Comparison of candidate dose–response models for the associations between frequency and duration greenspace exposure with mental health responses. Panels a1–a6 show the frequency analysis, and panels b1–b6 show the duration analysis. Panels a1 and b1 present the scattered plot data points. Panels a2 and b2 present the non-parametric generalized additive model (GAM) fits, with effective degrees of freedom of 3.45 and 3.65, respectively. Panels a3/b3, a4/b4, a5/b5, and a6/b6 present the fitted linear, power, inverted-U, and sigmoid models, respectively. Points represent standardized observations, solid lines represent fitted relationships, and shaded bands represent 95% confidence intervals. The corresponding AIC, BIC, adjusted R^2, and p-values used for model comparison are reported in Table 1.

greenspace exposure, we collected 39 curves with 335 data points, and for the duration of greenspace exposure, we collected 27 curves with 341 data points. For the accessibility of greenspace exposure, we collected only 12 curves with 80 data points. Given this limited sample size, we report only the frequency and duration curve-refitting results in the main manuscript. The accessibility results are provided in Appendix J for transparency. We acknowledge the limitation brought by the insufficient sample size of the accessibility studies in the discussion section, and state that future studies can draw more solid conclusions from this dimension until more primary studies are available.

3.2. Results of the curve refitting: the increase-plateau sigmoid pattern best fits the dose of frequency and duration greenspace exposure and mental health responses

The scatter plots for duration and frequency of greenspace exposure indicated an inverted-U or S-curve pattern, and the actual relationship plotted by the GAM model supported that assumption (Fig. 3). Furthermore, the EDF (Effective Degrees of Freedom) value of the refitted frequency GAM model is 3.45, and the EDF value of the refitted duration GAM model is 3.65. Both suggested a Sigmoid S-curve instead of a quadratic relationship.

To choose the best-fitting model, we further compared the AIC, BIC, and adjusted R^2 values of the four models. The results showed that for both frequency and duration greenspace exposure, the Sigmoid and inverted-U patterns have much better model performance than linear and power patterns. The sigmoid model has the lowest AIC, BIC, and highest R^2 among all (Table 1).

3.3. The recommended thresholds for frequency and duration of greenspace exposure

Using the identified best-fitting sigmoid pattern and the formula for the frequency and duration greenspace exposure, we calculated the Emax values and the recommended Estimated Dose Benchmarks (EDB) for both frequency and duration greenspace exposure. Since ED values are mostly used in health and pharmacological studies, whereas greenspaces provide mitigating but inherently limited effects, we adopt the term Estimated Dose Benchmarks (EDB) in place of ED values when making practical dose recommendations in these studies, including half of the maximum mental health benefits (EDB50, satisfactory effect), 90% of the maximum mental health benefits (EDB90, good effect), and 99% of the maximum benefits (EDB99, excellent effect) (Fig. 4). These Estimated Dose Benchmarks (EDB) should be understood as recommended thresholds for practical implications, not as precise prescriptions. Individual responses will vary based on demographic and socio-economic characteristics, quality of greenspace, activity types, and baseline mental health states.

First, we calculated the Emax values for both frequency and duration exposure. The plateau effects (Emax) refer to the theoretical maximum effects that the frequency or duration greenspace exposure can produce. An Emax value of 1 would represent the theoretical maximum mental health benefit achievable through this exposure dimension within our model. We need to acknowledge that this upper limit reflects the ceiling of observed effects in the literature rather than a guarantee of complete mental responses (Goutelle et al., 2008). The value of 0.8 indicates that greenspace exposure can only provide eighty percent of the Emax. The prolonged greenspace exposure can approach asymptotically but cannot exceed the maximum Emax value. In our study, the plateau Emax value of frequency greenspace exposure is 0.91, and the plateau Emax value of duration greenspace exposure is 0.74.

Second, we identified the EDB50 (50%), EDB90 (90%), and EDB99 (99%) of the maximal effects for the recommended thresholds for both frequency (how often) and duration (how long) greenspace exposures. For the frequency of greenspace exposure, the EDB50 value is 1.1 times per week, indicating that visiting the greenspace once a week can already achieve 50% of the mental health plateau effects. The EDB90 value of frequency is 4 times, meaning that visiting the greenspace 4 times can achieve over 90% of the maximum mental health plateau effects. EDB99 of 6.4 indicating that visiting the greenspace 6 times can almost achieve the plateau effect. Regarding the duration of greenspace exposure, the EDB50 value is 1.1 h per week, indicating that spending 1 h in the greenspace can achieve 50% of the mental health plateau effects. The EDB90 value of frequency is 4.1 h, meaning that spending 4 h in the greenspaces can achieve over 90% of the maximum mental health plateau effects. EDB99 of 7.8 indicates that spending 7.8 h per week in greenspaces can almost achieve the plateau effect.

To provide practical implication suggestions, we rounded the optimal thresholds to the nearest integer (Table 2). For example, 5.59 times of greenspace visitation was rounded to 6 times per week.

Table 1
Model comparison of frequency and duration greenspace exposure and mental health responses.

Model Type		AIC	BIC	Adj R^2	*p*-value
Frequency					
(c1)	Linear pattern	−5.6861	5.7563	0.4883	<2e-16***
(c2)	Power pattern	25.9979	37.4403	0.4376	<2e-16***
(c3)	Inverted-U pattern	−65.1430	−49.8864	0.5728	000***
(c4)	Sigmoid pattern	−68.6900	−49.6200	0.5818	000***
Duration					
(c1)	Linear pattern	104.8753	116.2543	0.2665	<2e-16***
(c2)	Power pattern	104.1352	115.5143	0.2681	<2e-16***
(c3)	Inverted-U pattern	65.62035	80.7924	0.3512	000***
(c3)	Sigmoid pattern	62.8900	82.0500	0.3901	000***

Note: ***$p < 0.001$, **$p < 0.01$, *$p < 0.05$, ns = non-significant.

4. Discussion

This study was designed and conducted to answer three questions: which curve shape best describes the dose–response relationship for frequency and duration of greenspace exposure and mental health; whether diminishing marginal effects are clear; and whether we can identify the recommended threshold values that inform practical implications. Our findings provide clear answers. First, a sigmoid curve best describes the dose–response relationships between greenspace exposure and mental health for both frequency and duration. Second, the Emax values indicate that frequency and duration each show strong potency to promote mental health, and diminishing marginal effects are evident beyond the EDB90 threshold. Third, EDB50 values show that a small weekly dose—about one visit or 1 h—achieves 50% of the maximum effect. Finally, EDB90 and EDB99 provide practical thresholds for near-plateau benefits and support recommended weekly doses for frequency and duration.

4.1. Why does the sigmoid curve with an increase-plateau pattern best describe the dose-response relationships for frequency and duration?

The association between dose of frequency and duration greenspace exposure and mental health responses can be best refitted as the sigmoid curve with an increase-plateau pattern, which is a rapid improvement in mental health with a small dose of exposure followed by a plateau with further increased exposure. While a full exploration of mechanisms is beyond the scope of this meta-analysis, we briefly speculate on plausible explanations for the sigmoid pattern, drawing on established theories in environmental psychology. First, the immediate effects help explain the rapid gains at low exposure (EDB50). Second, the accumulation effects help explain the approach to near-plateau thresholds (EDB90–EDB99). Third, the increased physical and social activity offers a possible mechanism to explain the near-plateau thresholds (EDB90-EDB99). Finally, the diminishing marginal effects help explain the small additional gains for the prolonged exposure.

The first mechanism is the immediate effects that help explain the rapid increase with minimal exposure (EDB50). The refitted sigmoid pattern revealed that the minimal dose of frequency (once per week) and duration (1 h per week) can achieve half of the maximum benefit. This can be explained by the immediate effects proposed by the classic Attention Restoration Theory (ART) and the Stress Reduction Theory (SRT). ART proposes that even brief nature contact supports cognitive recovery (Ulrich, 1981), SRT argues that nature exposure

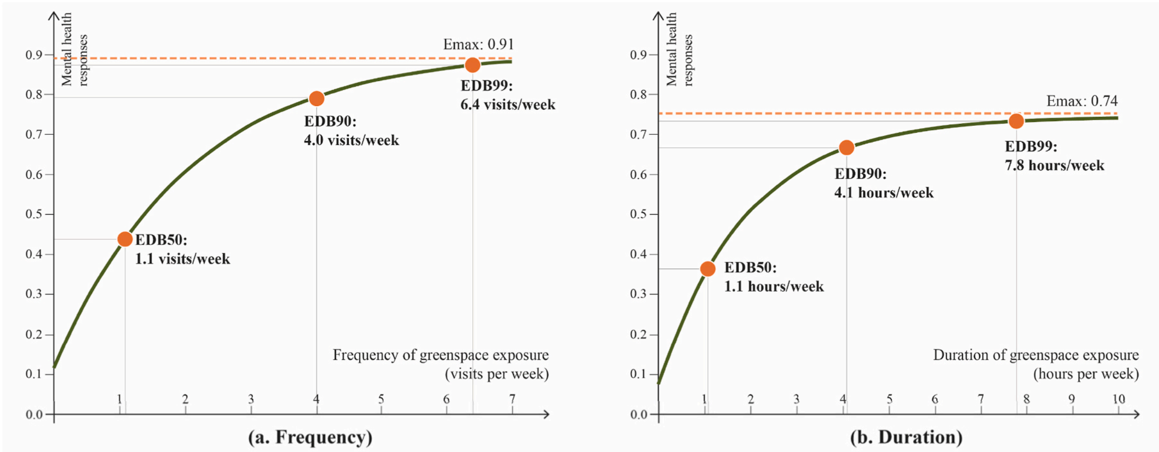

Fig. 4. Estimated Dose Benchmarks (EDBs) for the frequency and duration of greenspace exposure. The solid curves represent the best-fitting sigmoid relationships between greenspace exposure and standardized mental health responses. Panel a presents exposure frequency in visits per week; Panel b presents exposure duration in hours per week. Emax represents the model-estimated asymptotic maximum response. EDB50, EDB90, and EDB99 represent the estimated doses corresponding to 50%, 90%, and 99% of Emax, respectively. For frequency, the estimated benchmarks are 1.1 visits/week (EDB50), 4.0 visits/week (EDB90), and 6.4 visits/week (EDB99). For duration, they are 1.1 h/week (EDB50), 4.1 h/week (EDB90), and 7.8 h/week (EDB99). These values are model-derived average thresholds across heterogeneous studies and should not be interpreted as precise individual prescriptions.

Table 2
Three levels of recommendation: How often and how long time of greenspace exposure per week are needed to yield mental health benefits.

	EDB50 Satisfactory effect	EDB90 Good effect	EDB99 Excellent effect
Effect	50% of the maximal effect	90% of the maximal effect	99% of the maximal effect
Frequency (how often)	1 time per week	4 times per week	6 times per week
Duration (how long)	1 hour per week	4 hours per week	8 hours per week
Levels of Recommendation	**Basic**	**Moderate**	**High**

Note: The recommended doses are rounded to integer; the actual optimal thresholds can be found in Fig. 4.

rapidly calms human's minds and promotes both emotional well-being and healthy physical responses (Kaplan, 1987). Empirical studies echo these theories. Studies showed that visiting the UGS just once a week can largely reduce depression (Cox et al., 2017). Short durations can reduce blood pressure and support mental restoration, with notable stress relief from five to 60 min (Barton & Pretty, 2010; Lin et al., 2023; Shanahan et al., 2016).

The second mechanism is the accumulation effects that help explain the near-plateau thresholds (EDB90-EDB99). After the immediate rise with minimal exposure, the sigmoid curve will gradually rise to the near-plateau thresholds (EDB90-EDB99). Accumulation effects provide the plausible explanation for this pattern. Consistent contact with greenspace strengthens mental health outcomes over time (Yigitcanlar et al., 2020). Based on SRT, the cumulative effect of repeated nature exposure can deepen stress recovery and cognitive gains (Ulrich et al., 1991). Prolonged exposure often yields more reliable mental health benefits than single visits (Bratman et al., 2012). This helps explain why five weekly visits or 6 h per week align with near-plateau effects in our findings (Hong et al., 2019). Also, the repetitive greenspace visitation can generate post-exposure effects. Acute changes in mental health can persist for 2–4 h after a visit (Bressane et al., 2024). This delayed response suggests that benefits unfold across time (Tyrväinen et al., 2014).

The third mechanism is the increased physical and social activities that help explain the near-plateau thresholds (EDB90-EDB99). Urban greenspaces (UGS) provide settings for leisure, social interaction, and community building (Duku et al., 2023). More frequent or longer visits in UGS foster physical activity and social cohesion, which reinforce positive mood and reduce stress (Cox et al., 2018; Nutsford et al., 2013). These pathways help explain benefits at doses near the EDB90–EDB99 range.

The fourth mechanism is the diminishing marginal effects that help explain the marginal reaction for the prolonged exposure (Beyond EDB99). Studies report diminishing returns at high exposure levels. Further increases beyond key thresholds add limited further benefits (Cox et al., 2017; Fisher et al., 2021; Zhang et al., 2022). Long-term visits within greenspaces may involve qualitatively different activities, such as overnight camping, with mixed or complex outcomes (Barton & Pretty, 2010). Some work notes possible adverse effects. After the frequency or duration of greenspace exposure reaches a certain threshold, individuals become adapted to the environmental stimuli, the novelty effect drops and leads to the reduction of mental health benefits (Kondo et al., 2018; Ulrich, 1981). Excessive exposure can induce fatigue or stress and may undermine well-being (Millward et al., 2013; Yang et al., 2022). People also tend to increase nature visits during stressful periods, which can complicate causal interpretation of dose and benefit (Lin et al., 2023).

4.2. Theoretical contribution: A refined dose-of-nature framework

To our best knowledge, this study might be one of earliest studies that identified and rationalized a generalized dose-response curve that can describe the relationship between multifaceted greenspace exposure and mental health outcomes. Building on the optimal thresholds we identified, we propose a refined *Dose-of-Nature Framework*. It specifies the best-fitting curvilinear patterns for frequency, duration, and intensity, and offers threshold-based recommendations that can guide future research and policy.

The existing *Dose-of-Nature Framework*, raised by Jiang and later researchers, highlights the roles of intensity, frequency, duration, and accessibility in shaping mental health (Jiang, 2013; Jiang et al., 2014, 2015; Shanahan et al., 2016). Our findings deepen this framework. Through a meta-analysis of current empirical evidence, we identify the best-fitting dose–response curve pattern and optimal thresholds across exposure dimensions. This refined framework supports the design of natural experiments for future studies to test how greenspace interventions produce dose-dependent health effects.

Current studies on the association of multifaceted greenspace exposure and mental health responses lack guidance of a synthesized curvilinear pattern. The application of a single threshold or linear analysis led to inconsistent and generalized findings. Our study clarifies that frequency and duration follow an increase–plateau sigmoid pattern, while greenness intensity follows a quadratic pattern. This significant systematic finding allows future research to apply the suitable curve pattern and corresponding models in their studies and offer more evidence to strengthen the *Dose-of-Nature Framework*.

Another critical parameter of the *Dose-of-Nature Framework* is the recommended thresholds. Little is known about the optimal dose thresholds for the frequency and duration of greenspace exposure on mental health. Designing a reasonable experimental framework has been challenging due to these mixed findings. Our results align with prior theory and offer a more systematic framework to provide a clear guidance. Half of the maximum mental health (EDB50) is achieved with minimal weekly doses: about one visit or 1 h. Four to six visits per week or four to 8 h per week can approach near-plateau mental health benefits (EDB90 and EDB99). Researchers can use these values to set exposure levels and improve study design.

4.3. Practical implications of findings

How can we translate the findings into actions? The identified patterns and threshold values offer a clear basis for collaboration among policymakers, designers, and residents who aim to build healthier cities. Policymakers can align planning, transport, and safety measures to promote access to urban greenspaces. Designers can incorporate the identified Estimated Dose Benchmark (EDB) thresholds of multifaceted greenspace exposure into their projects and public space facilities. Residents can adjust daily routines to reach effective doses and gain mental health benefits.

For policymakers, we encourage diverse agencies to work together and integrate our findings of Estimated Dose Benchmark (EDB) as the recommendations of implications for their healthy city agenda. Planning agencies can embed threshold-based guidance in policies that range from large-scale land-use strategies to small-scale street connectivity improvements (Coutts, 2008; Giles-Corti et al., 2016). Public transportation agencies can work with local authorities to link neighborhoods to greenspaces within appropriate travel-time buffers (Chen et al., 2020). Pedestrian-friendly design and "20-min park" principles can ensure that affordable public transport connects residents to parks easily (Yigitcanlar et al., 2020). Public safety agencies can also enhance surveillance and maintenance in urban greenspaces to create safer environments that support longer and more frequent visits (Chen & Zhou, 2016).

For designers, the recommended weekly frequency and duration based on EBD 50/90/99 provide guidelines for nature-based interventions that support psychological health. Design and management can supply facilities that increase both the quantity and quality of activities in urban greenspaces. Shaded seating and well-designed picnic areas can encourage longer stays with family and friends. Bike racks and trail networks can support diverse activities and healthy behaviours. Community gardens and open lawns for yoga classes or festivals can attract regular visits and strengthen social ties. Streetscapes that improve walkability, remove barriers, and shorten travel time can raise accessibility and encourage more frequent exposure (Yigitcanlar et al., 2020).

For residents, education about forming a positive cycle of urban greenspace visitation involving recommended frequency and duration to achieve mental health benefits is essential. This support is especially useful for people facing mental health challenges, those who are currently inactive, or those with limited time. Small changes can deliver meaningful benefits. Residents can arrange nature contact into daily life by walking to local shops, choosing routes that go through parks, or adjusting commute paths to include greenspace.

4.4. Limitations and suggestions for future research

This study offers an initial effort to model dose–response curves between multifaceted greenspace exposure and mental health outcomes. Several limitations remain, and they point to clear directions for future work.

First, heterogeneity issues exist in how nature exposure and mental health responses are defined and measured. Even though the quantity of our search records (92,430) suggests comprehensive coverage of the core literature, the heterogeneity of the diverse greenspace types and mental health responses still existed. Some specific greenspace types may not be captured, the specific characteristics of these greenspaces like vegetation density, biodiversity, and size varied considerably across studies, and are rarely reported in sufficient detail to allow sub-group analysis. Also, a great range of mental health responses can hardly be standardized, and some inappropriate labelling exists. For example, the measurement for wellbeing index is typically as a composite construct encompassing physical health, social functioning, and life satisfaction in addition to mental health. While some scales labelled "wellbeing" specifically measured mental health states (e.g., the WHO-5 Wellbeing Index, which assesses mood and vitality). Including such multidimensional constructs would introduce substantial conceptual heterogeneity.

Although our study included evidence labelled as "wellbeing" that in fact measured "mental health" by examining the original texts, future research should use more accurate and standardized measurement systems to facilitate transparent knowledge dissemination. Also, future research on the dose-of-nature modelling should use more appropriate search syntax to avoid the heterogeneity issue. The curve-refitting results should be more specific on the greenspace type, the mental health response, and other confouding factors like the gender, age, and region.

Second, measurement standards for greenspace exposure need improvement. Critical heterogeneity issues exit in the diverse and inaccurate audit methods for the frequency, duration, and accessibility of greenspace exposure. Primary studies use inconsistent units and time frames. For example, duration is reported as hours per day in some studies, per week in others, and occasionally per year. Also, the survey questions are rough and inaccurate; participant's responses like "few times a year, few times a month, few times a week" are difficult to be standardized and quantified. These problems could influence accuracy and reliability of data synthesis. Future research should aim to develop a more precise measurement audit for greenspace exposure, and try to collect data with weekly or monthly documentation but avoid the yearly documentation.

Third, the heterogeneity issues also exist in Estimated Dose Benchmarks (EDB) application. A critical limitation of our approach is that the Estimated Dose Benchmarks (EDB) treat greenspace as a relatively homogeneous 'treatment.' However, in reality, greenspaces vary enormously in quality, vegetation type, biodiversity, maintenance, size, and amenities. Our recommended thresholds represent average effects across this diversity, and tend to reveal the generalized relationship and approximate threshold values. The true dose–response relationship for any individual will depend on the specific characteristics of the greenspace visited, the activities undertaken, and personal preferences. Future research should disaggregate these curves by greenspace typology to provide more nuanced guidance.

Fourth, our analysis identifies a single generalized curve for each exposure dimension, but it is unlikely to apply universally. The sample studies included in our meta-analysis vary in age, gender, cultural background, ethnicity, and socioeconomic status. Individuals with clinical depression may respond differently to greenspace exposure than healthy populations, and residents of tropical cities may have different relationships with outdoor spaces than those in temperate climates. Our generalized curves represent average tendencies in the current literature and should be interpreted as starting points for more differentiated research. Future studies should stratify dose–response analyses by key demographic, cultural, and environmental moderators to develop more specific recommendations of greenspace exposure for diverse populations and individuals.

Fifth, the evidence on prolonged exposure is limited, particularly at the right-hand (high-dose) of the frequency and duration continuum. Few studies observe very high frequencies, such as more than seven visits per week, or very long durations, and the theoretical upper limit of exposure has not been empirically approached in the existing literature. Without sufficient high-dose observations, it is difficult to detect diminishing returns or possible reversals. Future research should extend exposure ranges and, where feasible, test high-dose conditions to strengthen inference.

Finally, the accessibility of greenspace exposure requires further evidence. We did not include the main dose–response results for accessibility because the sample size was limited. Studies of greenspace accessibility focused onmental health responses of depression, anxiety, and general mental health. To ensure credibility, we present the accessibility curve refitting in the Supplementary Information. Future work should expand accessibility analyses to a wider set of outcomes—such as cognition, preference, satisfaction, attention, and restoration—and increase sample sizes. Broader coverage will support more reliable curve refitting across all greenspace exposure dimensions.

CRediT authorship contribution statement

Jiali Li: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Resources, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Peng Gong:** Writing – review & editing, Investigation. **Gunter Schumann:** Writing – review & editing, Investigation. **Chris Webster:** Writing – review & editing, Validation. **Bin Jiang:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization.

Data availability statement

All datasets supporting the findings of this study are publicly accessible via GitHub repository at: https://github.com/jli1102/Dose_2025. The repository comprises two structured datasets: 1/Data 1_Inclusion; 2/Data 2_Extraction.

Note: To ensure repentance and the diverse implications of our findings, we shared all the critical database through the public repository with a full description (Data Availability Statement).

Materials & correspondence

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jenvp.2026.103211.

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