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Nature as Medicine: Prescribing Doses of Greenspace Visiting Behaviours to Promote Mental Health Based on Forty Years of Evidence

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Nature as Medicine: Prescribing Doses of Greenspace Visiting Behaviours to Promote Mental Health Based on Forty Years of Evidence

Abstract:

Greenspace exposure is a low-cost and effective strategy for improving mental health, yet the basic, satisfactory, and optimal doses of exposure behaviours remain unclear. We synthesized 92,430 studies (1980–2025) in a comprehensive meta-analysis. We collected sufficient data for frequency and duration, so analyses focused on these dimensions. We identified a generalized sigmoid, increase–plateau dose–response curves for mental health with both frequency and duration of greenspace exposure. Curve models indicate that frequency and duration significantly affect mental health, with frequency exerting greater effects than duration. Dose recommendations are: Emax value-50% (ED50)—once per week and one hour per week; ED90—four visits per week and four hours per week; ED99—six visits per week and eight hours per week. This is an initial study to find and rationalize a generalized 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.

Keywords: Contact with nature, urban greenspaces, mental health, dose-response curve, Sigmoid function

Highlights:

- A sigmoid curve describes dose of visiting greenspaces and mental health responses.
- Impacts of frequency and duration on mental health follow an increase-plateau pattern.
- ED50: One visit and one hour per week achieve 50% of maximal mental health.
- ED90: Four visits and four hours per week yield 90% of maximal mental health.
- ED99: Six visits and eight hours per week yield 99% of maximal mental health.

1 Introduction

1.1 Background

Urban residents worldwide face rising levels of mental distress and illness, including stress, anxiety, depression, and persistent negative mood. At the same time, cities have become denser and less green. Many people now have fewer chances to visit and enjoy greenspace in terms of how much greenspace they can access (intensity), how long they spend there (duration), and how often they go (frequency) (Cox et al., 2018; Dye, 2008; Jiang et al., 2015; Jiang et al., 2019). These trends highlight an urgent task for public health and urban planning. What levels of greenspace exposure best support mental health, and how should we advocate for them (Gong et al., 2012; Schumann et al., 2019)?

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 urban greenspaces under pressure (Pauchard et al., 2006). At the same time, 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 the effective approach for the comprehensive mental health strategies.

A large body of research links greenspace exposure to better mental health (Hartig et al., 2014; Jiang, He, et al., 2021). Yet critical questions remain. The dose-response relationship between multifaceted greenspace exposure (intensity, frequency, duration, and accessibility) and mental health benefits is limited and fragmented, and current evidence does not provide clear guidance on optimal doses (Cox et al., 2017). Also, past work often assumed a simple linear association, which overlook 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. 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

The dose of nature framework was introduced and developed by Jiang and later expanded by Shanahan to quantify non-linear associations between multiple exposure dimensions and mental health outcomes (e.g., Jiang et al., 2014; Jiang et al., 2015; Jiang, Shen, et al., 2021; Shanahan et al., 2016). In 2013, Bin Jiang published a dissertation on the dose-response relationship between greenspace exposure and mental health benefits and posited the dose of nature shall be measured from three dimensions, including intensity, duration, and frequence. In later years, other researchers echoed this framework and add accessibility as one more dimension (Frumkin et al., 2017; Hunter & Askarinejad, 2015; Hunter et al., 2019; Shanahan et al., 2015).

This body of work established a clear framework but did not offer a systematic test of the full curvilinear pattern of each greenspace exposure. It also left open whether critical thresholds exist and how strong the diminishing returns are at the extreme dose values.

1.2.2 Empirical evidence: Non-linear patterns of multifaced greenspace exposure

An increasing body of empirical work reports 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.

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 as little as one weekly visit was associated with 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 appears as important as frequency and 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 between duration and mental health. The association revealed large benefits from short duration (ten minutes) in green space, with diminishing but still positive returns for longer exposure (Barton & Pretty, 2010). Hazer et al. (2018) also reported that one hour of greenspace exposure per week was associated with the significant reduction in perceived stress (Hazer et al., 2018). Reported duration thresholds for near-plateau mental health responses range from brief sessions to several accumulated hours. Many studies identified 30 to 90 minutes 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). Some research suggests that five or more hours of greenspace duration per week may be optimal for reducing depression, while a few studies note possible reversed effects for the prolonged greenspace exposure.

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 minutes, consistent with the widely cited "20-minute park theory" (Xie et al., 2022). Nutsford et al. (2013) found that improved accessibility to useable 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).

1.2.3 Circumstantial theoretical models: Curvilinear dose–response relationships between external stimuli and health outcomes

The dose of nature framework provides a solid theoretical base and identifies the multifaceted types of greenspace exposure. Empirical studies suggest non-linear associations and diminishing marginal effects for mental health outcomes. To identify the best-fitted dose-response curve pattern, it is useful to consider three classic curvilinear models rooted in environmental psychology and pharmacology. These models are widely used to describe how

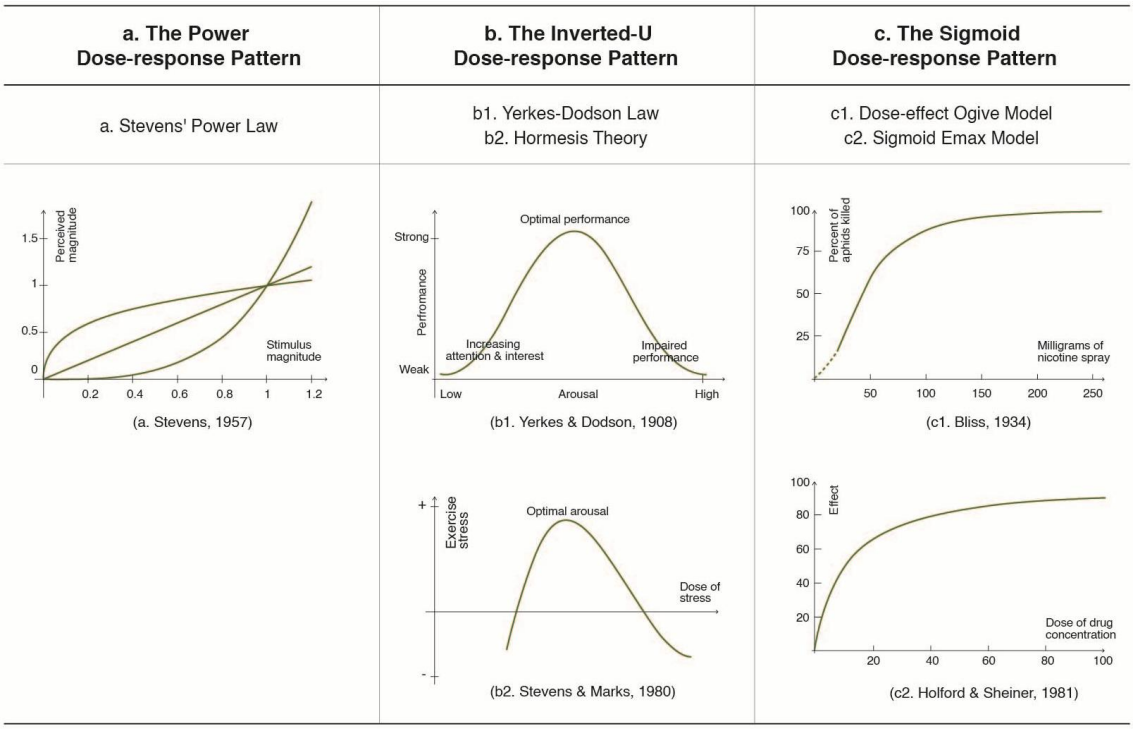


Fig 1. Three types of circumstantial curvilinear theory models. (a) Power dose-response pattern: The Stevens's Power Law; (b) Inverted-U pattern: The Yerkes-Dodson Law (b1) and The Hormesis Theory (b2); (c) Sigmoid dose-response pattern: The Dose-effect S-curve (c1) and The Sigmoid Emax Model (c2).

external stimuli relate to human responses: the power pattern, the inverted-U pattern, and the sigmoid pattern (Davis & Svendsgaard, 1990; Stevens & Marks, 1999; Yerkes & Dodson, 1908).

a. The power dose-response pattern: Stevens' Power Law. The Steven's power law is a foundational theory in psychology. It describes how perceived intensity changes as a power function of stimulus magnitude (Xiao et al., 2011). This non-linear pattern has been applied to explain how the perceived environmental stressors like noise or pollution grows as a power function of the mental health responses (Stevens, 1957).

b. The inverted-U dose-response pattern: Yerkes-Dodson Law and Hormesis Theory. The Yerkes-Dodson Law describes an inverted U-shaped relationship between environmental exposure and human mental health (Cook & Calabrese, 2006). This law highlights how the moderate stimulation of the environmental factors may optimize the effects of mental health performance like well-being, creativity of productivity. The extreme doses will impair the mental responses (Yerkes & Dodson, 1908). The Hormesis Theory also demonstrates the inverted-U pattern, and the significance of optimal thresholds. These findings point to optimal thresholds at moderate doses and adverse effects at high doses (Davis & Svendsgaard, 1990; Stevens & Marks, 1980).

c. The sigmoid dose-response pattern: Dose-effect Ogive Model and Sigmoid E_{max} Model. Studies in the pharmacology field identified that the association between dosage of drug concentration and effects can be expressed as the asymmetrical S-shaped curve (Bliss, 1934; Goutelle et al., 2008; Holford & Sheiner, 1981). Bliss published the critical paper in *Science* that revealed the probability of the sigmoid dose-effect ogive between the dosage and its effectiveness. Later, Holford and Sheiner's classic literature review confirmed the sigmoid Emax model between the dose of drug concentration and its effects, and pointed out the decreased effect for the prolonged drug exposure (ED50). In this model, the effect rises steeply at low doses, slows in the middle range, and approaches a maximum as it nears saturation. ED50 denotes the dose that achieves 50% of the maximum effect (Emax). A lower ED50 indicates greater drug efficiency, while Emax represents the upper limit of the achievable effect.

These models suggest that the dose–response relationship between greenspace exposure and mental health could follow power, inverted-U, or sigmoid forms. A meta-analysis of existing evidence can compare these potential models and identify which pattern best fits each exposure dimension. Furthermore, these classic theories imply diminishing marginal effects for prolonged or very high exposure. The immediate and moderate doses may offer the significant benefits, while higher doses may have limited beneficial effects. Identifying those thresholds is essential for practical guidance.

1.3 Research gaps: Three issues

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 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). Policymakers need evidence on how often people should visit and how long they should stay to achieve measurable mental health gains. More importantly, current studies also use diverse contexts and outcome measures, which makes synthesis difficult. 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 frequency,

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

1.4 Research questions

To address these gaps, we examine dose–response relationships for the frequency, duration, and accessibility of greenspace exposure and their links to mental health. We aim to identify the best-fitting non-linear patterns, optimal thresholds, and the presence of diminishing marginal effects.

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 years (1980-2025) to identify all studies on the multifaceted greenspace exposure 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 database 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 large "dose of nature" project that collected all the related dose of greenspace exposure and mental health data. The first paper of this project focused on the intensity of greenspace exposure, and published in *Nature Cities* this year (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 Sciences 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. The "topic" field of the search included at least one keyword from both sides of "Green space" and "Mental health." 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 significant or insignificant, negative, or positive results. Fig 2 shows the results of systematic review. Studies were excluded for the following reasons (Appendix B): Irrelevant greenspace exposure variables (339 studies, 38.22%); Irrelevant mental health variables including social contacts, physical behaviours, general health, and aesthetics (176 studies, 19.84%); Pathway study without quantitative data (153 studies, 17.25%); Studies without statistical association between greenspace exposure and mental health (81 studies, 9.13%); Studies with binary measurements (73 studies, 8.23%); Not research article (33 studies, 3.72%); Qualitative studies without quantitative data (15 studies, 1.69%); Not written in English (13 studies, 1.47%); Articles not available (4 studies, 0.45%).

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.

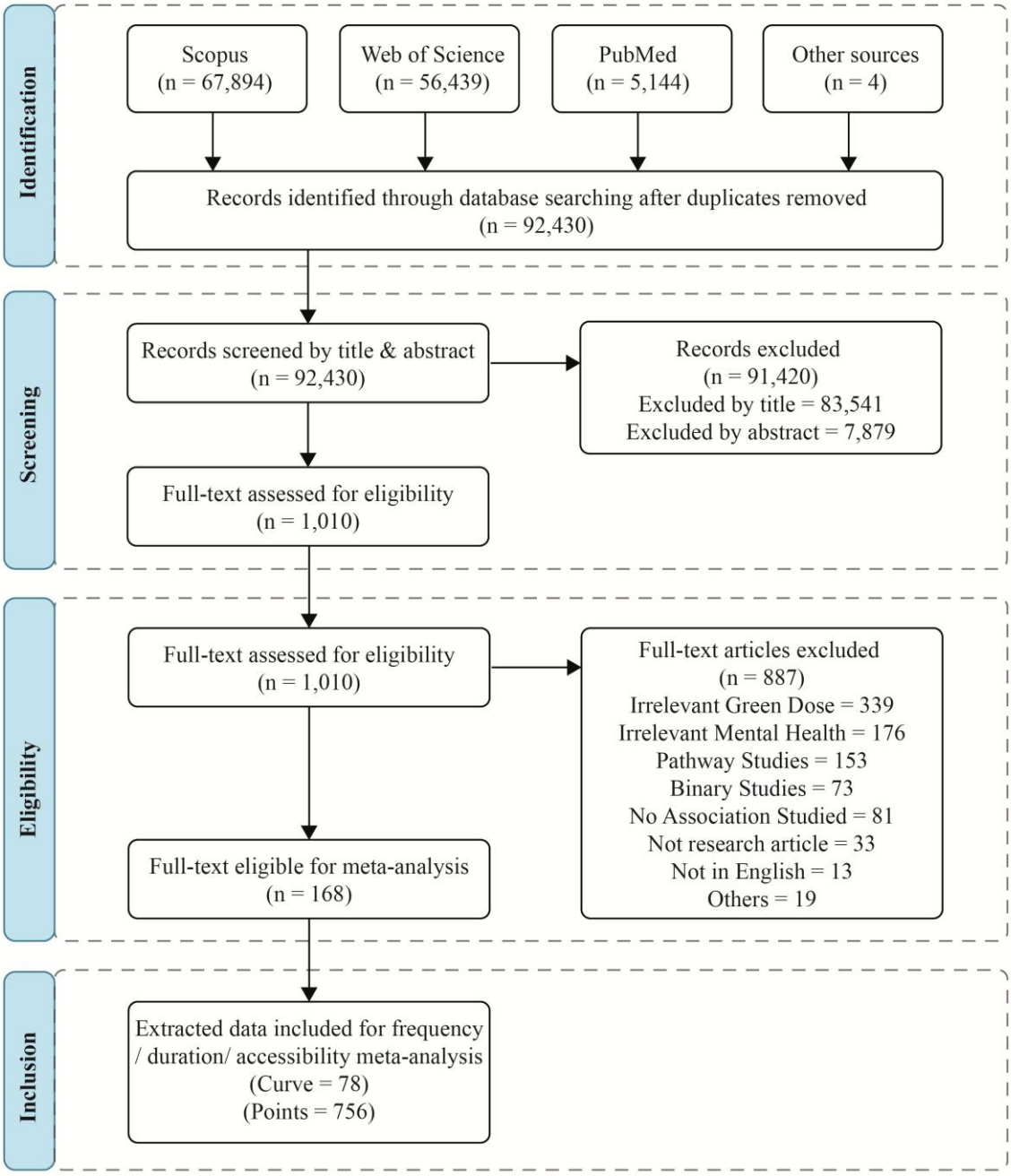


Fig 2. Preferred Reporting Items for Systematic Reviews and Meta-analyses (PRISMA) process and results.

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2.1.2 Quality assessment and bias check

We developed an evaluation framework that integrates two validated tools frequently employed in researches on built environment-human health field: the Risk of Bias in Non-randomized Studies (ROBINS-E) and the Effective Public Health Practice Project Quality Assessment Tool (EPHPP). The evaluation framework encompasses four critical domains relevant to greenspace-mental health associations: study design, exposure assessment, outcome assessment, and confounding assessment. Based on the selected tools (ROBINS-E and EPHPP) and previous systematic reviews in environmental psychology, we set the domain-specific evaluation criteria (Appendix H1). 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. Consistent with previous review studies in our field, we designed a five-tier classification system for the final quality: 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. We reran the curve-refitting meta-analysis using studies of excellent and good qualities for the sensitivity analysis, and the results remained consistent.

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 only papers that cannot provide data for the meta-analysis, while all significant/insignificant and positive/negative results were retained.

2.2.2 Curve data standardization

We applied standardization methodologies to minimize heterogeny 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). Frequency of the greenspace exposure indicates self-reported visits to green spaces within a time range; duration measures the total time spent in greenspace spaces; and accessibility of greenspace exposure measures the travel time to the nearest green space by foot. Within the selected curves, 100% of the frequency, duration, and accessibility measurements were the self-reported questionnaire data. 78% of the frequency and duration measurement documented the times within a week, while the remaining 12% varied from months to a year. 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. 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 hours.

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. 94% of the measurement of depression, anxiety, and stress utilized the Depression, Anxiety, and Stress Scale (DASS-21). Only one study applied biomarkers (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 unequal contribution bias, we applied mean normalization of the mental health values with a common range of 0 to 1, where 0 indicates worst mental health performance and 1 indicates best performance.

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 suggest Sigmoid curves.

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

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 characters of the existing dose-response curves between multifaceted green exposure and mental health responses can be observed from descriptive statistics: 1/ the rapid 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. Over 78% of the selected curves published within recent five years (Appendix D2).

Second, after the data extraction and standardization, the refitting curves did not exhibit significant heterogeneity issue (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, over 85% of the selected curves focused on the major representative mental issues, including the depression, anxiety, stress, and mood. Also, the scales applied to measuring the mental health responses are also highly representative and standardized. Over 50% of the depression, anxiety, and stress applied the same DASS-21 Depression, Anxiety, and Stress Scale to measure. Also, within the collected curve data, over 70% reported the curvilinear results. Another critical character observed in collected curves was the description of "greenspace" in the context of "greenspace exposure."

over 90% of the collected frequency, duration, and accessibility curves defined green space as "urban/ public green spaces" This finding enhanced the credibility of the curve-refitting results and the practical implications of our study.

In all, we collected 78 curves and 756 points. For the frequency of 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, since there were only 12 curves with 80 data points, to ensure the credibility of the study, we only reported the curve-refitting results of the frequency and duration in our manuscript. The results of dose-response curve refitting pattens of accessibility of greenspace exposure were in Appendix J.

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 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 pattern have much better model performance than linear and power pattern. The sigmoid model has the lowest AIC, BIC, and highest R^2 among all (Table 1).

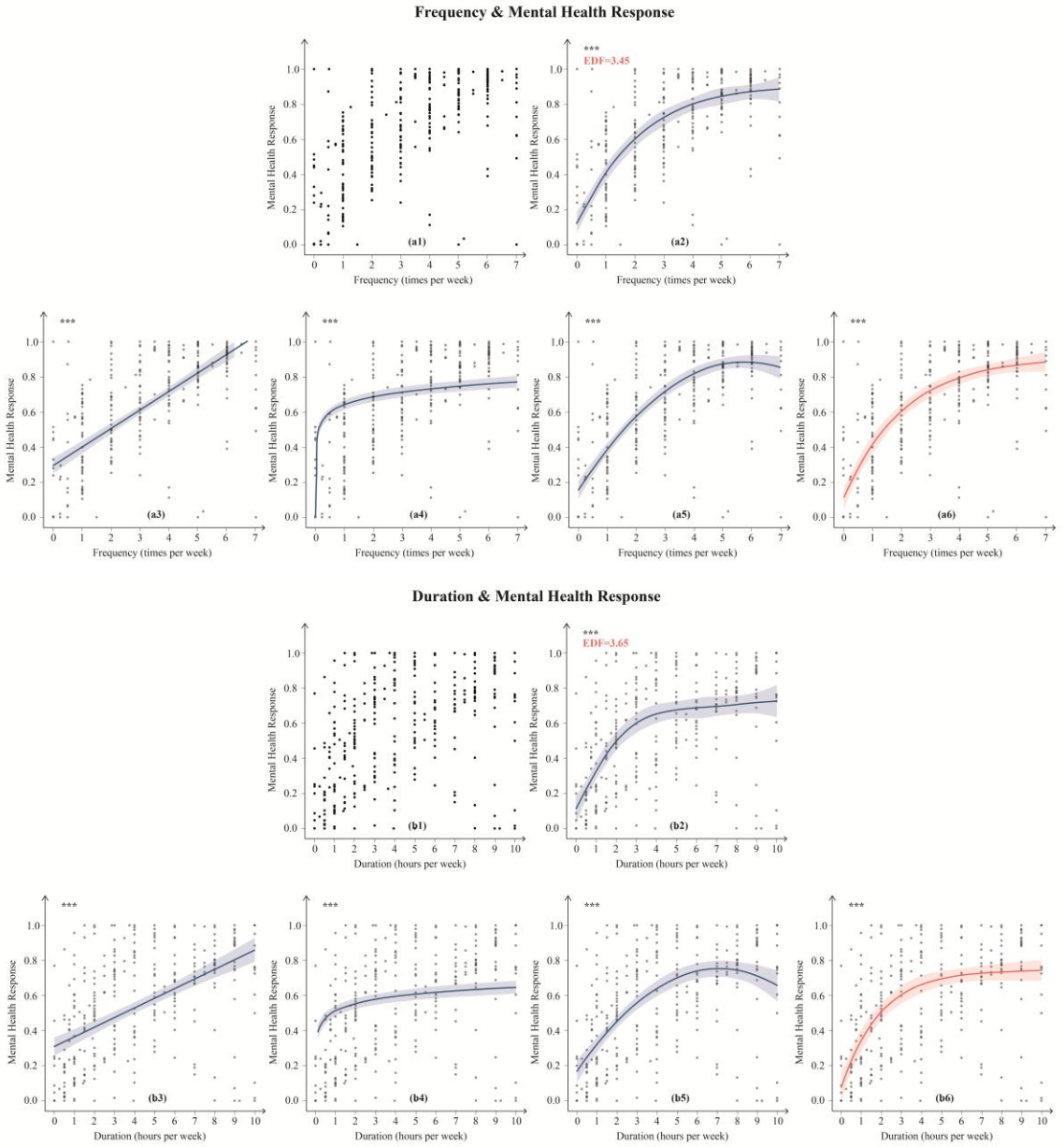


Fig 3. Meta-analysis of curve-refitting between dose of frequency (a1-a6) and duration (b1-b6) and mental health performance. (a1, b1) show the results of scatter plot of all the standardized collected points; (a2, b2) are the non-parametric Generalized Additive Model (GAM) curve-refitting; (a3-a6, b3-b6) show the results of four parametric models. Both GAM model and the comparison of four models show that the sigmoid curve is the best fit for the association (See details of statistical information in Table 1). ***p< 0.001, **p< 0.01, *p< 0.05, ns= non-significant.

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

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

Using the identified best-fitting sigmoid pattern and the formula for the frequency and duration greenspace exposure, we came up with two major discoveries. First, the predicted mental health plateau effects (Emax value) of the frequency greenspace exposure were higher than duration. Second, we calculated the recommended threshold doses for both frequency and duration greenspace exposure, including the half plateau effects (ED50, basic recommendation), the near-plateau effects (ED90, moderate recommendation), and the asymptote effects (ED99, high recommendation) (Fig 4).

First, we discovered that the predicted mental health plateau effects (Emax value) of the frequency greenspace exposure were higher than duration. The plateau effects (Emax) refer to the maximum effects that the frequency of duration greenspace exposure can produce. For instance, the Emax value of 1 refer to the complete mental health benefits, whereas the value of 0.8 indicates that greenspace exposure can only provide partial mental health benefits. 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. This shows that frequency greenspace exposure provides better mental health beneficial efficiency that duration, and the prolonged duration exposure has limited effects.

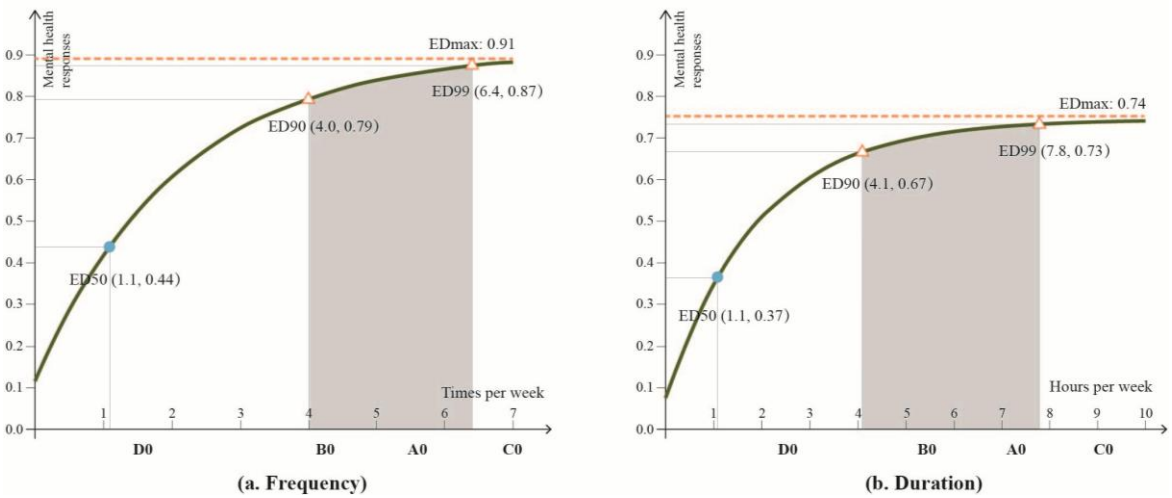


Fig 4. Results of curve refitting and doses of the moderate (ED50), highly beneficial (ED90), and optimal (ED99) mental health effects for the frequency (a) and duration (b) of greenspace exposure. The Emax means the predicted mental health plateau effects. The optimal (ED99) means the 99% of the plateau effect; the highly beneficial (ED90) matches the range of green exposure that is associated with the 90% of the plateau effect; The moderate (ED50) matches the range of mental health effects over 50%.

Second, we identified the ED50 (50%), ED90 (90%), and ED99 (99%) of the maximal (plateau) effects for the recommended thresholds for both frequency (how often) and duration (how long) greenspace exposures. ED50 is the most classic parameter for the sigmoid model (Ritz et al., 2015), it refers to the dose required to produce the 50% of the Emax effect. The lower ED50 value represents greater potency, indicating that a small (basic) dose of greenspace exposure can provide 50% mental health benefits already. ED90 and ED99 refer to the required dose of the greenspace exposure that can provide 90% and 99% of the plateau effects (Emax) (Motulsky & Christopoulos, 2004; Ritz et al., 2015). Unlike ED50 that points out the medium dose, ED90 and 99 parameters are can offer us the recommended doses of the near-plateau effects (Motulsky & Christopoulos, 2004).

For the frequency of greenspace exposure, the ED50 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 ED90 value of frequency is 4 times, meaning that visiting the

greenspace 4 times can achieve over 90% of the maximum mental health plateau effects. ED99 of 6.4 indicating that visiting the greenspace 6 times can almost achieve the plateau effect. Regarding the duration of greenspace exposure, the ED50 value is 1.1 hours per week, indicating that spending one hour in the greenspace can achieve 50% of the mental health plateau effects. The ED90 value of frequency is 4.1 hours, meaning that spending 4 hours in the greenspaces can achieve over 90% of the maximum mental health plateau effects. ED99 of 7.8 indicating that spending 7.8 hours 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 2. Recommendations of implications for the policymakers and practitioners that are based on threshold values of dose of greenspace exposure found in this study

	ED50 **Medium effect**	**ED90** **Near-plateau effect**	**ED99** **Asymptote effect**
Effect	50% of the maximal (plateau) effect	90% of the maximal (plateau) effect	99% of the maximal (plateau) effect
Frequency	1 time per week	4 times per week	6 times per week
Duration	1 hour per week	4 hours per week	8 hours per week
Level of Recommendations	Basic	Moderate (satisfactory)	High (optimal)

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

4 Discussion

This study identified four main findings. 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, with frequency exerting a larger effect. Third, ED50 values show that a small weekly dose—about one visit or one hour—achieve 50% of the maximum effect. Finally, ED90 and ED99 provide practical thresholds for near-plateau benefits and support recommended weekly doses for frequency and duration.

4.1 Why does as 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. Several mechanisms help explain this pattern: 1/ Immediate effects account for the rapid gains at low exposure (ED50). 2/ Accumulation effects help explain the approach to near-plateau thresholds (ED90–ED99). 3/ Increased physical and social activity contributes to the near-plateau thresholds (ED90-99). 4/ Diminishing marginal effects explain the small additional gains for the prolonged exposure.

1/ The immediate effects to explain the rapid increase with minimal exposure (ED50). The refitted sigmoid pattern revealed that the minimal dose of frequency (once per week) and duration (one hour 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 shows that nature exposure rapidly calms our minds and promotes both emotional well-being and healthy physical responses (Kaplan, 1987). Empirical studies echo these theories. Studies showed that visited 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 sixty minutes (Barton & Pretty, 2010; Lin et al., 2023; Shanahan et al., 2016).

2/ The accumulation effects to explain the near-plateau thresholds (ED90-99). After the immediate rise with minimal exposure, the sigmoid curve will gradually rise to the near plateau thresholds (ED90-ED99). This pattern can be explained by the accumulation effects. Consistent contact with greenspaces 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 six hours per week align with near-plateau effects in our findings (Hong et al., 2019). Also, the repeat greenspace visitation can generate post-exposure effects. Acute changes in mental health can persist for 2–4 hours after a visit (Bressane et al., 2024). This delayed response suggests that benefits unfold across time (Tyrväinen et al., 2014).

3/ The increased physical and social activities to explain the near-plateau thresholds (ED90-99). 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 ED90–ED99 range.

4/ The diminishing marginal effects to explain the marginal reaction for the prolonged exposure (Beyond ED99). 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; Jiang et al., 2015; Shanahan et al., 2016). Our findings deepen this framework. Through a meta-analysis of current empirical evidence, we identify best-fitting dose–response curve patterns, 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 a guidance of a synthesized curvilinear pattern. The application of the single threshold or linear analysis led to the 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 study 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 the 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 the clear guidance. Half of the maximum mental health (ED50) is achieved with minimal weekly doses: about one visit or one hour. Four to six visits per week or four to eight hours per week can approach near-plateau mental health benefits (ED90 and ED99). Researchers can use these values to set exposure levels and improve study design.

4.3 Practical implications of findings

How can these thresholds translate into action? The identified 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 optimal 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 optimal thresholds into 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-minute 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 optimal weekly frequency and duration 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, the education about forming a positive cycle of UGS visitation involving optimal 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, comprehensive 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, evidence on prolonged exposure is limited. Few studies observe very high frequencies, such as more than seven visits per week, or very long durations. 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.

Second, measurement standards for greenspace exposure need improvement. We have standardized the measures of the frequency, duration, and accessibility to avoid heterogony, yet 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. Such mixed approaches reduce accuracy and complicate synthesis.

Third, accessibility requires further evidence. We did not include the main dose–response results for accessibility because the sample size was limited. Studies that explored the statistical associations with the accessibility mostly focused on the representative mental health responses of depression, anxiety, and general mental health. To ensure the 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.

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