A One Health Sustainability framework for nature-based wellbeing

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Abstract

Human health benefits of nature are increasingly documented, yet the ecological conditions underpinning these benefits and the sustainability of nature-based interventions remain poorly measured. We introduce an integrated One Health Sustainability framework that links human health outcomes with ecological integrity, landscape pressures, and sustainability dimensions. This framework provides a basis for multi-domain indicators capable of evaluating health benefits, ecological dependencies, and trade-offs that shape the long-term sustainability of nature-based wellbeing interventions.

Main

The intentional use of natural environments to promote human health and wellbeing is rapidly gaining global interest, as health systems and emerging markets seek preventive, low-cost, and non-pharmacological interventions. Initiatives such as nature-based social prescribing exemplify this momentum[1], yet the evidence base supporting nature-based health interventions remains uneven and fragmented. Persistent uncertainty surrounds the types, durations, frequencies, and ecological qualities of nature exposure required to yield measurable health outcomes[2-4], and the majority of studies rely on proxies such as greenness or park access, rather than ecological metrics that reflect biodiversity, habitat condition, or ecosystem function[5-8].

While these approaches are often promoted as benefiting both people and the planet by positioning engagement with nature as a pathway to environmental awareness and stewardship, a deeper tension is emerging: short-term gains for human wellbeing may come at the expense of the ecosystems that sustain long-term human health. This potential planetary health paradox[9] underscores the need to address not only the health benefits of nature exposure to humans but also its dependencies on ecological quality and potential environmental costs.

Understanding these interconnected dimensions requires a framework capable of mapping bidirectional relationships between exposure dose, ecological impact, and human benefit. Developing such an approach is essential for informing sustainable policy and practice.

Insights from a rapid evidence review

To examine how research integrates human health, ecological, and sustainability dimensions of nature-based wellbeing, we conducted a rapid evidence review[10] of studies at the human–nature interface. Using a structured Web of Science search (2015–2025) and citation-based prioritisation, we selected highly cited, peer-reviewed articles across public health, ecology, environmental science, and sustainability. Eligible studies were identified based on relevance to nature exposure and measurable health outcomes. Data were extracted using an AI-based template and subsequently verified and refined manually. Fifty-four studies met inclusion criteria and were analysed using standardised taxonomies (**Supporting Information**) for health and environmental context, enabling cross-domain synthesis of ecological quality, environmental pressures, and sustainability considerations.

Most research on health–nature relationships has been conducted in urban, managed or otherwise human-modified settings rather than in ecologically intact or well-characterised ecosystems (**Supporting Information, Table S2**). Exposure assessments were dominated by anthropocentric, landscape-scale indicators such as the normalised difference vegetation index (NDVI), land-cover percentages, proximity-based metrics or self-reported visit frequency [11,12], rather than by ecological metrics that capture biodiversity, habitat condition, or ecosystem function. While such proxies capture broad vegetation patterns or access to green space, they do not map onto gradients of ecosystem naturalness, biodiversity, or ecological function and therefore offer limited insight into the ecological systems hypothesised to generate health benefits.

Using our dose–response evidence taxonomy, we found that most studies relied on spatial proxies or categorical contrasts, and only rarely reported interpretable exposure–response functions (**Supporting Information, Table S3**). Few studies identified threshold or plateau patterns, or used longitudinal or quasi-experimental designs that enable stronger causal or prescribable inferences. Reported effects primarily quantified exposure quantity (for example NDVI increments, green space proximity or visit frequency), but almost none assessed whether associations vary with ecosystem integrity, biodiversity or socio-demographic context. Consequently, the evidence base remains too limited to evaluate how dose–response relationships depend on ecological quality or to inform robust, transferable guidance for nature-based health interventions.

Ecological costs and trade-offs were also rarely examined. Well-documented consequences of anthropogenic pressure such as habitat disturbance, visitor impacts, wildlife disruption, trampling, resource extraction or pollution were rarely incorporated into analyses, despite their importance for long-term ecosystem stability[13,14]. This lack of attention to environmental impacts limits our ability to determine whether health-promoting interventions are ecologically sustainable or whether they risk degrading the ecosystems on which future human health depends.

Towards a One Health Sustainability framework for nature-based wellbeing

Taken together, these insights reveal not merely gaps in evidence on nature's health benefits but a broader structural misalignment in an evidence base shaped by an anthropocentric scientific worldview. Human health outcomes of exposure to nature are increasingly well documented, yet the ecological conditions underpinning these outcomes and the sustainability of nature-based wellbeing interventions remain insufficiently measured[15]. In an era of accelerating biodiversity loss, fragmented landscapes, and climate-driven hazards[16], as well as rising demand for nature-based wellbeing services[17], this gap is increasingly untenable.

To address this, we propose a unifying One Health Sustainability framework that explicitly integrates four interlinked domains:

1) Human health outcomes and modes of exposure and engagement with natural environments,

2) Local habitat condition and ecological integrity,

3) Landscape-level environmental pressures and hazards, and

4) Sustainability, restoration, and human equity and justice considerations.

By linking these dimensions, the framework provides a structured approach for synthesising ecological and health evidence, identifying meaningful indicators, guiding interdisciplinary research, and informing policies that ensure nature-based interventions are both effective for human wellbeing and ecologically sustainable (**Figure 1; Table 1**).

Framing nature-based wellbeing research and policy agenda

A unifying One Health Sustainability framework offers the conceptual foundation for multi-domain indicator systems capable of evaluating nature-based wellbeing interventions holistically.

Such systems must assess not only human health outcomes but also the ecological conditions that enable those benefits, the environmental pressures associated with increased use and the broader sustainability implications across scales. Clarifying these domains and their connections creates a pathway towards achieving 'healthy people in healthy environments', grounded in empirical evidence and spanning realistic ecological and socio-economic gradients.

A critical requirement is the establishment of clearly defined ecological reference conditions and habitat baselines. Without systematic characterisation of habitat types, quality and integrity, it is impossible to compare interventions across space and time or determine whether reported health benefits depend on specific ecological attributes. In the absence of such baselines, it becomes difficult to disentangle the health effects attributable to the intervention itself from those arising from broader landscape-level differences in environmental quality, exposure to hazards, or pre-existing gradients in population health. Meaningful evaluation must therefore be anchored not in minimal or degraded green infrastructure as is common in urban studies but, rather, in reference ecosystems that reflect intact, biodiverse and functionally robust habitats against which variation in exposure, impact, and health outcomes can be systematically assessed.

Ecological costs can differ markedly across exposure types. Passive engagement at the margins of semi-natural spaces may impose low ecological impacts, while intensive or unsustainable activities such as off-trail movement, cycling or motorised access, campfires or high visitor densities, can degrade sensitive ecosystems. Conversely, when wellbeing is pursued primarily in semi-natural or developed settings such as commercial wellness facilities or nature-based tourism enterprises, nature-for-health initiatives can contribute to overdevelopment, resource depletion, and habitat degradation. From a restoration perspective, if meaningful health benefits depend on access to biodiverse or ecologically intact environments, commercial health-nature enterprises could, in principle, be incentivised to support ecological enhancement[18].

Realising this potential requires a decisive shift in the research landscape. Future studies must systematically quantify ecological quality, habitat condition, biodiversity and landscape-level pressures alongside health outcomes. Equally important is the need to measure the environmental costs of wellbeing practices, including visitor pressure, carbon footprints, habitat disturbance, waste streams and transport emissions. Only by embedding ecological metrics within health research can we determine the conditions under which nature exposure is most beneficial, equitable and sustainable.

Aligning nature-based prescriptions with rigorous ecological evidence, equitable access and nature-positive practices could transform them from individual-level interventions into catalysts for ecological stewardship. The growing momentum around nature prescribing reflects recognition that human and planetary wellbeing are inseparable[19]. Yet without explicit attention to ecological limits and restoration needs, such interventions risk increasing environmental pressure and undermining the benefits they aim to deliver. If implemented narrowly, nature prescribing may become ecologically unsustainable and ultimately counterproductive, yielding short-term gains while neglecting the ecological and social foundations of long-term and population-level health. At the same time, the movement presents an opportunity to link rising clinical interest in nature's benefits with efforts in restoration, rewilding, equitable landscape planning and access to high-quality green and blue spaces[19,20].

Future research and policy must therefore place ecosystem integrity, ecological limits and long-term sustainability at the core of nature-based wellbeing initiatives. Rather than assuming that all forms of nature contact are uniformly beneficial, dual metrics are needed to track both human health gains and ecological conditions. Such an approach would enable evidence-based decisions that foster positive feedbacks between human wellbeing, ecological recovery and long-term sustainability, advancing a One Health Sustainability agenda capable of addressing the interconnected challenges of biodiversity loss, climate change and population health.

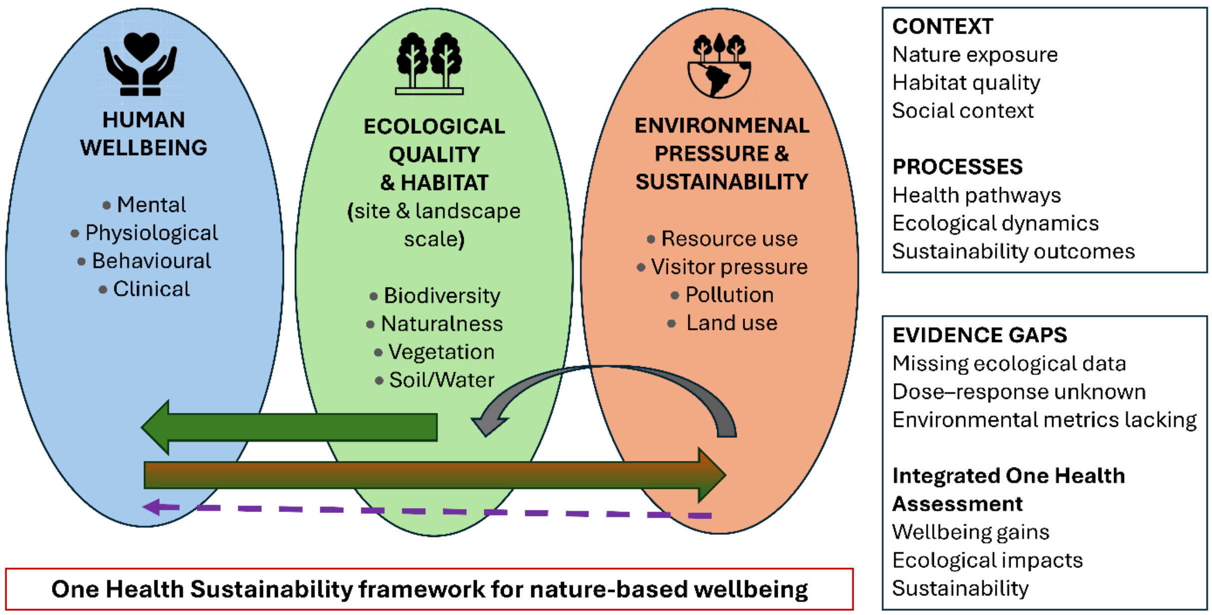

Figure 1. A One Health Sustainability framework for nature-based wellbeing. The framework links three interacting domains: human wellbeing (mental, physiological, behavioural, clinical), ecological quality and habitat (biodiversity, naturalness, vegetation, soil/water quality), and environmental pressures and sustainability (resource use, visitor pressure, pollution, land-use change). Arrows indicate key interactions: ecological quality supports wellbeing (green), human activity can generate positive and negative environmental impacts (mixed green/orange), sustainability feedback shape long-term ecological conditions (grey), and direct environmental stressors affect human health (purple dashed). Context, processes, and evidence gaps frame the system, while integrated One Health assessment combines wellbeing, ecological, and sustainability outcomes to inform equitable, nature-positive policy and practice.

Table 1. A cross-domain One Health Sustainability indicator framework for integrating human health, ecological integrity, and sustainability in research on nature-based wellbeing. This framework outlines key indicator families and candidate metrics to inform the development of future multi-domain and integrated assessment systems.

Indicator families	**Candidate indicators**	**Analytical potential**
Self-reported wellbeing; Clinical and physiological outcomes; Exposure and hazard indicators; Preventive behaviours	Wellbeing, mood, attention restoration; sleep quality; physical activity; adiposity, micronutrients; morbidity/mortality; cardiovascular and neuroendocrine stress markers; exposure to air pollutants, allergens, heat, bioaerosols, microplastics, zoonotic pathogens	Quantifying dose–response relationships; distinguishing perceived vs. measured outcomes; linking health responses to ecological exposure and habitat quality
Habitat type and quality; Biodiversity attributes; Naturalness and disturbance measures	Habitat classification; vegetation structure; richness of plants, birds, insects; soil and water quality, indicators of naturalness and degradation	Testing whether ecological integrity modulates health benefits; identifying habitat-dependent exposure quality; identifying minimum ecological thresholds for wellbeing benefits
Anthropogenic pressures; Habitat degradation; Resource use and emissions	Visitor pressure; trampling, erosion metrics; CO_2 and transport footprints; waste generation; wildlife disturbance indicators	Evaluating trade-offs; identifying low-impact exposure models; integrating environmental cost into dose–benefit analyses
Landscape-scale pressures; Connectivity; Mixed-use compositions	NDVI/greenness; urbanisation and land use gradients; noise, light, and chemical pollution indices; landscape fragmentation metrics; accessibility metrics	Understanding cumulative or spatially mediated effects; situating local health interventions within wider ecological and social systems
Ecosystem services; Resource flows; Equity and access; Lifecycle and systems assessments	Ecosystem service indicators (regulation, cultural, provisioning); socio-environmental equity metrics; life-cycle impacts of intervention infrastructure	Linking health outcomes to ecosystem service provision; identifying socio-environmental dependencies; informing sustainable and equitable planning
Joint assessment across health benefits, ecological conditions, environmental costs, hazards, restoration potential, and equity	Synthetic indices; cross-domain models; multi-criteria sustainability assessments	Enabling systems-level understanding of reinforcing benefits and trade-offs; supporting nature-positive, evidence-based policy and practice

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Supplementary Information

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Rapid review methods

Search strategy and study selection for rapid literature review

A systematic literature search was conducted in the Web of Science Core Collection (accessed 17/11/2025) using an advanced Boolean search string designed to capture studies linking exposure to natural environments with human health and wellbeing outcomes, while also addressing ecological or sustainability dimensions (see **Box S1** for the full search string). The search strategy was developed iteratively and reviewed by team members to ensure reproducibility, and alignment with Cochrane rapid review guidance [1]. The search was limited to English-language, peer-reviewed journal articles published between 1/01/2015 and 17/11/2025.

Given the breadth and disciplinary heterogeneity of the topic (13,488 initial records), we employed a rapid-review sampling strategy focussing on the most-cited records to capture the most influential contributions across public health, ecology, environmental science, and sustainability research. Bibliographic data were downloaded in *.ciw* format for the 1,000 most cited articles and processed in R version 4.3 [2] using the *revtools* and *dplyr* packages to standardise metadata, remove duplicates, and assign unique identifiers. Records were further prioritised based on citation rate (>4 citations per year) and publication in established international publishers (e.g., Elsevier, Springer Nature, Wiley, PLOS, and high-impact open-access outlets), yielding 283 articles for data extraction. We used this citation-based prioritisation as an accepted rapid-review approach for mapping dominant research patterns when full screening of all records is infeasible.

AI-assisted data extraction and manual validation and processing

To streamline synthesis and reduce manual workload, data extraction was performed using a large language model (ChatGPT, GPT-5, OpenAI, accessed in November 2025) guided by a structured extraction framework developed by the research team and following Cochrane guidance on automation and human oversight [1]. A structured data extraction framework was developed a priori, encompassing 21 predefined fields spanning both human and ecological dimensions, including study location, design, exposure metrics, health outcomes, ecological costs, and sustainability indicators (**Table S1**).

Following Cochrane recommendations for automation with human oversight, all extracted entries were independently verified against the original articles by human reviewers. Extracted fields were corrected where necessary, harmonised using a controlled vocabulary, and standardised using consistent terminology and spelling rules.

Screening and taxonomy development

Initial relevance screening of titles, abstracts, and extracted metadata was performed by one reviewer (KW) to identify studies reporting both human–nature associations and measurable health or wellbeing outcomes. Sixty-four studies met these inclusion criteria. References and entries were cross-checked by two reviewers to ensure the accuracy of extracted information. Discrepancies were resolved by consensus and 56 studies were retained for the final evidence synthesis.

Four taxonomies were developed to classify study populations, health outcome domains, and habitat types, and types of dose-response relationships measured (if studied). Taxonomies were derived using a hybrid deductive-inductive approach: deductively from established One Health and ecological frameworks, and inductively refined through iterative coding of the extracted dataset. All taxonomic categories were reviewed and agreed upon by the full author team.

Human sample taxonomy: The Human sample taxonomy captures the demographic and contextual characteristics of study populations. From the raw descriptors, populations were grouped into coherent sample classes based on age, life stage, and residential context. The final taxonomy comprises: *H-1*) General population – adults, *H-2*) General population – mixed ages, *H-3*) General population – residents, *H-4*) General population – regional, *H-5*) General population – households, *H-6*) Students / university populations, *H-7*) Children, *H-8*) Older adults / elderly, *H-9*) registry cohorts, *H-9*) Travelers / mobile populations.

Health aspect taxonomy: to synthesise the heterogenous terminology used across studies, all raw health outcome descriptors were systematically mapped onto a standardised health aspect taxonomy. The taxonomy included aspects of domain (e.g., mental, physical, cognitive), subdomain (e.g., depression, respiratory health, attention), specific outcome (e.g., stress recovery, mortality, immune tolerance), measurement type (self-reported, clinical, epidemiological, experimental), and study context, which identified whether the outcome operated within a health promotion/ preventive, clinical, hazard exposure, intervention, or experimental framework. Health domains were categorised following previously used taxonomies in nature–health research (WHO International Classification of Functioning, Disability and Health; https://www.who.int/standards/classifications/international-classification-of-functioning-disability-and-health, accessed in November 2025), with some adaptations to reflect the distribution of outcomes across included studies. The final taxonomy comprised the following major health domains: *W-1*) Mental health/ psychological wellbeing (e.g., subjective wellbeing, psychological distress, depression, anxiety, stress recovery, psychological restoration), *W-2*) Physical health (e.g., respiratory, cardiovascular, metabolic, general physical health, mortality, thermal comfort, physical activity–related health), *W-3*) Cognitive health (e.g., attention, cognitive performance, cognitive restoration, cognitive development), *W-4*) General or self-rated health (e.g., global self-rated health, general health status), *W-5*) Quality of life (multidomain) (e.g., physical, social, psychological, and environmental quality of life composites), *W-6*) Immune or allergy-related health (e.g., immune tolerance, atopy, allergy outcomes), *W-7*) Environmental exposure–related physical health (e.g., heat exposure, air pollution, occupational pesticide exposure, environmental neurological risk), *W-8*) Multidomain health (combined mental, physical, social, and/or environmental wellbeing indicators).

Habitat taxonomy: The habitat taxonomy reflects the type of natural or nature-based environment assessed in each study. Categories were derived by grouping raw exposure descriptions according to ecosystem structure, degree of human modification, and dominant environmental feature following conceptual distinctions outlined elsewhere [3,4]. The final taxonomy includes: *E-1*) Urban green space (parks, street greenery, residential vegetation, campus gardens, green infrastructure), *E-2*) Urban/rural green space landscapes (mixed green + blue space at regional scale), *E-3*) Mixed landscapes (forests, agricultural semi-natural areas, lakeshores, coastal, mountains, recreational zones), *E-4*) Green infrastructure / built green (streetscapes, managed corridors), *E-5*) Blue space (urban/coastal water bodies), *E-6*) Forested landscapes (managed/unmanaged forests), *E-7*) Hazardous or degraded landscapes (peatland smoke, burned forest, air pollution–affected areas), *E-8*) Wetland / freshwater agroecosystems, *E-9*) Virtual / simulated nature exposures.

Dose–response evidence taxonomy: To systematically evaluate and compare ***dose–response evidence*** across studies in our meta-analysis, we developed a four-dimensional taxonomy designed to capture the interpretability and actionability of nature–health dose–response relationships beyond simplistic categorisation by statistical model type. The structure draws on established principles of causal inference, exposure classification, and intervention-relevant design considerations [5-8].

1) Dose definition quality: we categorised how exposure metric reflects quantifiable and potentially actionable dose of nature as

d1-i) Behaviourally prescribable doses (e.g., activity and/or time spent in natural environments, number of visits per week) that can directly inform health interventions;

d1-ii) Spatially defined doses (e.g., NDVI, canopy cover, percentage of green space) that are measurable but not directly prescribable to individuals;

d1-iii) Experiential or perceptual doses (e.g., perceived greenness or naturalness) that are subjective and less generalisable.

2) ***Dose–response functional interpretability***: we classify studies according to the interpretability of their reported dose–response relationships, i.e., the extent to which the data provide meaningful guidance on exposure–response relationships beyond merely detecting statistical significance:

d2-i) Threshold or plateau identifiable: study reports a minimum effective dose, threshold, plateau, or baseline level, or otherwise quantifies the point at which additional exposure confers little or no extra benefit; may model linear or non-linear relationships as long as a meaningful threshold or plateau can be derived. Provides actionable information for policy, public health, or intervention design;

d2-ii) Functional relationship reported, but interpretation limited: study models a dose–response relationship (e.g., linear regression, spline, GAM, polynomial), but does not provide a threshold, plateau, or baseline, or does so in a way that prevents meaningful quantification of “how much exposure is enough or efficient”; interpretation is limited to the existence and direction of an association, but marginal effects or actionable guidance cannot be extracted;

d2-iiii) No dose–response tested: study compares binary or categorical exposure groups only, without estimating a continuous or functional relationship between exposure and outcome; provides minimal information for identifying meaningful exposure levels or quantifying dose-dependent effects.

3) **Causal or confounding robustness**: we categorised the degree to which reported associations are likely to represent causal effects:

d3-i) High robustness through longitudinal or quasi-experimental designs (e.g., repeated measures, natural experiments, mixed-effects models) with appropriate confounder adjustment;

d3-ii) Moderate robustness: cross-sectional designs with comprehensive adjustment for potential confounders;

d3-iii) Low robustness: cross-sectional studies with minimal confounder control.

4) **Policy or intervention scalability:** we categorised the extent to which the dose–response evidence can inform actionable interventions or public health guidelines:

d4-i) High scalability: behaviourally prescribable doses with clear effect estimates;

d4-ii) Moderate scalability: spatial doses that can guide planning but not individual prescriptions;

d4-ii) Low scalability: subjective or ecological quality metrics with limited translation to interventions.

Evidence synthesis

We conducted a structured descriptive synthesis to assess the extent to which health, ecological, and sustainability dimensions were represented across studies. Qualitative analysis followed a transparent, taxonomy-guided content-analysis approach in which findings were derived against the harmonised categories and interpreted within a One Health–oriented conceptual framework. The resulting evidence statements reflect consistent patterns observed across the 56 validated studies.

Box S1. Search string combining aspects of nature, health, quantitative relationships and exposure measures, and ecological impact used to obtain reference from Web of Science for a rapid literature review.

TS=(("nature" OR "green space*" OR "park*" OR "urban vegetation*" OR "forest" OR "woodland" OR "wetland" OR "blue space*" OR "outdoor" OR "wilderness" OR "garden" OR "nature-based intervention" OR "forest bathing" OR "shinrin-yoku")
AND
("health" OR "wellbeing" OR "well-being" OR "mental health" OR "psychological health" OR "physical health" OR "stress" OR "anxiety" OR "depression" OR "cardio*" OR "immune" OR "cognitive function" OR "attention restoration" OR "emotional" OR "sleep" OR "blood pressure" OR "heart" OR "HRV" OR "cortisol")
AND
("dose*" OR "duration" OR "frequency" OR "intensity" OR "extent" OR "amount" OR "time spent" OR "length of stay" OR "visit frequency" OR "exposure" OR "exposure level" OR "exposure measure*" OR "degree of exposure" OR "NDVI" OR "greenness" OR "residential greenness" OR "vegetation index" OR "proximity" OR "distance" OR "cumulative exposure" OR "time in nature")
AND
("human*" OR "participant*" OR "adult*" OR "child*" OR "adolescent*" OR "student*" OR "resident*" OR "visitor*" OR "patient*")
AND
("dose-response" OR "regression" OR "correlation" OR "association" OR "effect size" OR "linear model*" OR "regression" OR "mixed-effects" OR "generalized linear model*" OR "generalized additive model*" OR "structural equation model*" "multivariate" OR "linear model*" OR "ANOVA" OR "t-test" OR "quantitative" OR "longitudinal" OR "effect size")
AND
("ecological cost" OR "environmental impact" OR "sustainabil*" OR "unsustainabil*" OR "ecosystem degradation" OR "habitat degradation" OR "environmental degradation" OR "soil degradation" OR "habitat loss" OR "visitor pressure" OR "land-use change" OR "nature-based tourism" OR "resource use" OR "footprint" OR "species loss" OR "population decline" OR "population reduction" OR "species extinction" OR "endangered species" OR "threatened species" OR "biodiversity loss" OR "species richness" OR "conservation status" OR "conservation threat" OR "invasive species" OR "biological invasion" OR "alien species" OR "species stress" OR "animal stress" OR "overexploitation" OR "overharvesting" OR "predation pressure" OR "human-wildlife"))

OR
TS=(("nature" OR "green space*" OR "park*" OR "urban vegetation*" OR "forest" OR "woodland" OR "wetland" OR "blue space*" OR "outdoor" OR "wilderness" OR "garden" OR "nature-based intervention" OR "forest bathing" OR "shinrin-yoku")
AND
("health" OR "wellbeing" OR "well-being" OR "mental health" OR "psychological health" OR "physical health" OR "stress" OR "anxiety" OR "depression" OR "cardio*" OR "immune" OR "cognitive function" OR "attention restoration" OR "emotional" OR "sleep" OR "blood pressure" OR "heart" OR "HRV" OR "cortisol")

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AND
("dose*" OR "duration" OR "frequency" OR "intensity" OR "extent" OR "amount" OR "time spent" OR "length of stay" OR "visit frequency" OR "exposure" OR "exposure level" OR "exposure measure*" OR "degree of exposure" OR "NDVI" OR "greenness" OR "residential greenness" OR "vegetation index" OR "proximity" OR "distance" OR "cumulative exposure" OR "time in nature")
AND
("human*" OR "participant*" OR "adult*" OR "child*" OR "adolescent*" OR "student*" OR "resident*" OR "visitor*" OR "patient*")
AND
("dose-response" OR "regression" OR "correlation" OR "association" OR "effect size" OR "linear model*" OR "regression" OR "mixed-effects" OR "generalized linear model*" OR "generalized additive model*" OR "structural equation model*" "multivariate" OR "linear model*" OR "ANOVA" OR "t-test" OR "quantitative" OR "longitudinal" OR "effect size"))
AND
PY=(2015-2025)  AND DT=(Article) AND LA=(English)
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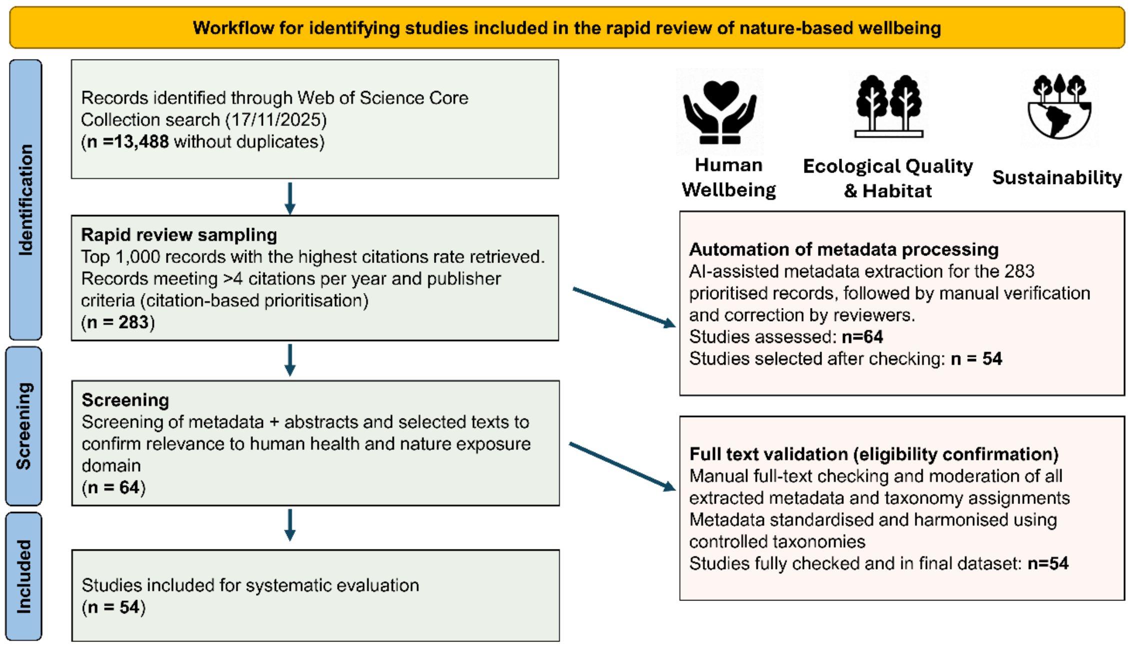

Figure S1. **Workflow for identifying studies included in the rapid review of nature-based wellbeing.** The diagram summarises the sequential process used to identify, prioritise, and screen studies. Records were retrieved from the Web of Science Core Collection (n = 13,488), followed by citation-based rapid-review sampling that retained the 1,000 most highly cited records and those exceeding ≥4 citations per year (n = 283). Metadata for these records were extracted using an AI-assisted pipeline and manually verified. Eligibility screening combined metadata checks with reviewer assessment of abstracts and methods (n = 64). Full-text validation yielded the final set of studies included in the systematic evaluation (n = 56).

Table S1. Data extraction framework used to extract information from screen articles.

Field	Description
Study location	Geographic location (country, region, city)
Study context	Broader setting/context of exposure or intervention (e.g., healthcare/social prescribing, community, workplace, school, public health, ecological program). Indicate whether study is clinical, population-level epidemiology, or ecological intervention.
Study focus	Main research question or aim (e.g., quantify dose-response, evaluate nature prescription, assess ecological costs, or biodiversity–health trade-offs).
Study type	Study design: observational (cross-sectional, cohort), experimental (randomized/quasi), intervention/trial, modelling/simulation, or mixed-methods.
Study approach	How the study measured humans' exposure to natural environments and the associated health or wellbeing outcomes; for example: self-report (time spent, visits, perceived nature contact), objective measures (GPS tracking, accelerometers, wearable sensors), ecological modelling of exposure (NDVI, land-cover maps linked to individuals), mixed-methods (qualitative interviews plus quantitative tracking), cost-benefit or life-cycle analysis of intervention, ecological momentary assessment (EMA) capturing in-nature experiences, or sensor-based environmental measurement tied to human responses.
Sample human characteristics	Human participant/sample characteristics: age range, sex/gender distribution, health status (general vs diagnosed), socioeconomic status, ethnicity/race (if reported), baseline nature exposure/green-space access, geographic equity.
Sample environment characteristics	Characteristics of the environment where participants were exposed: type of green/blue space (urban park, woodland, wetland), scale/size, management status (public park vs wilderness), biodiversity level (if measured), accessibility, visitor pressure, baseline ecological condition.

Health aspect	Domain(s) of human health studied: physical (cardiometabolic, cardiovascular, respiratory, musculoskeletal), mental (stress, anxiety, depression, wellbeing), social (connectedness, community cohesion), preventive/health promotion, or clinical outcomes.
Health indicators	Specific human health or wellbeing metrics studied, e.g., physiological measures (blood pressure, heart rate variability, cortisol), psychological/mental health scales (PHQ-9, HADS, DASS), activity metrics (steps, MVPA), self-rated health, clinical outcomes (hospital admissions, prescriptions, mortality). Indicate clearly whether each indicator is objective (e.g., device-measured, biomarker) or self-report (e.g., questionnaire).
Exposure metrics	How human exposure to natural environments is quantified in the study; for example: time spent (minutes/hours/days), frequency of visits, cumulative “dose” (e.g., minutes × sessions/week), distance or proximity from residence to green/blue space, vegetation or greenness index (e.g., NDVI), biodiversity proxy, type of nature-based activity (walking, forest bathing, conservation work, outdoor work), and whether each measure is self-reported (survey, diary) or objective (GPS tracking, wearable sensors, remote sensing).
Dose-response function	Whether the study reports a quantitative relationship between the dose or intensity of nature exposure and a health or wellbeing outcome. If so, document the shape of the relationship (e.g., linear, threshold, curvilinear, plateau), the units of dose, the effect size per unit dose (or equivalent parameter), and any reported moderators (e.g., age, baseline health, ecosystem quality).
Nature prescription component	Whether structured 'nature prescription' is involved: design (dose specified, monitoring, follow-up), guided vs self-directed, setting, duration, individual vs group.
Socioeconomic indicator(s)	Report only if the study directly measures socio-economic context related to human exposure to nature (e.g., income, education, deprivation index, employment, access to

	green/blue space, urban/rural setting, racial/ethnic composition).
Habitat type	Classification of habitat: urban park, forest/woodland, wetland/riparian, coastal/blue space, semi-natural grassland, agricultural landscape, wilderness, built green infrastructure. Note if managed/unmanaged. agricultural landscape, wilderness, built green infrastructure. Also note whether managed or unmanaged.
Habitat indicator(s)	Quantitative or qualitative metrics characterizing habitat: vegetation cover (NDVI), tree canopy, water bodies, maintenance/management, protection status, wilderness index, visitor pressure, perceived naturalness, biodiversity proxies.
Ecological process or service	Ecosystem processes/services linked to habitat: carbon sequestration, flood regulation, pollination, recreation, habitat provision, soundscape, nutrient cycling, microclimate regulation, or other ecosystem services.
Ecological cost or trade-off	Report any ecological costs or trade-offs that arise from the human interaction with natural environments (e.g., visitor disturbance, soil compaction/erosion from recreational access, habitat fragmentation from trail design, biodiversity loss due to high user pressure, carbon release from infrastructure built for nature-based activity, resource over-use linked to participants, energy footprint of guided nature interventions, pollution or trampling from repeated visitation). Include qualitative commentary if quantitative data are not provided.
Ecosystem state	Baseline or current ecosystem condition: intact, degraded, restored, urbanized, under pressure, recovering, unmanaged. Include fragmentation, patch size, anthropogenic stressors, conservation status if reported.
Sustainability aspect	Capture the broader sustainability dimension specific to the human–nature engagement evaluated in the study; that is, how sustainable the human interaction with the natural environment is over time. Consider aspects such as: the long-term viability of the

	nature-based activity or exposure (e.g., repeated visits vs a one-off); the integration of human health and ecosystem-health outcomes; the resource use or footprint associated with the engagement (e.g., energy, water, carbon); the resilience of the human-nature system (e.g., ability to maintain benefits across generations or cycles); and the legacy or regenerative potential of the nature-based experience (rather than a single encounter).
Sustainability indicator(s)	Quantitative or qualitative metrics that directly assess the sustainability of human engagements with nature—for example, number of visits per participant per year to natural spaces, CO_2 emissions per participant session in nature, visitor-days per hectare of natural area used, participant footprint (soil compaction rate, erosion rate) linked to visits, lifetime infrastructure impact per user of nature-based intervention, rate of regeneration of natural area used for human health activity, biodiversity functioning or habitat intactness post-use by participants, habitat fragmentation or connectivity changes associated with nature-based human activity, presence of invasive species or habitat disruption per user, water use or water-quality impacts per human nature engagement session, carbon sequestration capacity change per user or per session of human engagement, disturbance or trampling frequency linked to participants.
Equity and access dimension	Whether study addresses equity/access issues: unequal access to green/blue space, socio-economic/racial disparities, disability inclusion, urban/rural differences, cost/logistical barriers, digital access. Extract how measured (qualitative or quantitative).

Table S2. Summary of reviewed studies by health domain and habitat type. Each row summarises studies grouped under a standardised health taxonomy. "Habitat type" reports the most common or representative environmental contexts. "Typical exposure metrics" summarises the predominant measures used to quantify nature exposure. "Dose–response evidence / analytical approach" describes how studies examined exposure–response patterns, where applicable. It reflects the analytical methods used (e.g., linear or non-linear regression, categorical contrasts), rather than strictly defined biological dose–response functions, as many studies did not model a formal dose–response relationship. "No. of studies" indicates the number of included studies addressing each domain.

Health domain	Habitat type (most common/exemplar)	Typical exposure metrics	Dose–response evidence / analytical approach	No. of Studies
Mental health/ psychological wellbeing	Urban green space, mixed urban–rural green-blue landscapes	NDVI, proximity to green space, visit frequency	Linear or non-linear (curvilinear) associations; some categorical contrasts	23
Physical health	Urban/rural green space landscape	NDVI, land cover classifications	No dose–response analysis reported	2
Cognitive health	Urban green space	NDVI, presence/absence of green view	Non-linear (curvilinear) associations	2
General or self-rated health	Urban/rural green space landscape	Land cover proportions	No dose–response analysis reported	1
Quality of life (multidomain)	Urban green space	Residential vegetation proxy	No dose–response analysis reported	1
Immune or allergy-related health	Mixed landscapes	Forest and agriculture land cover metrics	Non-linear (curvilinear) associations	1

Environmental exposure–related physical health	Hazardous / degraded landscapes, Urban green space	Fire incidence/emissions, NDVI	Linear regression models	10
Multidomain health	Urban green space	NDVI, proportion of green space in landscape	Linear or non-linear models; some categorical contrasts; several studies lacked dose–response	14

Table S3. Summary of reviewed studies by dose–response evidence taxonomy. Studies are summarised based on dose definition, functional interpretability and assessed robustness.

Dose definition	**Functional interpretability**	**High robustness**	**Moderate robustness**	**Low robustness**	**Total**
Behaviourally prescribable	Threshold/plateau	0	2	0	**2**
Behaviourally prescribable	Functional relationship limited	0	1	2	**3**
Behaviourally prescribable	No dose-response tested	0	2	2	**4**
Spatially defined	Threshold/plateau	2	3	0	**5**
Spatially defined	Functional relationship limited	3	19	1	**23**
Spatially defined	No dose-response tested	1	3	5	**9**
Experiential/perceptual	Threshold/plateau	0	0	0	**0**
Experiential/perceptual	Functional relationship limited	0	1	2	**3**
Experiential/perceptual	No dose-response tested	2	1	2	**5**
TOTAL					**54**

Table S4. List of studies evaluated as part of the rapid review. Studies are listed with the name of the first author, year of publication, journal name, and doi.

1. White et al. (2019) *Scientific Reports*, doi:10.1038/s41598-019-44097-3
2. Dadvand et al. (2015) *Proceedings of the National Academy of Sciences of the United States of America*, doi:10.1073/pnas.1503402112
3. Martin et al. (2020) *Journal of Environmental Psychology*, doi:10.1016/j.jenvp.2020.101389
4. Wheeler et al. (2015) International Journal of Health Geographics, doi:10.1186/s12942-015-0009-5
5. Koplitz et al. (2016) *Environmental Research Letters*, doi:10.1088/1748-9326/11/9/094023
6. Mueller et al. (2020) *Environment International*, doi:10.1016/j.envint.2019.105132
7. Li & Sullivan (2016) *Landscape and Urban Planning*, doi:10.1016/j.landurbplan.2015.12.015
8. Triguero-Mas et al. (2015) *Environment International*, doi:10.1016/j.envint.2015.01.012
9. Dadvand et al. (2016) *Environment International*, doi:10.1016/j.envint.2016.02.029
10. Engemann et al. (2019) *Proceedings of the National Academy of Sciences of the United States of America*, doi:10.1073/pnas.1807504116
11. Wood et al. (2017) *Health & Place*, doi:10.1016/j.healthplace.2017.09.002
12. Helbich et al. (2019) *Environment International*, doi:10.1016/j.envint.2019.02.013
13. Southon et al. (2018) *Landscape and Urban Planning*, doi:10.1016/j.landurbplan.2017.12.002
14. Cox et al. (2017) *Bioscience*, doi:10.1093/biosci/biw173
15. van den Berg et al. (2016) *Health & Place*, doi:10.1016/j.healthplace.2016.01.003
16. White et al. (2021) *Scientific Reports*, doi:10.1038/s41598-021-87675-0
17. Astell-Burt & Feng (2019) *JAMA Network Open*, doi:10.1001/jamanetworkopen.2019.8209
18. Nutsford et al. (2016) *Health & Place*, doi:10.1016/j.healthplace.2016.03.002
19. Wong et al. (2018) *BMC Public Health*, doi:10.1186/s12889-018-5942-3
20. Gascon et al. (2018) *Environmental Research*, doi:10.1016/j.envres.2018.01.012
21. Akpinar (2016) *Urban Forestry & Urban Greening*, doi:10.1016/j.ufug.2016.01.011
22. McEachan et al. (2016) *Journal of Epidemiology and Community Health*, doi:10.1136/jech-2015-205954
23. Ko et al. (2020) *Building and Environment*, doi:10.1016/j.buildenv.2020.106779
24. Dzhambov et al. (2018) *Environmental Research*, doi:10.1016/j.envres.2017.09.015
25. Wang et al. (2019) *Environmental Research*, doi:10.1016/j.envres.2019.108535
26. Sarkar et al. (2018) *Lancet Planetary Health*, doi:10.1016/S2542-5196(18)30051-2
27. White et al. (2017) *Health & Place*, doi:10.1016/j.healthplace.2017.03.008
28. Liu et al. (2017) *Thorax*, doi:10.1136/thoraxjnl-2016-208910
29. Wyles et al. (2019) *Environment and Behavior*, doi:10.1177/0013916517738312
30. Samuelsson et al. (2018) *Landscape and Urban Planning*, doi:10.1016/j.landurbplan.2017.11.009

31. Jabbar et al. (2022) *GeoJournal*, doi:10.1007/s10708-021-10474-7
32. Berg et al. (2017) *Sustainability Science*, doi:10.1007/s11625-016-0409-x
33. Grande et al. (2020) *JAMA Neurology*, doi:10.1001/jamaneurol.2019.4914
34. Klompmaker et al. (2019) *Environment International*, doi:10.1016/j.envint.2019.05.040
35. Wei et al. (2019) BMJ-British Medical Journal, doi:10.1136/bmj.l6258
36. Mitchell et al. (2015) *American Journal of Preventive Medicine*, doi:10.1016/j.amepre.2015.01.017
37. Ruokolainen et al. (2015) *Allergy*, doi:10.1111/all.12545
38. Jiang et al. (2016) Environment and Behavior, doi:10.1177/0013916514552321
39. Venter et al. (2023) *Science of the Total Environment*, doi:10.1016/j.scitotenv.2022.160193
40. Poortinga et al. (2021) *Landscape and Urban Planning*, doi:10.1016/j.landurbplan.2021.104092
41. Dzhambov et al. (2018) *Environmental Research*, doi:10.1016/j.envres.2018.06.004
42. Klompmaker et al. (2018) *Environmental Research*, doi:10.1016/j.envres.2017.10.027
43. Dadvand et al. (2012) *Environmental Health Perspectives*, doi:10.1289/ehp.1104609
44. Ha & Kim (2021) *Urban Forestry & Urban Greening*, doi:10.1016/j.ufug.2021.127259
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46. Karner et al. (2015) *Journal of Transport & Health*, doi:10.1016/j.jth.2015.10.001
47. Puhakka (2021) *Journal of Outdoor Recreation and Tourism-Research Planning and Management*, doi:10.1016/j.jort.2021.100425
48. Völker et al. (2016) *Environmental Earth Sciences*, doi:10.1007/s12665-016-5839-3
49. Rufo et al. (2021) *Allergy*, doi:10.1111/all.14493
50. Taylor et al. (2018) *Urban Ecosystems*, doi:10.1007/s11252-017-0702-1
51. Qiu et al. (2021) *Tourism Management Perspectives*, doi:10.1016/j.tmp.2021.100855
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53. Butt et al. (2020) *Environmental Research Communications*, doi:10.1088/2515-7620/abb0db
54. Nita et al. (2018) Environmental Research, doi:10.1016/j.envres.2017.10.007

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3. van den Bosch, M. & Ode Sang, Å. Urban natural environments as nature-based solutions for improved public health – a systematic review of reviews. *Environmental Research* **158**, 373–384 (2017). https://doi.org/https://doi.org/10.1016/j.envres.2017.05.040
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