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Revisiting the role of the Nature-based Solutions Standards to promote climate adaptation in cities

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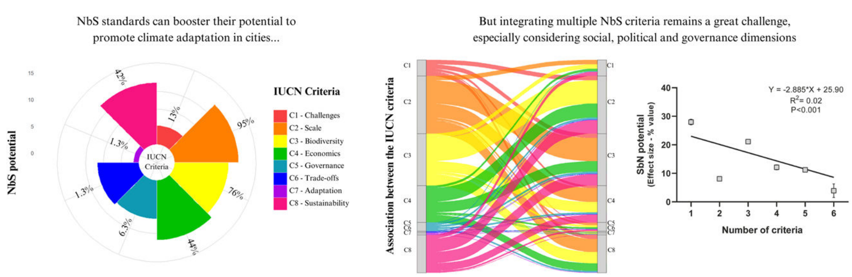
HIGHLIGHTS

- Implementing NbS criteria can be essential to ensure its full potential.
- Studies are still focused on NbS biophysical dimension.
- Increased complexity in NbS projects can reduce effect size but increase its variability.
- Social, economic, and political dimensions need greater consideration in NbS research.
- Interdisciplinary collaboration can be crucial for advancing NbS projects implementation.

GRAPHICAL ABSTRACT



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ABSTRACT

Nature-based Solutions (NbS) are increasingly recognized as key strategies for urban climate adaptation. To ensure effectiveness and avoid conceptual dilution, the International Union for Conservation of Nature (IUCN) established a Global Standard comprising eight guiding criteria. However, the extent to which these criteria are incorporated into scientific research remains unclear. Here, we conduct a meta-analysis of 79 peer-reviewed studies to evaluate how the IUCN criteria are applied in NbS literature focused on cities, and whether their inclusion relates to reported adaptation outcomes. Our results show that most studies emphasize biophysical aspects, such as temperature or runoff reduction, while largely overlooking social, institutional, and temporal dimensions. Criteria such as Governance, Trade-offs, and Adaptive management appear in less than 10% of the studies. We also find a negative association between the number of criteria considered and the mean effect size, with greater variability in outcomes as complexity increases. These findings suggest that while multidimensional integration is essential, it also poses implementation challenges. Bridging these gaps will require adaptive approaches that align ecological performance with governance, long-term monitoring, and social needs. Advancing NbS research through more comprehensive and standardized assessments is critical to ensure their credibility, equity, and long-term relevance in urban climate adaptation.

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Introduction

Urban areas, especially in low- and middle-income countries, are increasingly vulnerable to the impacts of climate change due to limited adaptive capacity in physical infrastructure, social systems, and institutional frameworks (IPCC, 2022). This vulnerability is particularly acute in informal settlements and smaller cities, where inequalities amplify disparities in the losses, risks, adaptive capacity, and transformations caused by climate change (IPCC, 2022). These patterns of inequity often emerge along social, spatial, and temporal scales (Borie et al., 2019; Chu et al.;, 2017; Long and Rice, 2019; Woroniecki et al., 2019), underscoring the need for comprehensive and innovative adaptation strategies (Frantzeskaki et al., 2019; IPCC, 2022; McPhearson et al., 2018; Seddon et al., 2020).

Nature-based solutions (NbS) have emerged as a promising approach to address urban climate challenges through an ecosystem services perspective (Cohen-Shacham et al., 2016; Kabisch et al., 2016). NbS can be defined as “actions to protect, sustainably manage, and restore natural or modified ecosystems that address societal challenges effectively and adaptively while providing human well-being and biodiversity benefits" (Cohen-Shacham et al., 2016) and integrate natural processes into urban planning (European Commission, 2021; Seddon et al., 2020). These solutions are especially effective in attenuating climate-related hazards, such as urban heat islands, stormwater management, and flooding, while also providing a range of co-benefits, including improved public health, enhanced biodiversity, and greater social equity (McPhearson et al., 2018; Prado et al., 2024; WHO, 2015). NbS are especially relevant in cities where traditional infrastructure is insufficient to cope with the growing impacts of climate change (European Commission, 2021). In these settings, NbS not only tackle immediate environmental challenges but also foster long-term resilience by promoting adaptive, inclusive, and sustainable urban development (European Commission, 2021). By offering an integrated, multidimensional approach to adaptation, NbS represent a vital tool in the effort to build cities that are more resilient to climate change (European Commission, 2021).

Despite the growing recognition of NbS as a promising win-win solution, their implementation remains challenging (Prado et al., 2024). A key difficulty lies in the lack of clear definitions and classifications of NbS, which often creates a significant gap between theoretical frameworks and practical application (Albert et al., 2019; Kabisch et al., 2016; Krauze and Wagner, 2019; Sarabi et al., 2019; Sowińska-Świerkosz and García, 2022). Urban settings face further obstacles, including competing demands for land and resources. Moreover, the risk of unintended consequences – such as gentrification or increased water demand (Anguelovski et al., 2018; Haase et al., 2017; Nouri et al., 2019; Turkelboom et al., 2018) – adds complexity to the effective implementation of NbS (IPCC, 2022). In response to these challenges, the International Union for Conservation of Nature (IUCN) developed the "Global Standards for Nature-based Solutions" (IUCN, 2020), which outline eight criteria designed to guide the planning, implementing, and evaluation of NbS projects. These standards emphasize the need for inclusive governance, ecological integrity, economic viability, scalability, and long-term sustainability (IUCN, 2020). A detailed description of the criteria is provided in Table 1. To ensure clarity and consistency, each criterion is referred to throughout the manuscript by its corresponding short name, as presented in Table 1. These short names appear in italics to enhance readability and distinguish them from other terms.

These criteria aim to ensure that NbS integrates well with environmental and socioeconomic systems. By offering a structured approach, the IUCN standards ensure that NbS can effectively meet the complex environmental and societal challenges it aims to address (IUCN, 2020). However, balancing ecological, social, and economic objectives may expose inherent trade-offs that require careful prioritization (Seddon et al., 2020). Yet, despite increasing recognition, a significant gap remains in understanding how the IUCN’s criteria are applied in NbS projects and studies (Seddon et al., 2020). This disconnection between theory and practice limits its full integration into climate adaptation strategies (Sarabi et al., 2019). While the Global Standard offers clear principles, their incorporation into empirical research is inconsistent and often partial, especially in urban contexts where implementation challenges are more acute (Davies et al., 2021; IUCN, 2020). As a result, key elements such as governance, adaptive management, and trade-offs are frequently underexplored (Frantzeskaki et al., 2019; Wamsler et al., 2020). Understanding this gap is essential to identify opportunities for more comprehensive and effective applications of NbS in response to climate challenges.

Table 1
Summary of the eight criteria from the IUCN Global Standard for nature-based solutions (IUCN, 2020), including an identification code, short name (used throughout the manuscript), and a brief description.

Code	Short name	Description
C1	*Societal challenges*	NbS effectively address societal challenges through inclusive decision-making, responding to community-identified needs
C2	*Scale*	The design should account for scale, considering the complexity of land/seascapes and factors such as biophysical, geographic, economic, policy, and cultural considerations
C3	*Biodiversity*	NbS should result in a net gain for biodiversity and ecosystem integrity, actively enhancing ecosystem functionality and connectivity for long-term resilience
C4	*Economic viability*	NbS should be economically viable, with design and monitoring ensuring a balance between short-term costs with long-term benefits
C5	*Governance*	NbS should be based on inclusive, transparent, and empowering governance processes, engaging diverse stakeholders, particularly rights holders, to ensure broader support
C6	*Trade-offs*	NbS should equitably balance trade-offs between achieving their primary goals and maintaining multiple benefits, managing land/resource trade-offs transparently while safeguarding ecological integrity
C7	*Adaptive management*	NbS should be managed adaptively, using evidence-based adaptive management and regular monitoring to minimize risks and ensure continued relevance
C8	*Sustainability*	NbS should be sustainable and mainstreamed within appropriate jurisdictional contexts, aligning with sectoral, national, and policy frameworks, and integrating with global initiatives (such as the Sustainable Development Goals (SDGs) and the Paris Agreement)

This study aims to evaluate how the IUCN’s established criteria are being considered in scientific research on nature-based solutions, particularly in the context of urban climate change adaptation. To this end, we pursue the following specific objectives: (i) to assess the extent to which the eight IUCN criteria are incorporated into peer-reviewed NbS literature; and (ii) to identify which criteria are more frequently addressed or overlooked; and iii) to analyze how the number of criteria considered relates to the reported effectiveness of NbS interventions, based on quantitative effect size metrics. In addition, we discuss the implications of underrepresenting specific criteria – particularly those related to governance, long-term adaptation, and trade-offs – as well as the practical challenges that may hinder the full integration of the IUCN framework into climate adaptation efforts. By addressing these points, we aim to offer insights into how the IUCN standards can guide more robust, multidimensional, and context-sensitive NbS strategies that contribute meaningfully to global adaptation agendas.

Methods

Literature review

We conducted a comprehensive literature review in the Web of Science database using the terms: *“nature-based solution*” OR “ecosystem-*

based adaptation" OR "green infrastructure" OR "blue infrastructure" AND "urban" OR "cit",* considering publications available online until the end of 2021. The initial search yielded 3,143 articles. These terms were selected to encompass the main expressions found in the literature that refer to nature-based approaches applied in urban contexts. While "nature-based solutions" has gained significant visibility in recent years, "green infrastructure" and "ecosystem-based adaptation" have a longer history of use and remain widely adopted in specific disciplinary and policy contexts.

The inclusion of "ecosystem-based adaptation" (EbA) was guided by three main considerations: first, EbA and NbS are conceptually interconnected; second, EbA predates NbS in the literature, enabling a broader temporal scope; and third, EbA is explicitly linked to climate change, in contrast to the broader framing of NbS. Although the eight IUCN criteria are central to our analytical framework, they were not included as search terms because they are rarely mentioned in titles or abstracts and would have substantially limited the scope of the search. The expression "cit*" was employed to capture variations such as "city" and "cities." Although this approach may have returned some non-targeted records, all retrieved articles were manually screened to confirm their relevance to the study.

Articles were screened according to four inclusion criteria: (i) explicit focus on climate change adaptation, (ii) relevance to urban or peri-urban areas, (iii) publication in English, and (iv) provision of quantitative results regarding adaptation effectiveness relative to a defined reference scenario. We excluded articles that (i) lacked usable reference values or prevented quantitative assessment; (ii) reported outcomes exclusively as maximum, minimum, or absolute values – unless no average values were available; or relied on secondary parameters derived from previously analyzed variables. After applying these criteria, 79 articles were selected for analysis, resulting in 4,293 individual observations. We highlight that, in this study, the term "NbS projects" refers to the interventions described and analyzed within the selected peer-reviewed articles, rather than initiatives directly evaluated by the authors.

Data were extracted directly from texts, tables, and figures using DataThief III. After data extraction, we applied the ROUT method (Motulsky and Brown, 2006) for the detection and removal of statistical outliers. This step aimed to identify extreme values within the reported effect sizes and did not influence article selection or classification. NbS strategies were classified into six typologies based on their ecological characteristics and design functions: green infrastructure (strategies using nature to create or improve infrastructure, such as green roofs), scattered vegetation (small-scale vegetated elements such as isolated trees), urban parks (medium to large green areas), rain gardens (small green areas that store and infiltrate water), water-based solutions (measures aimed at the conservation or management of water-related ecosystem), and combined solutions (combinations of two or more NbS categories).

Importantly, no preliminary filters were applied to exclude specific types of climate-related hazards, allowing a comprehensive assessment of the literature. The observations were initially classified into six hazard categories based on standard definitions from the literature: runoff increase (increase in surface water flow), peak flow increase (maximum flow rates), flooding (water overflowing onto land), water pollution increase (water contamination increase), temperature increase (changes in overall temperature), and thermal comfort decrease (discomfort perception due to environmental factors). For analytical purposes, these six types were grouped into two broader categories: hydrological hazards (runoff, peak flow, flooding, and water pollution) and temperature-related hazards (temperature increase and thermal discomfort). While this classification approach follows the protocol established in Prado et al. (2024), all key elements necessary to understand the typologies and categories employed in the present study are explicitly described here, ensuring clarity and methodological transparency without reliance on external sources.

IUCN criteria evaluation

To evaluate how the articles addressed each of the IUCN's criteria, we conducted a detailed review, aiming to minimize subjectivity by defining clear premises for each classification. Criterion 1 was considered present when studies explicitly incorporated community-identified needs in the initial stages, ensuring that the problem definition reflected social priorities. C2 (*Scale*) was marked when the intervention was embedded in a broader spatial or policy context, indicating potential for replication or scaling. C3, *Biodiversity*, was recognized when articles demonstrated a measurable net gain in biodiversity or ecosystem integrity. For example, studies using remote sensing to describe existing vegetation patterns were excluded from this category, as they did not show explicit improvements. C4 (*Economic viability*) was considered when the respective measure were already implemented and operational; even in the absence of explicit economic indicators, their continued maintenance was interpreted as indirect evidence of financial feasibility.

Criterion 5 *(Governance)* was identified in cases where governance arrangements ensured inclusive participation, granting communities decision-making power at least at one stage of planning, implementation, or monitoring. C6 (*Trade-offs*) required the explicit recognition of trade-offs between ecological, social, or economic outcomes, which we interpreted as evidence of critical reflection on the balance between multiple objectives. C7 (*Adaptive management*) was marked when studies incorporated adaptive management, such as iterative adjustments based on monitoring or feedback loops, indicating responsiveness to changing conditions. Finally, C8 *(Sustainability)* was recognized when interventions were supported by normative or policy frameworks that that conditioned or directed their implementation. This systematic procedure provided greater consistency to our assessment and enhanced the reproducibility of the classification, while also clarifying the rationale for including or excluding specific cases.

Each article was classified according to the number of IUCN criteria it addressed, ranging from one to eight, to provide an overview of which criteria were commonly addressed and which were often overlooked. It is important to note that this classification was based on our interpretation of the IUCN's criteria use and may be limited by the information provided by the studies' authors regarding their research formulation. Studies explicitly identifying themselves as exploring NbS initiatives and/or those aligning with the NbS principles (even if not labeled as such) were included in our analysis. We also emphasize that the evaluation performed seeks to assess the impact of the values contained in these criteria, rather than the impact of their formalization in the publication itself.

NbS potential and statistical analyses

Effect size values were calculated to assess the NbS' potential associated with the different IUCN criteria using a previously established approach (see Prado et al., 2024 for full description). Effect size was calculated as the percentage difference between the benefits obtained by implementing NbS and the reference condition, following Eq. (1):

$$Effectsize = \frac{(x - y)}{y} \times 100$$

The values of x and y represent, respectively, the observed outcomes when NbS is implemented and under the reference condition. The reference condition was established based on three potential scenarios: (i) full impermeability of soil (100% coverage), typically derived from water-related hazards models; (ii) existing landscape configurations with limited NbS adoption; and (iii) current landscape without any NbS intervention. These reference scenarios were consistently applied to all NbS strategies evaluated. Positive effect size values reflect a decrease in the frequency and/or severity of a given climate-related hazard, whereas negative values indicate a diminished effectiveness of NbS in fostering environmental adaptation.

To assess how each IUCN criterion contributes to NbS effectiveness, one-sample t-tests were conducted, comparing the effect size values against a hypothetical mean of zero. Additionally, to explore the influence of NbS criteria inclusion on effect size, a generalized linear mixed model (GLMM) was employed, treating the IUCN criteria as fixed effects and study identity as a random effect to control for variability across studies. A regression analysis was used to assess trends in effect size as additional criteria were incorporated.

To evaluate the importance of incorporating specific IUCN criteria to determine NbS potential, we categorized the mean effect size values obtained in each study into five groups: negative (effect size < 0), low (effect size between 0–3.54), moderate (effect size between 3.54–9.68), high (effect size between 9.68–24.56), very high (effect size > 24.56). The limit of the last four categories was defined considering the quartiles of the mean effect size values obtained in the 79 studies. Then, we performed a permutational multivariate analysis of variance (PERMANOVA) using the eight IUCN criteria as predictors of the differences among the five effect size groups established by using the Jaccard dissimilarity index.

To visualize how IUCN criteria are co-applied across studies, we constructed a Sankey diagram using the classification obtained from the 79 studies. The flow between the input and output criteria represents the transition of observations based on the studies' focus and their connections to these criteria. All statistical analyses and visualizations were performed using R Software (R Core Team, 2020), including the *vegan* and *ggplot2* packages and GraphPad Prism version 8.0.1 (GraphPad Software, San Diego, California, USA, www.graphpad.com, 2022).

Results and discussion

We revealed that of the eight criteria outlined in the NbS framework, four received minimal attention in studies on urban climate adaptation: *Societal challenges*, *Governance*, *Trade-offs*, and *Adaptive management*, which were addressed in only 10, 5, 1 and 1 studies, respectively. In contrast, *Scale* was the most frequently explored, appearing in nearly 95% (n = 75) of the articles, followed by *Biodiversity* (about 76%, n = 59), *Economic viability* (approximately 44%, n = 34), and *Sustainability* (about 42%, n = 33). In fact, most evaluations of NbS in urban climate adaptation emphasize biophysical outcomes, such as surface temperature reduction and flow regulation. This emphasis is further illustrated by the fact that the most commonly addressed criteria align with key elements in studies focusing on biodiversity's role, such as (i) defining the study area and boundaries (*Scale*), (ii) assessing increases in biodiversity (*Biodiversity*), (iii) focusing on established sites, *i.e.*, economically viable (*Economic viability*), and (iv) incorporating legal mechanisms into official planning documents (*Sustainability*).

Despite the multidisciplinary potential of the concept, this narrow focus on ecological components often neglects equally critical dimensions, limiting a comprehensive understanding of NbS in promoting climate adaptation (Sommese, 2024). The limited attention given to *Societal challenges* and *Governance* reinforces this gap, underscoring the need to better integrate societal demand into NbS research (Dunlop et al., 2024; Karam-Gemael et al., 2018). Nature-based solutions have proven effective in promoting climate adaptation in cities, particularly through strategies that enhance biophysical aspects (Prado et al., 2024), but strengthening their effectiveness requires greater emphasis on underrepresented dimensions – especially *Governance* and *Adaptive management*. Recent studies have begun to reflect this shift (Anderson and Renaud, 2021; Kauark-Fontes et al., 2023).

Our findings emphasize the need for more comprehensive assessments that integrate ecological, social, economic, and governance dimensions of NbS. This aligns with ongoing policy developments, as NbS initiatives increasingly shape policy agendas, particularly with the IUCN's upcoming revision of its Global Standard for NbS[1] . The IUCN's efforts to update the NbS Standard reflect a growing recognition that NbS strategies must encompass not only ecological benefits but also broader social governance dimensions (IUCN, 2025). Such integration is particularly important considering recent work highlighting the integration of NbS with broader policy and governance systems as a determinant of long-term success (Frantzeskaki and Bush, 2021; Kauark-Fontes et al., 2023). These findings reinforce the urgency of incorporating institutional, procedural, and adaptive elements into the evaluation of NbS interventions, especially in urban settings.

Governance gaps, particularly in relation to societal engagement and policy alignment remain underexplored or insufficiently reported in current NbS research focused on urban climate adaptation (Hölscher et al., 2023), undermining the long-term viability of NbS in urban settings (Mahajan, 2025). Another critical aspect that remains overlooked is the temporal dimension *(Adaptive management),* which is often disregarded in assessments of ecosystem services provisioning (Rau et al., 2020). This limitation is particularly evident in studies focused on biodiversity, where constraints such as limited funding, researcher availability, and limited stakeholder engagement hinder long-term field assessments and compromise the ability to preserve original or expected outcomes (Lindenmayer and Likens, 2010; Mills et al., 2023; Wang et al., 2024).

Ensuring adequate and sustained funding for NbS projects is therefore crucial to align them with long-term biodiversity goals and to generate more robust outcomes supported by reliable indicators (Key et al., 2022; UNEP-CCC, 2024; UNEP FI, 2024). Moreover, recent syntheses emphasize that neglecting criteria such as trade-offs and adaptive management may compromise the long-term resilience of NbS, especially in rapidly urbanizing regions (Kabisch et al., 2022; Seddon et al., 2020). Strengthening the incorporation of these dimensions remains a critical challenge for mainstreaming NbS into complex, multi-actor governance systems (Frantzeskaki et al., 2023).

As illustrated in Fig. 1, our analysis revealed that all criteria significantly contribute to the additionality of NbS climate adaptation potential (for all criteria, t-test, $p < 0.05$, Table S1). In other words, the inclusion of each criterion has the potential to increase effect sizes, reflecting greater resilience in the urban environments analyzed. *Scale*, presented the highest mean effect size (18.1%), followed by *Sustainability* (17.5%), *Economic viability* (16.9%), *Biodiversity* (15.3%), *Trade-offs* (11.7%), *Governance* (11.0%), *Societal challenges* (5.4%) and *Adaptive management* (1.5%). However, it is important to note that the limited number of observations for some criteria, especially *Adaptive management*, may influence the strength of this effect, highlighting the need for more studies that incorporate these criteria to better assess their role in urban climate adaptation. Additionally, recent reviews have emphasized the need for better integration of biodiversity outcomes with urban sustainability planning, especially in contexts where ecological gains are not automatically aligned with social equity or long-term resilience (Nesshöver et al., 2017; Wang et al., 2024).

The Sankey diagram (Fig. 2) illustrates the multiple potential associations among the IUCN criteria, showing how frequently different criteria co-occur within the same studies. The width of each flow is proportional to the number of studies in which a given pair of criteria is addressed together, revealing patterns of integration, omission and emphasis in the literature. For instance, while *Scale* (C2) frequently appears in combination with other criteria such as *Sustainability* (C8) or *Economic viability* (C4), criteria like *Governance* (C5) or *Adaptive*

[1] IUCN's upcoming revision of global standard for NbS can be verified at https://engage.iucn.org/discussion/iucn-global-standard-nature-based-solutions. Access: 20.01.2025

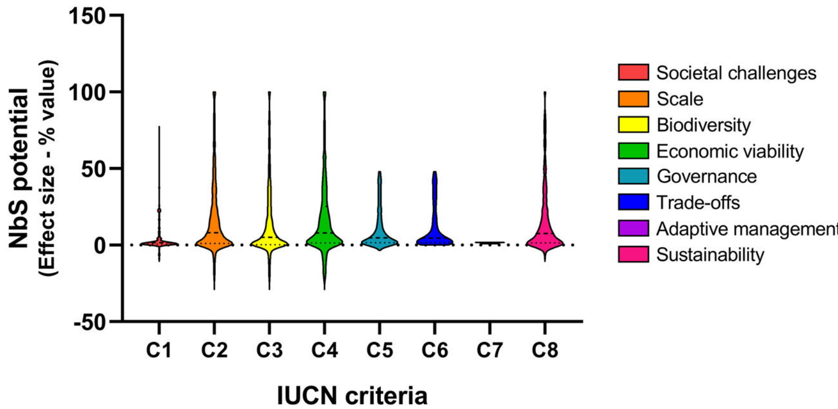

Fig. 1. Mean effect size (%) describing the NbS potential across the eight IUCN criteria (C1–C8, Table 1). Each violin represents the distribution of effect sizes for studies addressing each specific criterion. For all IUCN criteria, a one-sample t-test demonstrated a significant positive effect ($p < 0.05$).

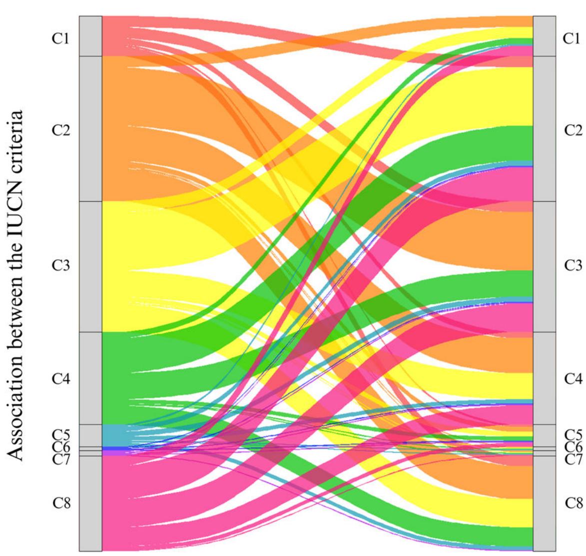

Fig. 2. Sankey diagram showing the associations among the eight IUCN criteria based on their co-occurrence across the 79 studies analyzed. Each node represents one of the criteria, and the flows between them indicate how frequently two criteria were addressed together within the same study. The width of each flow is proportional to the number of co-occurrences. This visualization highlights patterns of integration, omission, and emphasis across the literature. Colors were assigned to enhance clarity and follow the same scheme used in Fig. 1.

management (C7) are rarely addressed, and when they are, they often appear in isolation. Such uneven combinations suggest that some criteria are systematically integrated into NbS assessments, while others remain marginal or disconnected, contributing to the intricate pattern of associations represented in the diagram. For instance, the study by McConnell et al. (2022), which evaluates the performance of green roofs in Chicago, centers on the physical effectiveness of green infrastructure (C3 and C4) but also incorporates considerations related to societal needs, spatial context, and long-term planning (C1, C2, and C8). This example illustrates how multiple criteria can be addressed within a single study, even if they are not the central analytical focus.

Notably, *Scale* exhibited a strong association with *Economic viability* and *Sustainability* criteria, both of which were extensively evaluated. This result is expected, as it reflects the intrinsic connection between economic approaches and public policies in urban climate adaptation (Beszedics-Jäger, Buzási, 2024; EEA, 2024; IPCC, 2014). The emphasis on scale is particularly significant, given that adaptation efforts must be spatially tailored to the unique characteristics of each urban context (Prado et al., 2024). However, the absence of a clear association between *Scale* and both *Societal challenges* and G*overnance* criteria raises concerns. Effective NbS development relies on strong governance frameworks and social engagement, which are essential for optimizing adaptive strategies and fostering synergies across the diverse dimensions of urban society (McPhearson et al., 2023; Raymond et al., 2017).

Biodiversity demonstrated an important relation with *Sustainability*, which holds particular relevance in the context of public policies aimed at biodiversity conservation. This suggests that research efforts are increasingly shaped by official normative frameworks, a critical factor in the face of intensifying climate extremes that directly affect urban communities' quality of life (Ni et al., 2023). As already mentioned above, *Biodiversity* was also particularly related to *Scale*, *Economic viability* and *Sustainability*.

It is important to note that none of the studies included in our analysis incorporated all of the criteria recommended by the IUCN. At most, two studies incorporated six criteria simultaneously. The majority of studies included only two criteria ($n = 30$), followed by three ($n = 18$), four ($n = 12$), one ($n = 9$), five ($n = 8$), and six ($n = 2$). One study, although selected after the initial screening for relevance, scope, and data availability, was subsequently excluded from the IUCN criteria analysis as it did not address any of the eight criteria defined by the Global Standard. These findings suggest at least two potential, non-mutually exclusive explanations. First, as several authors have pointed out, the complexity of the NbS concept makes it difficult for scientific studies to address or describe multiple criteria simultaneously (Albert et al., 2019; Eggermont et al., 2015; Kabisch et al., 2016; Krauze and Wagner, 2019; Nesshöver et al., 2017; Sarabi et al., 2019). Second, research focused on developing NbS concepts needs to be strategically designed from the outset, with a clear framework for incorporating the various elements (Albert et al., 2021; European Commission, 2015).

Our analysis revealed a significant negative relationship between the number of criteria integrated into NbS projects and the observed effect size (GLMM: $F_{1,78} = 28.72$, $p < .0001$), suggesting potential trade-offs between criteria and/or multiple dimensions of the NbS concept (Fig. 3). The results show that the highest mean effect size (28.9%) was observed in studies or projects that focused only on one criterion, accompanied by a confidence interval of 27% to 30.8%. As additional criteria were integrated, the mean effect size tended to decrease (Fig. 3). Incorporating all six criteria resulted in the lowest mean effect size (3.92%), with a broad range for the confidence interval (−3.64% to 11.5%), underscoring the high degree of uncertainty due to the small sample size. These findings suggest that the inclusion of multiple criteria, despite ensuring that NbS projects are being designed considering all dimensions, may be associated with lower biophysical effects, with greater variability observed in studies focusing on fewer criteria.

Several factors may explain the reduction in effect size observed as

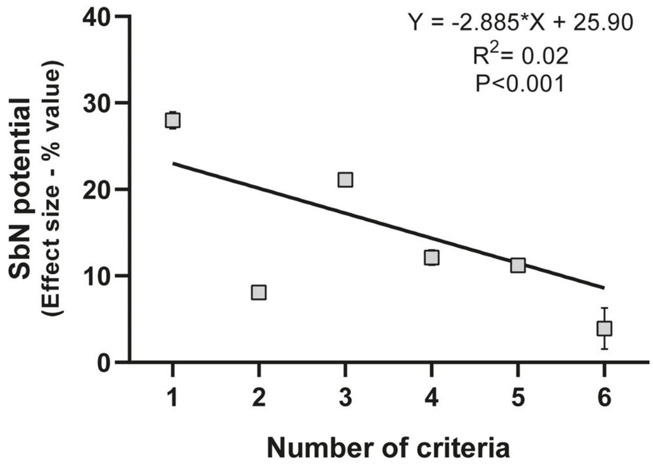

Fig. 3. Mean effect size (± SD) of NbS projected as a function of the number of IUCN criteria incorporated in the projects, with standard deviation represented. The trend line shows the regression model, along with its equation and statistical significance.

we increase the number of IUCN criteria identified in the studies. First, the increasing complexity of interactions: as more criteria are incorporated, the number of interrelations between variables grows, potentially attenuating the observed biophysical effect. Second, the dilution of impact: when multiple criteria are considered, their individual effects may become less distinct, especially when these criteria are weakly correlated or inadequately implemented and evaluated. Third, the diversity of contexts: applying various solutions across different settings could obscure the true effects, as the effectiveness of NbS strategies may depend on the specific combination of criteria in each context. It is important to emphasize that this pattern should not discourage the incorporation of multiple criteria into NbS projects. Rather, it highlights the need for a careful, well-thought-out approach that adequately addresses these potential trade-offs between the various standards of the NbS framework. The key lies not in simplifying projects but in understanding and managing the intricate relationships among criteria and dimensions to maximize NbS outcomes.

Thus, designing NbS projects that explicitly account for this complexity is essential to maximize their effectiveness (Albert et al., 2021; Dunlop et al., 2024). However, it is important to highlight that our study explores the contribution of the criteria to the NbS potential by using meta-analytical and statistical techniques to integrate studies that used multiple criteria in an unstructured design. We emphasize that future studies should be designed specifically to evaluate the importance of each criterion, allowing the establishment of direct causality between its presence and the NbS potential.

Moreover, NbS potential was mostly assessed by evaluating its biophysical effects, which highlights the need for more comprehensive assessments that incorporate other dimensions – social, economic, and political – into the analysis (Dunlop et al., 2024; Palomo et al., 2021). We were unable to discern significant differences between the use of specific criteria in the different effect size groups. As a consequence, we could not identify a specific combination of criteria that can ensure a higher NbS effect to promote adaptation in cities (Fig. 4). Even when examining distinct hazards, such as hydrological and temperature-related risks, the analysis did not reveal a clear pattern of studies reporting the IUCN criteria (PERMANOVA, $p > 0.05$; Fig. 4, Table S2). Thus, we argue that integrating a broad spectrum of criteria, rather than focusing on a subset or particular combination, may be crucial to enhancing the overall effectiveness of NbS.

Indeed, the NbS concept is inherently multifaceted, encompassing a wide range of perspectives and demands. Despite substantial theoretical progress in the framework, which now integrates previously overlooked aspects of ecosystem services provisioning, there remains a significant gap in scientific literature (Remme et al., 2024). This gap stems from the tendency to neglect crucial elements necessary for a holistic understanding of NbS, especially its role in promoting climate change adaptation in cities (Frantzeskaki et al., 2019). We advocate that it is essential to recognize that NbS is not a single, rigid concept; rather, it requires contributions from diverse scientific disciplines to achieve its full potential.

Since the publication of the IUCN Global Standard, recent studies have discussed and reinforced some outcomes of our review. The incorporation of all NbS dimensions present in its standard can support sustainability assessments, though variability in system compliance points to the need for more flexible, context-sensitive applications (Le Gouvello et al., 2023). It can allow for broader scope and process-oriented values, yet note gaps in evaluating outcomes and adapting to specific environmental settings (Berg et al., 2024). By doing that, it is fundamental to integrating social-ecological understanding,

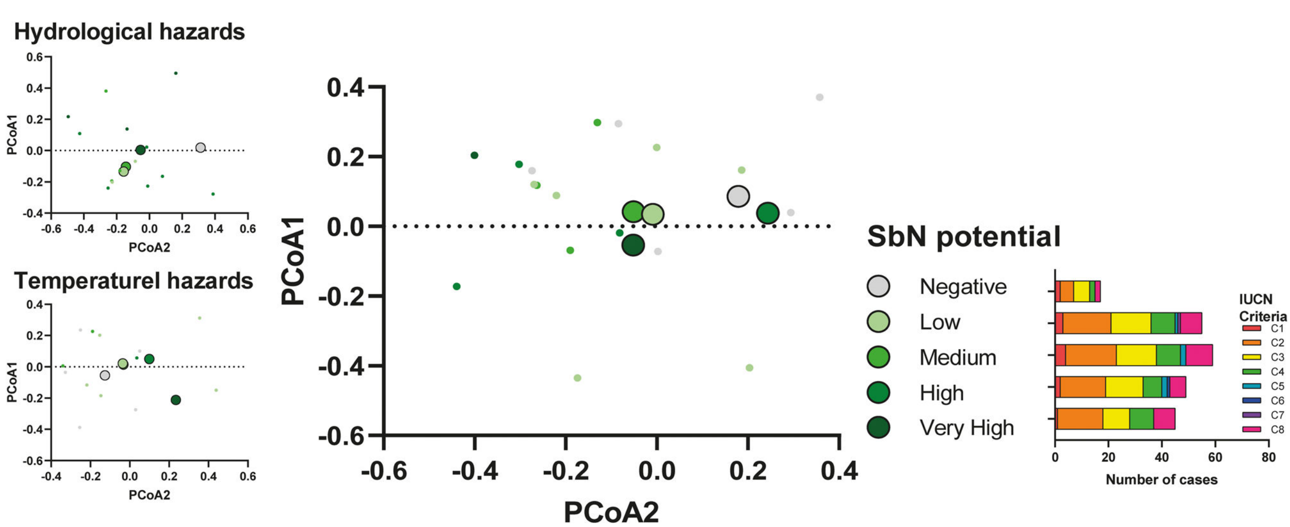

Fig. 4. Differences in the composition of IUCN criteria used among the five established effect size groups (negative, low, medium, high, and very high) for hydrological and temperature hazards (small panels) and integrated approach (big panel) demonstrated through the PERMANOVA performed. Points closer each other represent more similar criteria composition among studies, and the bigger circles in all panel represent the mean distribution of each NbS potential group (centroid). A small panel on the bottom-right side of the figure demonstrates the similarities in the use of the eight criteria across the five groups, reinforcing the absence of significant differences among them.

particularly for criteria like adaptive management and local acceptability, which remain underdeveloped (Vasseur and Andrade, 2023), but could be reached by promoting stakeholder engagement based on the IUCN criteria, drawing attention to resource constraints and governance tensions that influence implementation (Ibrahim et al., 2025; O'Leary et al., 2023). Our results contribute with such recent discussion by reinforcing that while the IUCN standard is increasingly adopted, social and temporal dimensions still face operational and conceptual challenges, highlighting the need for more adaptive, equitable, and context-aware approaches to NbS.

While scientific advancements are vital, they alone are insufficient to ensure the successful implementation of NbS strategies (Frantzeskaki et al., 2019). Breaking down existing scientific silos is crucial for realizing the broader impacts of NbS (Hölscher et al., 2023; Wang et al., 2024). For instance, biodiversity researchers must collaborate closely with experts in social, political, and economic sciences to address the full range of challenges posed by climate change (Cairns et al., 2020; DePuy et al., 2025; Leach et al., 2018). In this sense, skill development within traditional biology-focused disciplines should extend to incorporating metrics from the social sciences, such as human well-being, safety, and health – dimensions that are often underexplored in studies primarily focused on biodiversity. This interdisciplinary collaboration – whether through formal partnerships or the acquisition of new skills – can be triggered by incorporating NbS strategies into climate adaptation plans.

Conclusion

The initiative to establish criteria for defining and implementing the NbS concept arises from several concerns, notably the risk of its indiscriminate use. As NbS gain widespread attention in national agendas and international agreements, there is a genuine concern that its broad application could dilute its core essence. While NbS is a relatively new concept, it is crucial to preserve its integrity within scientific discourse. Although the criteria are aspirational rather than mandatory, it is essential to uphold them rigorously in research endeavors. Doing so not only addresses existing knowledge gaps, such as those surrounding governance structures and long-term monitoring mechanisms necessary for adaptive management, but also enhances NbS' credibility and resonance among stakeholders. Our findings underscore this concern. The observed trade-offs in the incorporation of multiple NbS criteria and the challenges linked to their effective implementation align closely with the ongoing efforts by IUCN to update the NbS Standard. As the IUCN Standard is revised, it will be crucial to integrate more precise guidelines on balancing the complexity and diversity of NbS projects to ensure that they remain impactful and relevant across varying contexts. The update process offers an opportunity to further refine the NbS framework and strengthen its scientific and practical foundations. Moreover, this framework was designed to address multiple demands simultaneously. Oversimplifying the concept and focusing too heavily on specific aspects, such as biodiversity conservation alone or the biophysical effect of NbS projects, risks deviating from its central purpose – as articulated in its definition – of addressing societal challenges and promoting both biodiversity benefits and human well-being. The IUCN's ongoing review process provides a timely platform to reinforce this balanced approach, ensuring that NbS initiatives continue to foster comprehensive and sustainable solutions. Ultimately, reinforcing the integrative nature of NbS through balanced and transparent criteria will be key to advancing resilient and inclusive climate adaptation strategies in urban systems.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.pecon.2025.09.002.

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