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Exploring nature-based solutions' effectiveness indicators for climate change adaptation: a systematic review

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Nature-Based Solutions (NBSs) are increasingly incorporated for climate change adaptation and risk reduction, yet the lack of a standardized evaluation framework and definitions hinder the accurate assessment of their effectiveness. This systematic review, covering articles published between 2008 to 2023 obtained through Scopus, aims to bolster NBS applicability by focusing on effectiveness indicators and evaluation methods used within a wide array of case studies where NBS influence climate adaptation through ecosystem service provisioning. The 27 analyzed key articles include a diverse range of coastal NBSs, including 36 case studies, often implemented at the micro- or meso-scale, each designed to address facets of climate adaptation through the provisioning of ecosystem services such as carbon sequestration (n = 16), erosion reduction (n = 11), flood reduction (n = 16), or improvement of water quality (n = 15). The review revealed a prevalent reliance on process-based performance indicators (51.9%) often applied without accounting for synergies and trade-offs, and/or incorporating impact indicators (70.4%) that assess changes in environmental conditions in order to evaluate NBSs' effectiveness. Monitoring focused primarily on environmental, hydrological, climatic, and biological performance and impact indicators, while frequently neglecting socio-economic factors. A shift towards a nested, performance-centric approach that incorporates a broader range of socio-economic impact indicators and expands spatio-temporal scales could enhance NBSs adoption. Utilizing advanced data techniques and modelling indicators can further strengthen the evidence base and facilitate the adoption of NBSs for climate adaptation.

KEYWORDS

climate change adaptation, coastal and transitional ecosystems, ecosystem services, effectiveness indicators, nature-based solutions

1 Introduction

Assessing the progress on climate adaptation is a burning scientific and policy question (Magnan et al., 2023), and a paradigm shift towards Nature-Based Solutions (NBSs) is occurring (Arkema et al., 2017). NBSs primarily depend on the processes and functions of ecosystems to deliver valuable services to people, with the underlying rationale that NBSs mitigate the effects of climate change by promoting the integrity and natural functioning of ecosystems - thereby enhancing their capacity to regulate the environment, buffer environmental impacts and reduce climate-related risks (Bueno-Pardo et al., 2024).

Coastal and transitional areas are disproportionally affected by the combined climatic and anthropogenic pressures creating critical risks (European Environmental Agency, 2024). These ecosystems support a large portion of global biodiversity and provide major contributions to society, harboring key climate regulating processes and habitats (Murillas-Maza et al., 2023). With NBSs becoming increasingly integrated within climate and biodiversity strategies (Goodwin et al., 2024), their rapid uptake has the potential to catalyze an extensive reframing and integration of Ecosystem Services (ESs) and infrastructure resilience (Nelson et al., 2020). ESs are a crucial part of the NBSs evaluation (Chairat and Gheewala, 2024), and to maximize NBS's effectiveness for climate adaptation, it is critical to advance knowledge on links between coastal biodiversity, ecosystem health, vulnerability, functions, and ESs (O'Leary et al., 2023).

To support decision makers with the design, implementation, and replication of NBSs for risk reduction, and to navigate adaptation assessment, clear criteria are needed to describe the potential benefits and effects of interventions (Magnan et al., 2020; Skodra et al., 2021). This necessitates a robust evidence-base, capable of assessing the efficacy, long term impacts, and ways to design and manage coastal and transitional NBSs (Frantzeskaki et al., 2019; Kabisch et al., 2016). While studies have begun unraveling NBS effectiveness, particularly in urban context (e.g., Chausson et al., 2020; Dumitru et al., 2020; Majidi et al., 2019), including the establishment of several evaluation frameworks (e.g., Raymond et al., 2017; Sowińska-Świerkosz and García, 2021; Xing et al., 2017), such evaluations for coastal measures remain behind, and streamlining assessment approaches able to track changes remains crucial (Murillas-Maza et al., 2023). To date, the effectiveness of NBSs in providing adaptive or other co-benefits is often discussed through indicators considering the different environmental challenges afflicting ecosystems (Bueno-Pardo et al., 2024; Goodwin et al., 2024). Indicators can also be seen as one way of collecting information that can be used to monitor, evaluate, and learn from adaptation actions (Goodwin et al., 2024). Understanding which indicators are good to capture the effectiveness of coastal NBSs for risk reduction can support the capacity building for adaptation, accelerate their adoption and improve the monitoring and implementation practices.

Thus, this article employs a systematic review to unravel the concept of effectiveness by focusing on the indicators used to measure NBSs impact on climate adaptation through the lens of ES provisioning for risk reduction. A clearer understanding of the indicators currently used to evaluate NBS's effectiveness can strengthen the evidence-base for nature-based adaptation, improve monitoring frameworks while informing implementation practices. In this setting, through an analysis of NBS case studies, this review aims to provide a comprehensive overview of the current state of assessing NBS effectiveness in coastal and transitional ecosystems, with a focus on the challenges these solutions are designed to address, the ecosystem services (ESs) they provide, and the approaches used for their monitoring and evaluation. Specifically, it seeks to answer the following research questions: i) What are the primary objectives of coastal and transitional NBSs in terms of ESs provisioning, hazard mitigation, and risk reduction? ii) Which indicators are used to evaluate NBSs and how do these indicators relate to effectiveness? and iii) In what ways can these indicators support monitoring efforts to inform coastal adaptation and planning? Consequently, the review discusses the methodology applied for data collection, selection, and revision (Section 2. Materials and methods), the results in terms of publication characterization, NBS effectiveness indicators and monitoring frameworks (Section 3. Results of the review), and the implications of these findings for NBSs mainstreaming in climate change adaptation (Section 4. Discussion).

2 Materials and methods

A dual-phase review was performed to augment the knowledge base regarding the evaluation of NBSs effectiveness in coastal and transitional environments, following two main phases (Figure 1): i) a systematic review including data collection and article selection based on the PRISMA[1] approach, and ii) a scientometric analysis embedded within the systematic review. Due to its comprehensive, complete, and accurate coverage of serial content, containing over 76 million records (Baas et al., 2020), Scopus has been selected as the main source of information for this review. Building on the objective of this review two queries have been constructed to represent its scope by combining a set of keywords, corresponding with terminology associated to coastal and transitional ecosystem, NBSs, ESs, and effectiveness (SM1). Within the broader category of coastal and transitional ecosystems, a sub-divide based on geomorphological and hydrological characteristics into coastal, deltaic, estuarine, and lagoonal ecosystem archetypes is introduced. Simultaneously, for terminological clarity, this review adopts the definitions proposed in the EKLIPSE urban NBS evaluation framework (Raymond et al., 2017, p.10). While not considering any coastal or transitional ecosystems, nor providing an exhaustive list of NBSs, the framework offers well-defined terms for effectiveness, performance and impact. Effectiveness captures the overarching goal achievement, defined as "the degree to which objectives are achieved and the extent to which targeted problems are solved". Performance introduces a contextual element, focusing on "the degree to which NBS address an identified challenge and/or fulfil a specified objective in a specific place (territory), time and socio-economic context". Finally, impact examines the resultant changes, specifically "the effect of a NBS in achieving a specified objective and/or dealing with a (...) challenge, evidenced as a change in environmental, social, economic and ecological conditions". Given the absence of site-specific criteria for the effectiveness term, the evaluation surrounding NBSs is expected to primarily converge upon quantifiable performance and impact metrics.

When ran in Scopus, these queries resulted in 233 publications (excluding seven duplicates) of which 188 were written in English between 2008 and June 2023, aligning the timeframe with the introduction of NBS by the World Bank in its 2008 biodiversity portfolio (Mackinnon et al., 2008; Sowińska-Świerkosz and García, 2022). A scientometric analysis, nested within the systematic review,

1 Preferred Reporting Items for Systematic Reviews and Meta-Analysis.

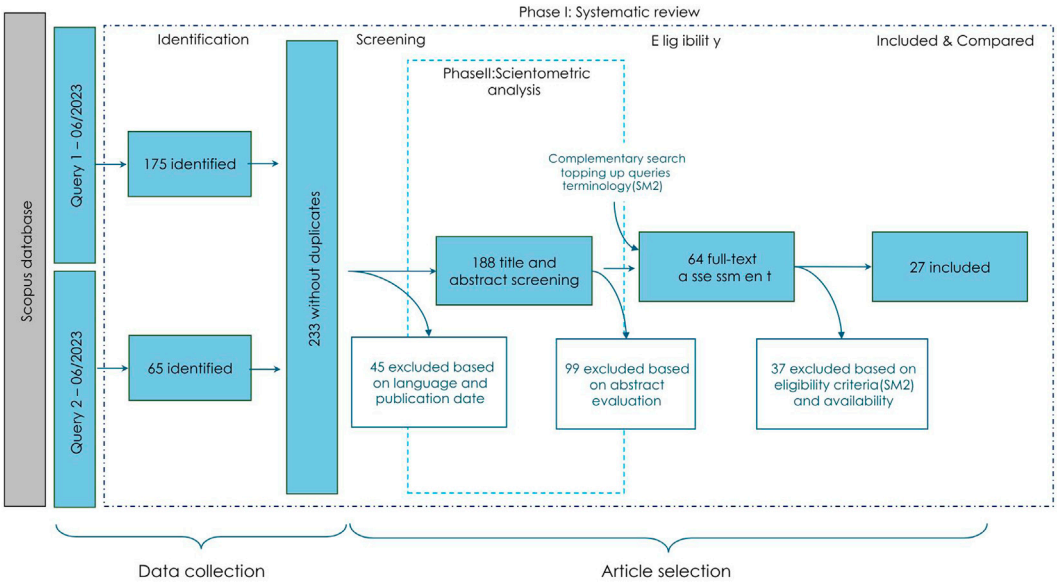

FIGURE 1
Methodological approach for the review on coastal and transitional NBSs' effectiveness - queries and eligibility criteria described in SM1 and SM3.

can help identify structures and capture the development of a discipline to generate a comprehensive and objective portrait of the state of knowledge (Zhu et al., 2021). The integration of both approaches allows for a more descriptive analysis, mapping the academic field, the trends, gaps, and challenges building on the papers metadata using the open-source Bibliometric Package (SM2). The 188 publications have subsequently been processed - under cooperation of a multi-disciplinary research team with expertise related to coastal management, environmental planning, and climate risk and adaptation - in an iterative manner following the PRISMA approach (Page et al., 2021). This screening was done in accordance with a set of eligibility criteria (SM3) to keep only the most appropriate and relevant publications. To support this screening effort, Rayyan an automated systematic review screening tool was used, this web application allowed each of the members of the research team to independently label the articles as to "include", "exclude" or "maybe" (Ouzzani et al., 2016; Valizadeh et al., 2022) based on the publications' titles, abstracts, and keywords. Following the initial screening of the 188 articles, a final top-up was conducted in Scopus to strengthen to focus on deltaic and estuarine ecosystems (see SM2), yielding an additional 20 eligible articles. This narrowed the publication pool to 64 eligible articles focusing on the evaluation of NBSs effectiveness, in terms of performance or impact, monitored or modelled through a set of indicators or metrics, implemented in coastal, deltaic, estuarine, and lagoonal ecosystem archetypes. Additionally, this initial screening focused on the inclusion of regulating ESs such as water quality purification, erosion reduction, flood control and carbon sequestration, as these particular ESs touch upon urgent coastal problems that will be exacerbated by habitat degradation and climate change. The eligible publications (n = 64) were read in full to create a selection of the most relevant publications that align with the objective of this review. During this process, papers were excluded if they were not available (n = 1), did not present original data (e.g., reviews, n = 4), or the reference to NBSs, regulating ESs or evaluation metrics was lacking or insufficient (e.g., only mentioned in the abstract or discussion, n = 32). The resulting 27 key publications were compared and discussed through a set of comparison criteria (SM4) in a narrative synthesis that aim to clarify the main features of NBS effectiveness, performance and impact indicators in coastal and transitional ecosystems.

3 Results of the review

NBS research has steadily grown in the years following the introduction of the term by the World Bank (Seddon et al., 2021), within this result section the findings are structured to move from a comprehensive overview of the overall papers dataset through the scientometric review followed by a detailed systematic analysis of the selected key articles. The scientometric review focused on the initial 188 publications identified in Scopus under the 2008–2023 timeframe (SM3). The analysis of the annual scientific production allowed for the identification of trends, showing an increase in publications since 2013 (see Supplementary Figure SM3.1A), corresponding with the adoption of the NBS term by the IUCN in 2013, and subsequently by the European Commission in 2015 (Seddon et al., 2021). Furthermore, through the analysis of the annual scientific production an intensification in publications can be observed, with 72.3% of the publications being published since 2018 (see Supplementary Figure SM3.1A). This trend is also mirrored in grey literature, with the inclusion of NBSs in various global assessment reports, e.g., the Global Commission on Adaptation Report, the IPBES Global assessment, and various IPCC Special reports (Seddon et al., 2021), as well as in the EU Biodiversity Strategy for 2030 and Strategy on Adaptation to Climate

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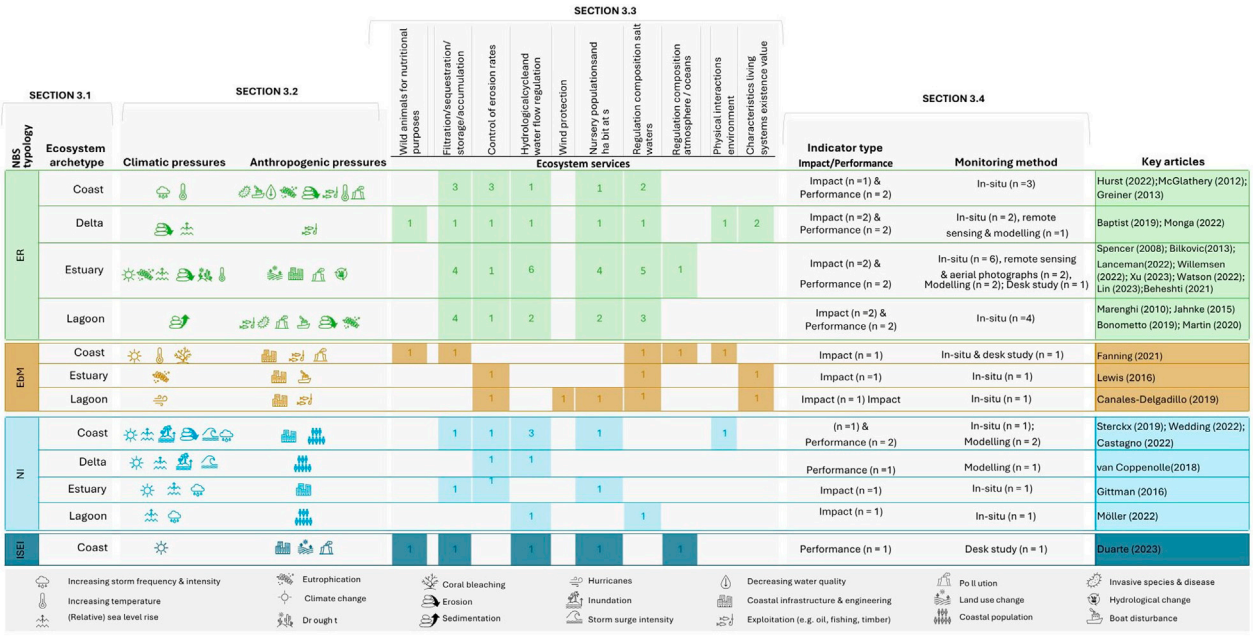

FIGURE 2
Synthesis of the 27 key articles in terms of NBS typology -ER (Ecosystem Restoration), EbM (Ecosystem based Management), NI (Natural Infrastructure) and ISEI (Issue-Specific Ecosystem Improvement- and ecosystem archetype (Section 3.1), climate and anthropogenic pressures (Section 3.2), expected ecosystem services (Section 3.3), and performance or impacts indicators and monitoring methods (Section 3.4).

Change (Calliari et al., 2022). The scientometric review, through the co-occurrence network (Supplementary Figure SM3.D), also highlighted the interlinkages between keywords used in the publications, such as: NBS, ecosystem services, natural capital, biodiversity, coastal resilience, (habitat) restoration and reclamation. Moving beyond the scientometric review, the 27 key publications that were systematically reviewed regarding coastal and transitional NBSs' effectiveness evaluation were synthesized in Figure 2 according to the established comparison criteria (SM4). These comparison criteria, reflected in the headers of Figure 2, aim to specify for each key article: i) the ecosystem archetypes and NBSs implemented (Section 3.1); ii) the climatic and anthropogenic pressures afflicting these areas (Section 3.2); iii) the ESs tackled by these NBSs (Section 3.3); and iii) the number of performance or impact indicators and the monitoring methods applied to keep track of the NBSs' effectiveness (Section 3.4.). What can be observed in Figure 2 is that a wide range of pressures afflict the coastal, deltaic, estuarine and lagoonal ecosystems. Nevertheless, some variability may be observed in the types of pressures associated to each NBS typology, where climatic pressures seem particularly relevant for 'Natural Infrastructure', which could be explained by its objective to reduce erosion and flood control and thus highlighting associated pressures such as sea level rise or storm surge intensity. Which is then also mirrored in the ESs provided by NBSs in this category, focusing mostly on control of erosion and hydrological regulation. On the other hand, 'Ecological Restoration' and 'Ecosystem-based Management' NBSs cover a wider spectrum of ESs provisioning and frequently consider these ESs as a performance indicator for the NBS effectiveness evaluation. More details regarding the different elements are presented in the next sections.

3.1 Type of NBSs addressed in the case studies

The evidence for the 27 key publications is distributed over 36 case studies in coastal (n = 8), deltaic (n = 3), estuarine (n = 10), and lagoonal (n = 6) ecosystem archetypes (Figure 3) concentrated primarily in Europe (28.6%), North America (25.7%), and Asia (22.9%). The publications principally focused on single case studies (Figure 3A) at the micro- and meso-scale, with only one publication discussing a multi-case study comparison in deltaic environments (Figure 3B). The key articles utilize a mix of terminology to describe the NBS including terms such as but not limited to, living shorelines, managed realignment, building with nature, habitat restoration, and blue carbon ecosystems. For the purpose of this analysis and to aid the comparison between key articles, the different NBS terminology in the key articles has been translated to the overarching IUCN NBS typology (Cohen-Shacham et al., 2016; Cohen-Shacham et al., 2019) including: Ecosystem Restoration, Ecosystem-based Management, Natural Infrastructure, Issue-Specific Ecosystem-Improvement, and Area-based Conservation (defined in SM4). In Figure 3C it can be observed that the majority of the NBSs considered in this review can be classified as 'Ecological restoration' (63%). These NBSs focus on the recovery of ecological functioning through the restoration of habitats. 'Natural infrastructure' (22.2%) instead focuses on NBSs to reduce erosion and enhance coastal protection through various techniques such as living shorelines and utilizing a broad range of habitats including saltmarshes and riparian areas. 'Ecosystem-based Management' (11.1%) focuses on measures such as the reconstruction or transplantation of seagrasses to maintain ecosystem health, resilience and ESs. Finally, 'Issue-specific

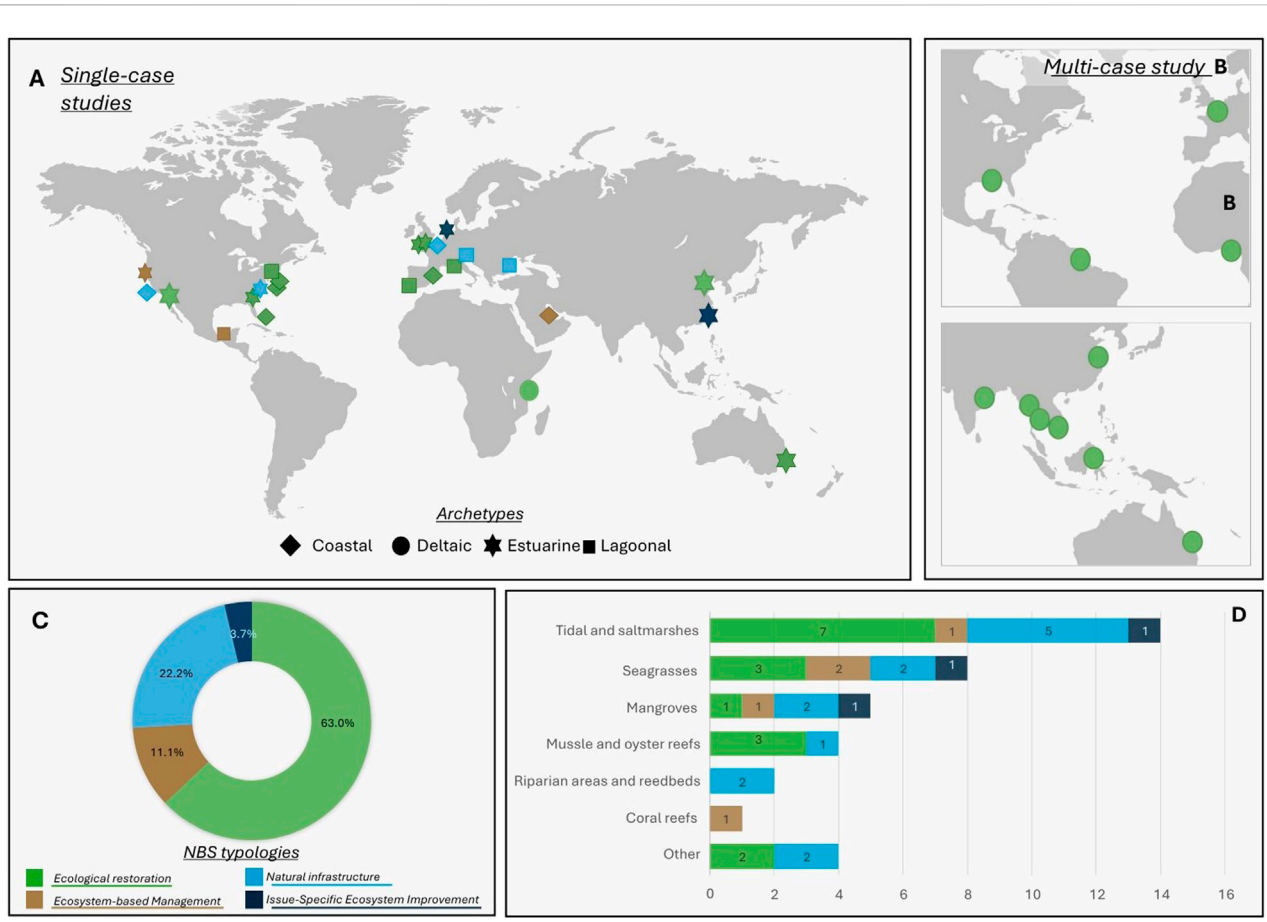

FIGURE 3
(A,B) Global distribution of the single and multiple case studies, **(C)** the percentage of NBSs' typologies (adopted from Cohen-Shacham et al. (2016) and **(D)** the number of habitats utilized in the 27 key articles.

Ecosystem-Improvement' (3.7%) refers to the use of biodiversity and ESs as part of an overall adaptation strategy to help people adapt to, mitigate or reduce adverse effects of climate change, through for instance blue carbon ecosystems. Within the 27 key articles, the habitats most frequently utilized as part of the NBS strategy include tidal and saltmarshes, seagrasses and mangroves (Figure 3D). While this focus may in part be introduced due to the phrasing of the queries (SM1), it can also be attributed to the functions and ESs they offer, which directly address the pressures experienced by the NBS as discussed in the next section.

3.2 NBSs' interaction with climatic and anthropogenic pressures

Understanding the potential of NBSs to withstand and tackle climate related pressures through regulating ESs is essential for the incorporation of NBSs in climate adaptation. Across the 27 key publications, 78 climatic and anthropogenic pressures were identified (Figure 4). Most key publications (81.5%, n = 22) underlined the influence of multiple pressures afflicting the ecosystems archetypes. Relative sea level rise and climate change emerged as the most prominent natural pressure, appearing in 40.7% (n = 11) and 25.9% (n = 7) of key publications respectively. Anthropogenic pressures were discussed in 20 out of 27 articles, focusing primarily on coastal infrastructure and engineering (19.5%, n = 8), pollution (14.6%, n = 6), and eutrophication (12.2%, n = 5); while few key publications focused on pressures such as boating disturbances (n = 3), land use changes (n = 3), coastal population (n = 2), water quality degradation (n = 1) or hydrological changes due to ecosystem alterations (n = 1). While half of the publications noted that both climatic and anthropogenic pressures (48.1%) affecting the ecosystems and NBS, the vast majority of key publications did not explicitly discuss their interplay but treat them as contextualizing factors instead. These findings corroborate statements in the reviewed key articles including Lin et al., (2023) who stated that climatic and anthropogenic pressures are known to interact simultaneously with ecosystem dynamics; however, they are typically reported independently. Aligning the role of NBSs with the multifunctionality of restored habitats in light of multiple hazards, and explicitly integrating the synergetic behaviour of the protective benefits these interventions provide would allow for a better understanding of their functioning and improved hazard prevention as underlined by another key article (Gittman et al., 2016).

Climatic pressures	Ecosystem archetype: Coastal	Deltaic	Estuarine	Lagoonal	SUM
Increasing storm frequency & intensity	2	-	-	1	3
Increasing temperature	2	-	1	-	3
(Relative) sea level rise	3	2	5	1	11
Erosion	1	1	1	-	3
Eutrophication	-	-	2	-	2
Climate change	4	1	2	-	7
Drought	-	-	1	-	1
Sediment accumulation	-	-	-	1	1
Coral bleaching	1	-	-	-	1
Hurricanes	-	-	-	1	1
Naturaldisasters	1	-	-	-	1
Inundation	1	1	-	-	2
Storm surge intensity	-	1	-	-	1

Anthropogenic pressures	Ecosystem archetype: Coastal	Deltaic	Estuarine	Lagoonal	SUM
Decreasing water quality	2	-	-	-	2
Increasing temperature	1	-	-	-	1
Coastal infrastructure & engineering	3	-	4	1	8
Exploitation (e.g. oil, fishing, timber)	2	1	-	2	5
Pollution	3	-	1	2	6
Eutrophication	2	-	1	2	5
Land use change	1	-	2	-	3
Coastal population	-	1	-	1	2
Hydrological change	-	-	1	-	1
Boat disturbance	1	-	1	1	3
Invasive species & disease	2	-	-	1	3
Erosion	-	-	-	1	1
Sedimentation	1	-	-	-	1

Number of pressures: 0 1 2 3 4 5

FIGURE 4
Number of climatic and anthropogenic pressures in the 27 key articles across the 8 coastal, 3 deltaic, 10 estuarine, and 6 lagoonal archetypes.

3.3 Expected ecosystem service provisioning

Coastal and transitional ecosystems are ranked amongst the most important habitats regarding ESs provisioning (Baptist et al., 2019). To allow for the comparability of the ESs identified in the key articles (Table 1), they have been translated into the CICES V5.1. – Common International Classification of Ecosystem Services–terminology (SM5). The prevalence of regulating ecosystem services (88.1%) within the key articles reflects the core ES of the review (SM1), which is consistent with their role in NBS climate adaptation. What can be noted in Table 1 is that the NBSs considered in estuarine ecosystems consider a wide range of regulating ESs, including flood control (6 mentions), nursery habitats and biodiversity, (6 mentions) water quality regulation (6 mentions) and sequestration (5 mentions). Coastal NBSs instead seem to be more focused on filtration and sequestration (6 mentions) and flood control (5 mentions), while lagoonal NBS highlight nursery habitats and biodiversity (5 mentions) instead.

Within the key articles, these ESs present a dichotomy, where on the one hand the services present the objectives of numerous NBS; while on the other hand the ESs are the manner in which effectiveness is monitored. Thus, the evaluation of NBSs effectiveness in the key articles blend performance and impact indicators. Where performance indicators focus on process-based ESs delivery, while impact indicators examine a range of broader environmental changes to gauge the NBSs success. For example, the ESs *2.1.1.2 Filtration/sequestration/storage/accumulation by micro-organisms, algae, plants, and animals (59.3%) is* evaluated in terms of performance through the carbon sequestration rate (e.g., key article Lanceman et al., 2022). While at the same time this NBS effectiveness evaluation can be complemented by monitoring impact indicators that can be used to forecast the potential of carbon abatement such as environmental variables and

TABLE 1 Number of mentions per ecosystem services classified according to CICES V5.1 (SM5) within each ecosystem archetype across the key articles (n = 27).

Ecosystem services	Coastal	Deltaic	Estuarine	Lagoonal
Provisioning ecosystem services (3 mentions; 3.6%)				
1.1.6.1. Wild animals (terrestrial and aquatic) used for nutritional purposes	2	1	—	—
Regulating ecosystem services (74 mentions; 88.1%)				
2.1.1.2. Filtration/sequestration/storage/accumulation by micro-organisms, algae, plants and animals	6	1	5	4
2.2.1.1. Control of erosion rates	4	2	3	2
2.2.1.3 Hydrological cycle and water flow regulation (including flood control and coastal protection)	5	2	6	3
2.2.1.4. Wind protection	-	-	—	1
2.2.2.3. Maintaining nursery populations and habitats (including gene pool protection)	3	1	6	5
2.2.5.2. Regulation of the chemical composition of salt waters by living processes	3	1	6	1
2.3.5.1. Regulation of chemical composition of atmosphere and oceans	2	—	1	—
Cultural ecosystem services (7 mentions; 8.3%)				
3.1.1. Physical and experimental interactions with the natural environment	2	1	—	1
3.2.2.1. Characteristics of living systems that have an existence value	—	2	1	1

biogeochemical properties (e.g., key articles Duarte de Paula Costa et al., 2023; Hurst et al., 2022). Similarly, the ES *2.2.5.2 Regulation of the chemical condition of salt waters by living processes*, discussed in 55.6% of the key articles, can be assessed through plant and sediment parameters (e.g., McGlathery et al., 2012) that quantify the removal of nutrients (e.g., Bonometto et al., 2019). Furthermore, the ESs *2.2.1.3 Hydrological cycle and water flow regulation* (59.3%) and ES *2.2.1.1 Control of erosion rates* (40.7%) are often evaluated in terms of performance, considering the site-specific natural processes underpinning ES delivery, such as wave height reduction (Castagno et al., 2022) and shoreline stabilization (Sterckx et al., 2019). Both of which critically depend on environmental characteristics such as vegetation to stimulate accretion, reduce erosion, and start positive feedback processes, e.g., lower the hydrodynamic load and thus increase sedimentation and reduce erosion potential. Which in turn leads to the use of vegetation characteristics as an impact indicators by some key articles, including Baptist et al. (2019), McGlathery et al. (2012), and Willemsen et al. (2022).

3.4 Indicators for NBSs' effectiveness

Within this review the indicators identified used to measure effectiveness can predominantly be categorized as performance or impact indicators (Figure 5). Performance indicators highlight the ESs provisioning of NBSs, these were frequently assessed through metrics related to nutrient (N, P) and carbon (C) provisioning benefits - such as carbon sequestration- or through measures quantifying the reduced exposure to erosion and flooding Impact indicators instead focus on physical, hydrological, climatic, and biological parameters, thereby characterizing how NBS influence underlying environmental processes of the system. Various key articles, attribute these parameters into two categories: functional attributes focusing on ecological attributes such as vegetation characteristics, and structural characteristics considering geomorphic and physical attributes of the ecosystem such as slope or topography. In addition, few of the key articles evaluate impact in terms of the suitability of the site for NBSs after its implementation. Finally, impact can also be considered as the balance between the cost and benefit of the NBS. Moreover, as illustrated in Figure 5, the monitoring approaches reported in the reviewed articles predominantly relied on in-situ measurements (n = 21). These were often complemented by modelling efforts (n = 6) using tools such as InVEST, SWAN, GIS, or BlueCAM. Additional methods included the use of remote sensing and aerial photography (n = 3), as well as desk-based analyses of historical datasets (n = 3).

A closer examination reveals that impact indicators were considered by 48.1% of the key articles (n = 13), are effective and practical measures of the condition of an ecosystem, as well as an effective tool for monitoring change (Lewis and Henkel, 2016), and include indicators such salt marsh extent (Baptist et al., 2019), vegetation cover (Willemsen et al., 2022), seagrass density and coverage (Lewis and Henkel, 2016), or avian species richness, abundance and community structure (Canales-Delgadillo et al., 2019). At the same time, a significant portion of the key articles (29.6%, n = 8) displays a reliance on performance evaluations including the monitoring of process-based ESs including carbon sequestration. Whereas 22.2% of the cases combine both approaches to evaluate NBS. Changes in ecosystem state and condition, i.e., environmental and ecological indicators expressing information about the habitat utilized, its use and functioning, are tightly linked to changes in ESs supply (Watson et al., 2022). To be able to effectively create salt marshes for their ESs provisioning, such as coastal protection and carbon sequestration, it is key to quantify morpho-dynamics and vegetation presence through active monitoring, as it will provide insight in the stability of the system and its sediment erosion/accretion (Willemsen et al., 2022).

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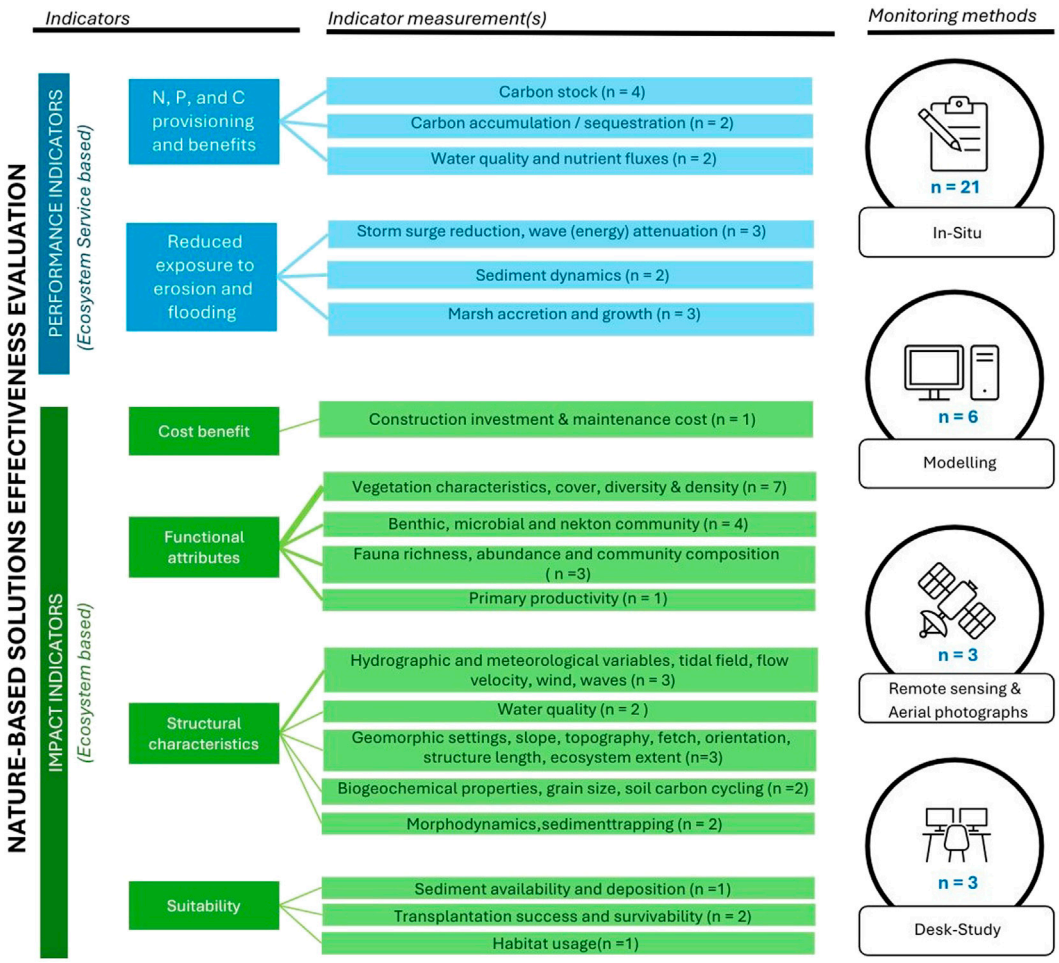

FIGURE 5
Evaluation of NBS effectiveness through performance and impact indicator and monitoring methods of the 27 key articles.

Finally, as mentioned by McGlathery et al. (2012) to achieve a better understanding of NBSs it is necessary to establish mechanistic studies and continuous monitoring. In order to address this, multiple key articles (48.1%, n = 13) evaluate NBSs performance by measuring the ES provisioning of a specific NBS against a desired threshold or evaluate impact by assessing the environmental changes resulting from the NBS implementation (e.g., Baptist et al., 2019; Hurst et al., 2022; Spencer et al., 2008; Willemsen et al., 2022). A pair-wise comparison between the NBS and a control site was the most frequent (n = 9), e.g., comparing environmental impact indicators for habitat suitability for nekton at natural and hardened shorelines (Bilkovic and Mitchell, 2013) or comparing habitat characteristics - e.g., species richness, abundance and percentage coverage, and water quality - between transplanted and established eelgrass beds (Lewis and Henkel, 2016). Other key publications focused on estimating the performance of NBSs by evaluating changes before and after their implementation, e.g., salt marsh growth before or after the implementation of a mud motor (Baptist et al., 2019) or the impact of an NBS on salt marsh vegetation before and after managed realignment (Spencer et al., 2008).

4 Discussion

4.1 Unravelling the nuances of NBSs' effectiveness

A shared understanding of NBSs' effectiveness evaluation is essential for meaningful comparisons and robust adoption of nature-based adaptation. While effectiveness appears as a prevalent term in NBSs discourse (Chausson et al., 2020), a closer examination often reveals a stronger emphasis on performance or impact. This trend might reflect the respective ease of measuring the context-specific functioning of NBSs and their tangible environmental effects, compared to the long-term goals devoid of spatial context associated to effectiveness. As such it could be noted that performance focuses on a quantifiable metric, often evaluating single processes under site-specific conditions (Seddon et al., 2020). Impact instead assesses a broader set of long-term effects on environmental, social, and economic conditions related not only to the objective of the restoration, i.e., ESs provisioning. This conceptualization of impacts, in a causal manner, would support a nuanced, nonlinear view of the

interactions taking place in complex socio-ecological systems (Dumitru et al., 2020). This tendency, to focus on performance and impact, as a way to quantify the effectiveness of NBS is mirrored in the articles evaluated in this review.

Most of the key articles focused on a single micro- or meso-scale study site. This aligns with the findings of Saunders et al. (2020) indicating that the majority of coastal restoration projects cover less than 1 ha. The small scale of case studies relates to the experimental nature of the sites, as locations to test new adaptation approaches, simultaneously limiting the risk and resources involved (Buuren et al., 2018; DeAngelis et al., 2020; Saunders et al., 2020). While this small scale may hamper the broader uptake of the NBSs, this barrier may be overcome with evidence-supported adaptation recommendations (Hansen et al., 2023) quantifying degradation levels, target states, and pace and scale needed to achieve this target (Sánchez-Arcilla et al., 2022). The growing body of research, actively supported by the European Union through initiatives like Horizon2020 and projects such as MaCoBios (macobios.eu), WaterLANDS (waterlands.eu), and REST-COAST (rest-coast.eu), presents a significant opportunity to solidify the evidence underpinning the effectiveness of NBS for climate adaptation, particularly in coastal environments. Simultaneously, most articles considered singular restoration objectives such as re-establishing carbon stores and sinks (Greiner et al., 2013), or pollution reduction (Martín et al., 2020), or erosion protection (Gittman et al., 2016). The evaluation of these singular objectives relied on performance indicators (e.g., carbon accumulation, pollutant removal, sediment fluxes, wave dissipation, etc.), neglect complex interactions including the omission of synergies and trade-offs between ESs (Kabisch et al., 2016; Sowińska-Świerkosz and García, 2021), that are fundamental to NBSs and their holistic evaluation. This focus could be partially driven by the goal drives the design of restoration projects (Thom et al., 2005), the type of NBS and challenges to (Sowińska-Świerkosz and García, 2021), the complexity surrounding NBSs' influence on multiple ESs provisioning (Xu et al., 2023), and subsequent risk reduction (Zhou et al., 2024).

4.2 Diving into the NBSs' evaluation indicators

Indicators help assess NBSs, their effects and systematic evaluation by simplifying the complexity of ecosystems (Dai et al., 2024; Kabisch et al., 2016; Sowińska-Świerkosz and García, 2021). This review align with previous studies, indicating that NBS performance and impact indicators mostly focus on environmental, hydrological, climatic, and ecological parameters, neglecting those related to e.g., economic feasibility, balancing trade-offs, or adaptive management (Châles et al., 2023; Cohen-Shacham et al., 2019; Giordano et al., 2020). This narrow focus aligns with the scope of this review and its aim to evaluate how NBSs address climate adaptation through ESs provision, hazard mitigation and risk reduction. Which in turn is reflected in the evaluation of NBSs impacts through the measurement and description of physical environmental parameters (Raymond et al., 2017), and performance in terms of regulating ESs focusing on ecological and hydrological processes (Krauze and Wagner, 2019).

The extensive focus on environmental parameters can be associated with conceptualization of the relation between NBSs and ESs (Dumitru et al., 2020), and indicates the evaluation of NBS performance. This relationship is often expressed through site-specific information that allows for the evaluation of a variety of environmental indicators which might fluctuate in space and time, representing key parameters and processes that function as proxies for the habitats affected by the NBS's implementation. Nevertheless, the explicit quantification of ESs is essential to assess how NBSs influence the local ecosystem and community, especially in the face of climate change (Baustian et al., 2020), whereas evidencing the link between ecosystem conditions and ESs provisioning justifies the effort and cost of maintaining and restoring such coastal and transitional ecosystems (Watson et al., 2022). However, information on how to measure the ESs provisioning by coastal and transitional ecosystems is limited (O'Leary et al., 2023), ESs are not sufficiently incorporated into risk planning (Ruckelshaus et al., 2020), and the causal relation between NBSs and ESs is often not quantified (Kabisch et al., 2016). A further investigation of these relationships, learning from the identified indicators, metrics, and established approaches, is needed to support the creation of a comprehensive evidence-based for coastal and transitional NBSs performance.

Monitoring the success of NBSs, and understanding the performance and impact indicators that can be used to evaluate effectiveness, provides essential tools for adapting their design and implementation (Dumitru et al., 2020). Monitoring should be a transversal process across the NBS stages, e.g., design, planning, implementation, strategically devised as a platform to gather evidence on NBSs' performance and impact once specific actions are deployed (Gonzalez-Ollauri et al., 2021). Through the monitoring of multiple indicators a more complete picture of habitat functioning will appear, while long term monitoring will demonstrate whether these NBSs reach their objectives (Bilkovic and Mitchell, 2013). While currently there is no standard protocol for monitoring coastal NBSs, monitoring a variety of indicators would allow for the investigation of various ecosystem processes and a more in-depth insight in the ESs provided by these habitats. Thereby, creating a comprehensive picture of the trajectory NBSs follow to reach their full potential, and how these interventions compare to their natural equivalents. At the same time, by streamlining the metrics between regions, albeit with some flexibility for site-specific indicators, would allow for the comparability of NBSs at different scale, and under different socio-economic and climatic conditions.

4.3 Data and knowledge to scale NBS potential

Currently, the effectiveness of NBSs, measured through performance and impact indicators, is often considered in a static manner (Giordano et al., 2020), with their long-term effectiveness assessed as if they are immutable and unaffected by change (Calliari et al., 2019). As underlined in the reviewed articles (e.g., Willemsen

et al., 2022), future research on time scales surpassing years and single decades is needed to assess the influence of climate change and allow for NBSs to reach their full potential (Raymond et al., 2017; Sowińska-Świerkosz and García, 2022). In part this ought to be supported by continuous monitoring of performance and impact indicators, allowing for a complete picture of the effectiveness of NBSs when implemented in the coastal and transitional ecosystems. While at the same time allowing for the inspection of the observed lag time needed for NBSs to reach their full effectiveness and ESs provisioning potential. Continuous monitoring would allow for the exploration of ecosystem dynamics, and the evaluation of processes occurring within relatively short periods of time. Through these observations, climate change strategies can take into account changing habitat suitability and identify opportunities for future NBS upscaling (Pittman et al., 2022). Another challenge with creating a strong evidence-base is to develop a balance between in-situ experiments providing bio-geophysical information, numerical modelling to evaluate the effectiveness of these NBSs while taking into consideration climate change and multi-hazards (Gonzalez-Ollauri et al., 2023; Kumar et al., 2021a) and, as indicated in the reviewed articles (e.g., McGlathery et al., 2012), create a better understanding of the synergic behaviour between ecosystem components and ESs. In this setting, the strongest benefit of numerical models is their capability to test NBSs potential through evaluating effectiveness indicators against different developmental stages, in different configuration, and considering different climate and management scenarios (Kumar et al., 2021b). Therefore, modelling the implementation of NBSs addresses the limitation mentioned in this review by Spencer et al. (2008), and can be used as knowledge base for developing scalability frameworks to move beyond the small-scale. In the past few years, machine learning (ML) and artificial intelligence (AI), alongside numerical models, have transformed from a theoretical concept to a practical tool. These advancements in climate big data processing support the identification of much more comprehensive future climate change scenarios and intelligent early warning systems (Leal Filho et al., 2022). Framed in this way the exploitation of new data sources for the evaluation of effectiveness can facilitate the adoption of NBSs for climate adaptation (Ruckelshaus et al., 2020), act as enablers to support the up- and out-scaling of NBSs in coastal and transitional environments (Sánchez-Arcilla et al., 2022), and help decisionmakers better defining climate risks and adaptation options.

5 Conclusion

The increasing interest in NBSs has the potential to reframe and integrate ESs for coastal and transitional resilience into climate adaptation strategies and management. In attempting to expand the evidence base for NBS and unravelling the nuances surrounding the effectiveness through performance and impact indicators, this review presents a snapshot analysis and discussion of existing literature starting from the introduction of NBSs by the World Bank in 2008. Diving deeper into the reviewed publications it can be noted that the interventions are primarily implemented at the micro-scale, focusing on single habitats and their performance or impact through the evaluation of physical attributes of the restored or created habitat, predominantly though monitoring environmental processes and characteristics with respect to a benchmark or reference site. This focus in part could be related to the sole consideration of peer-reviewed articles published in English, potentially introducing a bias towards smaller, academically published studies. While these studies provide valuable insights, the broader understanding of long-term effectiveness, ESs provisioning at larger spatio-temporal scales, and the integration of socio-economic impact indicators remains limited. Moreover, utilizing ML and AI to evaluate performance and impact indicators provides the opportunity to broaden the understanding of ecosystem processes occurring at various time scales and the trajectories followed by NBSs to reach their full effectiveness. The creation of an evidence-base, that conveys information related to the impact and performance indicators of the implemented NBSs, that can easily be understood and communicated to stakeholders and decision-makers, is crucial for co-design and implementation of more ambitious and informed NBSs in coastal and transitional ecosystem adaptation.

Author contributions

FH: Conceptualization, Data curation, Formal Analysis, Investigation, Methodology, Visualization, Writing – original draft, Writing – review and editing. ST: Conceptualization, Funding acquisition, Methodology, Supervision, Writing – original draft, Writing – review and editing. EF: Conceptualization, Methodology, Writing – review and editing. AC: Conceptualization, Supervision, Writing – review and editing.

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Conflict of interest

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Supplementary material

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