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Review

Eight recommendations to enhance biodiversity outcomes of nature-based solutions at multiple scales

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ABSTRACT

Ambitions to mainstream Nature-based Solutions (NbS) and achieve global implementation are hampered by the lack of transdisciplinary integration across disciplines and practice. Ecological knowledge, including an understanding of how biodiversity can support, and be supported by, NbS design and implementation remains an under-studied component of the NbS concept despite its critical importance. Starting with a brief primer on the major roles that biodiversity plays in NbS performance, we present eight recommendations for enhancing biodiversity in NbS planning and implementation. This narrative expert synthesis draws from an interdisciplinary literature search and decades of experience across landscape ecology, environmental engineering, urban planning, wildlife management, ecological restoration, and conservation science. Recommendations emphasize the importance of considering the ecological mechanisms that support biodiversity (i.e., viable populations of coexisting species) and understanding the role of organismal life history, species interactions, habitat preferences, and metapopulation dynamics in determining NbS features' ecological resilience and contributions to biodiversity enhancement (i.e., IUCN Global Standard Criterion 3). We also emphasize the importance of assessing biodiversity across spatial scales and dimensions (e.g., functional, phylogenetic) and monitoring and ecological management for anticipating and adapting to unexpected outcomes, invasive species, and ecosystem dis-services. This review is intended to increase connections between ecological science, conservation biology, and NbS implementation to support more biodiverse projects with more robust, resilient, and multifunctional performance and greater contributions to global conservation.

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1. Introduction

Nature-based Solutions (NbS) have gained widespread attention as a means for addressing societal challenges while benefitting both people and nature (Cohen-Shacham et al., 2016; Dunlop et al., 2024). The appeal of NbS (and practices subsumed under this umbrella term, including Natural Infrastructure, Green Infrastructure, Natural Climate Solutions, Ecosystem-based Adaptation) lies in their multiple benefits, resilience to extreme events, cost effectiveness, environmental sustainability, and contributions to biodiversity conservation (Keesstra et al., 2018; McKay et al., 2023). Growing enthusiasm for NbS is evident in the academic literature (e.g., Dunlop et al., 2024), government and non-governmental organization initiatives (e.g., European Investment Bank, 2023), shifts in private- and public-sector investment (e.g., Brill et al., 2021), and major international policy agendas (e.g., Durkin et al., 2024). As ambitions around NbS grow, experts have advocated for mainstreaming these approaches to achieve envisioned large-scale benefits and tackle societal and environmental issues globally (Seddon et al., 2021; McPhearson et al., 2025).

The growing literature around mainstreaming NbS reveals a substantial disparity between policy goals, knowledge, and evidence-based practice; what has been called the NbS implementation gap (Martin et al., 2025). Recent reviews highlight gaps in planning and assessment frameworks, cost-benefit analysis, stakeholder engagement and social equity, governance approaches, and performance monitoring (Frantzeskaki et al., 2025; Herath et al., 2025; Chambers et al., 2023; Albert et al., 2021; Ibrahim et al., 2025). However, this literature has been slower to address critical knowledge gaps regarding the ecological dynamics of NbS, neglecting the living components (i.e., biodiversity) that set them apart as "Nature-based". This is despite widely cited reviews highlighting the neglect of biodiversity as a major risk for the field (Seddon et al., 2021; Key et al., 2022). Benefits to biodiversity have become a core requirement for projects to be considered NbS under the International Union for the Conservation of Nature's (IUCN) Global Standard for Nature-based Solutions (NbS-GS; Cohen-Shacham et al., 2025). Although this overlap is increasingly referenced in the literature (Keesstra et al., 2018; Suedel et al., 2022), it is typically with little critical assessment of how to realize biodiversity gains in practice (e.g., Mohd Nazir et al., 2025).

Studies establishing or empirically examining concrete links between biodiversity conservation and NbS are limited (Key et al., 2022; van Rees et al., 2023; Hoegh-Guldberg et al., 2024), as is research on how ecological communities and the traits of their component parts promote NbS performance (Ramachandran et al., 2024). Thus, guidance for sustaining, enhancing, and leveraging biodiversity is needed for NbS to achieve their potential (Seddon et al. 2021; Suedel et al., 2022). To address this gap, we present eight recommendations for enhancing biodiversity in NbS implementation, drawing from landscape ecology, wildlife management, ecological restoration, and conservation biology. Importantly, decisions about incorporating biodiversity outcomes into NbS implementation are influenced by governance structures (Martin et al., 2025), stakeholder rights and engagement (e.g. Ibrahim et al., 2025; Kiss et al., 2022), land-use trade-offs (e.g. Finch et al., 2023; Miralles-Wilhelm, 2023), and funding availability (e.g. Chausson et al., 2023; Thompson et al., 2023) that vary considerably across contexts and communities. Therefore, these recommendations are intended to support NbS projects in which decision-makers have already decided to incorporate biodiversity goals or practitioners interested in incorporating biodiversity objectives into planned projects. Because all NbS ultimately rely on biodiversity (see Section 2- Biodiversity and Nature-based Solutions), these recommendations are relevant to all studies seeking to enhance the resilience, cost-efficiency, and performance of NbS.

We begin by reviewing the major justifications for enhancing biodiversity via NbS projects, then present recommendations and best practices for managing and sustaining biodiversity for more robust, resilient, and high-performing NbS. Wherever possible, we connect these with criteria and indicators from the IUCN NbS-GS with a specific focus on Criterion 3 (biodiversity enhancement). These recommendations stem from the experiences of a diverse author team with expertise in freshwater, agricultural, urban, and coastal NbS systems, and are intended provide a much-needed infusion of ecological thinking to the expanding transdisciplinary discourse on mainstreaming NbS.

2. Biodiversity and Nature-based solutions

Biodiversity is a critical component of the NbS concept in two important ways, and exploring these clarifies how ecological theory can enhance NbS practice. First, biodiversity fundamentally underpins NbS performance (constituting the "nature" in Nature-based), manifesting the natural processes by which NbS address societal problems and providing the resilience and sustainability that set NbS apart from other approaches (Seddon et al., 2021; Standish and Parkhurst, 2024). These natural processes are ecosystem services, that is, ecosystem functions or processes that benefit humans (Fu et al., 2013; Wong et al., 2015). Ecosystem functions are in turn determined by ecosystem structure, which is defined by local biodiversity and its myriad interactions, resulting in an "ecosystem service cascade" (Haines-Young and Potschin, 2010; Weiskopf et al., 2022, Fig. 1). Where the NbS concept treats nature as an engine for producing societal benefits, biodiversity must be understood as the "nuts and bolts" responsible for their sustained delivery. The second and more intuitive connection between NbS and biodiversity is the potential for NbS projects to enhance biodiversity (Cohen-Shacham et al., 2016; Mohd Nazir et al., 2025), in other words, as a means of ecological restoration and species conservation (van Rees et al., 2023; Jambhekar et al., 2026). Practitioners view biodiversity as an additional endpoint (or, somewhat circularly, as an ecosystem service) of NbS that can be integrated into decision-making, making it both a working component and an outcome of their successful implementation. Here, we briefly explore these two connections as a prelude and justification for our ecology-informed recommendations for NbS implementation.

2.1. The role of biodiversity in NbS service delivery and resilience

Biodiversity enhances NbS by (1) generating ecosystem services (Fig. 1), and (2) increasing the resilience of NbS features and therefore the durability of their benefits (Mori et al., 2021; Shchipanov and Kalinin, 2024;Seddon et al., 2021). Depending on the disciplinary lexicon, resilience can mean either the ability for the NbS feature or its services to resist disturbance or quickly recover from it (Standish and Parkhurst, 2024; Reed et al., 2024). Field and lab experiments have demonstrated linkages between different types of biodiversity and ecosystem function and resilience (e.g., van der Plas, 2019; Jochum et al., 2020). Although these relationships are influenced by several factors (e.g., community composition, intraspecific variation, and abiotic conditions; Sanders et al., 2024), more biodiverse ecosystems and communities are typically associated with more efficient ecosystem functioning, a wider array of ecosystem services, greater resistance to stressors, or potentially greater recovery following disturbance (Bouma and van Beukering, 2015). Increased biodiversity typically enhances ecosystem services like carbon sequestration while sustaining delivery through resilience (Xie and Bulkeley, 2020). From a natural infrastructure perspective, biodiversity may reduce life-cycle costs, by increasing capacity for adaptation and self-repair (Nelson et al., 2020; McKay et al., 2023). This addresses criterion 4 of the NbS-GS that "NbS are financially feasible and economically justified" and criterion 8 that "NbS contribute to the enhancement of the enabling conditions for their implementation, sustainability and mainstreaming". For example, recent work on the ecology of plants (e.g., mangroves) used in NbS emphasizes the role of biodiversity in ensuring the functioning and resilience of nature-based features under extreme weather events and climatic shifts (Mahecha

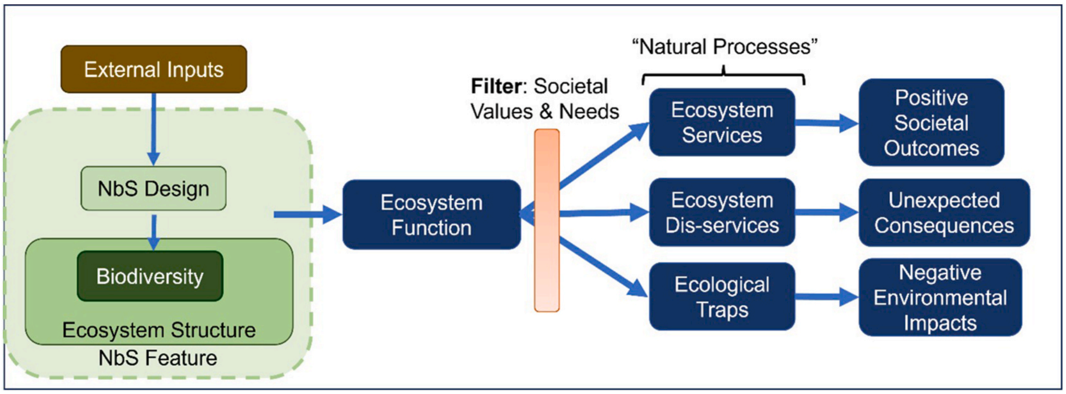

Fig. 1. Conceptual diagram of the relationship between biodiversity and the positive societal outcomes for which NbS are designed and implemented. Biodiversity is a determinant of the ecosystem structure of a given NbS feature, which in turn dictates ecosystem function and therefore services, which contribute to desired outcomes.

et al., 2024; Rafferty and Cosma, 2024).

2.2. NbS benefits for biodiversity conservation

The NbS literature is rich in references to their environmental benefits, emphasizing how they create, restore, mitigate, or avoid the conversion or loss of habitat for native species (Seddon, 2022; Warnell et al., 2023). The potential for such conservation benefits and the scale at which they might be achieved are critically important to emerging biodiversity conservation paradigms (Obura et al., 2023), including the Kunming-Montreal Global Biodiversity Framework's 2030 targets and 2050 vision (Convention on Biological Diversity, 2022). NbS may also provide a pathway for achieving ambitious goals like 30x30 (restoring 30% of degraded habitats on Earth by 2030; Convention on Biological Diversity, 2022; Brancalion et al., 2025) and bending the curve of freshwater biodiversity loss (van Rees et al., 2023).

Positive conservation impacts (i.e., biodiversity enhancement) are explicitly described in the NbS-GS, in the U.S. Department of the Interior's Nature-based Solutions Roadmap and related criteria ("Expected to benefit nature"; Warnell et al., 2023), and the Nature-based Solutions Initiative's guidelines ("NbS support or enhance biodiversity"; Seddon, 2022). These reflect growing formal recognition of the oft-referenced conservation benefits of NbS, and represent important progress toward realizing such aims. An ecological understanding of NbS as ecosystems that support assemblages of interacting organisms will be essential to achieving biodiversity enhancement and mainstreaming NbS.

3. Recommendations for enhancing biodiversity in nature-based solutions

Given the essential importance of biodiversity to the ecosystem services provided by NbS, efforts to achieve NbS-GS criterion 3 would benefit greatly from guidelines for achieving more biodiverse NbS features, and in stakeholder co-produced NbS projects, community members may prioritize biodiversity outcomes during co-design. The following recommendations are the product of an interdisciplinary critical review of the literature conducted by the authors and a series of virtual conversations convened by the Network for Engineering With Nature's (N-EWN, https://n-ewn.org/) Biodiversity Working Group.

Scoping conversations were held via Zoom during November 2024-August 2025, and co-authors built a combined annotated bibliography from independent, non-systematic searches using Google Scholar and Web of Science, and a snowballing approach using both cited and citing literature (Fig. 2). All literature searching was done from November 2024 to January 2026 (see Supplemental Material 1 for search terms). Co-authors independently reviewed results of their keyword searches and screened papers for relevance using the title, keywords and abstract (see Supplemental Material 2 for the list of citations reviewed after screening, and Supplemental Material 3 for screening criteria and examples). Publications were prioritized for inclusion when they directly informed ecological mechanisms underlying biodiversity enhancement, biodiversity monitoring, ecological resilience, species interactions, habitat quality, connectivity, or management considerations relevant to NbS implementation. Papers included after screening were read in full by at least one co-author, and major themes were chosen based on group discussions during and after the reading process. The list of recommendations was assembled iteratively over the course of those conversations, and co-authors were divided into teams for writing based on their interest and expertise. All co-authors had the opportunity to review sections they had not participated in writing and to share relevant literature across groups.

As an expert narrative review, the goal of this paper was not to systematically assess the current state of the literature on this topic (which recent reviews find to be minimal), but rather to provide expert recommendations based on our experiences and research to strengthen implementation toward more biodiverse and resilient NbS features. We organized these recommendations based on their relevance to different stages of the NbS life cycle and across phases like spatial planning, NbS selection and site prioritization, design, construction, maintenance, and monitoring (Kurth et al., 2024, Table 1, Table 2). Although NbS are implemented across contexts with variable enabling environments, and relatively few NbS explicitly monitor for biodiversity or evaluate trade-offs (Cohen-Shacham et al., 2025; e.g. Penning et al., 2023), we highlight examples of socio-economic implementation considerations wherever possible. Readers specifically interested in restoration-based NbS should also consult excellent recent reviews of relevant ecological theory for enhancing ecosystem restorations (Silliman et al., 2024; Brancalion et al., 2025) (see Table 2).

3.1. *Assess both habitat quantity and quality from a life-history perspective*

The conventional approach to supporting biodiversity in NbS centers on the assumption that ecological manipulations for implementation provide habitat for local, native biodiversity (Mohd Nazir et al., 2025), an assumption that is rarely examined critically or mechanistically (Wild et al., 2026). Understanding specifically *how* NbS can provide habitat, and what that means ecologically is critically important for NbS planning, design, construction, and assessment, as it allows practitioners to prioritize design elements or physical features that provide necessary resources. Biodiversity is ultimately maintained by the persistence of viable populations of species coexisting in space (Cardinale and Murdoch, 2025). Viable populations are those in which a sufficient number of individuals survive and reproduce, such that the population

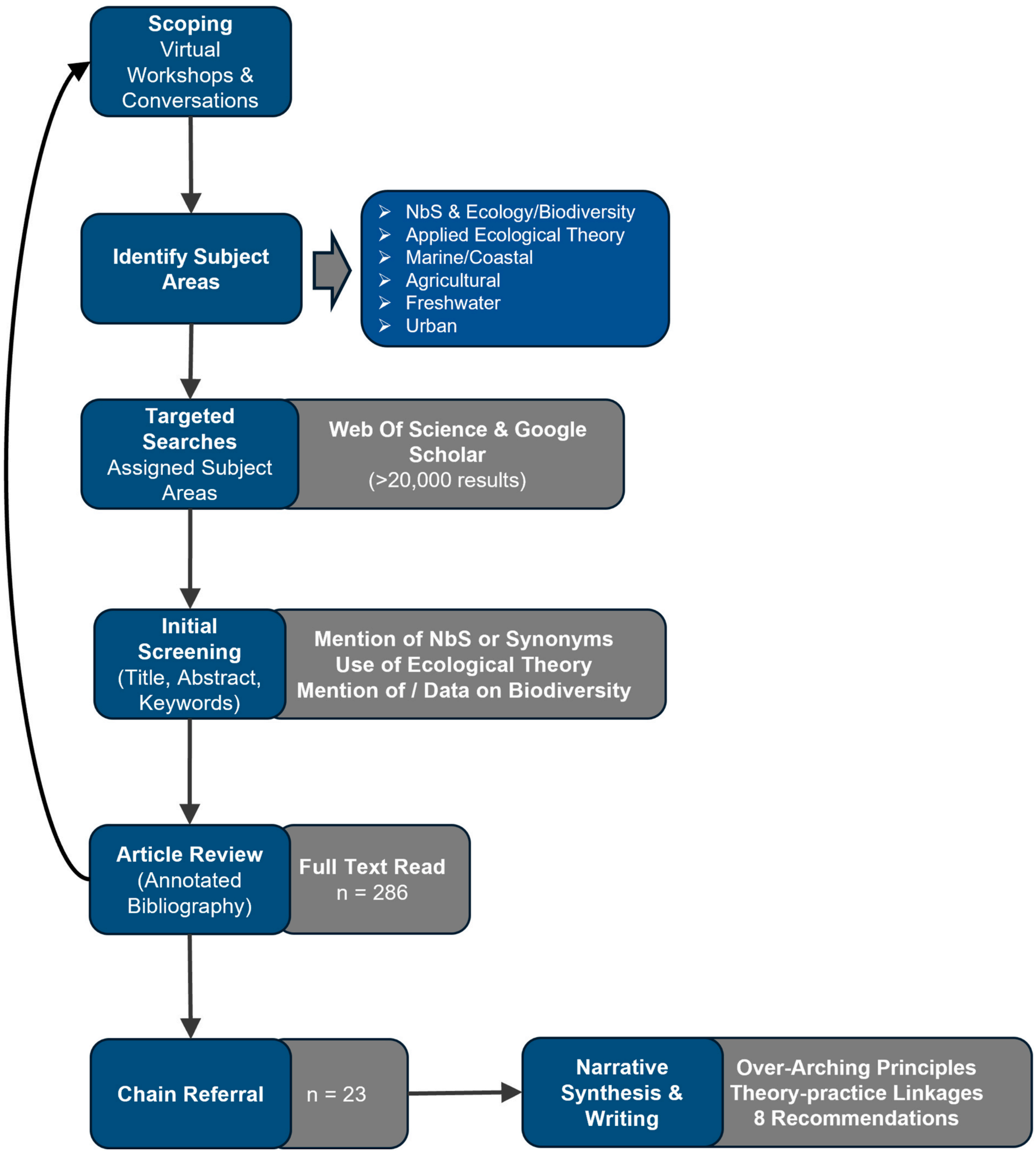

Fig. 2. Schematic of the workflow conducted in support of this literature synthesis. A series of workshops were held to identify key subject areas pertaining to NbS and biodiversity, then participants conducted independent literature searches using Web of Science and Google Scholar, screening results and building an annotated bibliography of relevant papers. Additional meetings were held to further refine subject areas and exchange literature. Additional papers were added as encountered in selected paper citations.

persists in a location (Shaffer, 1981; Reed et al., 2002). This persistence requires that organisms complete their life cycle, the predictable sequence of biological events that make up their lifetime. Life cycles are composed of life stages (e.g., seed, sapling, and tree) through which an organism transitions (e.g., birth or hatching, development, metamorphosis; Alonzo and Kindsvater, 2008). When enough individuals of a given species complete their life cycle to (at least) replace themselves demographically over time (or are replaced by immigration from elsewhere), populations remain viable. Thus, a specific mechanism by which NbS support biodiversity is through the provisioning of resources (e.g., food, shelter, water) that help species complete at least one part of their life cycle, enhancing survival or reproduction and thus population-level persistence.

On average, larger areas contain a greater diversity of habitat types, microhabitats, and/or environmental gradients, which in turn support a greater number of species; this phenomenon is called the species-area relationship (Matthews et al., 2020). Despite the importance of habitat heterogeneity in driving this general pattern (and sometimes overriding it – see Lizée et al., 2012 and Section 3.2; Table 2), it is common practice in NbS decision-making, particularly in benefits accounting, to document the total area of habitat (often categorized coarsely as “greenspace” or “natural vegetation”) contributed by a project as a measure of

Table 1
Synthesis table linking recommendations for biodiverse NbS to stages of the NbS life cycle, and potential or example management actions, indicators, and trade-offs.

NbS Life Cycle Stage	Recommendation	Example Action(s)
Spatial Planning	1 (Life History Perspective; Section 3.1)	Prioritize sites that will create necessary ecotones for species of interest that use multiple habitat types. **Example:** Selecting more topographically complex riparian areas for a levee setback project to provide increased refugia for juvenile fish. Opt for larger, contiguous patches of habitat to support higher abundances (and thus more stable populations/communities) of target species. **Example:** Other factors being equal, selecting the region with the largest available area of suitable depth for coral in planning for an artificial reef establishment.
	2 (Habitat Heterogeneity; Section 3.2) 4 (Dimensions of Biodiversity; (Section 3.4)	Choose NbS features that will contribute to landscape-scale biodiversity by providing different or complementary habitats or resources to those available to biodiversity in the vicinity. **Example:** Prioritizing a stormwater retention pond rather than a bioswale to create open-water habitat not found elsewhere in the nearby landscape.
	3 (Connectivity; Section 3.3)	Account for proximity to other habitat patches like protected areas, greenspace, or other NbS, when siting NbS, placing greater priority on those that are more accessible to dispersing organisms. Include functional or structural connectivity modeling in spatial prioritization algorithms. **Example:** Parameterize a movement model for oyster egg/larval drift with movement data and source populations to select sites for a living shoreline that are well positioned to receive dispersing larvae.
Design	1 (Life History Perspective; Section 3.1)	Intentionally design NbS to provide key trophic or spatial resources in support of target species' or communities' life histories. **Example:** Introduce or retain snags for cavity-nesting species (urban park), use structurally complex cement tiles to support sessile organisms (coastal seawall)
	2 (Habitat Heterogeneity; Section 3.2)	Design NbS features to provide a range of habitat conditions, including different substrates, structures, and temperature or moisture regimes to provide niches for different assemblages of species. **Example:** Design a moisture gradient, a range of substrate particle sizes, or add large stones into planters of a green roof to provide different niches for invertebrates.
Construction or Implementation	5 (Unexpected Outcomes; Section 3.5)	Consult with ecologists and local community members about potential risks or negative ecological consequences of designs or implementation plans. Prioritize the use of native plant species or removal of invasive species in site preparation or restoration. **Example:** Design stormwater ponds to avoid attracting breeding amphibians where water quality might be harmful to eggs or larvae by increasing drainage to shorten hydroperiod or provide barriers to prevent amphibians from reaching the ponds.
	6 (Species Interactions; Section 3.6)	Take advantage of biotic facilitation by leveraging foundation species, ecosystem engineers, and other taxa that provide ecosystem structure or enhance biodiversity. **Example:** Achieve cost savings in wetland restoration for flood control and groundwater recharge via beaver rewilding.
Monitoring	1 (Life History Perspective; Section 3.1)	Different stages of a target organism's life history may be easier or less expensive to monitor, or may be more informative of other ecological conditions of interest. **Example:** Counting hatchling sea turtles rather than nesting adults on a sandy living shoreline to avoid attributing value to unsuitable nesting areas being preferentially selected by gravid females (i.e., ecological trap).
	4 (Dimensions of Biodiversity; Section 3.4)	Monitor multiple facets and dimensions of biodiversity, including different ecological guilds, functional and phylogenetic diversity, as well as parameters like abundance (evenness). **Example:** Assess the biodiversity benefits of a mangrove restoration by monitoring both aquatic and terrestrial biodiversity and quantifying the biomass of a culturally important crab species in addition to the diversity of avian guilds using the restored forest.
	5 (Unexpected Outcomes; Section 3.5)	Use NbS monitoring data to watch for unexpected ecological outcomes like ecosystem disservices, IAS proliferation, or ecological traps. **Example:** Leverage remote sensing imagery to monitor a protected forest uphill from a large city for invasive tree encroachment that may decrease landslide protection or groundwater recharge ecosystem services.

(*continued on next page*)

Table 1 (*continued*)

NbS Life Cycle Stage	Recommendation	Example Action(s)
	7 (Biodiversity Monitoring; Section 3.7)	Make biodiversity a key component of NbS monitoring; expand monitoring parameters beyond habitat characteristics (e.g., total tree cover, available water storage) to include resident organisms. **Example:** Track dragonfly species abundance, richness, and timing around an urban stormwater retention pond via a citizen science effort led by local schoolchildren.
Maintenance	3 (Connectivity; Section 3.3)	Ecological connectivity can reduce maintenance costs by facilitating organism dispersal from nearby habitats, stabilizing populations and communities within the NbS feature. **Example:** Jays from an adjacent forest tract cache tree nuts inside a restored forest designed to prevent landslides, complementing outplantings or accelerating recovery from storms and fires.
	5 (Unexpected Outcomes; Section 3.5)	Ecological management (i.e., maintenance) of NbS features will often be necessary to maintain ecosystem services and biodiversity net-gain or prevent ecosystem dis-services. **Example:** The area within a levee setback realignment must be burned at intervals to maintain the desired hydraulic roughness of plant community structure for flood control, and to maintain openness for herbaceous plant species of conservation concern.
	6 (Species Interactions; Section 3.6)	Take advantage of species interactions wherever possible to reduce the need for ecological management or make management more efficient. **Example:** Install boxes to house small raptors or aerial insectivorous birds and bats to control pest insects or rodents in terrestrial or coastal NbS.
	8 (Ecological Management; Section 3.8)	Maintenance of NbS features must include ecological management; like conventional infrastructure solutions, NbS require some continued investment of energy. **Example:** A constructed offshore island that provides storm wave protection and horseshoe crab nesting habitat must be periodically replenished with dredge spoils.

conservation benefit. This typically involves land-cover mapping from remote sensing platforms and assumes that increased area will result in greater species richness. Thus, habitat quantity is the dominant indicator used in biodiversity accounting for NbS. In practice, this translates to a "more-is-better" heuristic, where large habitat areas generated, restored, or protected as part of an NbS are prioritized for their increased conservation value (Table 1).

Habitat *quality* also has well-known impacts on site-scale biodiversity via the availability of essential resources like food or nesting sites. For plants, especially those planted to deliver or support NbS benefits, abiotic conditions should be carefully assessed with respect to physiological tolerance to ensure project sustainability (NbS-GS Criterion 8), because ambient temperatures, water availability, and edaphic conditions have strong impacts on the survival and reproduction of plants and other foundation species (Pearlmutter et al., 2021; Suedel et al., 2022; Buckley et al., 2024). At the site scale, some NbS characteristics can strongly affect local biodiversity despite a small spatial footprint (Dondina et al., 2025). For example, cavities in dead trees provide nesting habitat for many small animal species, while areas that collect water or provide shade act as microhabitats for species sensitive to drought, cold, or heat (Parajuli et al., 2021; Hohl et al., 2022). Adding artificial resources like water features, birdfeeders, nest boxes, brushpiles, rotting logs or bee hotels is a simple environmental management strategy that makes use of this principle to support additional animal taxa via habitat and supplemental habitat or food resources. Practitioners can consult local community members, naturalists, and ecologists to identify such important resources and how they can be maintained to support desired biodiversity (Table 1).

Importantly, resources at a given site may not be sufficient to support a species of interest across all stages of its life cycle. In such cases, landscape-level planning can contribute greatly to increasing biodiversity of NbS features. During site selection and landscape design, practitioners can juxtapose NbS with landscape features offering complementary resources (e.g., water bodies, sandy substrate) and position these resources to be accessible to mobile organisms (Table 1; see also Section 3.3). Given the prevalence of NbS strategies in anthropogenic landscapes, planning and designing for habitat quality as well as quantity will be important to accurately quantify tradeoffs (NbS-GS Criterion 4, 8) associated with biodiversity enhancement measures and avoid potential negative impacts (NbS-GS Indicator 3.4) like ecological traps (Zhang et al., 2020; see Section 3.5). This can be accomplished through deliberate engagement with ecologists and local communities with longstanding ties to place, in the interest of leveraging natural history knowledge about species or assemblages of interest (Hall and van Rees, 2026).

3.2. *Preserve or design for habitat heterogeneity across scales*

Different environmental conditions create opportunities for organisms with contrasting life history requirements, environmental tolerances, or resource needs to persist in the same location, or to coexist despite competition (Chen et al., 2020). Such habitat heterogeneity is also strongly associated with increased biodiversity at multiple scales (Heidrich et al., 2020). Habitat heterogeneity also creates ecotones (i.e., transition zones between different habitat types), which support organisms with complex life cycles (i.e., using different habitats across life stages; Hood et al., 2022). For example, many amphibians require at least some standing water to breed but may range widely in terrestrial habitats for foraging and shelter (Duellman and Trueb, 1994).

Thus, NbS design and implementation that preserves, maintains, or creates habitat heterogeneity will more often support higher biodiversity (Fig. 3). This can be accomplished by engaging with landscape architects and designers to juxtapose structurally and compositionally different habitats (e.g., vegetation communities, tidal conditions, soil types) and providing a range of conditions across environmental gradients to support increased biodiversity within individual NbS features (Suedel et al., 2022). One simple approach in practice would be to assess habitat cover at the site- and landscape-scale and prioritize NbS strategies that add new habitat types (Table 1). While incorporating habitat heterogeneity into NbS design can help maintain local biodiversity, it may not be sufficient in situations where other factors like environmental stressors (e.g., pollution; Palmer et al., 2010) limit biodiversity, where species of concern need large, uninterrupted habitat areas (i.e., area sensitivity; Willmer et al., 2022), or where societal constraints like policy mechanisms or stakeholder preferences directly conflict with NbS strategies that might otherwise increase heterogeneity.

Table 2
NbS case studies and recognized biodiversity outcomes, and their implications for NbS practice.

Case Study (Category)	Indicator(s)	Biodiversity Outcome(s)	Lesson(s) Learned	Citation
San Francisco Estuary Living Shorelines (Coastal)	Invertebrate abundance and species identity, community structure	Invertebrate community assembly differed between eel grass and oyster bed restorations. Some recruited species increased landscape-scale biodiversity. Some expected species did not appear in expected densities.	Biodiversity outcomes will vary based on different ecosystem types. NbS features can contribute to landscape-scale biodiversity by attracting species not found in other local habitats. Even where habitat is appropriate, target species may be limited by recruitment ability or connectivity, necessitating deliberate introduction (i.e., management & maintenance)	Pinnell et al. (2021)
Savannahs in Democratic Republic of the Congo (Forest/Carbon Sequestration)	Tree species richness, diversity, and community composition, aboveground biomass	Exclusion of anthropogenic fire rapidly recovers species richness (10-20 years), but species composition recovers much more slowly.	Ecological management/maintenance actions as part of NBS can yield substantial biodiversity gains. Species abundance/evenness and other community-level parameters may respond differently than richness and diversity.	Djiofack et al. (2024)
Melbourne Green Roofs (Urban)	Vegetation Composition, Invertebrate abundance & species richness	Invertebrate community was largely determined by surrounding habitats in the landscape.	Landscape context may have significant influence over biodiversity in NbS, in some cases more than design elements (e.g., choice of planted vegetation), necessitating consideration in planning prior to implementation.	Dromgold et al. (2020)
Abiaca Creek Levee Setback (Riverine)	Water chemistry, fish abundance, biomass, species richness	Fish communities in borrow pits were similar to the creek channel, but pond size affected fish community composition.	Feature size and design (i.e., habitat area) can strongly affect the supported biodiversity community even if habitat types are largely the same.	Shields and Knight (2013)
Taiwan Stormwater Treatment Wetlands (Urban)	Water chemistry, species richness, community composition, and abundance of birds, fish, and invertebrates	Bird biodiversity increased with wetland area, fish biodiversity with area and dissolved oxygen, and invertebrate biodiversity with area and aquatic macrophyte cover.	Biodiversity outcomes can vary dramatically by taxon. Habitat area is often a dominant driver of species richness. Key microhabitats and structural elements (i.e., sources of habitat heterogeneity) can greatly enhance biodiversity for some taxonomic groups.	Hsu et al. (2011)

At the landscape scale, habitat heterogeneity often manifests as patchiness, the spatial interspersion of discrete areas (patches) of different habitat types. For a given species, one or more land cover types may function as habitat, while others are considered matrix (areas that do not provide resources; Ricketts, 2001). The spatial arrangement of these patches, their relative size, and their boundaries strongly influence resident biodiversity (Lizée et al., 2012) and delivery of ecosystem services to people (Dong et al., 2026). For example, these relationships control whether subpopulations inhabiting patches of favorable habitat are connected by dispersal (*see* Section 3.3), whether additional resources like water are available to resident organisms (resource supplementation), or if negative pressures are introduced from adjacent, contrasting habitats (edge effects; Willmer et al., 2022).

From an NbS planning perspective, most nature-based features are isolated patches of habitat or greenspace in an urban or agricultural matrix. This ecological “syndrome” of NbS features can lead to isolated subpopulations of organisms with increased probability of extirpation (i.e., localized extinction; Faeth et al., 2011) and thereby reduce their performance and conservation value. Some species can persist in small patches of habitat (Steigerwald et al., 2024), but they are more exposed to edge effects like higher temperatures, wind, or human-associated predators (e.g., domestic cats), necessitating careful planning or management to support viable populations and avoid creating ecological traps. Similarly, if the contiguous area of a given habitat type is reduced below a certain threshold, area-sensitive species may be lost from the landscape, even if the total amount of area of that habitat has not changed at the landscape scale. However, incorporating heterogeneity into NbS design can increase NbS performance through improved ecosystem function and enhanced biodiversity (Tortosa et al., 2023). Looking beyond the design of individual NbS, area prioritization for NbS development should include ecological variables like species of interest, habitat preferences, and dispersal behavior (van Rees et al., 2024, Table 1) to better capture how or whether anticipated trade-offs with other land uses can deliver desired biodiversity outcomes. Landscape planners and decision-makers could account for patch dynamics in consultation with ecological experts and local people, especially using participatory modeling approaches (see also Box 2).

3.3. Incorporate local biodiversity dynamics into connectivity planning and prioritization

In an ecological context, connectivity describes how a landscape facilitates or impedes movement between or among patches of habitat or resources. Where connectivity is high, mobile organisms readily disperse between patches, potentially increasing resource availability and landscape-level biodiversity (Crooks and Sanjayan, 2006). NbS features that are accessible to organisms or propagules (e.g., seeds, planktonic larvae) from adjacent habitats will be more biodiverse and support more taxa, even if they don't offer all of the necessary resources for organisms to complete their life cycles (Crooks and Sanjayan, 2006). In other words, the connectivity of NbS features with other habitats modulates their ability to support local biodiversity. Connectivity can also increase the resilience of biodiversity contributions to NbS performance by facilitating natural population dynamics across landscapes that would otherwise limit or inhibit these processes. Connectivity is thus an important consideration for site planning and spatial prioritization for NbS projects (Prodanovic et al., 2024), and can be included in the process using movement data and connectivity models for species of interest (Préau et al., 2022; van Rees et al., 2024; see examples in Table 1).

Metapopulation dynamics *(see* Box 1) describe the interactions between spatially separate subpopulations via movement (Hanski, 1999) and the theory of metapopulations is especially relevant for how biodiversity is maintained in small and isolated habitats within NbS. Isolated populations have higher extinction risk due to inbreeding

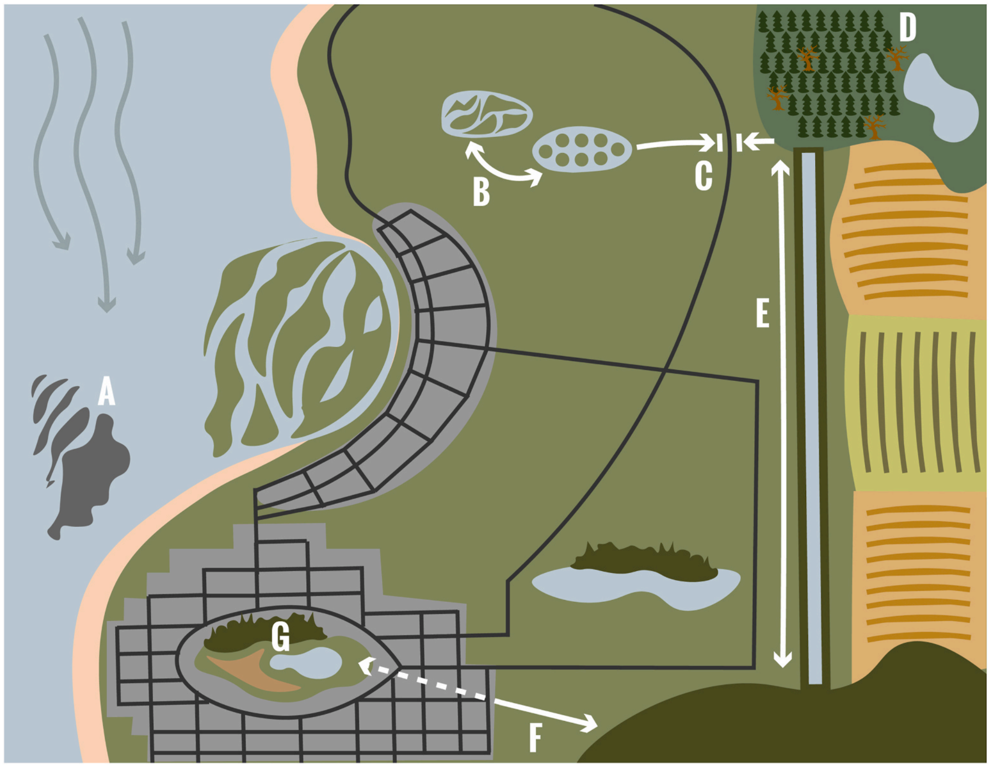

Fig. 3. Conceptual diagram of key concepts for maintaining and supporting biodiversity within NbS and their larger landscape. A-F: (A) an artificial oyster reef is positioned in line with tidal currents to receive dispersing larval propagules, thus increasing resilience and stability. (B) an artificial wetland (right) built adjacent to a natural wetland exhibits increased biodiversity due to organismal movement (connectivity) between habitats. (C) A road blocks movement between the artificial wetland and a nearby forest. (D) Habitat features like dead trees (snags) provide resources for supporting additional species in a planted forest for sequestering carbon. (E) Linear NbS features like two-stage drainage ditches can provide corridors, facilitating organismal movement and population or habitat connectivity among protected areas or other NbS. (F) Different landscape types have different permeability to movement (solid vs. dotted lines), differentially affecting connectivity between a forest patch and urban greenspace. (G) Habitat heterogeneity within an NbS feature increases the diversity of supported taxa and provides complementary resources for organisms with complex behaviors or life cycles.

depression (the accumulation of deleterious alleles) and random events (environmental and demographic stochasticity). However, metapopulation dynamics may introduce new genetic variation (so-called genetic rescue) or replace scarce demographic classes like breeding females (demographic rescue) to bolster such populations. Even limited connectivity allows for the persistence of a species in highly fragmented landscapes, although individual populations in semi-isolated patches may regularly go extinct and be re-established (Hanski, 1999). Connectivity can also counteract Allee effects (Stephens et al., 1999) whereby smaller populations have lower growth rates, increasing their extinction risk. These considerations may be particularly relevant for projects seeking to adhere to the NbS-GS' guidance to choose “formerly existing species of vegetation when restoring” (Cohen-Shacham et al., 2025) when populations of the species are small or geographically patchy to ensure their on-site persistence (NbS-GS Criterion 8). By designing or prioritizing to maximize connectivity, practitioners can take advantage of metapopulation dynamics, increasing community stability and potentially reducing costs (Table 1).

Although conventional NbS approaches typically overlook the value of ecological connectivity (Key et al., 2022; Standish and Parkhurst, 2024), recent research and synthesis in urban systems provide increasingly robust guidance on promoting connectivity via planning and landscape architecture (Donati et al., 2022; Prodanovic et al., 2024) by providing ecological corridors and steppingstones (Croeser et al., 2024). NbS features themselves may also promote exchange between isolated subpopulations in protected areas or other suitable habitats (Franklin et al., 2024, Fig. 3). For example, genetic evidence suggests that linear surface water features including drainage ditch networks may serve as dispersal corridors for endangered waterbirds in the urbanized landscape of O'ahu, Hawai'i, reducing extinction risk for small populations in isolated reserves (van Rees et al., 2018).

Resources like Movebank (www.movebank.org/) in conjunction with global databases of species distributions and movement simulations (e.g., Omniscape; McRae et al., 2016) may provide an excellent starting point for modeling the potential of alternative NbS locations or designs to promote connectivity. In marine systems, combining tidal and current modeling with empirical data on animal movements might similarly facilitate an understanding of whether taxa of interest can reach a site (Table 1). Collaboration between planners, surrounding property owners, local stakeholders, and ecologists at early stages of project design is thus a critical part of realizing the conservation potential of NbS at landscape scales (see Box 2), and in contexts where NbS features span more than one jurisdictional entity, collaborative and/or innovative governance arrangements may also be required to overcome social barriers and achieve NbS outcomes (e.g. Scarlett and McKinney, 2016).

Connectivity can also have negative consequences for certain taxa or habitats, for example by facilitating the spread of invasive alien species (IAS) that degrade ecosystem structure and function or promoting dispersal and settlement into sub-optimal habitats like ecological traps (Zhang et al., 2020; Potgieter et al., 2026). In levee setback systems, restored floodplains increase lateral connectivity to the river channel and may introduce predatory fishes, reducing habitat value for amphibians (Michael et al., 2023). Accordingly, we recommend careful consideration of the ecological impacts of different types of connectivity (hydrological, landscape) and the NbS feature's position in the landscape early in planning and implementation to predict and manage for the effects of connectivity on resident biodiversity.

Box 1
Glossary of terms

Box 1: Glossary of terms. Note that many terms will have distinct usages differing by discipline; here we list those definitions in the sense that they are used in this manuscript.

α-Diversity: Site-level measurements along one or more of biodiversity dimensions.

β-Diversity: Turnover or differences between sites (thus including an element of species composition), which helps to describe the degree of landscape heterogeneity.

γ-Diversity: Landscape or regional-level biodiversity combining site-level indices and between-site differences, integrating local metrics and turnover across sites.

Ecosystem services: Benefits to people produced by ecosystems, including provisioning, regulating, supporting, and cultural services.

Ecosystem dis-services: Negative impacts on people (e.g., disease vectors like biting insects, unpleasant odors) produced by ecosystems.

Ecosystem function: Processes that are driven by interactions between living organisms and the physical environment (e.g. energy flow and nutrient cycling). From an ecological engineering perspective, processes, actions, or tasks that an ecosystem can perform (e.g., a floodplain ecosystem is capable of denitrification).

Functional trait: Ecologically relevant and measurable organism characteristics related to function, performance, or resilience that define a trait linked to ecosystem processes and NbS performance.

Nature-based Solutions: Actions to address societal challenges through the creation, protection, sustainable management and restoration of ecosystems, benefiting both biodiversity and human well-being.

Natural Infrastructure: Uses natural processes and ecosystem services to support infrastructure engineering objectives, such as reducing flood damages or securing safe and ample water supplies. Examples include marshes and dunes that protect coastal property and infrastructure against storms and erosion, as well as forests and wetlands that reduce river flooding and purify water for downstream communities.

Biodiversity (Biological Diversity): The variability among living organisms from all sources including, inter alia, terrestrial, marine and other aquatic ecosystems and the ecological complexes of which they are part; this includes diversity within species, between species, and of ecosystems. Defined here following the 1993 Convention on Biological Diversity (CBD) (http://www.cbd.int/convention/articles). The CBD formally defines 'Biological Diversity', which is assumed to be equivalent to 'Biodiversity'.

Population Viability: The ability of a population to persist over time, often quantified as a probability of extinction within specified time window.

Habitat Heterogeneity: Variation in habitat patches or vegetation types within a site or landscape.

(Ecological**) Connectivity:** The degree to which a landscape facilitates the movement of individuals, propagules, or resources between disjunct habitat patches.

Ecological Management: The deliberate alteration of some aspect of an ecosystem or its resident biodiversity to achieve a desired outcome (e.g., a given successional stage or the persistence of a given species).

Other Effective area-based Conservation Measure (OECM): A geographically defined area other than a Protected Area, which is governed and managed in ways that achieve positive and sustained long-term outcomes for the *in situ* conservation of biodiversity, with associated ecosystem functions and services and, where applicable, cultural, spiritual, socioeconomic, and other locally relevant values.

Invasive Alien Species (IAS): Non-native organisms, often introduced to an ecosystem by human activities, which may cause economic or environmental harm or adversely affect human health.

(Ecological) Corridor: Linear habitat, embedded in a dissimilar matrix, that connects two or more larger blocks of habitat and is proposed for conservation on the grounds that it will enhance or maintain the viability of specific wildlife populations in the habitat blocks.

Nuisance Species: A native or non-native species that has negative interactions or effects on people and/or infrastructure.

Matrix: Land use, cover, and/or environmental conditions that differ from either species' habitat or reference/natural conditions.

Ecotone: Zone of transition between adjacent ecological systems, having a set of characteristics uniquely defined by space and time scales and by the strength of the interactions between ecological systems.

Ecocline: Intermediate gradients or boundaries between habitat types, which are often centers of habitat complementarity.

Species richness: A count of the number of species within a site or defined spatial unit.

Species evenness: The relative abundance and distribution of species which helps to define community structure and function.

3.4. Plan and design for different scales and dimensions of biodiversity

The ways in which biodiversity is conceptualized and measured are critical for understanding its interactions with NbS performance and accurately tracking conservation benefits (van Rees et al., 2026). Several dimensions of biodiversity (e.g., phylogenetic or functional traits, species evenness) are relevant to the ecological processes underlying NbS performance and resilience (Le Provost et al., 2023; Rafferty and Cosma, 2024; Ramachandran et al., 2024; see box 1), making them critically important for NbS planning, design, monitoring, and evaluation. Biodiversity can also be assessed at multiple scales, where α-biodiversity refers to site-level measurements along one or more of these dimensions, β-diversity to turnover or differences between sites (thus including an element of composition), and γ-diversity a landscape-level total combining these values across several sites (Cardinale and Murdoch, 2025).

Box 2
Important social considerations and connections for implementing biodiverse Nature-based Solutions.

Ultimately, NbS are implemented within a local sociopolitical and economic context, and their success depends on coordination with local communities, compatibility with local governance structures, and strategic land-use planning (described in NbS-GS 5 and 6). Many important manifestations of biodiversity and social contexts are local in nature, making careful attention to place-based ecological mechanisms and issues of equity critical for successful NbS (Hall and van Rees, 2026). Stakeholder engagement is increasingly recognized as integral to NbS development, including for conservation benefits (Ibrahim et al., 2025). We emphasize that local communities provide relevant information not only for identifying the most important ecological challenges to address in a system, but also for identifying locally relevant metrics for monitoring (van Rees et al., 2026) and in flagging ecosystem dis-services that might negatively affect community members. The place-based ecological knowledge of Indigenous People and Local Communities is critical to maintaining local variants or species assemblages (β-Diversity) particular to an area and avoiding landscape homogenization through NbS mainstreaming.

Stakeholder consultation and coordination can also support monitoring and maintenance, providing potential cost efficiencies where most budgets allocate little toward these tasks (Seddon et al., 2021; van Rees et al., 2022). Especially where NbS features are implemented in working landscapes actively used by local people, human presence on the landscape can constitute a powerful form of monitoring, especially when facilitated by smartphone technology, nature identification apps, and organized volunteer programs (Johnston et al., 2023). From a management standpoint, where local stakeholders directly use resources provided by an NbS or have a culture of stewardship and reciprocity with the ecosystem, management and maintenance activities can become a standard societal practice; for Indigenous and other communities with long-standing ties to place, this may simply be a historical default (Nelson and Reed, 2025). Co-management of NbS features by local people could also contribute to meeting global objectives to increase the contribution of OECMs (Box 1) to supporting biodiversity (Alves-Pinto et al., 2021).

Land management decisions around NbS may involve tradeoffs between desired ecosystem services, biodiversity goals, and stakeholder needs, necessitating decision-making frameworks that can navigate these complexities and avoid adverse impacts on local communities (Albert et al., 2021). This is particularly common in the context of agricultural landscapes (Miralles-Wilhelm, 2023), necessitating allocation of space for living, production, and biodiversity goals (Liu et al., 2025). For example, prioritizing locations for NbS in areas that enhance ecological connectivity might not be compatible with existing patterns of land ownership, or with other needs, for example accessibility for recreation. Participatory frameworks involving co-design are needed to ensure equitable implementation across stakeholder groups and to identify and navigate tradeoffs where they may exist (Slinger et al., 2023). Stammel et al. (2026) highlight the success of a recent case study in Serbia where tradeoffs for floodplain restoration NbS were addressed using workshops. We recommend deliberately including biodiversity data, for example from public databases of species occurrences or movement, along with participatory modeling approaches used in wildlife conservation (e.g., Vukomanovic et al., 2023) to more effectively enhance biodiversity while promoting social equity.

Importantly, resident biodiversity within NbS features may help address critical social obstacles to implementation mainstreaming NbS, for example a lack of public awareness, trust in NbS performance, or project visibility (Cuenca-Cambronero et al., 2023). Charismatic species can give projects a “face”, providing an entry point for education and outreach efforts. This might provide a synergistic benefit to NbS implementation in general while addressing the prevailing under-recognition of conservation goals in practice.

The most common metric used to quantify site-scale (α) biodiversity is species richness (i.e., number of local species), which excludes useful information on other dimensions of biodiversity that are needed to assess species persistence or ecosystem service delivery (Fletcher et al., 2025). For example, species richness does not distinguish between native and introduced species, so increases in richness may be driven by habitat degradation (i.e. IAS colonization) rather than ecological improvements. Incorporating metrics that include species identity would help avoid attributing conservation value to IAS and instead prioritize NbS features that make unique contributions to improving native biodiversity. Ecological communities that contain different species from those in another area (β-diversity) increase the overall (landscape-scale; γ) diversity, even if they are similar in total number of species (Table 2). For example, sea grass restoration associated with oyster-reef living shorelines has been shown to increase landscape-scale invertebrate biodiversity, supporting species not otherwise found in an area (Pinnell et al., 2021). The relative abundances (number of individuals) of different species (evenness; Box 1) also modulate ecosystem service delivery (Zhou et al., 2025), suggesting that careful attention to patch size (Section 3.2) and initial population sizes of stocked organisms like plants have major implications for NbS performance and resilience. Relative abundance, when paired with additional data (traits and evolutionary relatedness), can also be used to calculate functional and phylogenetic metrics of biodiversity (Chao and Colwell, 2022), which may be particularly useful when a project seeks to increase ecosystem multifunctionality but the exact species or processes that deliver individual functions are poorly understood (Ramachandran et al., 2024). Increasing multiple dimensions and facets of biodiversity can be achieved through addressing gaps in life history needs of key species (Section 3.1; Table 1) and increasing habitat heterogeneity (Section 3.2; Fig. 3).

Attention to species identity and other dimensions of biodiversity in conservation efforts is critical for setting appropriate goals and developing outcome-relevant monitoring and evaluation plans (Socolar et al., 2016; Filazzola et al., 2019), and protecting and restoring local (sub) species, populations, and assemblages will be necessary to enhance biodiversity through mainstreaming NbS. Thus, we recommend that planning and accounting for biodiversity in NbS siting, design, and implementation take into account multiple dimensions and forms of biodiversity, and not just site-level species richness (Table 2). We note, however, that there are variable resource costs (time, money, etc.) associated with monitoring different dimensions of biodiversity (e.g. Kühl et al., 2020; Callaghan et al., 2024) that impose constraints on the capacity to monitor NbS ecology. Setting project goals requires consultation with local people and communities, rather than relying purely on top-down approaches like species distribution models and remotely sensed data (Kühl et al., 2020; Hall and van Rees, 2026). Local community and land-owner knowledge is an under-utilized source of local biodiversity information, especially for identifying cases where species identity is particularly important (e.g., beneficial, culturally valuable, or harmful species), and involving these stakeholders in monitoring can help overcome some of the resource costs and strengthen capacity (Schmeller et al., 2017; Kühl et al., 2020 but see Johnston et al. (2023) for potential challenges). Garnering such information also provides a meaningful opportunity for stakeholder engagement and inclusion in NbS planning and design (NbS-GS Criterion 5; see Box 2).

3.5. Consider unexpected ecological outcomes for and from biodiversity

Ecological dynamics can lead to unexpected outcomes, especially in human-dominated landscapes where ecosystems may have a simplified structure and where novel assemblages of species interact. Unexpected outcomes in NbS applications might include ecological traps, ecosystem disservices like nuisance species, disease vectors, or loss of NbS function due to IAS (Box 1; Lyytimäki and Sipilä, 2009;Zhang et al., 2020; Prodanovic et al., 2024). These potential negative consequences have cross-cutting implications for the NbS life cycle; practitioners can anticipate such impacts through research in planning, detect them via asset monitoring, and mitigate them during the design and implementation process, or through post-hoc management.

Stormwater wetlands are well-studied NbS for which ecological traps have been documented. Frog larvae (tadpoles) hatched in these artificial wetlands can exhibit reduced survival rates, although adults do not avoid ovipositing in them and may have no local alternatives for spawning (Sievers et al., 2018; Zhang et al., 2020). In agricultural and urban landscapes, NbS surrounded by potentially hazardous matrix (e.g., high vehicle traffic, pesticide applications) result in high dispersal mortality, leading to negative population-scale impacts on local biodiversity (Vasiliev and Greenwood, 2022).

So-called "nuisance species" are often favored by disturbed, artificial, or modified ecosystems in human-dominated landscapes, exhibiting increased population densities or modified behaviors that lead to negative impacts on people or the ecosystem. For example, water management strategies in rice fields in Southern Spain alter seasonal space use patterns in gulls (*Larus* spp.) that feed in landfills, transporting heavy metals, antibiotic-resistant bacteria, and microplastics to agricultural and conservation areas where they roost at night (van Rees et al., 2021; Martín-Vélez et al., 2024). He et al. (2024) documented a large nesting colony of gulls that formed around a green roof in New York City and resulted in elevated fecal coliform levels from runoff, counteracting planned water quality benefits.

IAS are among the greatest threats to biodiversity globally, driving declines that can greatly compromise ecosystem resilience and ecosystem delivery. Their abundance and ecological impacts are often greater in human-modified and anthropogenic environments (Comte et al., 2021; MacDougall and Turkington, 2005), making them a serious risk for NbS (Potgieter et al., 2026). In the eastern U.S., the invasive reed *Phragmites australis* rapidly colonizes living shoreline sites (McCormick et al., 2020). Studies suggest that *Phragmites* can reduce the capacity of restored salt marsh to both attenuate waves and migrate upland in response to sea level rise in its invaded range, compromising shoreline protection ecosystem services (Coleman et al., 2023). IAS encroachment can negate biodiversity enhancement benefits of floodplain reconnection NbS within 5-10 years of project completion, reducing return on investment (Parajuli et al., 2026). Such impacts suggest the need for ecological management to maintain NbS performance and reduce the potential for negative spillover effects on ecosystems including conservation areas (Hardaway, 2017).

While IAS typically reduce ecosystem services, some non-native and invasive species can perform helpful functions like erosion control. The intentional introduction of non-native species for ecosystem service delivery has led to problematic ecological decline and ecosystem disservices in many instances (e.g., mangroves in Hawai'i; Allen, 1998). Careful ecological design and management of NbS is important to maintain their resilience and performance while avoiding the propagation of IAS or nuisance species that degrade local biodiversity, reduce NbS performance, or create unexpected ecosystem dis-services (Sotka and Byers, 2019). Practitioners should consult local communities or regional ecological literature to identify potential IAS of concern and consider strategies to prevent their establishment and spread (Table 1).

3.6. Leverage species interactions for cost efficiency, resilience, and conservation performance

Species interactions are a critical biotic determinant of biodiversity, making species identity especially important for NbS performance and cost-efficiency. The importance of these interactions for local biodiversity is implicit in recommendations for selecting native plant species for NbS (Zhang et al., 2020; NbS-GS Indicator 3.2), which assume that native plant species support more local biodiversity (e.g., pollinators or herbivores). For example, many insect species are specially adapted for coping with the defensive secondary metabolites of plants with which they have had a sufficient evolutionary history to overcome those defenses. Where such plants are abundant, more native herbivores and their predators and symbionts can complete their life cycles, directly increasing local biodiversity, with the opposite trend where invasive or non-native plants are prevalent (Narango et al., 2017). In marine systems, IAS like non-native seagrasses reduce food quality and availability, supporting fewer herbivores than native species (Muthukrishnan et al., 2020)

Such trophic (i.e., food web) interactions indirectly support additional biodiversity via secondary production (the production of primary consumers that are in turn consumed by predators), which supports additional trophic tiers of organisms. For example, where native plant communities support sufficient populations of herbivorous insects, the diversity and abundance of songbirds increases (Burghardt et al., 2009). Understanding the potential for such interactions to support higher biodiversity and NbS function is critical for achieving positive conservation outcomes and more robust performance.

Facilitative interactions between species, in which organisms confer non-consumptive benefits to other organisms (e.g., pollination, seed dispersal, shelter) also strongly affect biodiversity at patch and landscape scales (Yeakel et al., 2020). Some species, like ecosystem engineers (*sensu* Jones et al., 1994) have a disproportionate impact on the physical structure of ecosystems, creating conditions or habitats that favor other taxa (Byers, 2024). Such facilitative interactions suggest the utility of rewilding efforts from a management point of view, where reintroducing or supporting one species leads to outsized enhancement of local biodiversity (Law et al., 2017).

A key advantage of facilitative interactions for NbS practice is that species like ecosystem engineers guide the trajectory of an ecological community toward a desired state (Moustakas et al., 2019; Byers, 2024), potentially reducing the need for ongoing interventions (i.e. enhancing sustainability; NbS-GS Criterion 8) and thus providing cost savings (NbS-GS Criterion 4). Such facilitation may be especially important for projects in areas with stressful abiotic conditions, such as in semiarid climates, high temperature variation, or at early stages of succession (Bertness and Callaway, 1994). In these cases, facilitative interactions can enable colonization and buffer abiotic conditions, promoting positive feedbacks ameliorate environmental conditions. For example, oyster reefs assemble via the recruitment of pelagic, larval oysters to existing structures. Oyster shell has long been recognized as the best substrate for recruitment and thus reef-building efforts that take advantage of this self-facilitation can optimize outcomes (Rupasinghe et al., 2024). Communities characterized by more ecological interactions often show stability and reduced extinction risk (Yeakel et al., 2020) and can be more resistant to invasive species and their negative impacts (Zhang et al., 2020), reducing maintenance, management, and even construction or restoration costs where targeted species introductions leverage facilitative interactions.

Careful selection of native species during NbS implementation, especially those with outsized roles in the community (e.g., keystone or foundational species, ecosystem engineers), can thus increase cost-efficiency and reduce maintenance costs and increase performance across functions. We therefore recommend that information on ecological relationships leveraged by practitioners through collaboration with ecologists (Table 1). This will allow key species to be either intentionally added or encouraged by establishing optimal site conditions for their natural establishment (e.g. installing beaver dam analogues to retain water in dryland streams). Strategic thinking by planners in consultation with ecologists, naturalists, and knowledgeable local people will be essential for properly leveraging species interactions for more effective and biodiverse NbS.

3.7. Frame biodiversity monitoring as asset monitoring

Post-construction monitoring is a key part of the infrastructure life cycle, ensuring that engineered assets are performing as expected and identifying needs for maintenance or adaptive management (Kurth et al., 2024). Despite being a core part of the NbS-GS, ecological monitoring is rarely implemented in NbS practice (Filazzola et al., 2019; van Rees et al., 2022). Monitoring data on biodiversity are critical to understanding the relationship between NbS ecological structure and performance, and to develop an evidence base for potential conservation benefits (Seddon et al., 2021; Standish and Parkhurst, 2024; van Rees et al., 2026). Without quality monitoring data across taxonomic groups, functional guilds, ecosystem processes and/or levels of biological organization, practitioners will have an incomplete understanding of the ecological dynamics of NbS projects and risk suboptimal performance, especially under changing environmental pressures (e.g., pollution, extreme weather). This can lead to poor performance, losses of ecosystem service delivery or conservation value over time (e.g., due to successional change or IAS), or unexpected outcomes like ecosystem disservices *(see* 3.5, Unexpected Outcomes and NbS-GS Criterion 6). Monitoring NbS features, as with any other asset, is critical for adaptive management (NbS-GS Criterion 7), enabling responses to changing conditions that maintain function and sustain performance (Kurth et al., 2024).

Importantly, NbS require different approaches to monitoring compared to conventional infrastructure, including measurements of complex ecological dynamics and multi-faceted biodiversity parameters that will vary over time and space (van Rees et al., 2022; Warner et al., 2025; see Section 3.4). This presents a substantial challenge in designing appropriate metrics and indicators (Burgess et al., 2024; Wauchope et al., 2024; van Rees et al., 2026). In the rare cases where biodiversity is explicitly monitored in NbS implementation, (see Section 3.4), metrics based on plant species richness are common, failing to capture management-relevant aspects of species identity and ecological dynamics that affect management goals (Key et al., 2022; Salvo-Tierra and Ruiz-Valero, 2025).

NbS share these challenges with the field of ecological restoration, where post-intervention monitoring is time-consuming, costly, and rarely implemented (Zu Ermgassen and Löfqvist, 2024). This reality can create tension between NbS-GS Criteria 3 (enhanced biodiversity) and 4 (financial feasibility and economic justification) (Cohen-Shacham et al., 2025). New technological tools, including rapid or remote sensing methods like eDNA, acoustic monitoring, GIS and remote sensing, as well as following NbS-GS practices like collaborating with community members to co-design and implement monitoring have great promise to lower some of the resource barriers to long-term monitoring (Table 1; Ross et al., 2023; Leandro et al., 2024; O'Brien et al., 2024).

The appropriate indicators, metrics, and facets of biodiversity, as well as the most appropriate spatial scales at which to monitor, are an active research field (Kühl et al., 2020; van Rees et al., 2026), and the best approaches will be context dependent. Government guidelines for NbS implementation in the European Commission (Dumitru and Wendling, 2021) and United States (Warnell et al., 2023) recommend indicators based on species richness derived from range maps or habitat-level indices from land cover datasets, for example the proportion of nearby protected areas, area of habitat restored, or total length of ecotone. These simplified, top-down approaches risk missing or under-recognizing local ecological characteristics and dynamics (Hall and van Rees, 2026).

Better integration with local stakeholders can play a large role not only in collecting monitoring data but also in identifying which aspects of biodiversity are most informative of or influential to meeting societal needs (Sangha et al., 2025). Indigenous communities, for example, have monitored and cared for ecosystems for millennia and can contribute context-specific expertise for adaptive management of NbS (Nelson and Reed, 2025; Hall and van Rees, 2026; Box 2). Where funding is limited, biodiversity may function as a cost-saving indicator of other NbS characteristics, tracking not only ecological dynamics affecting performance but also the achievement of biodiversity net-gain requirements (van Rees et al., 2026). Combining new data streams with emerging frameworks and guidelines for selecting targets, indicators, and metrics (TFND, 2023), biodiversity monitoring of NbS should enhance, rather than burden, implementation.

3.8. Treat ecological management as maintenance

Maintenance is a standard part of conventional infrastructure management, as additional inputs are necessary to maintain structural integrity and performance over time (Kurth et al., 2024). Although NbS are commonly thought to require less upkeep (Nakamura et al., 2020), many ecosystems, especially those in human-dominated landscapes, require continuous or repeated intervention (Fig. 4; Table 2). As external stressors (e.g., pollutants) or IAS (see salt marsh example above; Fig. 4) alter ecosystem structure, potentially degrading functions and useful services in an NbS system, ecological management is necessary to maintain performance and should be anticipated when allocating resources for NbS implementation (e.g. Thompson et al., 2023; Girot et al., 2025, Table 1). Human beings have managed ecosystems throughout our evolutionary and recorded history, using controlled burns, grazing, flooding, ditching, and thinning and planting of vegetation to achieve desired characteristics (McMichael et al., 2023). In coastal environments, substrate modifications like constructed fishponds were also historically common and required frequent repair from the effects of wave action (Kikuchi, 1976). Managing and maintaining NbS must also respond to the rights and interests of local communities affected by NbS outcomes to achieve long-term success and achieve equity (Santini and Miquelajauregui, 2022).

The concept of ecological succession, the process of directional, predictable change in the biodiversity of an ecosystem over time, is especially pertinent to NbS management. Even in the absence of external stressors, ecosystem structure and function may change over successional stages, altering ecosystem services (Sharafatmandrad and Khosravi Mashizi, 2021) and habitat value (Buckley et al., 2024; Lovelock et al., 2024). It is thus important to consider the present versus desired successional stage of a managed ecosystem and its effects on ecosystem service delivery and conservation benefits.

From a biodiversity enhancement standpoint, many species are dependent on successional or transitional habitats which need disturbance (e.g., burning, logging) to prevent total extirpation from a superior competitor (e.g. sessile species in the rocky intertidal zone) and require ecological "maintenance" to persist. NbS management practices are an opportunity for environment management in support of such dependent taxa (Miralles-Wilhelm, 2023). Furthermore, succession-dependent species are likely to differ from those inhabiting NbS features at other successional stages, increasing β-diversity. For example, if levee setback must maintain low floodplain tree density to moderate hydraulic roughness, then vegetation management to sustain open grassland or shrub habitat would support specialist insects and birds not occurring in floodplain forests. At the landscape scale, NbS that support habitats at different successional stages increase habitat heterogeneity and γ-diversity.

Ecological succession and the resulting changes in ecological communities are disrupted by disturbances, which are events that bring about drastic changes in abiotic or biotic conditions (Chang and Turner, 2019). Common disturbances include storm events, sea ice, fire, grazing,

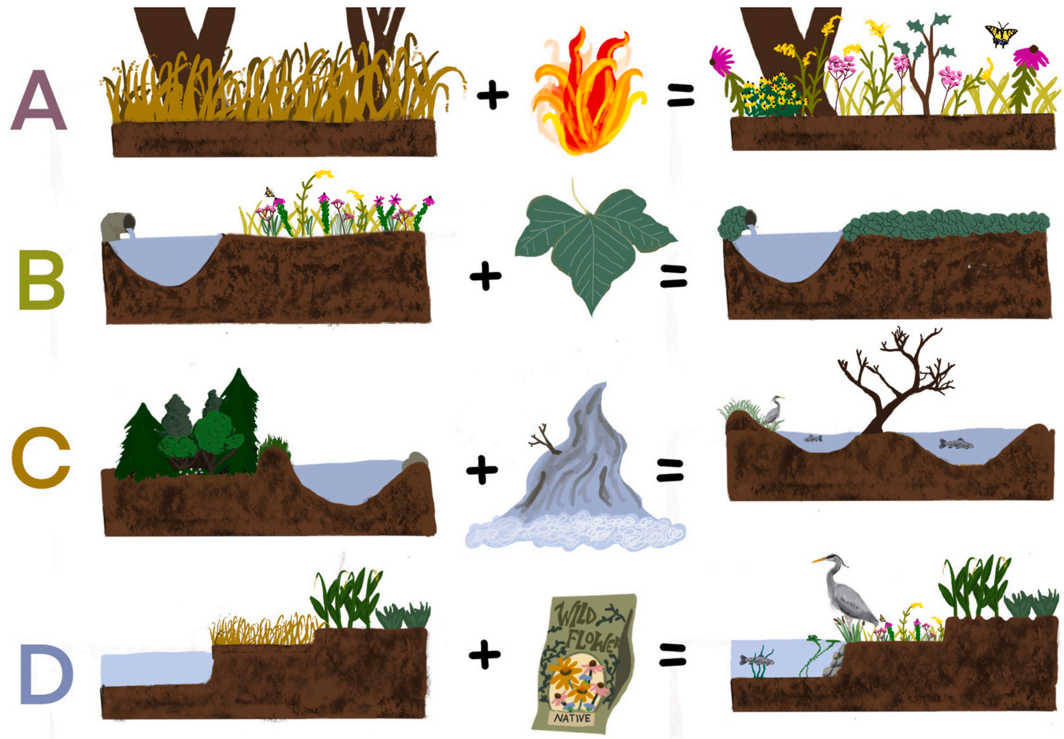

Fig. 4. Examples of natural disturbances or management actions and their general influence on site-level biodiversity. A: Wildfires (natural disturbance) or controlled burns (active management) can promote plant diversity, contributing in turn to animal, microbial, and fungal diversity. B: Invasive alien species (e.g., kudzu, *Pueraria montana* in North America) can degrade habitat quality, resulting in significant biodiversity loss; preventing such losses may require regular management and maintenance of Nature-based features. C: Flooding (natural disturbance) or controlled inundation (active management) can increase habitat heterogeneity and promote colonization of isolated waterbodies by additional taxa. D: Native out-planting can promote native vegetation assemblages, supporting higher biodiversity.

or disease outbreaks among primary producers or structural keystone species (e.g., canopy trees or corals). By altering the physical landscape and successional state of different communities within a land- or seascape, disturbances typically increase habitat heterogeneity and biodiversity where their magnitude and frequency are within the tolerance of the regional species pool (Kumar et al., 2022). Conversely, more extreme disturbance events, including anthropogenic stressors like the construction of infrastructure or land development, can reduce biodiversity and degrade ecosystem function (Gaynor, 2024). NbS may in some cases change dramatically after disturbance, with significant implications for performance and maintenance. Awareness of the types of disturbances an NbS might experience, how these might change successional stage of trajectory, and any subsequent effects on feature performance is thus an important part of implementing NbS. Where naturally occurring disturbances might help maintain a desired successional stage without management, cost savings (NbS-GS Criterion 4) might be achieved by initial design (e.g., coastal elevation profile) to encourage disturbance that maintains that desired state.

Post-implementation actions like monitoring and maintenance are likely to incur additional costs (Kiss et al., 2022) and willingness to pay can depend on the realization of NbS benefits and changes in governance (Neumann and Hack, 2022). However, maintenance may be required for sustaining social NbS benefits beyond enhanced biodiversity over time (Gonzalez-Flo et al., 2023) and can be supported by local community engagement (Kiss et al., 2022). NbS practitioners may also achieve efficiencies by head-starting ecosystems with foundation species (*see* 3.6) that allow natural processes of succession to bring about a desired ecosystem state for ecosystem service delivery, rather than directly transporting mature organisms (e.g., larger corals) to start at a more advanced successional stage. Overall, we encourage NbS practitioners, and their funders, to view NbS features and individual projects as dynamic ecosystems that must be managed and maintained to various degrees beyond the initial construction or implementation phase, rather than static assets.

4. Conclusions

We outlined eight key recommendations for NbS researchers and practitioners to integrate ecological theory into implementation in mainstreaming NbS. These recommendations build upon and generalize recent contributions that identify strategies for specific implementation contexts and NbS types (e.g., Zhang et al., 2020; Donati et al., 2022; Suedel et al., 2022; Prodanovic et al., 2024), and provide greater detail into the ecological mechanisms underlying common assumptions about biodiversity in NbS and related features. The insights offered by this review illustrate the value of ecological and conservation science for informing NbS planning and implementation alongside considerations about land use, governance, and local stakeholder rights, among others (e.g. Key et al., 2022; Ibrahim et al., 2025). Future research can contribute to mainstreaming biodiversity in NbS implementation by testing the use of publicly available biodiversity data for site prioritization and design, trialing proactive and low-cost approaches to reducing the impact of IAS, and developing methods or frameworks for quantifying multiple dimensions and facets of biodiversity. Active biodiversity monitoring and ecosystem management, especially through (and as part of) engagement with local communities, must be seen as a crucial part of durable NbS implementation, which should yield synergistic benefits in project legitimacy, public awareness, and ecosystem service performance. Ecological monitoring is also a critical part of building the necessary evidence base for NbS, and emphasize the need for practitioners to collect and share data about their experiences designing and implementing biodiverse NbS to improve practice (Key et al., 2022; van Rees et al., 2022).

Keeping in mind the "nature" in Nature-based Solutions, the growing NbS community of practice must more intentionally engage with decades of useful knowledge in ecosystem ecology, ecological restoration, and conservation biology to increase NbS performance and resilience and achieve goals for biodiversity net-gain. Achieving more ecologically informed planning, design, monitoring, and management of these features will require the deliberate inclusion of ecologists, conservation scientists, local community members, wildlife managers, and other biodiversity experts in all stages of the NbS life cycle (Ibrahim et al., 2025) and can lead to improved NbS performance (e.g. Préau et al., 2022; Tortosa et al., 2023). This implies a substantial role for ecological consultants, partnerships with academic institutions like thinktanks and universities, conservation non-profits, as well as citizen scientists like hobby naturalists and birdwatchers. We strongly encourage NbS practitioners to engage with these stakeholders and consider biodiversity and ecosystem dynamics explicitly in NbS planning implementation rather than assuming biodiversity enhancement and NbS sustainability based on coarse metrics like land cover.

CRediT authorship contribution statement

Charles B. van Rees: Conceptualization, Investigation, Project administration, Resources, Supervision, Writing – original draft, Writing – review & editing. **Collin VanBuren:** Conceptualization, Project administration, Writing – original draft, Writing – review & editing. **Lori A. Han:** Conceptualization, Writing – original draft, Writing – review & editing. **Andrew Altieri:** Conceptualization, Writing – original draft, Writing – review & editing. **Matt Bilskie:** Conceptualization, Writing – original draft. **James E. Byers:** Conceptualization, Writing – original draft, Writing – review & editing. **Jon Calabria:** Conceptualization, Writing – original draft. **Matthew L. Chambers:** Conceptualization, Writing – original draft. **Daniel J. Coleman:** Conceptualization, Writing – original draft. **Katie Foster:** Conceptualization, Writing – original draft. **Aliza Leit:** Conceptualization, Writing – original draft. **Alec Nelson:** Conceptualization, Writing – original draft. **Christopher Streb:** Conceptualization, Writing – original draft. **Burton Suedel:** Conceptualization, Writing – original draft. **Seth J. Wenger:** Conceptualization, Writing – original draft. **C. Brock Woodson:** Conceptualization, Writing – original draft.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Charles B. van Rees reports financial support was provided by NASA. If there are other authors, they 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 data to this article can be found online at https://doi.org/10.1016/j.jenvman.2026.130518.

Data availability

No data was used for the research described in the article.

References

Albert, C., Brillinger, M., Guerrero, P., Gottwald, S., Henze, J., Schmidt, S., Ott, E., Schröter, B., 2021. Planning nature-based solutions: principles, steps, and insights. Ambio 50, 1446–1461. https://doi.org/10.1007/s13280-020-01365-1.

Allen, J.A., 1998. Mangroves as alien species: the case of Hawaii. Global Ecol. Biogeogr. Lett. 7, 61. https://doi.org/10.2307/2997698.

Alonzo, S.H., Kindsvater, H.K., 2008. Life-history patterns. In: Jørgensen, S.E., Fath, B.D. (Eds.), Encyclopedia of Ecology. Academic Press, Oxford, pp. 2175–2180. https://doi.org/10.1016/B978-008045405-4.00856-9.

Alves-Pinto, H., Geldmann, J., Jonas, H., Maioli, V., Balmford, A., Ewa Latawiec, A., Crouzeilles, R., Strassburg, B., 2021. Opportunities and challenges of other effective area-based conservation measures (OECMs) for biodiversity conservation. Perspect. Ecol. Conserv. 19, 115–120. https://doi.org/10.1016/j.pecon.2021.01.004.

Bertness, M.D., Callaway, R., 1994. Positive interactions in communities. Trends Ecol. Evol. 9, 191–193. https://doi.org/10.1016/0169-5347(94)90088-4.

Bouma, J.A., van Beukering, P.J.H. (Eds.), 2015. Ecosystem Services: from Concept to Practice. Cambridge University Press, Cambridge. https://doi.org/10.1017/CBO9781107477612.

Brancalion, P.H.S., Hua, F., Joyce, F.H., Antonelli, A., Holl, K.D., 2025. Moving biodiversity from an afterthought to a key outcome of forest restoration. Nat. Rev. Biodivers. 1, 248–261. https://doi.org/10.1038/s44358-025-00032-1.

Brill, G., Shiao, T., Kammeyer, C., Diringer, S., Vigerstol, K., Ofosu-Ammah, Naabia, Matosich, Michael, Müller-Zantop, Carla, Larson, Wendy, Tim, Dekker, 2021. Benefit Accounting of Nature-based Solutions for Watersheds: Guide United Nations CEO Water Mandate and Pacific Institute. Oakland, California.

Buckley, Y.M., Austin, A., Bardgett, R., Catford, J.A., Hector, A., Iler, A., Mariotte, P., 2024. The plant ecology of nature-based solutions for people, biodiversity and climate. J. Ecol. 112, 2424–2431. https://doi.org/10.1111/1365-2745.14441.

Burgess, N.D., Ali, N., Bedford, J., Bhola, N., Brooks, S., Cierna, A., Correa, R., Harris, M., Hargey, A., Hughes, J., McDermott-Long, O., Miles, L., Ravilious, C., Rodrigues, A.R., Van Soesbergen, A., Sihvonen, H., Seager, A., Swindell, L., Vukelic, M., Durán, A.P., Green, J.M.H., West, C., Weatherdon, L.V., Hawkins, F., Brooks, T.M., Kingston, N., Butchart, S.H.M., 2024. Global metrics for terrestrial biodiversity. Annu. Rev. Environ. Resour. 49, 673–709. https://doi.org/10.1146/annurev-environ-121522-045106.

Burghardt, K.T., Tallamy, D.W., Gregory Shriver, W., 2009. Impact of native plants on bird and butterfly biodiversity in suburban landscapes. Conserv. Biol. 23, 219–224. https://doi.org/10.1111/j.1523-1739.2008.01076.x.

Byers, J.E., 2024. Using ecosystem engineers to enhance multiple ecosystem processes. Funct. Ecol. 38, 22–36. https://doi.org/10.1111/1365-2435.14130.

Callaghan, C.T., Santini, L., Spake, R., Bowler, D.E., 2024. Population abundance estimates in conservation and biodiversity research. Trends Ecol. Evol. 39, 515–523. https://doi.org/10.1016/j.tree.2024.01.012.

Cardinale, B.J., Murdoch, J.D., 2025. Conservation Biology, second ed. Oxford University Press, New York.

Chambers, M.L., van Rees, C.B., Bledsoe, B.P., Crane, D., Ferreira, S., Hall, D.M., Lammers, R.W., Landry, C.E., Nelson, D.R., Shudtz, M., 2023. Nature-based solutions for leveed river corridors. Anthropocene 44, 100417. https://doi.org/10.1016/j.ancene.2023.100417.

Chang, C.C., Turner, B.L., 2019. Ecological succession in a changing world. J. Ecol. 107, 503–509. https://doi.org/10.1111/1365-2745.13132.

Chao, A., Colwell, R.K., 2022. Biodiversity: concepts, dimensions, and measures. In: Loreau, M., Hector, A., Isbell, F. (Eds.), The Ecological and Societal Consequences of Biodiversity Loss. John Wiley & Sons, Ltd, pp. 25–46. https://doi.org/10.1002/9781119902911.ch2.

Chausson, A., Welden, E.A., Melanidis, M.S., Gray, E., Hirons, M., Seddon, N., 2023. Going beyond market-based mechanisms to finance nature-based solutions and foster sustainable futures. PLOS Clim. 2, e0000169. https://doi.org/10.1371/journal.pclm.0000169.

Chen, D., Liao, J., Bearup, D., Li, Z., 2020. Habitat heterogeneity mediates effects of individual variation on spatial species coexistence. Proc. Biol. Sci. 287, 20192436. https://doi.org/10.1098/rspb.2019.2436.

Cohen-Shacham, E., Cabecinha, E., Abdrade, A., 2025. Applying the IUCN global standard for nature-based solutions: 21 case studies from around the globe. https://doi.org/10.2305/RFTD6180.

Cohen-Shacham, E., Walters, G., Janzen, C., Maginnis, S., 2016. Nature-Based Solutions to Address Global Societal Challenges, vol. 97. IUCN, Gland, Switzerland, p. 2036.

Coleman, D.J., Cassalho, F., Miesse, T.W., Ferreira, C.M., 2023. The role of invasive Phragmites australis in wave attenuation in the Eastern United States. Estuaries Coasts 46, 404–416. https://doi.org/10.1007/s12237-022-01138-x.

Comte, L., Grantham, T., Ruhi, A., 2021. Human stabilization of river flows is linked with fish invasions across the USA. Global Ecol. Biogeogr. 30, 725–737. https://doi.org/10.1111/geb.13258.

Convention on Biological Diversity (CBD), 2022. Decision Adopted by the Conference of the Parties to the Convention on Biological Diversity 15/4. Kunming-Montreal Global Biodiversity Framework.

Croeser, T., Bekessy, S.A., Garrard, G.E., Kirk, H., 2024. Nature-based solutions for urban biodiversity: spatial targeting of retrofits can multiply ecological connectivity

benefits. Landsc. Urban Plann. 251, 105169. https://doi.org/10.1016/j.landurbplan.2024.105169.
Crooks, K.R., Sanjayan, M., 2006. Connectivity conservation. Cambridge University Press, UK.
Cuenca-Cambronero, M., Blicharska, M., Perrin, J.-A., Davidson, T.A., Oertli, B., Lago, M., Beklioglu, M., Meerhoff, M., Arim, M., Teixeira, J., De Meester, L., Biggs, J., Robin, J., Martin, B., Greaves, H.M., Sayer, C.D., Lemmens, P., Boix, D., Mehner, T., Bartrons, M., Brucet, S., 2023. Challenges and opportunities in the use of ponds and pondscapes as Nature-based solutions. Hydrobiologia 850, 3257–3271. https://doi.org/10.1007/s10750-023-05149-y.
Djiofack, B.Y., Beeckman, H., Bourland, N., Belanganayi, B.L., Laurent, F., Ilondea, B.A., Nsenga, L., Huart, A., Longwwango, M.M., Deklerck, V., Lejeune, G., Verbiest, W.W. M., Van den Bulcke, J., Van Acker, J., De Mil, T., Hubau, W., 2024. Protecting an artificial savanna as a nature-based solution to restore carbon and biodiversity in the Democratic Republic of the Congo. Glob. Change Biol. 30, e17154. https://doi.org/10.1111/gcb.17154.
Donati, G.F.A., Bolliger, J., Psomas, A., Maurer, M., Bach, P.M., 2022. Reconciling cities with nature: identifying local blue-green infrastructure interventions for regional biodiversity enhancement. J. Environ. Manag. 316, 115254. https://doi.org/10.1016/j.jenvman.2022.115254.
Dondina, O., Tirozzi, P., Viviano, A., Mori, E., Orioli, V., Tommasi, N., Tanzi, A., Bazzoli, L., Caprio, E., Patetta, C., Pastore, M.C., Bani, L., Ancillotto, L., 2025. Spatial and habitat determinants of small-mammal biodiversity in urban green areas: lessons for nature-based solutions. Urban For. Urban Green. 104, 128641. https://doi.org/10.1016/j.ufug.2024.128641.
Dong, X., Ye, Y., Su, D., Haase, D., Lausch, A., 2026. Optimizing urban tree species composition to maximize nature-based solutions. npj Urban Sustain. 6, 47. https://doi.org/10.1038/s42949-026-00361-w.
Dromgold, J.R., Threlfall, C.G., Norton, B.A., Williams, N.S.G., 2020. Green roof and ground-level invertebrate communities are similar and are driven by building height and landscape context. J. Urban Ecol. 6. https://doi.org/10.1093/jue/juz024.
Duellman, W.E., Trueb, L., 1994. Biology of amphibians. JHU press, Baltimore.
Dumitru, A., Wendling, L., 2021. Evaluating the Impact of Nature-based Solutions: a Handbook for Practitioners. European Commission EC.
Dunlop, T., Khojasteh, D., Cohen-Shacham, E., Glamore, W., Haghani, M., van den Bosch, M., Rizzi, D., Greve, P., Felder, S., 2024. The evolution and future of research on Nature-based solutions to address societal challenges. Commun. Earth Environ. 5, 132. https://doi.org/10.1038/s43247-024-01308-8.
Durkin, L., Llyod, J., Zhang, J., Chang, T., Denver, T., Nausėde, M., Pusztai, R., 2024. Nature-Based Solutions (Nbs) Policy Tracker. Arboretica, Rotterdam, Netherlands. https://nature4climate.org/wp-content/uploads/2024/10/NbS_Report_2024NbSTracker_v02_CB-lr.pdf.
European Investment Bank (EIB), 2023. Investing in Nature-based Solutions: State of Play and Way Forward for Public and Private Financial Measures in Europe. Publications, Office, LU.
Faeth, S.H., Bang, C., Saari, S., 2011. Urban biodiversity: patterns and mechanisms. Ann. N. Y. Acad. Sci. 1223, 69–81. https://doi.org/10.1111/j.1749-6632.2010.05925.x.
Filazzola, A., Shrestha, N., MacIvor, J.S., 2019. The contribution of constructed green infrastructure to urban biodiversity: a synthesis and meta-analysis. J. Appl. Ecol. 56, 2131–2143. https://doi.org/10.1111/1365-2664.13475.
Finch, T., Bradbury, R.B., Bradfer-Lawrence, T., Buchanan, G.M., Copping, J.P., Massimino, D., Smith, P., Peach, W.J., Field, R.H., 2023. Spatially targeted nature-based solutions can mitigate climate change and nature loss but require a systems approach. One Earth 6, 1350–1374. https://doi.org/10.1016/j.oneear.2023.09.005.
Fletcher, R.J., Green, R.E., Bladon, E.K., Atkinson, P.W., Phalan, B.T., Williams, D., Visconti, P., Balmford, A., 2025. Beyond species richness for biological conservation. Conserv. Lett. 18, e13124. https://doi.org/10.1111/conl.13124.
Franklin, P.A., Bašić, T., Davison, P.I., Dunkley, K., Ellis, J., Gangal, M., González-Ferreras, A.M., Gutmann Roberts, C., Hunt, G., Joyce, D., Klöcker, C.A., Mawer, R., Rittweg, T., Stoilova, V., Gutowsky, L.F.G., 2024. Aquatic connectivity: challenges and solutions in a changing climate. J. Fish. Biol. 105, 392–411. https://doi.org/10.1111/jfb.15727.
Frantzeskaki, N., Wijsman, K., Kabisch, N., McPhearson, T., 2025. Inter- and transdisciplinary knowledge is critical for nature-based solutions to contribute to just urban transformations. Proc. Natl. Acad. Sci. USA 122, e2315911121. https://doi.org/10.1073/pnas.2315911121.
Fu, B., Wang, S., Su, C., Forsius, M., 2013. Linking ecosystem processes and ecosystem services. Curr. Opin. Environ. Sustain. 5, 4–10. https://doi.org/10.1016/j.cosust.2012.12.002.
Gaynor, K.M., 2024. A big-headed problem drives an ecological chain reaction. Science 383, 370–371. https://doi.org/10.1126/science.adn3484.
Girot, E., Tscheikner-Gratl, F., Curt, C., Taillandier, F., Cherqui, F., 2025. Scattered seeds, missing garden: a critical review of asset management for nature-based stormwater solutions. Blue-Green Systems 7, 558–579. https://doi.org/10.2166/bgs.2025.040.
Gonzalez-Flo, E., Romero, X., García, J., 2023. Nature based-solutions for water reuse: 20 years of performance evaluation of a full-scale constructed wetland system. Ecol. Eng. 188, 106876. https://doi.org/10.1016/j.ecoleng.2022.106876.
Haines-Young, R., Potschin, M., 2010. The links between biodiversity, ecosystem services and human well-being. In: Frid, C.L.J., Raffaelli, D.G. (Eds.), Ecosystem Ecology: a New Synthesis, Ecological Reviews. Cambridge University Press, Cambridge, pp. 110–139. https://doi.org/10.1017/CBO9780511750458.007.
Hall, Damon M., van Rees, Charles B., 2026. Implementing nature-based solutions requires distinguishing place from space. Ambio 55 (8), 1732–1749. https://doi.org/10.1007/s13280-026-02373-3. https://link.springer.com/10.1007/s13280-026-02373-3. (Accessed 26 March 2026).
Hanski, I., 1999. Metapopulation Ecology. Oxford University PressOxford. https://doi.org/10.1093/oso/9780198540663.001.0001.
Hardaway Jr., C.S., 2017. Living shoreline design guidelines for shore protection in Virginia's Estuarine environments. https://doi.org/10.21220/V5CF1N.
He, Jinjie, Owusu-Asumeng, Elrod, Zidar, Kate, Stolper, Julian, Attri, Sudipti, Price, Jacob R., Partridge, Dustin, Montalto, Franco, Sales, Christopher M., 2024. Impacts of a herring gull colony on runoff water quality from an urban green roof. Science of The Total Environment 946, 174430. https://doi.org/10.1016/j.scitotenv.2024.174430. https://linkinghub.elsevier.com/retrieve/pii/S0048969724045789, 174430.
Heidrich, L., Bae, S., Levick, S., Seibold, S., Weisser, W., Krzystek, P., Magdon, P., Nauss, T., Schall, P., Serebryanyk, A., Wöllauer, S., Ammer, C., Bässler, C., Doerfler, I., Fischer, M., Gossner, M.M., Heurich, M., Hothorn, T., Jung, K., Kreft, H., Schulze, E.-D., Simons, N., Thorn, S., Müller, J., 2020. Heterogeneity–diversity relationships differ between and within trophic levels in temperate forests. Nat. Ecol. Evol. 4, 1204–1212. https://doi.org/10.1038/s41559-020-1245-z.
Herath, P., Croke, B., Prinsley, R., Vaze, J., Pollino, C., 2025. A systematic review of forest cover for catchment-scale flood mitigation: a nature-based solution. J. Flood Risk Manag. 18, e70125. https://doi.org/10.1111/jfr3.70125.
Hoegh-Guldberg, F., Visintin, C., Lentini, P., Selinske, M., Bekessy, S., 2024. Where is the nature in nature-based flood management? Biodiversity is not considered enough. Sci. Total Environ. 957, 177698. https://doi.org/10.1016/j.scitotenv.2024.177698.
Hohl, D., Stoycheva, T., Kilgour, R.J., Anderson, E.C., LaMontagne, J.M., 2022. Changes over time in tree cavity availability across urban habitats. SSRN Journal. https://doi.org/10.2139/ssrn.4230172.
Hood, W.G., Blauvelt, K., Bottom, D.L., Castro, J.M., Johnson, G.E., Jones, K.K., Krueger, K.L., Thom, R.M., Wilson, A., 2022. Using landscape ecology principles to prioritize habitat restoration projects across the Columbia River Estuary. Restor. Ecol. 30, e13519. https://repository.library.noaa.gov/view/noaa/63158/.
Hsu, C.-B., Hsieh, H.-L., Yang, L., Wu, S.-H., Chang, J.-S., Hsiao, S.-C., Su, H.-C., Yeh, C.-H., Ho, Y.-S., Lin, H.-J., 2011. Biodiversity of constructed wetlands for wastewater treatment. Ecol. Eng. 37, 1533–1545. https://doi.org/10.1016/j.ecoleng.2011.06.002.
Ibrahim, A., Marshall, K., Carmen, E., Blackstock, K.L., Waylen, K.A., 2025. Raising standards for stakeholder engagement in Nature-based solutions: navigating the why, when, who and how. Environ. Sci. Pol. 163, 103971. https://doi.org/10.1016/j.envsci.2024.103971.
Jambhekar, Ravi, Satish, Ryan, Sharma, Swarnika, Bakhale, Gayatri, Ranganathan, Priya, Naidu, Dilip G.T., Deshpande, Kadambari, Krishnaswamy, Jagdish, 2026. Nature-based solutions and urban biodiversity conservation in the Global South. Ecological Indicators 183, 114627. https://doi.org/10.1016/j.ecolind.2026.114627. https://linkinghub.elsevier.com/retrieve/pii/S1470160X26000233, 114627.
Jochum, M., Fischer, M., Isbell, F., Roscher, C., van der Plas, F., Boch, S., Boenisch, G., Buchmann, N., Catford, J.A., Cavender-Bares, J., Ebeling, A., Eisenhauer, N., Gleixner, G., Hölzel, N., Kattge, J., Klaus, V.H., Kleinebecker, T., Lange, M., Le Provost, G., Meyer, S.T., Molina-Venegas, R., Mommer, L., Oelmann, Y., Penone, C., Prati, D., Reich, P.B., Rindisbacher, A., Schäfer, D., Scheu, S., Schmid, B., Tilman, D., Tscharntke, T., Vogel, A., Wagg, C., Weigelt, A., Weisser, W.W., Wilcke, W., Manning, P., 2020. The results of biodiversity–ecosystem functioning experiments are realistic. Nat. Ecol. Evol. 4, 1485–1494. https://doi.org/10.1038/s41559-020-1280-9.
Johnston, A., Matechou, E., Dennis, E.B., 2023. Outstanding challenges and future directions for biodiversity monitoring using citizen science data. Methods Ecol. Evol. 14, 103–116. https://doi.org/10.1111/2041-210X.13834.
Jones, C.G., Lawton, J.H., Shachak, M., 1994. Organisms as ecosystem engineers. Oikos 69, 373. https://doi.org/10.2307/3545850.
Keesstra, S., Nunes, J., Novara, A., Finger, D., Avelar, D., Kalantari, Z., Cerdà, A., 2018. The superior effect of nature based solutions in land management for enhancing ecosystem services. Sci. Total Environ. 610–611, 997–1009. https://doi.org/10.1016/j.scitotenv.2017.08.077.
Key, I.B., Smith, A.C., Turner, B., Chausson, A., Girardin, C.A.J., Macgillivray, M., Seddon, N., 2022. Biodiversity outcomes of nature-based solutions for climate change adaptation: characterising the evidence base. Front. Environ. Sci. 10. https://doi.org/10.1007/s11356-022-23242-y.
Kühl, H.S., Bowler, D.E., Bösch, L., Bruelheide, H., Dauber, J., Eichenberg, David, Eisenhauer, N., Fernández, N., Guerra, C.A., Henle, K., Herbinger, I., Isaac, N.J.B., Jansen, F., König-Ries, B., Kühn, I., Nilsen, E.B., Pe'er, G., Richter, A., Schulte, R., Settele, J., van Dam, N.M., Voigt, M., Wägele, W.J., Wirth, C., Bonn, A., 2020. Effective biodiversity monitoring needs a culture of integration. One Earth 3, 462–474. https://doi.org/10.1016/j.oneear.2020.09.010.
Kikuchi, W.K., 1976. Prehistoric Hawaiian Fishponds: indigenous aquaculture influenced the development of social stratification in Hawaii. Science 193, 295–299. https://doi.org/10.1126/science.193.4250.295.
Kiss, B., Sekulova, F., Hörschelmann, K., Salk, C.F., Takahashi, W., Wamsler, C., 2022. Citizen participation in the governance of nature-based solutions. Environ. Pol. Govern. 32, 247–272. https://doi.org/10.1002/eet.1987.
Kumar, A., Kumar, G., Saikia, P., Khare, P.K., Khan, M.L., 2022. Spatial pattern of tree diversity and impacts of ecological disturbances on forest structure in tropical deciduous forests of Central India. Biotropica 54, 1363–1375. https://doi.org/10.1111/btp.13068.
Kurth, M.H., Piercy, C.D., Jackson, C.R., Lemasson, B.H., Harris, B.D., 2024. Life cycle management of natural infrastructure: assessment of state of practice and current tools. Front. Built Environ. 9, 1181835. https://doi.org/10.3389/fbuil.2023.1181835.

Law, A., Gaywood, M.J., Jones, K.C., Ramsay, P., Willby, N.J., 2017. Using ecosystem engineers as tools in habitat restoration and rewilding: beaver and wetlands. Sci. Total Environ. 605–606, 1021–1030. https://doi.org/10.1016/j.scitotenv.2017.06.173.

Le Provost, G., Schenk, N.V., Penone, C., Thiele, J., Westphal, C., Allan, E., Ayasse, M., Blüthgen, N., Boeddinghaus, R.S., Boesing, A.L., Bolliger, R., Busch, V., Fischer, M., Gossner, M.M., Hölzel, N., Jung, K., Kandeler, E., Klaus, V.H., Kleinebecker, T., Leimer, S., Marhan, S., Morris, K., Müller, S., Neff, F., Neyret, M., Oelmann, Y., Perović, D.J., Peter, S., Prati, D., Rillig, M.C., Saiz, H., Schäfer, D., Scherer-Lorenzen, M., Schloter, M., Schöning, I., Schrumpf, M., Steckel, J., Steffan-Dewenter, I., Tschapka, M., Vogt, J., Weiner, C., Weisser, W., Wells, K., Werner, M., Wilcke, W., Manning, P., 2023. The supply of multiple ecosystem services requires biodiversity across spatial scales. Nat. Ecol. Evol. 7, 236–249. https://doi.org/10.1038/s41559-022-01918-5.

Leandro, C., Jay-Robert, P., Pétillon, J., 2024. eDNA for monitoring and conserving terrestrial arthropods: insights from a systematic map and barcode repositories assessments. Insect Conserv. Diversity 17, 565–578. https://doi.org/10.1111/icad.12726.

Liu, B., Wang, C., Liu, D., Xiong, C., Yang, X., Xu, C., 2025. Research on the suitability and resilience enhancement of coastal development based on the "three-living spaces.". Mar. Environ. Res. 211, 107367. https://doi.org/10.1016/j.marenvres.2025.107367.

Lizée, M.-H., Manel, S., Mauffrey, J.-F., Tatoni, T., Deschamps-Cottin, M., 2012. Matrix configuration and patch isolation influences override the species–area relationship for urban butterfly communities. Landscape Ecol 27, 159–169. https://doi.org/10.1007/s10980-011-9651-x.

Lovelock, C.E., Bennion, V., de Oliveira, M., Hagger, V., Hill, J.W., Kwan, V., Pearse, A.L., Rossini, R.A., Twomey, A.J., 2024. Mangrove ecology guiding the use of mangroves as nature-based solutions. J. Ecol. 112, 2510–2521. https://doi.org/10.1111/1365-2745.14383.

Lyytimäki, J., Sipilä, M., 2009. Hopping on one leg – the challenge of ecosystem disservices for urban green management. Urban For. Urban Green. 8, 309–315. https://doi.org/10.1016/j.ufug.2009.09.003.

MacDougall, A.S., Turkington, R., 2005. Are invasive species the drivers of passengers of change in degraded ecosystems? Ecology 86, 42–55. https://doi.org/10.1890/04-0669.

Mahecha, M.D., Bastos, A., Bohn, F.J., Eisenhauer, N., Feilhauer, H., Hickler, T., Kalesse-Los, H., Migliavacca, M., Otto, F.E.L., Peng, J., Sippel, S., Tegen, I., Weigelt, A., Wendisch, M., Wirth, C., Al-Halbouni, D., Deneke, H., Doktor, D., Dunker, S., Duveiller, G., Ehrlich, A., Foth, A., García-García, A., Guerra, C.A., Guimarães-Steinicke, C., Hartmann, H., Henning, S., Herrmann, H., Hu, P., Ji, C., Kattenborn, T., Kolleck, N., Kretschmer, M., Kühn, I., Luttkus, M.L., Maahn, M., Mönks, M., Mora, K., Pöhlker, M., Reichstein, M., Rüger, N., Sánchez-Parra, B., Schäfer, M., Stratmann, F., Tesche, M., Wehner, B., Wieneke, S., Winkler, A.J., Wolf, S., Zaehle, S., Zscheischler, J., Quaas, J., 2024. Biodiversity and climate extremes: known interactions and research gaps. Earths Future 12. https://doi.org/10.1029/2023EF003963.

Martin, J.G.C., Scolobig, A., Linnerooth-Bayer, J., Irshaid, J., Aguilera Rodriguez, J.J., Fresolone-Caparrós, A., Oen, A., 2025. The nature-based solution implementation gap: a review of nature-based solution governance barriers and enablers. J. Environ. Manag. 388, 126007. https://doi.org/10.1016/j.jenvman.2025.126007.

Martín-Vélez, V., Navarro, J., Figuerola, J., Aymí, R., Sabaté, S., Planell, R., Vila, J., Montalvo, T., 2024. A spatial analysis of urban gulls contribution to the potential spread of zoonotic and antibiotic-resistant bacteria. Sci. Total Environ. 912, 168762. https://doi.org/10.1016/j.scitotenv.2023.168762.

Matthews, T.J., Triantis, K.A., Whittaker, R.J., 2020. The species-area relationship: both general and protean? In: Matthews, T.J., Triantis, K.A., Whittaker, R.J. (Eds.), The Species-Area Relationship: Theory and Application. Cambridge University Press, Cambridge, UK, pp. 3–19.

McCormick, M.K., Whigham, D.F., Stapp, J.R., Hazelton, E.L.G., McFarland, E.K., Kettenring, K.M., 2020. Shoreline modification affects recruitment of invasive Phragmites australis. Wetl. Ecol. Manag. 28, 909–919. https://doi.org/10.1007/s11273-020-09757-6.

McKay, S.K., Wenger, S.J., Van Rees, C.B., Bledsoe, B.P., Bridges, T.S., 2023. Jointly advancing infrastructure and biodiversity conservation. Nat. Rev. Earth Environ. 4, 675–677. https://doi.org/10.1038/s43017-023-00484-z.

McMichael, C.N.H., Bush, M.B., Jiménez, J.C., Gosling, W.D., 2023. Past human-induced ecological legacies as a driver of modern Amazonian resilience. People Nat. 5, 1415–1429. https://doi.org/10.1002/pan3.10510.

McPhearson, T., Frantzeskaki, N., Ossola, A., Diep, L., Anderson, P.M.L., Blatch, T., Collier, M.J., Cook, E.M., Culwick Fatti, C., Grabowski, Z.J., Grimm, N.B., Haase, D., Herreros-Cantis, P., Kavonic, J., Lin, B.B., Lopez Meneses, D.H., Matsler, A.M., Moglia, M., Morató, J., O'Farrell, P., Roy, P., Singh, C., Wang, J., Zhou, W., 2025. Global synthesis and regional insights for mainstreaming urban nature-based solutions. Proc. Natl. Acad. Sci. USA 122, e2315910121. https://doi.org/10.1073/pnas.2315910121.

McRae, B., Popper, K., Jones, A., Schindel, M., Buttrick, S., Hall, K., Unnasch, R.S., Platt, J., 2016. Conserving nature's stage: mapping omnidirectional connectivity for resilient terrestrial landscapes in the Pacific Northwest. https://doi.org/10.13140/RG.2.1.4158.6166.

Michael, D.R., Bino, G., Conallin, A., Maguire, J., Wassens, S., 2023. Pump my wetland: potential benefits of using water pumps fitted with large-mesh screens to conserve anurans in regulated floodplain environments. Mar. Freshw. Res. 74, 1445–1454. https://doi.org/10.1071/MF23158.

Miralles-Wilhelm, F., 2023. Nature-based solutions in agricultural landscapes for reducing tradeoffs between food production, climate change, and conservation objectives. Front. Water 5, 1247322. https://doi.org/10.3389/frwa.2023.1247322.

Mohd Nazir, N.Z., Lee, K.E., Ab Rahim, A.R., Goh, T.L., Mokhtar, M., Rahim Wan Abdullah, W.A., Husain, H., Raja Mamat, R.B., 2025. Delineating the fundamental attributes and traits of nature-based solutions in wastewater management. J. Environ. Manag. 380, 124811. https://doi.org/10.1016/j.jenvman.2025.124811.

Mori, A.S., Dee, L.E., Gonzalez, A., Ohashi, H., Cowles, J., Wright, A.J., Loreau, M., Hautier, Y., Newbold, T., Reich, P.B., Matsui, T., Takeuchi, W., Okada, K., Seidl, R., Isbell, F., 2021. Biodiversity–productivity relationships are key to nature-based climate solutions. Nat. Clim. Change 11, 543–550. https://doi.org/10.1038/s41558-021-01062-1.

Moustakas, A., Daliakopoulos, I.N., Benton, T.G., 2019. Data-driven competitive facilitative tree interactions and their implications on nature-based solutions. Sci. Total Environ. 651, 2269–2280. https://doi.org/10.1016/j.scitotenv.2018.09.349.

Muthukrishnan, Ranjan, Chiquillo, Kelcie L., Cross, Candice, Fong, Peggy, Kelley, Thomas, Toline, C. Anna, Zweng, Regina, Willette, Demian A., 2020. Little giants: a rapidly invading seagrass alters ecosystem functioning relative to native foundation species. Marine Biology 167 (6), 81. https://doi.org/10.1007/s00227-020-03689-8. https://link.springer.com/10.1007/s00227-020-03689-8. (Accessed 19 May 2020).

Nakamura, F., Ishiyama, N., Yamanaka, S., Higa, M., Akasaka, T., Kobayashi, Y., Ono, S., Fuke, N., Kitazawa, M., Morimoto, J., Shoji, Y., 2020. Adaptation to climate change and conservation of biodiversity using green infrastructure. River Res. Appl. 36, 921–933. https://doi.org/10.1002/rra.3576.

Narango, D.L., Tallamy, D.W., Marra, P.P., 2017. Native plants improve breeding and foraging habitat for an insectivorous bird. Biol. Conserv. 213, 42–50. https://doi.org/10.1016/j.biocon.2017.06.029.

Nelson, D.R., Bledsoe, B.P., Ferreira, S., Nibbelink, N.P., 2020. Challenges to realizing the potential of nature-based solutions. Curr. Opin. Environ. Sustain. 45, 49–55. https://doi.org/10.1016/j.cosust.2020.09.001.

Nelson, M.K., Reed, G., 2025. Indigenous critiques and recommendations for reclaiming nature-based solutions. Proc. Natl. Acad. Sci. USA 122, e2315917121. https://doi.org/10.1073/pnas.2315917121.

Neumann, V.A., Hack, J., 2022. Revealing and assessing the costs and benefits of nature-based solutions within a real-world laboratory in Costa Rica. Environ. Impact Assess. Rev. 93, 106737. https://doi.org/10.1016/j.eiar.2022.106737.

O'Brien, C.M., Mossman, M., Chamberlain, L., Jenkins, J., Watson, J., Wilson, R., Williams-Clark, D., Singer, A., Riggio, K., Gallet, D., Miller, W.M., Packman, A.I., 2024. Community-centered instrumentation and monitoring of nature-based solutions for urban stormwater control. Front. Water 6, 2024.

Obura, D.O., DeClerck, F., Verburg, P.H., Gupta, J., Abrams, J.F., Bai, X., Bunn, S., Ebi, K. L., Gifford, L., Gordon, C., Jacobson, L., Lenton, T.M., Liverman, D., Mohamed, A., Prodani, K., Rocha, J.C., Rockström, J., Sakschewski, B., Stewart-Koster, B., van Vuuren, D., Winkelmann, R., Zimm, C., 2023. Achieving a nature- and people-positive future. One Earth 6, 105–117. https://doi.org/10.1016/j.oneear.2022.11.013.

Palmer, M.A., Menninger, H.L., Bernhardt, E., 2010. River restoration, habitat heterogeneity and biodiversity: a failure of theory or practice? Freshw. Biol. 55, 205–222. https://doi.org/10.1111/j.1365-2427.2009.02372.x.

Parajuli, R., Dixon, M., Blalock, A., Fowler, A., Sigdel, S., Magnuson, K., Wenger, S., Suedel, B., Crane, D., van Rees, C.B., 2026. A global systematic review of the effects of hydromorphological floodplain restoration on biodiversity. J. Appl. Ecol. 63, e70485. https://doi.org/10.1111/1365-2664.70485.

Parajuli, R., O'Brien, M.J., Timilsina, B., Pugnaire, F.I., Schöb, C., Ghimire, S.K., 2021. Facilitation by a dwarf shrub enhances plant diversity of human-valued species at high elevations in the Himalayas of Nepal. Basic Appl. Ecol. 54, 23–36. https://doi.org/10.1016/j.baae.2021.04.004.

Pearlmutter, D., Pucher, B., Calheiros, C.S.C., Hoffmann, K.A., Aicher, A., Pinho, P., Stracqualursi, A., Korolova, A., Pobric, A., Galvão, A., Tokuç, A., Bas, B., Theochari, D., Milosevic, D., Giancola, E., Bertino, G., Castellar, J.A.C., Flaszynska, J., Onur, M., Mateo, M.C.G., Andreucci, M.B., Milousi, M., Fonseca, M., Lonardo, S.D., Gezik, V., Pitha, U., Nehls, T., 2021. Closing water cycles in the built environment through nature-based solutions: the contribution of vertical greening systems and green roofs. Water 13, 2165. https://doi.org/10.3390/w13162165.

Penning, E., Peñailillo Burgos, R., Mens, M., Dahm, R., de Bruijn, K., 2023. Nature-based solutions for floods AND droughts AND biodiversity: do we have sufficient proof of their functioning? Cambridge Prisms. Water 1, e11. https://doi.org/10.1017/wat.2023.12.

Pinnell, C.M., Ayala, G.S., Patten, M.V., Boyer, K.E., 2021. Seagrass and oyster Reef restoration in living shorelines: effects of habitat configuration on invertebrate community assembly. Diversity 13, 246. https://doi.org/10.3390/d13060246.

Potgieter, L.J., Cadotte, M.W., Dong, X., Midgley, G.F., Richardson, D.M., 2026. Nature-based solutions: a double-edged sword for biological invasions? Trends Ecol. Evol. 41, 638–650. https://doi.org/10.1016/j.tree.2026.04.006.

Préau, C., Tournebize, J., Lenormand, M., Alleaume, S., Boussada, V.G., Luque, S., 2022. Habitat connectivity in agricultural landscapes improving multi-functionality of constructed wetlands as nature-based solutions. Ecol. Eng. 182, 106725. https://doi.org/10.1016/j.ecoleng.2022.106725.

Prodanovic, V., Bach, P.M., Stojkovic, M., 2024. Urban nature-based solutions planning for biodiversity outcomes: human, ecological, and artificial intelligence perspectives. Urban Ecosyst. 27, 1795–1806. https://doi.org/10.1007/s11252-024-01558-6.

Rafferty, N.E., Cosma, C.T., 2024. Sustainable nature-based solutions require establishment and maintenance of keystone plant-pollinator interactions. J. Ecol. 112, 2432–2441. https://doi.org/10.1111/1365-2745.14353.

Ramachandran, A., Dee, L., Hayden, M., Suding, K., 2024. Leveraging plant functional traits in the design of nature-based solutions: a research agenda. J. Ecol. 112, 2492–2501. https://doi.org/10.1111/1365-2745.14371.

Reed, J.M., Mills, L.S., Dunning Jr., J.B., Menges, E.S., McKelvey, K.S., Frye, R., Beissinger, S.R., Anstett, M.-C., Miller, P., 2002. Emerging issues in population viability analysis. Conserv. Biol. 16, 7–19. https://doi.org/10.1046/j.1523-1739.2002.99419.x.

Reed, J.M., Wolfe, B.E., Romero, L.M., 2024. Is resilience a unifying concept for the biological sciences? iScience 27. https://doi.org/10.1016/j.isci.2024.109478.

Ricketts, T.H., 2001. The matrix matters: effective isolation in fragmented landscapes. Am. Nat. 158, 87–99. https://doi.org/10.1086/320863.

Ross, S.R.P.-J., O'Connell, D.P., Deichmann, J.L., Desjonquères, C., Gasc, A., Phillips, J. N., Sethi, S.S., Wood, C.M., Burivalova, Z., 2023. Passive acoustic monitoring provides a fresh perspective on fundamental ecological questions. Funct. Ecol. 37, 959–975. https://doi.org/10.1111/1365-2435.14275.

Rupasinghe, Madhuwanthi, Nicolas, Rackel San, Lanham, Brendan S., Morris, Rebecca L., 2024. Sustainable oyster shell incorporated artificial reef concrete for living shorelines. Construction and Building Materials 410, 134217. https://doi.org/10.1016/j.conbuildmat.2023.134217. https://linkinghub.elsevier.com/retrieve/pii/S0950061823039351, 134217.

Salvo-Tierra, Á.E., Ruiz-Valero, Á., 2025. Why urban greening requires more than just species biodiversity. Academia.Environ. Sci.Sustain. 2. https://doi.org/10.20935/AcadEnvSci7981.

Sanders, T., Solan, M., Godbold, J.A., 2024. Trait-mediated processes and per capita contributions to ecosystem functioning depend on conspecific density and climate conditions. Commun. Earth Environ. 5, 79. https://doi.org/10.1038/s43247-024-01237-6.

Sangha, K.K., Ahammad, R., Russell-Smith, J., Woolley, L.-A., 2025. A nature-based solutions assessment framework integrating indigenous biocultural and ecosystem services perspectives: an Australian example. Ecol. Indic. 172, 113230. https://doi.org/10.1016/j.ecolind.2025.113230.

Santini, N.S., Miquelajauregui, Y., 2022. The restoration of degraded lands by local communities and Indigenous Peoples. Front. Conserv. Sci. 3, 873659. https://doi.org/10.3389/fcosc.2022.873659.

Scarlett, Lynn, McKinney, Matthew, 2016. Connecting people and places: the emerging role of network governance in large landscape conservation. Frontiers in Ecology and the Environment 14 (3), 116–125. https://doi.org/10.1002/fee.1247. https://esajournals.onlinelibrary.wiley.com/doi/10.1002/fee.1247. (Accessed 4 April 2016).

Schmeller, D.S., Böhm, M., Arvanitidis, C., Barber-Meyer, S., Brummitt, N., Chandler, M., Chatzinikolaou, E., Costello, M.J., Ding, H., García-Moreno, J., Gill, M., Haase, P., Jones, M., Juillard, R., Magnusson, W.E., Martin, C.S., McGeoch, M., Mihoub, J.-B., Pettorelli, N., Proença, V., Peng, C., Regan, E., Schmiedel, U., Simaika, J.P., Weatherdon, L., Waterman, C., Xu, H., Belnap, J., 2017. Building capacity in biodiversity monitoring at the global scale. Biodivers. Conserv. 26, 2765–2790. https://doi.org/10.1007/s10531-017-1388-7.

Seddon, N., 2022. Harnessing the potential of nature-based solutions for mitigating and adapting to climate change. Science 376, 1410–1416. https://doi.org/10.1126/science.abn9668.

Seddon, N., Smith, A., Smith, P., Key, I., Chausson, A., Girardin, C., House, J., Srivastava, S., Turner, B., 2021. Getting the message right on nature-based solutions to climate change. Glob. Change Biol. 27, 1518–1546. https://doi.org/10.1111/gcb.15513.

Shaffer, M.L., 1981. Minimum population sizes for species conservation. Bioscience 31, 131–134. https://doi.org/10.2307/1308256.

Sharafatmandrad, M., Khosravi Mashizi, A., 2021. Ecological succession regulates the relationship between biodiversity and supporting services in arid ecosystems. Arabian J. Geosci. 14, 1370. https://doi.org/10.1007/s12517-021-07796-8.

Shchipanov, N.A., Kalinin, A.A., 2024. The Role of Biodiversity in Ensuring the Functioning of Ecosystems: Paper 2. Small Mammals in the Ecological Monitoring System: Obtaining Data and Assessment of the Diversity, State, and Dynamics of Ecosystems. Biology Bulletin 51 (2), 443–462. https://doi.org/10.1134/s106235902360530x. https://link.springer.com/10.1134/S106235902360530X. (Accessed 2 April 2024).

Shields, F.D., Knight, S.S., 2013. Floodplain restoration with flood control: fish habitat value of levee borrow pits. Ecol. Eng. 53, 217–227. https://doi.org/10.1016/j.ecoleng.2012.12.046.

Sievers, M., Parris, K.M., Swearer, S.E., Hale, R., 2018. Stormwater wetlands can function as ecological traps for urban frogs. Ecol. Appl. 28, 1106–1115. https://doi.org/10.1002/eap.1714.

Silliman, B.R., Hensel, M.J., Gibert, J.P., Daleo, P., Smith, C.S., Wieczynski, D.J., Angelini, C., Paxton, A.B., Adler, A.M., Zhang, Y.S., 2024. Harnessing ecological theory to enhance ecosystem restoration. Curr. Biol. 34, R418–R434. https://doi.org/10.1016/j.cub.2024.03.043.

Slinger, J.H., Cunningham, S.C., Kothuis, B.L.M., 2023. A co-design method for including stakeholder perspectives in nature-based flood risk management. Nat. Hazards 119, 1171–1191. https://doi.org/10.1007/s11069-023-06139-y.

Socolar, J.B., Gilroy, J.J., Kunin, W.E., Edwards, D.P., 2016. How should beta-diversity inform biodiversity conservation? Trends Ecol. Evol. 31, 67–80. https://doi.org/10.1016/j.tree.2015.11.005.

Sotka, E.E., Byers, J.E., 2019. Not so fast: promoting invasive species to enhance multifunctionality in a native ecosystem requires strong(er) scrutiny. Biol. Invasions 21, 19–25. https://doi.org/10.1007/s10530-018-1822-0.

Stammel, B., Jähnig, S.C., Mehl, D., Pusch, M., Srđević, Z., Tschikof, M., Wulf, S., Scholz, M., 2026. Assessing ecosystem services across scales to support nature-based solutions in river floodplains: a review of non-monetary tools. NC 62, 95–119. https://doi.org/10.3897/natureconservation.62.148716.

Standish, R.J., Parkhurst, T., 2024. Interventions for resilient nature-based solutions: an ecological perspective. J. Ecol. 112, 2502–2509. https://doi.org/10.1111/1365-2745.14377.

Steigerwald, E., Chen, J., Oshiro, J., Vredenburg, V.T., Catenazzi, A., Koo, M.S., 2024. Microreserves are an important tool for amphibian conservation. Commun. Biol. 7, 1177. https://doi.org/10.1038/s42003-024-06510-0.

Stephens, P.A., Sutherland, W.J., Freckleton, R.P., 1999. What is the allee effect? Oikos 87, 185. https://doi.org/10.2307/3547011.

Suedel, B.C., Calabria, J., Bilskie, M.V., Byers, J.E., Broich, K., McKay, S.K., Tritinger, A. S., Woodson, C.B., Dolatowski, E., 2022. Engineering coastal structures to centrally embrace biodiversity. J. Environ. Manag. 323, 116138. https://doi.org/10.1016/j.jenvman.2022.116138.

Thompson, A., Bunds, K., Larson, L., Cutts, B., Hipp, J.A., 2023. Paying for nature-based solutions: a review of funding and financing mechanisms for ecosystem services and their impacts on social equity. Sustain. Dev. 31, 1991–2066. https://doi.org/10.1002/sd.2510.

Tortosa, A., Giffard, B., Sirami, C., Larrieu, L., Ladet, S., Vialatte, A., 2023. Increasing landscape heterogeneity as a win–win solution to manage trade-offs in biological control of crop and woodland pests. Sci. Rep. 13, 13573. https://doi.org/10.1038/s41598-023-40473-2.

van der Plas, F., 2019. Biodiversity and ecosystem functioning in naturally assembled communities. Biol. Rev. 94, 1220–1245. https://doi.org/10.1111/brv.12499.

van Rees, C.B., Aragonés, D., Bouten, W., Thaxter, C.B., Stienen, E.W.M., Bustamante, J., Green, A.J., 2021. Dynamic space use of Andalusian rice fields by lesser Black-backed Gulls (Larus fuscus) is driven by flooding pattern. Ibis 163, 1252–1270. https://doi.org/10.1111/ibi.12968.

van Rees, C.B., Chambers, M.L., Catalano, A.J., Buhr, D.X., Mansur, A.V., Hall, D.M., Nelson, A., Suedel, B., Hawley, R.J., Bledsoe, B., Nibbelink, N., 2024. An interdisciplinary overview of levee setback benefits: supporting spatial planning and implementation of riverine nature-based solutions. WIREs Water 11, e1750. https://doi.org/10.1002/wat2.1750.

van Rees, C.B., Jumani, S., Abera, L., Rack, L., McKay, S.K., Wenger, S.J., 2023. The potential for nature-based solutions to combat the freshwater biodiversity crisis. PLOS Water 2, e0000126. https://doi.org/10.1371/journal.pwat.0000126.

van Rees, C.B., Jumani, S., Chaudhary, V., German, L.A., Dekker, T., McKay, S.K., Wenger, S.J., 2026. Guideposts and guardrails for biodiversity accounting in the 21st century. Biol. Conserv. 313, 111527. https://doi.org/10.1016/j.biocon.2025.111527.

van Rees, C.B., Naslund, L., Hernandez-Abrams, D.D., McKay, S.K., Woodson, C.B., Rosemond, A., McFall, B., Altman, S., Wenger, S.J., 2022. A strategic monitoring approach for learning to improve natural infrastructure. Sci. Total Environ. 832, 155078. https://doi.org/10.1016/j.scitotenv.2022.155078.

van Rees, C.B., Reed, J.M., Wilson, R.E., Underwood, J.G., Sonsthagen, S.A., 2018. Landscape genetics identifies streams and drainage infrastructure as dispersal corridors for an endangered wetland bird. Ecol. Evol. 8, 8328–8343. https://doi.org/10.1002/ece3.4296.

Vasiliev, Denis, Greenwood, Sarah, 2022. Making green pledges support biodiversity: Nature-based solution design can be informed by landscape ecology principles. Land Use Policy 117, 106129. https://doi.org/10.1016/j.landusepol.2022.106129. https://linkinghub.elsevier.com/retrieve/pii/S0264837722001569, 106129.

Vukomanovic, J., Smart, L.S., Koch, J., Dale, V.H., Plassin, S., Byrd, K.B., Beier, C., Wilson, M., Doyon, F., 2023. Translating stakeholder narratives for participatory modeling in landscape ecology. Landsc. Ecol. 38, 2453–2474. https://doi.org/10.1007/s10980-023-01724-9.

Warnell, K., Mason, S., Siegle, A., Meritt, M., Olander, L., 2023. Department of the Interior Nature-based Solutions Roadmap. Durham, NC. https://www.doi.gov/sites/doi.gov/files/doi-nbs-roadmap.pdf.

Warner, E., Giuliani, L.M., Campbell, G.A., Smith, P., Seddon, N., Seddon, D., Smith, A. C., 2025. Integrated above- and below-ground ecological monitoring for nature-based solutions. Ecol. Solut. Evid. 6, e70043. https://doi.org/10.1002/2688-8319.70043.

Wauchope, H.S., Zu Ermgassen, S.O.S.E., Jones, J.P.G., Carter, H., Schulte To Bühne, H., Milner-Gulland, E.J., 2024. What is a unit of nature? Measurement challenges in the emerging biodiversity credit market. Proc. R. Soc. A B 291, 20242353. https://doi.org/10.1098/rspb.2024.2353.

Weiskopf, S.R., Myers, B.J.E., Arce-Plata, M.I., Blanchard, J.L., Ferrier, S., Fulton, E.A., Harfoot, M., Isbell, F., Johnson, J.A., Mori, A.S., Weng, E., HarmáČková, Z.V., Londoño-Murcia, M.C., Miller, B.W., Pereira, L.M., Rosa, I.M.D., 2022. A conceptual framework to integrate biodiversity, ecosystem function, and ecosystem service models. Bioscience 72, 1062–1073. https://doi.org/10.1093/biosci/biac074.

Wild, T., Rochelle, A.L., Evans, K., 2026. Invertebrate biodiversity is greater in urban sites with nature-based solutions than control sites: a cross-continental study. Urban For. Urban Green., 129368 https://doi.org/10.1016/j.ufug.2026.129368.

Willmer, J.N.G., Püttker, T., Prevedello, J.A., 2022. Global impacts of edge effects on species richness. Biol. Conserv. 272, 109654. https://doi.org/10.1016/j.biocon.2022.109654.

Wong, C.P., Jiang, B., Kinzig, A.P., Lee, K.N., Ouyang, Z., 2015. Linking ecosystem characteristics to final ecosystem services for public policy. Ecol. Lett. 18, 108–118. https://doi.org/10.1111/ele.12389.

Xie, L., Bulkeley, H., 2020. Nature-based solutions for urban biodiversity governance. Environ. Sci. Pol. 110, 77–87. https://doi.org/10.1016/j.envsci.2020.04.002.

Yeakel, J.D., Pires, M.M., De Aguiar, M.A.M., O'Donnell, J.L., Guimarães, P.R., Gravel, D., Gross, T., 2020. Diverse interactions and ecosystem engineering can stabilize community assembly. Nat. Commun. 11, 3307. https://doi.org/10.1038/s41467-020-17164-x.

Zhang, C., Wen, L., Wang, Y., Liu, C., Zhou, Y., Lei, G., 2020. Can constructed wetlands be wildlife refuges? A review of their potential biodiversity conservation value. Sustainability 12, 1442. https://doi.org/10.3390/su12041442.

Zhou, T., Reich, P.B., Pang, X., Tan, C., Zhou, G., Zhou, Z., Delgado-Baquerizo, M., 2025. Tree Evenness Sustains Multiple Ecosystem Services in boreal–temperate Ecotone. New Phytologist Online Early Access. https://doi.org/10.1111/nph.70771.

Zu Ermgassen, S.O.S.E., Löfqvist, S., 2024. Financing ecosystem restoration. Curr. Biol. 34, R412–R417. https://doi.org/10.1016/j.cub.2024.02.031.