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Nature-Based Solutions for Climate Resilient Urban Development: An Integrative Evidence Synthesis and Implementation Framework

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Abstract
Nature-based solutions (NBS) are increasingly viewed as a focal point in the implementation of climate-resilient cities, as they can be both an effective way to mitigate climate hazards and provide biodiversity, health, social and economic co-benefits. However, literature on urban NBS is scattered and is still divided between the concepts of green infrastructure, sustainable drainage, urban ecology, resilience planning, ecosystem services and environmental justice. This paper presents an integrative evidence synthesis of 60 DOI-bearing peer-reviewed studies from 2006 to 2025, and a practical framework for scaling up NBS from individual projects to the mainstream of urban infrastructure. The review categorizes each study by primary theme and considers evidence on various topics related to heat mitigation, storm water and flood management, ecosystem-service delivery, governance, monitoring, equity and scaling. The results reveal that since 2016, evidence has significantly increased with a shift from technology-specific performance questions to governance, justice, evaluation and transformative adaptation questions. The best and most complete evidence is for storm water control, urban cooling and multifunctional ecosystem services, whereas the most common gaps are in the length of monitoring period, the use of various measures, a lack of maintenance and life-cycle information, and geographic variability. A key result is that NBS performance is not solely dependent on ecological design; land availability, institutional co-ordination, finance, long term stewardship, social legitimacy and explicit equity protections are all important for successful NBS outcomes. The authors suggest an integrated planning framework combining the diagnosis of climate risks, the designing of climate-resilient portfolios, the co-benefit valuation, the co-production process, the financing process, the implementation process, monitoring and adaptive scaling. In other words, the message for cities looking to be resilient is that NBS is not about discretionary 'greening', but rather a multifunctional urban infrastructure component with measurable service levels. This reframing can help make NBS more reliable, legitimate and scalable; and less open to negative side-effects of maladaptation and green gentrification.

Keywords: nature-based solutions; urban resilience; climate adaptation; green infrastructure; blue-green infrastructure; ecosystem services; environmental justice; sustainable urban development

1. Introduction

Cities are places where people, assets, infrastructure and economic activity are clustered, but they are also a place of concentration of climate exposure. Impervious surfaces and lack of vegetation exacerbate heat waves, heavy rain overwhelms drainage systems, riverine and coastal flooding affect high-density populations, drought stresses water and vegetation resources, and compound events impact transport, energy and public health simultaneously. Solutions to these challenges have typically been formulated in the context of single-purpose engineering solutions – storm water is conveyed through pipes, floodwater through concrete channels, thermal stress through mechanical cooling, and water is made to stop by hard coastal structures. Although these systems are irreplaceable, they sometimes are limited in performance by design threshold boundaries, steep capital and maintenance expenses, limited space, and unknown performance under future climate conditions. The concept of a "safe-to-fail" system, however, has come in to the forefront of the resilience literature as a more diverse range of paths, a more distributed capacity, and a greater retention of adaptive flexibility are increasingly focused on, rather than fail-safe protection (Ahern, 2011; meerow et al., 2016).

In this context, interventions to protect, restore, manage or create ecosystems that respond to societal challenges and provide ecological and social benefits, are known as NBS. In urban settings, it's a very broad category that includes urban forests, street trees, parks, wetlands, restored streams, floodplains, green roofs and green walls, bios wales, rain gardens, permeable landscapes, constructed wetlands and blue-green corridors. The concept is related to the concepts of green infrastructure, blue-green infrastructure, sustainable urban drainage systems (SUDS), water-sensitive urban design, low-impact development (LID) and ecosystem-based adaptation (Fletcher et al., 2015; Hanson et al., 2020; Sowińska-Świerkosz & García, 2022). This terminological multiplicity has been used in the present paper to indicate rather a shift in the way city infrastructure is thought. Natural processes are now perceived as service-producing infrastructure which can be supplemented by the classical grey systems.

The motivation for this change is quite compelling, and is based on empirical evidence. Shading and evapotranspiration effects can lower surface and air temperatures in urban environments but the effectiveness of these effects depends on the type of vegetation, the scale, urban morphology and climatic conditions (Bowler et al., 2010; Gunawardena et al., 2017; Norton et al., 2015; Ziter et al., 2019). Rainfall can be captured by green roofs, rain gardens, vegetated swales and urban trees which can delay runoff, promote infiltration and reduce peak flows (Ahiablame et al., 2012; Berland et al., 2017; Carter & Jackson, 2007; Mentens et al., 2006). Parks, wetlands, floodplains and green-blue networks can serve multiple functions at larger scales (e.g., storage, cooling, habitat and recreation services) (Elmqvist et al., 2015; Hansen & Pauleit, 2014; Andersson et al., 2014). This multifunctionality sets NbS apart from most traditional investments, as a single action can help to address climate adaptation, community health, biodiversity, amenity, air-quality and place quality.

But it is not a given that multifunctionality will happen. A green roof that is not designed to have enough maintenance and/or substrate, may not provide a hydrologic benefit. Unsuitable species, rooting volume or future heat can result in an under-performing tree plantation. Access, safety, and/or community needs can be poorly met in a floodable park if it does not provide storage. A top-down project could even lead to an increase in property values and gentrification pressures, known as "green or climate gentrification" (Anguelovski et al., 2019; Wolch et al., 2014). The modern literature is therefore increasingly rejecting some simple notions that "more green" equates to "more resilience. Instead, the nature of the NBS, the place of NBS and their governance and distribution have a strong influence on their potential to either mitigate or exacerbate vulnerability (Kabisch & Haase, 2014; Keeler et al., 2019; Sekulova et al., 2021).

The second challenge is institutional. NBS often span multiple departments, as the benefits of NBS are used across multiple agencies, such as storm water, parks and recreation, transport, planning, health, utilities, and communities. However, in most cities, city budgeting and rule-making are done sector-wise.

The consequence is a lack of integration of multifunctional benefits and decision structures for a single purpose. The lack of coordination and governance, unclear ownership, limited technical knowledge, lack of funding for maintenance, short political cycles, and poor monitoring systems are all factors that have been identified in different studies as barriers to scaling NBS implementation (Frantzeskaki, 2019; Frantzeskaki et al., 2020; Malekpour et al., 2021; Sarabi et al., 2019, 2020). Technical quality can be adequate, but the intervention may fail to be durable infrastructure if it's unclear who is responsible, who will pay for it over time, or how it will be maintained.

The third challenge is that of evidence and evaluation. The field has grown in size very quickly and indicators and methods are not consistent. Studies vary in their measure of biophysical performance (e.g., runoff reduction, temperature change, habitat quality), perceptions (e.g., social justice, governance), co-benefits (e.g., ecosystem services or livelihoods), or social justice (e.g., equity or social justice). Strong and multidimensional monitoring frameworks are needed, as highlighted by Kabisch et al. (2016) and Dumitru et al. (2020), and it is shown that evidence of effectiveness of adaptation is not uniform across different types of interventions and outcomes (Chausson et al., 2020). There is also a geographical bias in more recent global reviews, with the Global North being overrepresented and the need to delve deeper into the concept of vulnerability, justice and transformative capacity (Goodwin et al., 2023; Mosisa et al., 2025).

Based on the literature reviewed, this paper poses four questions: (1) What does the reviewed literature indicate about the main mechanisms by which NBS in the city contribute to climate resilience? (3) What co-benefits, trade-offs and equity risks are common to the evidence base? Answers to the following questions will help understand how NBS transition from project scale experimentation to become part of mainstream infrastructure: (3) What implementation conditions enable NBS to move from project scale experimentation to mainstream infrastructure? (4) How can cities organize planning, financing and monitoring to enhance long term performance? In order to answer these questions the study carries out an integrative synthesis of 60 peer-reviewed, DOI bearing publications and proposes a practical climate-resilient urban development framework. The contribution is not a statistical meta-analysis, but it links up the various strands of scholarship and helps make sense of them in terms of an implementation-oriented model that incorporates ecological function, infrastructure performance, governance, justice and adaptive learning.

Table 1. Major urban nature-based solution types, functions and design variables

NbS type	Primary climate function	Typical co-benefits	Key design variables
Urban trees / street canopy	Shade, evapotranspiration, rainfall interception	Air quality, habitat, walkability, streetscape quality	Species, canopy size, rooting volume, irrigation, placement
Parks / urban forests	Area cooling, runoff storage, infiltration	Recreation, mental health, biodiversity, social interaction	Size, canopy structure, accessibility, soil, safety, connectivity
Green roofs / walls	Runoff retention, building-scale cooling	Insulation, habitat, amenity	Substrate depth, vegetation, structural load, irrigation, maintenance

BioswaleS / rain gardens	Runoff detention, filtration, infiltration	Streetscape, habitat, traffic calming	Inlet design, soil media, storage, overflow, maintenance
Wetlands / floodplains	Flood storage, peak attenuation, water treatment	Habitat, recreation, landscape value	Land area, hydrologic connectivity, sediment, safety, ecology
Blue-green corridors	Distributed cooling, conveyance and storage	Mobility, habitat connectivity, recreation	Network continuity, land control, hydraulic links, public access

2. Conceptual Foundations: From Urban Greening to Resilience Infrastructure

The concept of urban NBS can be seen as the synthesis of a number of pre-existing ideas: urban ecology, ecosystem services, green infrastructure, sustainable drainage, resilience theory and ecosystem based adaptation. First scholarship on green-infrastructure adopted a network perspective to its early focus and regarding natural and semi-natural areas as systems that could carry out multiple functions in favour of ecological processes and human welfare. Tzoulas et al. (2007) associated green infrastructure with ecosystem and human health and Gill et al. (2007) showed the applicability of urban green infrastructure to climate adaptation. Simultaneously, the engineering-based body of evidence for the roles of vegetation and soils in modifying urban hydrology (Carter & Jackson, 2007; Mentens et al., 2006; Ahiablame et al., 2012) was emerging. These works have laid the technical and conceptual bases for the current NbS agenda. The ecosystem-services point of view brought in a valuation and a planning perspective. Urban ecosystems can deliver regulating services (cooling services, air filtering services, flood regulation services, carbon storage services); cultural services (recreation and aesthetic value); and supporting services (habitat and nutrient cycling services). Gómez-Baggethun and Barton (2013) demonstrated the possibilities of categorizing and valuing urban ecosystem services for urban planning and Haase et al. (2014) provided an overview of the increasing number of such reports and the ongoing difficulties in their operational Hansen and Pauleit (2014) further developed the idea of multi functionality, suggesting that green infrastructure planning explicitly account for the provision of multiple services, as opposed to assuming that green space provides such services. The possibility of generating multiple public values in one spatial intervention is at the heart of NBS, as the appeal of their policy is based on that potential.

A second pillar is in the form of the resilience theory. Resilience, as defined in the urban context as the ability of urban systems to withstand shocks, absorb shocks, adapt to shocks and bounce back from shocks while continuing to perform their functions, is a term that is used frequently, but is not without debate as it is possible to have different types of systems, beneficiaries, and outcomes that entail resilience (Meerow et al., 2016). Ahern (2011) suggested "safe-to-fail" urbanism as a means of avoiding a dependency on fail-safe infrastructure. Safe to fail principles are more applicable to the NbS context, and include notions of distributed retention, redundant green-blue corridors, and spaces that flood and/or landscape systems that can tolerate disturbances without catastrophic collapse. McPhearson et al. (2015) also recognisation the different nature of ecosystem services' resilience to resilience through ecosystem services, in which cities require ecosystems to be resilient, but can also use the resilience of these ecosystem functions to make other urban systems less vulnerable.

NBS expanded on these concepts by making a clear connection between ecological functions and social problems, as well as more attention to co-benefits and governance and transformation. According to

Lafortezza et al. (2018), NBS involves a process for resilient landscapes/cities that links ecosystem function and sustainability with development. The European NBS agenda is considered as a policy innovation by Faivre et al. (2017), and it is emphasized that the concept has a science, policy and practice dimension, and thus should be interpreted interdisciplinary by Nesshöver et al. (2017). As seen in Dorst et al. (2019) and Hanson et al. (2020), NBS is a new and flexible concept that is closely related with the older 'green' concepts. This flexibility, however, means that NbS can be used in more than one sector but also has the risk of being interpreted as a general label, without reference to specific societal issues, biodiversity results and measurable performance.

Concept clarification is important, therefore. Sowińska-Świerkosz and García (2022) advocate for a number of key concepts for NBS: ecological processes should be used or driven by them; they should address a clearly defined societal challenge; they should produce biodiversity and ecosystem benefits; and they should be context-adapted. Similarly, Seddon et al. (2021) caution against NBS being seen as a replacement for a rapid phase-down of GHGs or as a panacea. In the urban development context, NBS cannot replace grey infrastructure, but should be used in addition. A resilient drainage strategy can include upstream wetlands, neighborhood bioswales, and permeable surfaces and pipes, and an urban heat strategy can include tree canopy, shade structures, cool materials, building design and public-health measures. Hybrid NBS strategies are therefore most credible, that is, context-specific and performance-based.

There is a third foundation that is environmental justice. Early planning strategies tended to focus on aggregate ecosystem service benefits, whereas the aggregate benefits may mask inequitable distribution of benefits; inequitable risk reduction and displacement effects may also be present. Kabisch and Haase (2014) show that the distribution of urban green space has to be considered in the context of population characteristics and user needs - not in the context of a city-wide average. Wolch et al. (2014) elegantly captured the conundrum as a call for "cities just green enough" that health and amenity benefits and real-estate strain are both met. This concern has been expanded by Anguelovski et al. (2019) to the issue of climate resilience, which means that green protective infrastructure can be responsible for climate gentrification when the new value is capitalized into land markets. Furthermore, governance studies have focused the implementation of NbS on justice and equity aspects which include distributional, procedural, and recognition aspects, as presented by Sekulova et al. (2021), Toxopeus et al. (2020), and van der Jagt et al. (2021).

All these conceptual streams come together when considering urban NBS as socio-ecological-technological infrastructure. Keeler et al. (2019) reveal that the value of urban nature can be dampened by the social, ecological and technological contexts. Surrounding imperviousness, population exposure, maintenance capacity, access, land value and infrastructure, for example, can be very different across neighborhoods, and thus the ability of the same park, wetland or tree canopy to perform can vary greatly. NBS planning should therefore begin with the service deficiencies and pathways for climate risks, not an agenda of green interventions. A neighborhood with high exposure to heat, low canopy, high pedestrian exposure, and/or vulnerable populations may be better served by shade trees, cool corridors, and accessible parks. Distributed retention, wetland storage, floodable public space and drainage upgrades may be needed in a flood prone district. Green roofs, facades and pocket landscapes may be more of a necessity in a dense commercial district as land is limited.

Multifunctionality also must be a compromise between different goals. There are more than a single benefit that can be achieved by a single intervention, but it is not always possible to maximize all benefits at the same time. All the characteristics of dense planting (cooling effect) can be at odds with the need for solar and landscape access, and underground utilities, while wetlands can serve as a storage and habitat solution, they need land, and green roofs can help reduce runoff while providing insulation, but require structural capacity and irrigation during drought, and floodable parks can help reduce flood exposure, but require operational protocols and public understanding. The question of how to measure co-benefits and costs across several challenge areas is proposed by Raymond et al. (2017); and Connop et al. (2016) illustrate how the concept of locally contextualized biodiversity-led design is crucial for the realisation of multifunctionality in practice. This implies that NBS should be assessed as portfolios of services, costs, risks and distributional effects rather than universally beneficial objects, as found in the analytical implications for this paper.

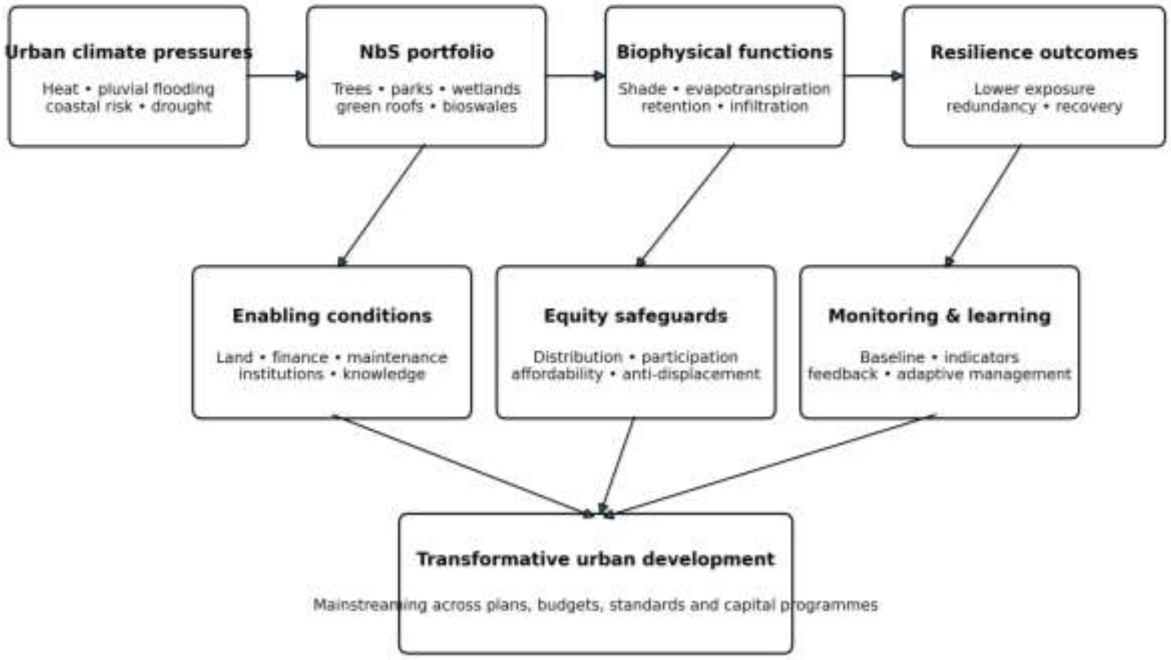

Figure 1. Integrated pathway from nature-based intervention to climate-resilient urban development.

3. Methodology

The study employs an integrative evidence-synthesis design to synthesise the disorganized and fragmented literature to develop an implementation framework for climate-resilient urban development. An integrative review should be used for a research problem that involves two or more methods and/or disciplines; the goal is to synthesize mechanisms, implementation context, outcomes, and conceptual advances or changes, rather than estimate a single pooled effect size. The final corpus consists of 60 peer-reviewed publications that have published their works from 2006 to 2025 and have DOIs. The sample contains basic research on green roofs, sustainable drainage, green infrastructure, ecosystem services and urban resilience as well as more recent literature specifically referring to NBS.

The corpus was not intended to be a bibliometric census but one that was conceptually comprehensive. The relevance of the inclusion was expressed in terms of at least one of six inclusion domains: urban climate adaptation or resilience; green/blue infrastructure performance; NBS planning or governance; ecosystem-service and multi functionality assessment; monitoring and evaluation; or environmental justice in urban greening. Publications were excluded if they were mainly rural, mainly agricultural or mainly coastal with no obvious urban-development application; if there was no evidence of a peer-reviewed publication history; or if the contribution was too special to be relevant to the questions raised during the review. In order to enhance the traceability, articles that appeared in journals with a DOI were selected. The last reference set covers urban planning, landscape architecture, environmental management, ecology, sustainability science, and hydrology and urban studies.

Every publication was allocated to a main theme, according to the most important contribution of the research. The coding categories were: flood and storm water management, heat mitigation, ecosystem service and biodiversity, resilience theory and concept development, planning and governance, science-policy integration, monitoring and evaluation, justice and equity, adaptation effectiveness and global evidence. To synthesize the codes visually, codes that are closely related were grouped into seven thematic groups. The publication years were also coded to investigate the change in the literature over the years. The numbers obtained are descriptive summaries of this 60 study corpus and cannot be understood as estimates of the whole of NBS field.

There were three stages to the qualitative synthesis. First, studies were read comparatively, to detect the common causal mechanisms that connect the interventions with the resilience outcomes. Second, the results were presented in three sections: climate hazards, co-benefits and implementation barriers and performance metrics. Third, a comparison of cross-cutting themes was made to understand when NBS may be scaled-up from individual projects to city-wide infrastructure. The principle of synthesis was based on the idea that urban resilience outcomes are the result of interaction between the four elements of ecological design, spatial context, governance, finance, and maintenance and social legitimacy. Therefore, in this analysis, NBS types are not ranked abstractly; rather they are analysis in terms of their functions, under what circumstances and with what trade-offs.

There are some restrictions to the method. Frequencies in Figures 2 and 3 are not representative of the entire universe of published research, but are reflective of the selected sample of the evidence corpus, which is purposive and integrative in nature. Effect sizes are not calculated because the outcomes of the studies reviewed are very diverse. Furthermore, the urban NBS literature is still geographically fragmented and there is a significant amount of evidence from Europe and other high-income settings (Hanson et al., 2020; Goodwin et al., 2023). The review takes this into account by pointing to transferability conditions and not copying the design solutions outright between cities. The main contribution is thus analytical synthesis and frame construction, rather than exhaustive coverage and causal meta analysis.

Table 2. Evidence-synthesis design and coding framework

Review element	Operational choice
Design	Integrative evidence synthesis and framework development
Corpus	60 peer-reviewed DOI-bearing publications, 2006-2025
Scope	Urban NBS, green/blue infrastructure, climate adaptation, ecosystem services, governance, justice and monitoring
Primary coding	Flood/storm water; heat; ecosystem services/biodiversity; resilience/concepts; governance; justice; effectiveness/evaluation; global evidence

Analysis	Descriptive coding plus qualitative mechanism and implementation synthesis
Not intended as	Exhaustive biblio-metric census or statistical meta-analysis

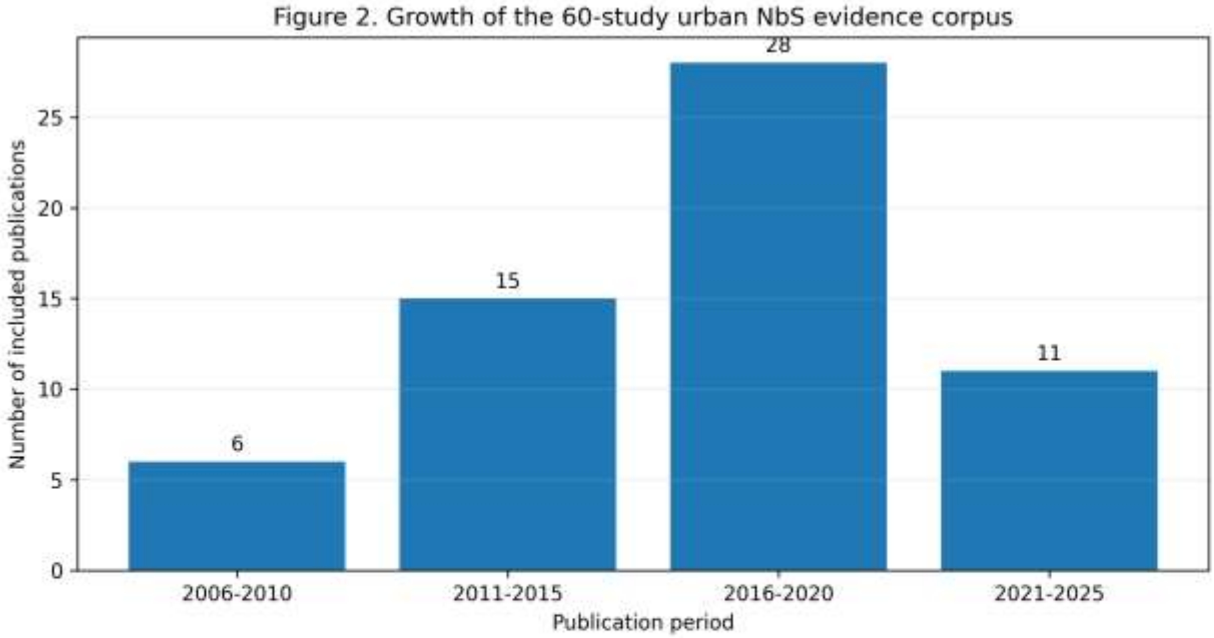

Figure 2. Growth of the 60-study urban NBS evidence corpus by publication period.

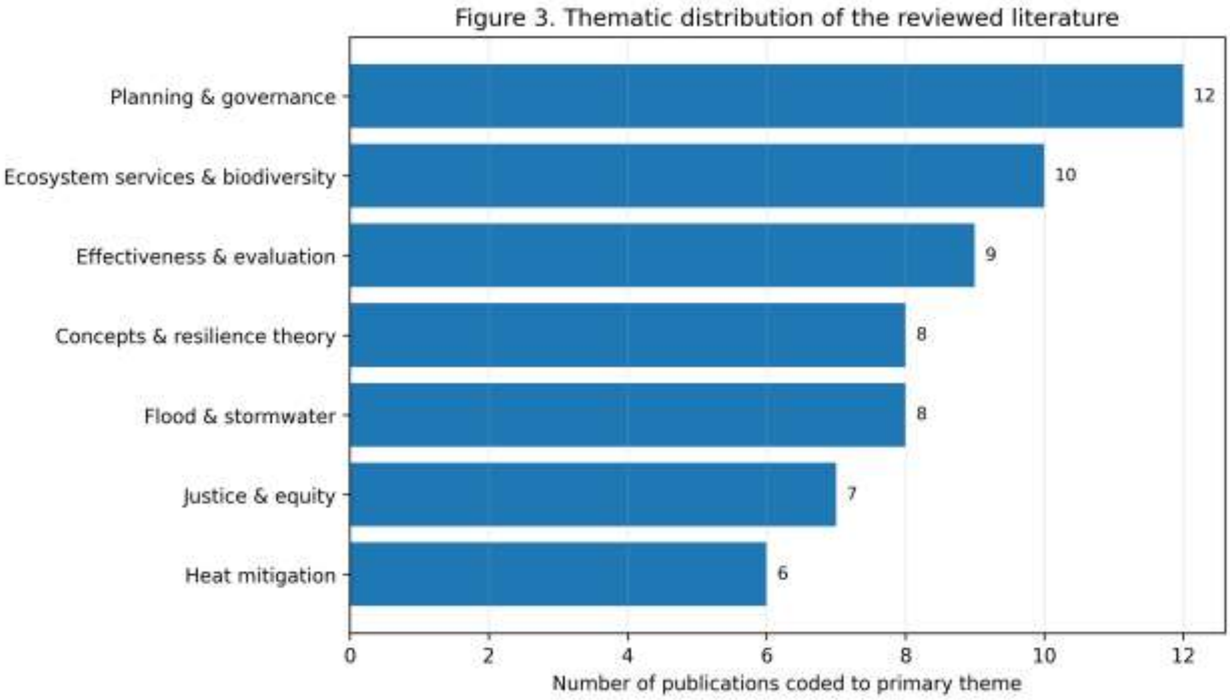

Figure 3. Thematic distribution of the reviewed literature based on primary study coding.

4. Results

4.1 Evolution of the evidence base

The 60-study corpus demonstrates a definite growth over time. A few key publications were published prior to 2011, most of which were on green roofs, green infrastructure, urban heat and sustainable drainage. In 2011-2015, the agenda was expanded to include resilience, ecosystem services and multifunctional planning. The NBS concept has diffused into European research and urban policy since 2016, resulting in the sharpest growth. Increasingly, recent studies not only are investigating impact of individual interventions, but they also address the question of how to govern, evaluate, fund, scale and make individual interventions socially just. This trend can be seen in Figure 2, and mirrors the concept evolution reported by Hanson et al. (2020).

This maturation is also illustrated in the thematic profile (figure 3). Because of the relative longevity of the performance record, flood and stormwater studies continue to be a major component – a performance record that is still being developed by LID, SUDS and green-roof research (Ahiablame et al., 2012; Eckart et al., 2017; Fletcher et al., 2015; Zhou, 2014). Planning and governance is also strong, and it is recognised that institutions as well as engineering are limiting aspects of implementation. Another large group of ecosystem services and biodiversity focuses on multifunctionality and on the value of urban nature in general. Since the late 2010s, justice and equity has gained separate research stream. While heat mitigation continues to be relevant, it is more niche, compared to recent global reviews that have incorporated a range of hazards and policy dimensions (Aghaloo et al., 2024; Goodwin et al., 2023; Mosisa et al., 2025).

Heat mitigation and thermal resilience.

One of the most confirmed parts of the NBS literature are the elements of urban cooling. The systematic review by Bowler et al. (2010) of empirical evidence on urban greening revealed that, overall, green spaces are cooler than similar non-green spaces, but that there remained methodological variation. Gill et al. (2007) placed green infrastructure as a strategic solution for the impacts of urban climate change related to vegetation and evapotranspirative cooling, shading and modified surface energy balance. Building on this, Norton et al. (2015) highlighted the need for spatial prioritization: cooling interventions should be targeted to the area(s) that is most vulnerable to exposure, urban morphology and thermal load.

The special significance of urban trees is that these functions (canopy shade and evapotranspiration) are combined. Performance, however, is determined by the characteristics of the crown, species, soil volume, and water availability and the relationship between the canopy and impervious surfaces. Ziter et al. (2019) show that tree canopy targets are not spatially neutral percentages because there are scale dependent interactions between tree canopy and imperviousness. The impacts of both green and blue spaces on the intensity of the urban heat island (UHI) have also been demonstrated by Gunawardena et al. (2017), who find that the effects differ depending on scale and context. Thermal-resilience planning implications: priority pathways of exposure (pedestrian pathways, transit stops, schools, care facilities, heat vulnerable neighborhoods, heat dense urban canyons) are more important than simply raising average amounts of green space per capita.

In urban areas, green roofs and facades may have a role to play where ground land is limited but their thermal performance will vary with large canopies. Santamouris (2014) discusses the technologies available for green roofs and reflective roofs and demonstrates how roof-level interventions can help to decrease surface temperature and heat loads. Shafique et al. (2018) also point out other benefits of green roofs, such as stormwater retention and ecological value, and design and maintenance issues. The synthesis implies a portfolio strategy: Trees and shaded green corridors are particularly important when it comes to outdoor thermal comfort, while roofs and facades can complement the cooling and water management in built-up areas. This sustains the overall principle of NBS location- and exposure-specific to the climate risk.

Pluvial flooding is a type of flooding caused by a high volume of water running off hard surfaces.Pluvial flooding is flooding caused by excessive amounts of water running off hard surfaces.

The stormwater evidence base is both sufficiently developed and is varied in language. Fletcher et al. (2015) describe the history of SUDS, LID, BMPs and water-sensitive urban design, and illustrate the convergence of various approaches in different regions to utilize soils, vegetation, storage and infiltration for runoff control. Ahiablame et al. (2012) and Eckart et al. (2017) collate the evidence to suggest that distributed LID practices can reduce runoff volume and peak flow, but that the benefits are dependent on the design, soil characteristics, rainfall and maintenance. Zhou (2014) notes that the focus on assessing sustainable drainage needs to be on the combined effects of climate change and urbanisation, not historical hydrology.

Green roofs are good examples of how the intervention can be performed at different levels and in different ways. Vegetated roofs can help to reduce and delay runoff as demonstrated in Mentens et al. (2006) and Carter and Jackson (2007) but a vegetated roof will have a role in helping to increase the network scale resilience only if it is used on an adequate scale and is incorporated into a suite of measures. Urban trees play a role in stormwater management through interception, evapotranspiration and soil processes, with a proviso that the role of urban trees is considered as part of the larger hydrologic systems by Berland et al. (2017). Aghaloo et al. (2024) conduct a comprehensive systematic review from which they draw up a more recent taxonomy, which shows that SUD is one of the most prevalent NbS strategies for flood adaptation, and that green roofs have multiple co-benefits to stormwater regulation management.

The collected evidence has been reviewed and three pluvial-flood resilience design principles are proposed. First, storage and infiltration should be spread throughout the catchment and not at the downstream bottlenecks. Second, NbS needs to be connected hydraulically and functionally to the conventional drainage, meaning that a bioswale or retention basin is not standalone, but part of a flow network. Third, testing of performance under future rainfall intensities and antecedent conditions, such as saturated soils and compound events should be conducted. These principles move beyond the status of NbS being an add-on to the stormwater infrastructure and towards the status of a functional part of the stormwater infrastructure.

The concept of ecosystem services, biodiversity and multifunctionality are introduced.

One of NbS's key tenets is that they deliver several benefits. As can be seen in the literature reviewed, there are clear indications of the potential of the concept of multifunctionality, but also it is clear that co-benefits have to be designed. Stewardship and restoring cities' connection to the biosphere is emphasized by Andersson et al. (2014), and Elmqvist et al. (2015) describe the wide-ranging benefits of restoring ecosystem services in cities. While the conceptual framework of Hansen and Pauleit (2014) is useful for conceptualizing the concept of multifunctionality for green-infrastructure planning, the work of Gómez-Baggethun and Barton (2013) shows the potential of applying ecosystem-service classification and valuation for supporting green-infrastructure decision-making.

Multifunctionality is of strategic value as it can be supported by investments in several budgets. Flood storage wetlands can also serve other purposes such as habitat creation, water quality improvement, recreation, and local amenity enhancement. A tree corridor can help to decrease the heat exposure, catch rainwater, promote biodiversity and encourage walking. A Green Roof can offer stormwater retention,

insulation and habitat. Raymond et al. (2017) put this logic into a framework to evaluate co-benefits and costs for societal challenges and to introduce monitoring throughout the implementation process.
However, the literature refutes their view that all services are necessarily provided by all green interventions. If green infrastructure is going to be designed to serve ecological functions, rather than merely cosmetic greening, then it is clear that biodiversity-led design and local context is essential, as shown by Connop et al. (2016). Similarly, Oberndorfer et al. (2007) consider green roofs as urban ecosystems and the services they provide as being dependent on the structures and processes within the ecosystem. The value of urban nature varies depending on social, ecological and technological factors, as demonstrated by Keeler et al. (2019) who discuss how an intervention can bring about different results in different urban contexts. The corollary is that project appraisal should be able to make a clear statement of services intended prior to project implementation and clearly define measurable indicators for each service, not make a statement of generic co-benefits.
This will address issues of governance and institutions and scaling as related to the project.
One of the most consistent patterns in governance studies is that NbS implementation is institutionally challenging due to the fragmentation of benefits, costs and responsibilities among the various organisations and over time. Based on several European cities, Frantzeskaki (2019) stresses the importance of co-creation, trust, collaborative governance and learning. The authors of Bush and Doyon (2019) emphasize the importance of urban planning as the decisions, including land-use and development control, and coordination of infrastructure, have a significant bearing on where and how NbS can be integrated. Frantzeskaki et al. (2020) list policy needs as knowledge, skills and partnerships, with systems thinking and negotiation and collaboration across administrative silos being listed.
Barriers are seldom stand-alone. Sarabi et al. (2019) list institutional, financial, knowledge and governance constraints as part of the implementation constraints, while Sarabi et al. (2020) demonstrate that political, institutional and knowledge-related constraints can play powerful roles in the implementation causality structure. Malekpour et al. (2021) highlight collaborative governance, noting that NBS can only be implemented if public agencies, private parties and communities can be coordinated. Cohen-Shacham et al., (2019) also emphasize key principles for implementation and upscaling, such as evidence, engaging stakeholders, adaptive management, and ensuring the protection of biodiversity.
All of these studies indicate that scaling is not a replication issue. It is not possible to replicate a successful demonstration park or bioswale city-wide without the standards, budgets, procurement, asset registers, maintenance contracts and regulatory practice changing. Institutionalisation must be a fundamental part of mainstreaming. Frantzeskaki and McPhearson (2022) call for NbS to be incorporated in other urban climate-resilience policies, and Faivre et al. (2017) term NbS as a policy innovation that can bring together environmental, social and economic objectives in an urban setting. The big shift is from projects to programmes: there must be replicable design guidelines, financing models, tracking frameworks and accountability for organisations.
The quality of the monitoring, evaluation and evidence is good.
Monitoring is connecting the dots between sensible design and effective infrastructure. Kabisch et al. (2016) list indicators, knowledge gaps and evaluation needs as key questions to address in the context of urban NbS, while Dumitru et al. (2020) provide principles of impact evaluation. A lack of uniformity is observed in the evidence of effectiveness across NbS types, climatic hazards and among outcome categories, highlighting the need for baselines, counterfactual thinking and long-term monitoring

(Chausson et al., 2020). Similar methodological shortcomings and inconsistent practices, along with poor primary data use are still cited as key gaps in more recent reviews (Mosisa et al., 2025).

The outputs, outcomes and impacts should be differentiated with a high-quality monitoring system. Outputs include the area of wetland created, number of trees planted or square meters of green roof installed. Outcomes are: Canopy survival, runoff, retained temperature, and habitat/access to users. Impacts include broader resilience benefits, like avoided flood damage, reduced heat-health risk, etc. or a more equitable distribution of cooling. Many urban programmes end at the output level, as this is the easiest to count. The reviewed evidence indicates that this is not enough: cities need to be able to track service performance on a seasonal and extreme weather basis, and to have maintenance and condition as aspects of their resilience metrics.

But social indicators are also required for evaluation. The authors of this paper, that is, Raymond et al. (2017) and Sekulova et al. (2021) and Toxopeus et al. (2020), argue that we must have a multidimensional approach to co-benefit assessment and show that governance quality and justice is not a function of biophysical performance. Important social indicators are access, perceived safety, participation in planning, investment distribution and the demographic profile of investment beneficiaries. This expands performance measurement from “Did the intervention keep water in the system?” to “Did the intervention alleviate vulnerability of the populations most vulnerable, without adding to burden on these same populations?”

4.7 Equity, justice and maladaptation risk(s)

Vulnerability is socially differentiated, making justice a core benefit of climate resilience. Kabisch and Haase (2014) demonstrate the potential for high spatial heterogeneity in the distribution of green space within cities and for the requirement for green space to be different in different contexts. Wolch et al. (2014) report that green measures have the capacity to enhance the public health as well as bring about property-value appreciation and displacement. When resilience investments make places where vulnerable communities reside more attractive and valuable, Anguelovski et al. (2019) call this green climate gentrification.

The problem of justice is made more explicit in later governance scholarship. Sekulova et al. (2021) examine the governance aspects of NbS from the perspective of justice and equity, Toxopeus et al. (2020) challenge the “justness” of hybrid governance and van der Jagt et al. (2021) argue why reflexive governance is needed in the absence of unjust results. In addition, Goodwin et al. (2025) highlight relational approaches to adaptation, which emphasize social and institutional relationships in which adaptation is felt.

There are four safeguards identified in the synthesis. The principle of distributional justice dictates that investment be concentrated in regions that are highly climate exposed, and have low existing environmental amenity. Means that there must be meaningful participation prior to locking in some major design decisions in the case of procedural justice. To achieve recognition justice, there is a need to look at cultural uses and knowledge and groups who are poorly served. Lastly, anti-displacement measures could be necessary where there is a likely increase in development pressure due to resilience investment. This can include affordable-housing protections, community land strategies, rent stabilization (if applicable), or benefit-sharing strategies. If NBS is not undertaken with adequate safeguards, it can lead to decreased physical exposure and increased social vulnerability.

4.8 Moving to integrated, transformative urban adaptation

NBS practice is fast spreading and is yet to be widespread at the global level, as shown by a series of global studies. Goodwin et al. (2023) identify 216 urban interventions and 130 cities while documenting a lack of consensus in existing practices regarding multidimensional vulnerability, social justice, public-private partnerships and the extent to which they offer co-benefits. They also identify a geographic imbalance, with a tendency towards the Global North. In line with this, Mosisa et al. (2025) also find that data-driven planning, stakeholder engagement and institutional framework and context sensitivity evaluations are key factors in implementation. However, Seddon et al. (2020, 2021) warn that NbS have boundaries and cannot be an excuse to postpone emissions reductions or inaction on other adaptation measures that are needed.

So, the key finding of this review is that the effectiveness of NBS is relational and systemic. Ecological function is a requirement but not sufficient. Where ecological processes are linked to infrastructure networks, institutional responsibilities and social priorities and adaptive monitoring, resilience emerges. This pathway is summarized in figure 1. A service deficit is caused by climate pressures, and an NbS portfolio is chosen to deliver certain biophysical functions, which only lead to resilience outcomes when the enabling conditions, equity safeguards and monitoring systems are in place. Transformation takes place when effective practices are integrated into plans, budgets, designs and capital programmes and are not just pilots.

Table 3. Climate hazards, NBS mechanisms, interventions and performance indicators

Hazard / objective	Dominant NBS mechanisms	Representative interventions	Performance indicators
Extreme heat	Shade, evapotranspiration, surface-energy modification	Trees, parks, green roofs, green facades, blue space	Air/surface temperature, PET/UTCI, shade coverage, heat exposure
Pluvial flooding	Retention, detention, infiltration, delayed runoff	Rain gardens, bioswales, green roofs, permeable landscapes	Runoff volume, peak flow, time to peak, overflow frequency
River/coastal flooding	Storage, roughness, floodplain reconnection	Wetlands, floodplains, restored channels, coastal vegetation	Water level, inundation extent, avoided damage, recovery time
Drought / water stress	Soil moisture retention, shading, reuse	Drought-tolerant planting, water-sensitive landscapes	Irrigation demand, soil moisture, vegetation survival
Biodiversity / ecosystem resilience	Habitat provision, connectivity, ecological succession	Native planting, green corridors, wetlands, diverse roofs	Species richness, habitat quality, connectivity, survival
Social resilience	Access, recreation, social interaction, risk communication	Parks, community green space, shaded corridors	Accessibility, use, perceived safety, distribution of benefits

Table 4. Common co-benefits and trade-offs associated with urban NBS

Value dimension	Potential co-benefits	Potential trade-offs / risks
Environmental	Biodiversity, water quality, carbon storage, cooler microclimates	Water demand, invasive species, habitat simplification if poorly designed
Social	Recreation, health, walkability, social cohesion, amenity	Unequal access, safety concerns, exclusionary design, displacement risk
Economic	Avoided damage, energy savings, property and place value, tourism	High land cost, maintenance liabilities, capitalization into rents/prices
Infrastructure	Distributed capacity, redundancy, reduced drainage load	Performance uncertainty, space requirements, dependence on maintenance
Governance	Cross-sector collaboration, community stewardship, learning	Fragmented responsibility, coordination costs, unclear ownership

Table 5. Recurrent implementation barriers and enabling responses

Barrier	Why it constrains scaling	Enabling response
Siloed institutions	Benefits cross departments but budgets and mandates are sectoral	Cross-department programme governance and shared performance targets
Uncertain finance	Benefits accrue over long periods and to multiple beneficiaries	Life-cycle business cases, blended funding, development contributions
Land constraints	High-value urban land competes with other uses	Multifunctional spaces, rights-of-way, roofs, floodable public realm
Knowledge gaps	Limited local performance data and design confidence	Pilots with monitoring, guidance, technical standards, knowledge partnerships
Maintenance uncertainty	Living assets degrade without stewardship	Asset registers, service-level agreements, dedicated maintenance budgets
Weak community legitimacy	Projects may not reflect local priorities or may raise displacement fears	Early co-design, transparent benefit distribution, anti-displacement safeguards
Inconsistent evaluation	Outputs are counted but resilience outcomes are not measured	Baseline indicators, event-based monitoring, independent evaluation

5. Discussion

The evidence base establishes a compelling argument for NBS as part of a climate resilient urban development, but also makes clear the conditions under which this can be a credible argument. NBS needs to be considered as infrastructure first. For a long time, the concept of "green infrastructure" has suggested this transition but, in many municipal systems, the design and maintenance of trees, parks, wetlands and landscaped drainage have focused on fitting them into a space that is primarily used as an amenity. The information reviewed suggests that these assets can provide measurable services that are closely related to infrastructure planning including (but not limited to) runoff control, peak flow attenuation, thermal control, habitat provision and exposure reduction. This approach to infrastructure involves establishing services' goals, determining who is responsible for the assets, allotment budget for maintenance, monitoring asset condition and performance, and making plans for renewals.

Secondly, NBS should be implemented as portfolios, rather than single technologies. It is important to keep in mind that there is no single solution to mitigate all urban climate risks. Strong cooling and water storage benefits for trees require space, water and maintenance; wetlands can store a good amount of water but are not effective at catchment scale if not widely distributed; green roofs are effective at the district scale but can limit the impact at catchment scale unless there is a high percentage of the total area; parks can have a strong cooling effect, water storage, and social benefit but can also lead to real estate pressures. Portfolio design can enable cities to mix interventions at multiple scales, and couple them to grey infrastructure. The combination of the two is in line with the “safe-to-fail” principle of Ahern (2011), the multifunctional planning of Hansen and Pauleit (2014) and the focus on context in Keeler et al. (2019).
Third, the co-benefits should not be rhetorically, but explicitly, appraised. The policy attractiveness of NBS is frequently based on the assumption that investments in NBS will bring about climate, biodiversity, health and economic benefits. These claims may be true, but should be linked to causal pathways and indicators. For instance, an active travel provision (shaded walking corridor) might help decrease heat exposure; a habitat provision (floodplain restoration) could help mitigate downstream peaks; a mental health and social interaction provision (community park) could help promote mental health and social interaction. If these outputs are not planned and monitored, however, it may be hard to establish whether a farm is “multifunctional”. There are solid foundations to transitioning from general claims to evaluation frameworks provided by both Raymond et al. (2017) and Dumitru et al. (2020).
4. Maintenance is a resilience factor. NBS are dynamic entities that change in their performance as a function of age, season, disturbance and management. It takes years for tree canopy to grow; soil compacts can occur; inlets can clog; green roofs can lose vegetation; wetlands can build up sediment and drought can impact cooling. Traditional project appraisal tends to put a high priority on capital investment and not sufficiently recognise stewardship. But maintenance is the critical factor in maintaining service in extreme events. The costs of the business case should, therefore, consider the entire life cycle of the building, including its failure modes, maintenance intervals, replacement schedules, and who is responsible for maintenance.
Fifthly, equity should be built-in during the problem definition phase. Investment can systematically exclude neighborhoods that are most vulnerable to climate change if cities limit investment to those projects that can easily be acquired or those that are already attractive for redevelopment. There should, therefore, be a consideration of hazard exposure, social vulnerability, and existing environmental-service deficits in the risk-based prioritization. This is especially relevant for adaptation to heat, as low canopy neighborhoods are often also areas of social disadvantage, and for adaptation to flooding, where disadvantaged households may not have as many resources available to them to recover. The justice literature examined here demonstrates that the distribution of benefits and burdens should be considered as a fundamental performance criterion in addition to being a social afterthought (Anguelovski et al., 2019; Sekulova et al., 2021; Wolch et al., 2014).
Sixth, governance innovation is needed in scaling.Sixthly, governance innovation is needed when scaling. Pilot projects frequently are successful because they have special grants, are championed by individuals or research collaborations. The challenge really begins after the pilot. A repeatable institutional architecture is needed for mainstreaming, including standards for design, for NbS to be regarded as infrastructures; for procurement processes to reflect consideration of life-cycle and co-benefits; for land-use regulations to ensure space for green-blue systems; for finance mechanisms to reflect the cross-sectoral benefits; and for asset-management systems to track performance. Skills, knowledge and partnerships are

crucial as indicated by Frantzeskaki et al. (2020), and institutional barriers do affect political and knowledge constraints, as highlighted by Sarabi et al. (2020). It is not a matter of more projects but rather a governance transformation, that is scaling.

The review additionally poses an issue about evidence requirements. While the mature literatures on stormwater and on heat both often use quantitative measures of performance, the literatures on governance and justice tend to use qualitative or mixed approaches. These domains ought not to be squeezed into one measure, but rather methodological pluralism with a clear causal logic should be employed in the development of a Scopus-quality research agenda. Biophysical results may need remote sensing, controlled comparisons, sensors and hydrologic modelling. Accessibility analysis may be needed, along with housing-market indicators and institutional analysis, as well as surveys and participatory approaches for social outcomes. The common requirement is that baselines are clear, and that there are clear connections between intervention, mechanism and outcome.

Another contribution of the synthesis is the research plan focusing on reliability, transferability and distribution. Scientific studies of reliability should be conducted to determine if designed ecosystem services remain during drought, are present during heat waves, are present when there are extended maintenance periods, and/or more frequent extreme rains. Transferability research should be conducted on the same NbS functions across climatic regions, urban morphologies and governance systems, not to assume that a transfer of evidence from one city to another is straightforward. Distributional research needs to be carried out in conjunction with environmental performance and exposure, access and changing the housing market at the household level. These would combine to transform the field from case studies of project success to a science of urban NbS performance. They would also serve to enhance the foundation for the standards, insurance, infrastructure appraisal and public investment decisions where decision makers are most likely to need more evidence than just demonstration projects to make the decision.

Lastly, the literature indicates the need for urban NBS to be mainstreamed into the broader mitigation and adaptation measures. The lessons learnt from Seddon et al. (2020, 2021) are to not claim too much from NBS. The lack of emissions reduction is not a problem that can be solved with urban greening. The lack of safe design of buildings and insufficient drainage is not a problem that can be solved with urban greening. The most effective is the complimentary approach: NbS increase the option set, provide redundancy and provide co-benefits, whereas grey and regulatory measures are for risks that NBS are not able to manage. The concept of 'climate resilient urban development' is then best seen as a 'coordinated socio-ecological-technological transition'.

6. A Land Use Management Plan

This paper suggests an NBS planning framework in eight steps, which can be implemented by municipalities, development agencies and infrastructure providers. This framework is not linear as monitoring should be used to redesign and scale (Figure 4).

Step 1: Identify pathways to climate risk and gaps in services. The first step in planning is to start with the hazard and the system that is exposed to the hazard, not with the preferred intervention. Heat-risk analysis should generate thermal hotspots and vulnerable populations and critical pedestrian networks. Runoff pathways should be identified and the drainage constraints should be identified in flood-risk analysis, with the possibility of distributed storage to lessen downstream peaks. Existing green-blue assets should also be mapped and neighbourhoods with low provision of ecosystem services should be identified as part of the diagnosis.

STEP 2: Establish measurable performance goals. Objectives should describe the outcomes that the intervention is expected to achieve: decrease the peak discharge for a specific design storm, decrease the thermal exposure of pedestrians, increase the amount of shade available for pedestrians, provide habitat connectivity, improve water quality or reduce the number of residents who are exposed to a threshold condition. Performance objectives reframe NBS from general sustainability goals into services of infrastructure.

Part 3: Co-design a portfolio across scales. Not all projects can be the key to resilience, on a city-wide scale. These can be implemented at the scale of the site, street-scale, neighborhood-scale, and catchment-scale including green roofs, rain gardens, bioswales, shade trees, parks, and retention landscapes, as well as catchment-scale wetlands and floodplains. Connectivity and interactions with grey infrastructure should be taken into account when designing a portfolio. It is a multi-scale perspective as is used in Demuzere et al. 2014 and a spatial planning as described in Meerow and Newell 2017.

Step 4: Evaluate co-benefits and trade-offs and assess equity. All options need to be considered with their impacts on ecology, social and economic issues. The co-benefits should be related to beneficiaries and indicators and trade-offs should be explicit. Questions that should be asked when doing an equity analysis include: Who benefits from risk reduction, who is on the hook for the construction or maintenance, who is included in access, and who might be added to the displacement pressure due to the investment. This is a step implementation of the justice concerns suggested by Kabisch and Haase (2014), Anguelovski et al. (2019) and Toxopeus et al. (2020).

Always put in place governance, land and finance before construction. Ownership and responsibility, land tenure and funding should be determined at the planning stage. Blended finance can be considered, as NbS benefits cut across sectors, for instance stormwater budgets, parks funding, climate adaptation funds, development contributions and health oriented programmes all have a legitimate stake. But, if there are gaps in accountability as a result of funding complexity, they should not be present. Although finance may be provided together, one entity should be responsible for the delivery of the services.

Step 6: Apply, using standards that will ensure ecological function. Construction quality matters. A project can fail to meet its goals based on the soil depth, compaction, species selected, drainage connectivity, rooting volume, inlet design and water supply. The standards should, therefore, contain specifications of the functional requirements as well as the visual design. The assessment of contractors for procurement should be based on ecological and engineering competence that is relevant, as should be the case with commissioning prior to handover.

Step 7: closely track throughout the life. Table 6 suggests a dashboard of a scheme for the integration of climate-service, ecological, social, governance and asset-condition indicators. Monitoring frequency should be based on the dynamics of the system: hydrologic performance monitoring may be event based; vegetation condition monitoring may be monitory seasonally; access and social outcome may be monitoring through periodic surveys and/or spatial analysis. Wherever possible, it is important that data are presented geographically and socially to avoid masking inequities by presenting citywide averages.

Learn, adapt and scale - Step 8 Monitoring should be used to prompt maintenance, redesign and policy learning. If a rain garden is not working properly and continues to bypass during moderate storms, it may be necessary to modify the inlet or storage components. Species, watering (or stewardship) practices should be adjusted in order to change a tree programme's survival rates in heat-sensitive areas when survival rates are low. Scaling should be in the form of an established pilot performance standard, capital budget and development regulations, as opposed to a single replication. This is a process in the institution where NBS can be integrated within the day-to-day development of cities.

The three differences between the framework and traditional project cycles are:The three differences between the framework and traditional project cycles are: It starts with not just vulnerability, but project opportunity; it makes equity a design and performance requirement; and it makes monitoring and maintaining capital delivery requirements. The features are directly driven by the gaps that were found in the literature reviewed. They also help to balance two key tensions. The first is between standardization and context: cities have to have the same indicators, design rules, but they need to be adapted at the local level, according to ecological and social conditions. The second one is between multifunctionality and accountability: a project could achieve a multitude of benefits, but for each benefit identified should there be an owner, a metric and a monitoring plan.

The framework holds other implications for the rapidly-urbanizing cities and the Global South. Goodwin et al. (2023) have noted a geographic bias, which will not allow one to merely move evidence from a temperate, high-income, context. Performance and feasibility can be affected by informal land tenure, lack of infrastructure, governance capacity, tropics precipitation, water scarcity and various maintenance regimes. The answer is not to say no to NbS, but to focus on context-specific pilots that are carefully monitored, involve communities and can be incrementally scaled up. NbS can be especially useful when it comes to tackling several gaps simultaneously, for instance in flood management, provision of public spaces and heat reduction; but institutional and social requirements for the delivery of NbS also need to be paid attention.

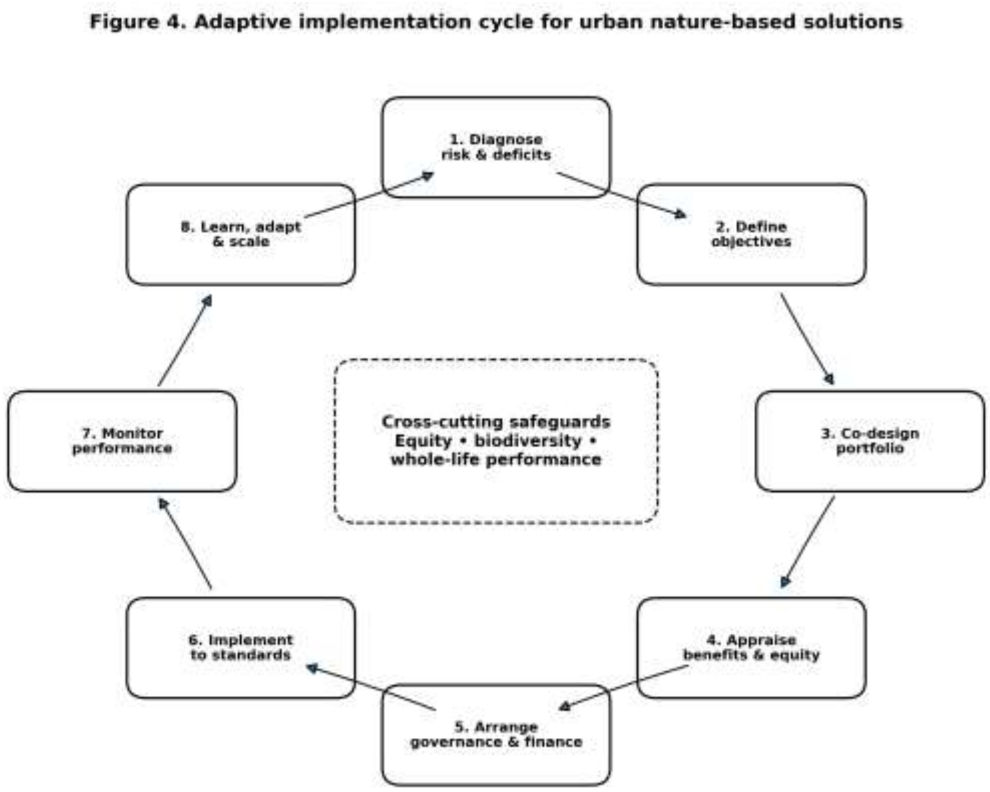

Figure 4. Adaptive implementation cycle for mainstreaming urban nature-based solutions.

Table 6. Proposed performance dashboard for urban NBS Programe

Dashboard domain	Example indicators	Suggested review interval
Climate service	Peak-flow reduction; runoff retained; thermal exposure reduction; shaded-route coverage	Event-based / seasonal
Ecological condition	Canopy survival; vegetation cover; habitat quality; soil condition; connectivity	Seasonal / annual
Social equity	Access by vulnerable groups; participation; affordability/displacement signals; user satisfaction	Annual / biennial
Asset performance	Blockage; irrigation failure; structural condition; maintenance backlog	Monthly-seasonal depending on asset
Governance	Responsible owner assigned; maintenance funding secured; cross-agency actions closed	Quarterly / annual
Economic value	Whole-life cost; avoided damage; energy savings; cost per unit service	Annual / major review

8. Conclusion

NBS are no longer new additions to the urban greening agenda, but they are now on the frontline of climate-resilience discussions thanks to their ability to concurrently address climate risk and biodiversity, public space and health, environmental quality and more – all while producing something conventional infrastructure cannot. The synthesis of the 60 studies carried out in this paper indicated that the highest level of evidence exists for the fields of urban cooling, storm water management and multifunctional ecosystem services, and the highest number of studies are found in the field of governance, monitoring, equity and scaling. This change is an important development in the area. An important question now is not just whether vegetation, soils and water can deliver useful services to the cities, but whether the cities can put in place the institutions, finance, maintenance and social protection measures to ensure that the services are reliable and equitably available over time.

Three conclusions follow. First, NBS should be considered as multi-functional infrastructure that has clear service goals and whole life asset management. Second, effectiveness is situational; meaning that it relies on the interaction of ecological design, urban form, grey infrastructure, land, governance, maintenance and population's vulnerability. Thirdly, ‘resilience' has to be assessed through the process of environmental improvement, not just the overall improvement, but whose it benefits, who is involved and whether new investments involve additional social hazards. These findings call for the shift away from one-off greening initiatives to NBS portfolios within a wider climate plan, land-use planning, infrastructure policy, and city budgets.

Further research should focus on long-term primary data monitoring, standardized, flexible indicators, life-cycle cost and performance data, comparative studies in different climatic and institutional settings, and more evidence from the Global South. World-class research should also be undertaken on NBS portfolios' effectiveness in responding to compound events and how anti-displacement policies can be tied to climate-resilience investment. However, NB solutions are not a replacement for measures to reduce emissions or vital gray infrastructure if used wisely. These are an additional source of living infrastructure that can enhance the resilience, adaptability and public value of urban development.

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