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Global synthesis and regional insights for mainstreaming urban nature-based solutions

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Nature-based solutions (NbS) have emerged as a key strategy for sustainably addressing multiple urban challenges, with rapidly increasing knowledge production requiring synthesis to better understand whether and how NbS work in different social, ecological, economic, or governance contexts. Insights in this Perspective are drawn from a thematic review of 61 NbS review articles supported by an expert assessment of NbS knowledge in seven global regions to examine key challenges, fill gaps in Global South assessment, and provide insights for scaling up NbS for impact in cities. Eight NbS challenges emerged from our review of NbS reviews including conceptual, thematic, geographic, ecological, inclusivity, health, governance, and systems challenges. An additional expert assessment reviewing literature and cases in seven global regions further revealed the following: 1) Local context-based ecological knowledge is essential for NbS success; 2) Improved technical knowledge is required for planning and designing NbS; 3) NbS need to be included in all levels of planning and governance; 4) Putting justice and equity at the center of urban NbS approaches is critical, and 5) Inclusive and participatory governance processes will be key to long-term success of NbS. We synthesized findings from the NbS review results and regional expert assessments to offer four critical pathways for scaling up NbS: 1) foster new NbS research, technological innovation, and learning, 2) build a global NbS alliance for sharing knowledge, 3) ensure a systems approach to NbS planning and implementation, and 4) increase financing and political will for diverse NbS implementation.

Nature-based solutions | urban | adaptation | cities | review

The increasing impacts of societal challenges in cities—including climate change, food and water security, health, and biodiversity loss—underline the need for multifunctional solutions that maximize cobenefits. The majority people, infrastructure, and economic activity is concentrated in cities, making them the global locus for social and economic risks as well as opportunity spaces for solutions. Cities around the world are rapidly investing in nature-based solutions (NbS) to complement, replace, or improve upon technological and engineered approaches to infrastructure-based solutions (1–5). To match the urgency of climate-related disruptions, costs, and impacts (6), NbS adoption and implementation must be accelerated. Yet, despite the demonstrated potential of NbS, uptake and knowledge is uneven globally (7). Knowledge on NbS in published literature is geographically biased from the Global North with less known

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from Global South regions (1, 7, 8). Even with proliferation of literature reviews on NBS, there remains a gap in studies that assess the state of knowledge in the literature and provide opportunity to augment insights from non-English literature and experiences from Global South contexts. Here, we help fill the gap in Global South knowledge assessment by combining a review of NbS review papers with a regionally focused expert review in diverse global regions to identify similarities and differences in barriers to NbS adoption and practice while synthesizing critical ways forward for addressing key challenges to implementation and research.

NbS should be conceived as systemic interventions to work with nature to address societal challenges (2, 9, 10). Yet, this inclusive term is viewed differently in various contexts with varying definitions but can be generally viewed as actions that restore, conserve, or protect nature to address societal challenges and may include established approaches such as ecosystem-based adaptation and disaster risk reduction, ecological infrastructure, green infrastructure, ecosystem restoration and conservation (11), and natural climate solutions (12). These nature-based approaches are already being used in cities around the world to support climate change adaptation and other strategies because they provide multiple benefits. NbS benefits include ecosystem services, or nature's contributions to people, such as stormwater absorption, air and water quality regulation, urban cooling, coastal protection, and recreational, health, and quality-of-life benefits. NbS can also contribute to climate change mitigation and sustain or enhance biodiversity (12–15). Indeed, a large part of the appeal of NbS is their multifunctionality and potential to address multiple Sustainable Development Goals simultaneously (2, 7, 9, 16).

The global research communities jointly with policy makers and practitioners (e.g., IUCN-International Union for Conservation of Nature, ICLEI-Local Governments for Sustainability) have made a convincing case for the importance of NbS in such fora as the UN Habitat III "New Urban Agenda" (2016), the Intergovernmental Panel for Climate Change (IPCC) "Cities and Climate Change" Charter (2018), and the UN Economic and Financial Committee convened in Nairobi in 2019. Since then, NbS are increasingly prominent in global policy and business discourse on climate change; being included in landmark synthesis reports by the IPCC (17, 18), the IPBES (19), World Health Organization (20), the World Economic Forum Global Commission on BiodiverCities (14), among others. Despite the rapid emergence of green infrastructure and other NbS strategies in urban climate adaptation policies and plans, research and knowledge globally are highly varied with unevenness in how NbS are applied, their efficacy, modes of governance, and variable adaptation impact (2, 3, 5, 16, 21).

In this Perspective, we draw insights from a systematic review of 61 NbS review papers (*SI Appendix*, Fig. S1; see *SI Appendix* for detail) combined with a global regional expert assessment of urban NbS practice across seven global regions (*SI Appendix*, Fig. S2) to 1) better connect global knowledge and strengthen the evidence base for mainstreaming NbS to improve climate change adaptation, 2) reveal the diversity of applications and challenges that NbS respond to across different global urban contexts, and 3) understand where research can better support the needs of urban practice (including policy, planning, design, management, and participation) for improving climate change adaptation at the local and regional scale. We discuss eight global challenges synthesized from the urban NbS review of reviews, and five key insights which emerged from the regional expert review process designed to fill regional gaps in published literature, especially from the Global South. Finally, we distill four key pathways forward for addressing challenges to better mainstream effective NbS research and practice (Fig. 1).

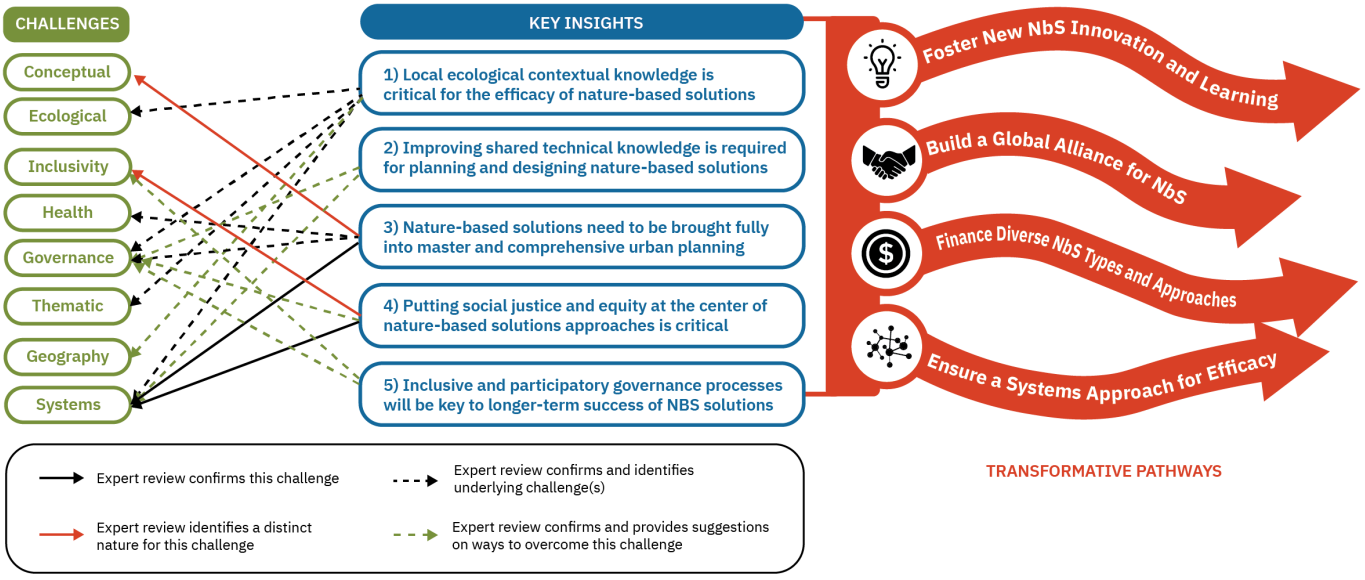

Fig. 1. Comparison of the NbS review of reviews with regional expert assessments resulting in four insights suggesting key pathways forward for advancing the science and practice of urban NbS. Synthesized pathways are drawn from eight key challenges identified across the global-scale thematic review of reviews and the five insights from the expert-driven assessment of regional literature and practice. Arrows show linkages where the expert assessment confirms key challenges and/or identifies opportunities to overcome a challenge such as 1) where findings from the expert review confirms one or several challenges identified in the high-level systematic review (plain black arrow); 2) where the expert review confirms a challenge and provides further insights through the identification of underlying challenges (dashed black arrow); 3) where the expert review confirms the challenge and also provides suggestions on ways to overcome it (dashed green arrow); 4) where the expert review identified a distinct nature of the challenge found in the review of reviews (plain red arrow).

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Key Challenges for NbS Research from a Review of Reviews

Our thematic review of NbS review papers (*SI Appendix*, Fig. S1) identified 61 review articles on urban NbS which were examined for key challenges and opportunities for mainstreaming NbS. We used NbS as our search term to better understand how the NbS concept is emerging globally in research and practice (see *SI Appendix*, Fig. S1, *SI Appendix* for detailed methods, and summarized review of NbS review results in *SI Appendix*, Table S1). Overarching questions guiding the review of reviews included: 1) What are the social challenges for implementing NbS in cities? 2) What are the ecological challenges for implementing NbS in cities? 3) What are the opportunities for future research and practice of NbS in cities? These questions were framed to assess key knowledge gaps important for advancing research and practice of NbS in cities. We focus here on points of overlap and agreement, highlighting also differences in key findings, to identify critical challenges needing addressed to enable the full potential of NbS.

Results from the thematic analysis of all review articles yielded a series of synthetic social, ecological, and knowledge challenges important for advancing research, mainstreaming implementation, and scaling up NbS practice (*SI Appendix*, Table S1). Each challenge highlights the need for science–policy interactions to advance knowledge and practice of NbS. Eight cross-cutting global urban NbS challenges emerged, including:

Conceptual Challenge: NbS is widely framed as an umbrella concept that brings together disparate but related research and applications of urban forestry, green and blue infrastructure, urban agriculture, ecosystem services, ecosystem-based adaptation and disaster risk reduction, and sustainable urban water drainage systems (5, 22, 23). NbS is thus the source of confusing and lengthy debates over its definition(s), and the question of whether it serves to divide the academic and practice communities further or unite them remains open. Reviews show that some argue for NbS to encompass any solution that utilizes ecosystems to address societal challenges, whereas others argue for a narrower definition (24, 25). Others still argue that breadth of conceptualizations might not be a problem in and of itself, rather we should pay attention to implication of various NbS-related terms and definitions in practice.

Thematic Challenge: Research on NbS has recognized their efficacy across social–ecological urban system challenges (23), though these aspects are not evenly researched. There is general agreement that a large majority of NbS research focuses on water-related challenges, especially flooding (25, 26). There is increasing attention to urban heat exposure globally, but there are relatively fewer scientific advances putting NbS into practice for other climate and weather-related threats, such as drought and air pollution (5, 27–33). Several reviews highlight how certain types of NbS studied in the Global North are less relevant for the Global South (34). Such disparities in NbS research directly relate to wider variations in the uptake of NbS across disciplines. Though disciplines such as urban planning, design, ecology, and conservation biology have strongly engaged with the concept of NbS, knowledge coproduction across a wider array of disciplines and beyond science is needed to shift toward interdisciplinarity and transdisciplinarity (26).

Geographic Challenge: NbS research epicenters are mainly in Europe and the United States (25, 33, 35). The Global South, including parts of Asia, Africa, and Latin America and the Caribbean (LAC) are newly emerging in the literature as contexts for NbS application, replication, scaling, and monitoring (36). However, most reviews highlight a strong geographical bias in knowledge production, as well uneven distribution of evidence of efficacy and social–ecological performance of NbS, which hampers implementation and wider adoption. Global South cities were often noted as locations of knowledge gaps (27, 34, 37), with regionally appropriate knowledge generally scant on how to adapt local NbS to larger scales (38).

Ecological Challenge: Research on NbS often focuses on their design yet fails to quantify their performance, particularly in relation to climate adaptation and resilience (39). An ecological relevance gap mirrors the geographical challenge with a preponderance of evidence originating primarily from northern hemisphere biomes at the expense of other regional ecological knowledge (27). Another dimension in the ecological challenge is the dominance of studies on terrestrial NbS with relatively limited research on aquatic and marine NbS and their cobenefits (34, 36). Additionally, review studies noted little evidence on comparative benefits between native and nonnative plants for NbS design (40), though recent assessments note that contributions of invasive species to people are largely negative (41, 42). Additionally, while urban trees and their role in climate adaptation and mitigation is commonly researched, there are disagreements over ways to maximize benefits especially regarding their spatial distribution and the scale of beneficial impacts (43).

Inclusivity and Justice Challenge: The most prominent societal challenge facing NbS is how to center justice and make inclusive planning for NbS a standard practice given limited participatory urban planning and governance (23, 24, 26, 32, 44–53). This challenge was emphasized in reviews noting needs for socioecological justice considerations in NbS planning. Though global studies emphasize different aspects of NbS features and their implementation, our thematic analysis suggests a need for incorporating aspects of gender inclusion in planning and governance of NbS (37). Generally, there is wide agreement over the need for more research on justice aspects and processes of NbS, notably on local community participation to address potential trade-offs for marginalized and disadvantaged groups (46). However, particular aspects of justice like ecological or multispecies justice are inconsistently researched, notably because benefits are often assumed (54, 55).

Health Challenge: There is strong evidence on the positive public health outcomes from engaging with nature and biodiversity and from living near urban green spaces in cities (44, 47, 56–62). This is further supported by positive benefits of NbS on human well-being (47, 63) from engaging with gardening and urban agriculture in general (22, 63) and employing NbS to lower health risks and vulnerabilities (30). Yet, despite evidence on such positive impacts of biodiversity, researchers also report inconsistencies that require attention (59, 64). For example, the relationships between NbS, plant diversity, climate change, and human psychology require more research (39, 64). Studies that examine different types of NbS and their role in positive physical or mental health outcomes are needed to elevate NbS as critical health infrastructure in cities.

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Governance Challenge: Governance challenges include the limited uptake of NbS in urban planning, limited project-based planning, and siloed approaches in planning practices (23, 31, 53, 65, 66). There is related inconsistency in science–policy integration and knowledge transfer at strategic and urban planning levels (26, 48, 56, 59, 63, 66–68) as well as limited evaluation of how NbS generate or contribute to financial benefits (69). In regions such as Africa, both formal and informal decision-making structures exist within governance. The former are supported by policies and legal frameworks; the latter are based on unspoken agreements and invisible power dynamics and are therefore more complex to grasp (70). Further, cross-scale and cross-sector urban planning, such as in the case of blue-green infrastructure and food–water–energy nexus planning, is often nonexistent or lacking integration (38, 71).

Systems Challenge: A fundamental science challenge is that urban NbS are not evaluated or planned as social–ecological–technological systems (SETS) solutions despite being embedded in diverse urban contexts requiring integration with critical infrastructure, social practices, and functioning ecosystems to be effective (72–74). NbS are still mostly studied for their ecological functions, although increasing attention is paid to their social contexts. To date, NbS research and practice continue to overlook critical technology and infrastructure relationships that may underpin effective NbS, thus driving implementation and management in a fragmented way (5, 23, 26, 45, 49, 75).

Five Key Insights for Contextualizing NbS Research and Practice from a Regional Expert Assessment

Our regional expert-driven assessment leveraged NbS experts located in, and with diverse knowledge from, seven global regions. We sought input from a range of global regions to compare insights and help fill the gap in Global South knowledge assessment that builds on regional literature, experience, and expert knowledge. Detailed methods on how experts were chosen, questions guiding regional assessment, and how five key insights were drawn from the results are detailed in *SI Appendix*, *supporting text*, Fig. S2, and Table S2). The regional expert assessment was designed to help address the Global North bias in published NbS literature (7) which not only augments findings from the NbS review of reviews but yields further, regional insights. Synthesis of how the presented challenges and opportunities relate across both review approaches is discussed below and summarized in Fig. 1, as well as *SI Appendix*, Fig. S3. Regional expert assessments (*SI Appendix*, Table S2) show that even though the review of review findings provided strong evidence for synthesized key challenges (*SI Appendix*, Table S1), actions to tackle them require regional insights to ensure fit-for-context methods, approaches, and strategies to advance the knowledge and science of NbS. Below, we synthesize five key *Insights* which emerged through strong overlap in the regional assessments. For each insight we briefly include the most evident regional examples and key literature, focusing primarily on Global South insights, though synthetic insights from all regions are highlighted in *SI Appendix*, Table S2.

Insight 1. Local Ecological Contextual Knowledge Is Essential for Effective NbS. Although the adoption of NbS for climate adaptation and resilience is widespread globally, effective NbS function in any given location depends on a diverse set of social, ecological, economic, and infrastructural factors (5, 16, 76). For example, early tree-planting campaigns in water-stressed cities have been conducted with insufficient allocations for irrigation resulting in tree stress and mortality during times of drought (77). Such cases demonstrate the critical need to match NbS to the local ecological context for NbS to be sustainable and effective in delivering multiple benefits. This matching implies that NbS design and siting need to ensure that any NbS can be ecologically resilient themselves and not produce unintended trade-offs (21, 78, 79). Ecological relevance of any NbS can often come down to understanding which native species (and their traits) are most relevant to a specific area, also as climate change may cause range shifts (80) stressing species' ability to adapt and thrive in NbS designs (17).

Currently, NbS tend to be conceptualized in the Global North and replicated in the Global South, which ignores disparities in ecological and socioeconomic contexts (34, 46). For Indian cities, Gajjar et al. (81) warns against path dependency leading to maladaptation. This concern emphasizes the need to reimagine NbS and locally test solutions that foster learning within and between cities to avoid maladaptation, such as focusing on indigenous plant species in urban green spaces, sourcing of climatically suitable genotypes, or implementing with community institutions that understand local cultural and social norms. The development of NbS needs to consider not only ecological contexts but also ensure that NbS are integrated into the local infrastructure and cultural context. As NbS are being deployed across most biomes, they are being used for different purposes, which require more networked and local knowledge to share successes, report on failures, and advance the efficacy of NbS (82).

In LAC countries, NbS research has often focused on environmental factors influencing implementation and the role of ecosystems in supplying local ecosystem services (50, 82). Yet, LAC has 178 ecological regions representing more than 50% of the planet's biodiversity (83). Regions require more extensive ecological and social research to address uncertainties on localized impacts to develop more effective NbS. For instance, Rodriguez-Dominguez et al. (84) listed 520 examples of constructed wetlands in the region. Yet, without comparable evidence from cities of diverse sizes, biomes, resilience challenges, and governance structures, knowledge gaps will persist and may impede effectiveness of NbS implementation. Drawing on examples from the Global North often has limited relevance because of socioenvironmental differences, thus cross-comparative research on the effectiveness of types of NbS across climate zones within countries is a critical need (85).

Indigenous, local and traditional knowledge in many countries of the Global South (as in the Global North) is essential to providing a core foundation for the relevance and practice of NbS (86, 87). In South Africa, historical planting practices to stabilize mobile sand—whether by public agencies or private individuals—demonstrate how remnant nature can serve as a critical enabling force for multiple benefits (88). In Lilongwe (Malawi) and Addis Ababa (Ethiopia), plans for the protection

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and restoration of urban natural assets have been successfully translated into action through the development of urban parks on restored riverbanks (86). However, where such examples exist, they are often buried in institutional reports and gray literature rather than in globally accessible sources. Often, cases from the Global North can be contextualized inappropriately in the region and locally devised cases remain a critical need. Across Africa, there is need for evidence drawn from NbS-related practices since the region needs clarity on NbS efficacy under diverse conditions and additional research to understand ecological, social, and economic outcomes (89). Additionally, informal settlements are important contexts within the Global South where NbS can prove valuable, but Global North evidence is little help in guiding application in these areas. Urban tinkering (90), an innovative approach to planning and service delivery, one that is tailored to specific needs of local city challenges, such as informality, have recently been piloted in Lilongwe, Malawi (86).

Insight 2. Improved Technical Knowledge Is Required for Planning and Designing NbS. Despite mounting evidence of opportunities for NbS in technical and economic development around the world, NbS have been underappreciated in urban planning and design. Regional experts argue that causes of this challenge relate to the limited ways through which scientific knowledge becomes available, accessible, and operationalizable to urban planners and city engineers. This notably concerns technical learning from small-scale pilot NbS being neither documented nor transferred to other areas or contexts for informing implementation (21, 31, 48). The lack of technical knowledge and skills in cities directly affects NbS design, implementation, and management (2, 31, 32) and the way multiple benefits can be monitored (23, 48, 75). Civil engineers and designers may need to be taught to integrate nature into their designs. Further, gaps in empirical evidence, data, and indicators of NbS functioning prevent accurate parameterization and validation of models and development of future scenarios (38, 91).

In Asia, for example, there is a growing body of implemented NbS projects that is largely dominated by low-cost solutions—especially in informal settlements—but learning remains insufficiently documented. Across regions, cities need to invest in upgrading the competencies of urban planners to support evaluation and monitoring schemes for NbS that will generate the evidence base needed to inform strategic plans and impactful NbS projects. In Africa, town planners traditionally use spatial development frameworks and land-use plans to identify key natural assets and make infrastructure-related decisions. To build resilient cities and prevent urban encroachment on open green spaces, innovation is required that shifts the focus from demarcating natural assets on land-use maps to using nature as a central tool to guide city planning.

NbS implementation, however, is not typically initiated from a system or transdisciplinary perspective. In LAC, there is persisting need to bridge diverse perspectives to consider multiple forms of NbS that can be integrated into design and planning approaches (50). In addition to the lack of training and knowledge of stakeholders and decision-makers, there is a shortage of local design guidelines because NbS are not typically the focus of local engineering and planning curricula (32, 92). Yet, there are important enabling forces for NbS implementation in LAC communities. These forces stem from collaborations with grassroots and other nongovernmental climate mitigation initiatives (93). For example, a consortium of public, private, academic, and community members in the city of Valdivia, Chile, has codesigned and gained support for green infrastructure projects (94). In Colombia, collaborative and participatory projects have brought interdisciplinary teams together with local and international universities, such as in Moravia, a neighborhood in Medellín, Colombia (95) and Altos de la Estancia in Ciudad Bolivar in Bogotá, Colombia. In all regions, shifting toward transdisciplinary approaches that leverage distributed, nature-based approaches will remain dependent on adequate expert training, job creation, and skill development, as well as the commitment of political actors and governance mechanisms to enable NbS implementation.

Insight 3. NbS Should Be Included in All Master and Comprehensive Urban Planning. Upscaling NbS remains scarce due to their limited uptake in urban planning. The regional assessment shows that urban planning needs to strategically prioritize NbS for urban resilience and to integrate urban biodiversity into urban planning projects and programs (29, 61, 67, 96). Barriers for scaling up NbS include the inability of urban planners to capitalize on social and policy learning from NbS that have been already implemented to devise strategic plans for city-wide or regional upscaling. Additional barriers include lack of systematic monitoring and evaluation schemes for assessing the multiple benefits of urban NbS (97). This in turn blocks information flows and evidence for making a business case for NbS critical for scaling up implementation (38). In some Global South contexts, the term NbS is increasingly seen as problematic and is actively resisted due to its potential to stimulate greenwashing practices, reinforce legacies of oppression, or to negate rights to land tenure (98, 99).

Globally, successful NbS projects that can serve as models for upscaling NbS through planning remain isolated. Limited evidence-based planning highlights an overall lack of city-scale empirical evidence on the combined economic and noneconomic benefits of NbS (100). Fragmented, siloed urban planning approaches undermine system-thinking approaches that are necessary for effective NbS. For example, in India, NbS are primarily implemented through project-based interventions, with few cities considering NbS comprehensively in their master plans. The Green Highways Policy in India is a useful, though isolated, case of a city-wide initiative for environmental compensation mechanisms integrated into infrastructure planning and coupled with livelihood generation (101). Yet, national policies such as the Atal Mission for Rejuvenation and Urban Transformation or the Smart Cities Mission tend to focus on infrastructural and technological solutions (81, 102). Indian cities also face inadequate decision-making and financial devolution to urban local governance bodies that together with time scale mismatches between mayoral terms and long-term planning horizons may hamper innovative NbS-related climate action (103). Yet in China, the design of "sponge cities" through green infrastructure approaches for urban stormwater management is expanding (104, 105). Despite limited evidence and experience with NbS under diverse local conditions, China has followed a learning-by-doing approach to pilot projects in selected cities and thereby created opportunities

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for NbS upscaling. Sponge city programs have not only showcased the efficacy of NbS but also the need for urban planning practitioners to better integrate engineering designs into onsite, low-impact development practices while meeting urban policy goals (106).

The regional assessment finds that fragmented governance structures fundamentally impede comprehensive urban planning. In LAC, as many national and local governments turn toward climate action in urban planning initiatives, the framing and acknowledgment of NbS for climate resilience is still limited. Climate adaptation plans are typically adopted at national levels (107). However, several LAC cities have begun to adopt the concept of NbS and integrate it into urban and regional planning for biodiversity preservation, including in São Paulo, Brazil and Lima, Peru (108, 109). Still, since most NbS projects are isolated, it remains difficult to scale-up planning and adopt connectivity approaches at larger scales or in more densely populated areas, including in informal settlements (27, 49).

Insight 4. Putting Justice and Equity at the Center of Urban NbS Approaches Is Critical. Globally, there is limited experience in urban planning and development with designing and implementing NbS to deal with social challenges such as legacies of discrimination and segregation that are both historically driven and continue to structure urban life (54, 110). Socioeconomic dimensions and context are underexamined in NbS research to date, and unappreciated in the role they play in the effective implementation of NbS (53, 111). Similarly, ecological research on NbS often pays limited attention to social dynamics and issues of equity, justice, global power imbalances, and distribution of benefits across communities (5, 49, 53).

In LAC, there is a need for more systematic involvement of community stakeholders in formal decision-making to measure the cultural and economic value of NbS (50) and in planning and implementation procedures (93). Highlighting the financial and social benefits, as well as understanding possible unintended tradeoffs, is important for the integration of NbS into future planning. In the context of informal settlements, there is evidence of NbS providing important socioeconomic benefits to residents but also of having reproduced patterns of environmental injustices where participatory processes have been weak (112). A key gap in LAC is limited study of the equitable distribution of NbS benefits in communities and the relationship of NbS with community vulnerability and social equity (49). Ultimately, NbS should neither be designed nor managed to operate in isolation from its social context but rather as part of place-making approaches to transform places, spaces, mindsets, and social relations simultaneously.

In Africa, engagement with communities for planning NbS is time-sensitive and time-demanding. This is especially the case where poverty and service delivery direct responsive action alongside histories of dispossession, sociopolitical instability, weak governance, and corruption that hinders policy implementation (89). Experiences from South Asian cities further point to the inadequate engagement with citizens and the corporate sector to increase interest and funding for NbS (100). However, the high degree of informality in these regions can allow for a degree of civic engagement in NbS generation that presents opportunities quite different from those in the Global North.

Though we primarily focus on Global South insights, equity and justice concerns in NbS projects have emerged as a major challenge in the Global North. In North America, NbS are being widely deployed across cities, particularly through green infrastructure programs, urban tree planting campaigns, and wetland restoration. Yet, despite calls for more inclusive planning processes, cities still fail to adequately include equity and justice in urban planning for green infrastructure and related NbS (98, 110). Historical injustices remain pervasive in the United States with cities marked by large inequalities in access to green amenities (113, 114), with a major concern about gentrification from "green" redevelopment (115). Green infrastructure planning efforts operate in the context of long running structural inequalities driven by racist and classist planning practices and prior efforts for urban improvement and renewal (116). Additionally, industry in the United States continues to have an outsized voice in environmental policy and planning (117). More recently, federal US policies such as Executive Order 14008 require federal agencies to analyze the impacts of their decisions on communities in relation to environmental justice (118). This presents the potential to shift NbS planning to be more inclusive, a prerequisite for bringing equity and justice into NbS planning and policy. Still, research is making clear that for NbS to be transformative, dedicated resources for participation should be made available alongside the creation of governance systems that include local communities. Such approaches have started to take shape in participatory budgeting processes and could be expanded for NbS (119).

Insight 5. Inclusive and Participatory Governance Processes Will Be Key to Long-Term Success. Globally, NbS are largely implemented through efforts led by federal and local governments creating programs that invest in climate adaptation and urban biodiversity (65, 96, 110, 111). Regional insights agree on the need for inclusive NbS governance. There is strong push from government in terms of agenda setting and investment of NbS occurring across regions that needs to be diversified for inclusive NbS governance. For example, in the European Union, a significant amount of financial investment has gone into research on the innovation potential of NbS as demonstrated by the review conducted by NetworkNature (120, 121). Although regional and national government action on NbS is desirable, involvement and investment from a wider diversity of actors is vital for long-term NbS impacts and integration into broader development efforts (e.g., beyond climate or biodiversity-focused strategies).

Inclusive governance for NbS needs to become standard practice rather than a requirement (110, 122) to ensure the delivery of multiple benefits and to alleviate rather than exacerbate issues of segregation and unequal access to NbS benefits. However, as the number and diversity of stakeholders increases in such participatory processes, potential for conflict can also increase. While there are good practices in many NbS cases that illustrate the advances and benefits of a multisectoral collaboration for their implementation, inclusive governance for NbS is far from standard practice in many regions, e.g., in the United States (110). Governing NbS

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inclusively means including multiple knowledge, including indigenous knowledge, in designing and implementing NbS and incorporating local customs and the role of community (31, 33, 55, 122). Examples from practice all around the world point to inclusive governance approaches that could be replicated. In Europe, the project NATURVATION identified stepping stones to tap into the potential of NbS for more inclusive cities, including in Spain and Hungary (123). In South Asia, recent lessons can be drawn from urban lake restoration efforts in Indian cities, such as the Mansagar Lake in Jaipur, and Kaikondrahalli Lake in Bengaluru, recognized for their multiple provisioning services and recently restored using diverse approaches with local communities. These examples show the potential to improve uptake, sustainability, and efficacy of NbS within more inclusive governance structures (31).

Finally, there is a misalignment of regulatory governance at local, national, and global levels for NbS. Additional barriers include fragmented environmental policies and the need for coordination of actors at different levels of governance for climate adaptation and biodiversity conservation (68). The expert assessment shows common misalignment of NbS governance mechanisms between local, national, and global levels. For example, urban planning in LAC has historically been hindered by ineffective governance, weak regulatory structures, lack of transparency, and a focus on economic and political concerns where the needs of the private sector are prioritized, often at the cost of urban green spaces (124, 125). There are often mismatches or tensions among stakeholders, such as between top–down governmental agendas for conservation and local, municipal needs for housing (126). There are considerable blind spots for designing and planning NbS for informal settlement conditions (27). This is particularly visible in the context of informal and unplanned urbanized areas where NbS development can enhance land-use conflicts (27, 126).

Four Pathways for Advancing the Science and Practice of NbS in Cities

The comparison of the regional findings above with the thematic review of reviews show results of both processes largely converge and confirm the wide range and complex nature of challenges that currently impede the proliferation and mainstreaming of NbS worldwide. Regional insights open avenues toward better understanding of the causes of several key global challenges ("underlying challenges" Fig. 1 dotted black arrows) and evidence of mechanisms that can be put in place to address critical challenges for NbS research and practice. Furthermore, regional experts highlighted distinct ways to understand some local and regional challenges ("distinct nature for this challenge" Fig. 1 red arrows) that remain understudied and were not drawn from the review of the reviews. Synthesizing results from both review processes and comparisons of key findings we suggest four critical pathways forward for advancing the science and practice of NbS in cities.

Pathway 1. Foster New NbS Innovation and Learning. Many NbS experiences from the Global South suggest that often simple solutions leveraging indigenous, local and traditional knowledge can far outpace the performance of those imported from other Global North contexts. By looking back at these solutions, often unwritten, forgotten, and passed on verbally through generations, urban NbS could find new innovations grounded in traditional, practical, place-based, and indigenous knowledge to examine what could work in a variety of urban contexts including modern rapidly growing cities. Recognizing these knowledge already as NbS and bringing them forward in new NbS practice can help revolutionize NbS projects. Yet, technological advances also hold great potential for improving the context specificity and fit of NbS in diverse regions. The advent of big data, robotics, and augmented computer capabilities offer the unprecedented ability to collect, analyze, and synthesize vast amounts of environmental, social, and climatic data to drive context appropriate urban NbS applications (127, 128). AI and new analytical tools hold promise for boosting the ability to model and predict complex systems including NbS and their interplay with social, climatic, and environmental factors and potentially increase our confidence when attempting to extrapolate outcomes to other urban areas. Engaging with both diverse knowledge and emerging technologies creates opportunities for evaluation and improved precision and effectiveness in NbS implementation (79).

Though current NbS research is relatively deeper in the Global North, literature as well as the regional expert review points to the need to carefully examine which types of NbS, and which practices for planning and governance may be suitable for Global South contexts, and vice versa. Taking a pluriversal epistemology can be a way forward for understanding how "nature" is perceived and valued to better leverage NbS to address urban challenges in the Global South. Such approaches can include social learning through codesign, cocreation, and cogovernance approaches such as through Living Labs, which have been expanding beyond proliferation in European cases to LAC (61). These more inclusive approaches can open the dialog and learning from these cities and geographies and will offer opportunities for different types of NbS to emerge and to systematically study and inform research and practice globally.

Pathway 2. Build A Global Alliance for NbS. To build a strong evidence base for the efficacy of NbS for climate adaptation and resilience, different researchers and disciplines engaging with research on NbS need to operate in a collaborative and integrated way weaving in different types of knowledge. Professional organizations (national, regional, or global) may be better positioned to support practice. To achieve this, greater regional and national government investments in the implementation, monitoring, and evaluation of NbS systems would need to create platforms in which cities could learn about different types of NbS and how they could be best governed. Such a pathway may vary regionally but can have coordination flows through a network of networks approach for NbS such as those that exist within ICLEI, C40, World Bank, UNEP, NATURA, OPPLA, and Cities with Nature. Long-term funding is needed to support such networks for knowledge sharing and alliance building, which will need to be financed by diverse mechanisms from research funding bodies to governments and philanthropy. In a post-COVID era where networking opportunities are increasingly digitally facilitated, enabled collaboration at a global level can help level the knowledge geography challenge, though internet and electricity supply limitations can hamper inclusion of Global

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South scholars. While challenges remain on the effective NbS knowledge and practice transfer, mainstreaming NbS will benefit from new ways of bridging diverse knowledge especially concerning climate knowledge and stressors, such as the creation of NbS climate-analogs and global NbS Climate Labs (21). The creation of shared platforms for real-time data sharing could significantly improve models and predictions of the environmental benefits that NbS can provide (91).

Pathway 3. Ensure a Systems Approach to Underpin Efficacy for NbS. Systematizing the knowledge of NbS is required at regional and global scales to understand which NbS types, planning practices, and approaches for their application and implementation are likely to work across different geographies, social, economic, ecological, and infrastructural contexts (122). NbS are complex, just as the urban systems they are embedded within, and so interdisciplinary and transdisciplinary systems approaches are needed to ensure NbS can reliably meet the climate, health, and sustainability goals they are designed to address. Multiple review and perspective articles have noted the challenges of mainstreaming NbS and the need for more systemic understanding and governance of their social-, ecological-, and technological-infrastructure dimensions because designing, planning, or managing dimensions of NbS in isolation fundamentally neglects critical subsystem interactions that influence their efficacy across multiple scales (5, 73). This will require a systems approach for NbS design, planning, management, monitoring, and evaluation (5, 73, 129) as well as evidence gathering to build a compelling economic, health, biodiversity, and climate adaptation case for nature in cities with and through NbS (35). The SETS framework holds promise for ensuring that diverse dimensions and feedbacks of NbS are considered from planning to evaluation (73).

Pathway 4. Finance Diverse NbS Types and Approaches to Drive Urban Climate Innovations. The experience from research and practice on NbS should be supported with funding while also targeting divestment from other gray solutions (or high-carbon solutions). However, numerous institutional and financial barriers still exist in relation to access to funding, cost forecasting, taxation and incentives, and transaction costs (69, 130). Innovative options include market-based mechanisms that account for public good benefits, such as through tax credits, property tax relief, bids, NbS-bonds, and sustainable finance initiatives related to climate change, as well as other economic, financial, and regulatory instruments that could offer greater opportunities for NbS buy-in (69, 131). If properly designed, these tools can be mechanisms for reduced public expenditure. These options can also help advance business-led opportunities for NbS implementation at scale dealing directly with financial governance challenges. Additionally, funding is needed to increase staff in relevant city agencies and to develop curricula within academic institutions to improve training on NbS. Improving education and research resources can help showcase how NbS, through their diversity and proven efficacy, can help drive other forms of urban innovations (132). Finally, while diverse financing options are critical to scaling up NbS implementation, there is also a need for improved knowledge on the costs and benefits of NbS over the longer term, emphasizing the need to bring life-cycle approaches into NbS evaluation and monitoring.

We assess global urban NbS knowledge with the aim of addressing NbS knowledge gaps, including in relation to the conceptual and epistemological dimensions, and application across different geographies in order to strengthen the evidence base for the mainstreaming of NBS, including in cities of the Global South. We suggest four key pathways for advancing the frontier of research and practice on urban NbS to help unleash the full potential of NbS to shift urbanization trajectories from vulnerable to resilient ones. Filling knowledge gaps, strengthening political and administrative frameworks, creating more equitable and inclusive processes, and changing regulatory and planning systems are critical to open windows for transforming urban systems through NBS.

Data, Materials, and Software Availability. All study data are included in the article and/or *SI Appendix*.

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1. F. J. Escobedo, V. Giannico, C. Y. Jim, G. Sanesi, R. Lafortezza, Urban forests, ecosystem services, green infrastructure and nature-based solutions: Nexus or evolving metaphors? *Urban For. Urban Green.* **37**, 3–12 (2019).
2. N. Frantzeskaki *et al.*, Nature-based solutions for urban climate change adaptation: Linking science, policy, and practice communities for evidence-based decision-making. *BioScience* **69**, 455–466 (2019).
3. S. Goodwin, M. Olazabal, A. J. Castro, U. Pascual, Global mapping of urban nature-based solutions for climate change adaptation. *Nat. Sustain.* **6**, 458–469 (2023), 10.1038/s41893-022-01036-x.
4. S. E. Hobbie, N. B. Grimm, Nature-based approaches to managing climate change impacts in cities. *Philos. Trans. R. Soc. B Biol. Sci.* **375**, 20190124 (2020).
5. B. L. Keeler *et al.*, Social-ecological and technological factors moderate the value of urban nature. *Nat. Sustain.* **2**, 29–38 (2019).
6. B. O'Neill *et al.*, "Key risks across sectors and regions" in *Climate Change 2022: Impacts, Adaptation and Vulnerability, Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, H.-O. Pörtner *et al.*, Eds. (Cambridge University Press, 2022).
7. T. Dunlop *et al.*, The evolution and future of research on Nature-based Solutions to address societal challenges. *Commun. Earth Environ.* **5**, 1–15 (2024).
8. X. Fang, J. Li, Q. Ma, Integrating green infrastructure, ecosystem services and nature-based solutions for urban sustainability: A comprehensive literature review. *Sustain. Cities Soc.* **98**, 104843 (2023).
9. A. Chausson *et al.*, Mapping the effectiveness of nature-based solutions for climate change adaptation. *Glob. Change Biol.* **26**, 6134–6155 (2020).
10. N. Kabisch *et al.*, Nature-based solutions to climate change mitigation and adaptation in urban areas: Perspectives on indicators, knowledge gaps, barriers, and opportunities for action. *Ecol. Soc.* **21**, art39 (2016).
11. E. Cohen-Shacham *et al.*, Core principles for successfully implementing and upscaling Nature-based Solutions. *Environ. Sci. Policy* **98**, 20–29 (2019).
12. B. W. Griscom *et al.*, Natural climate solutions. *Proc. Natl. Acad. Sci. U.S.A.* **114**, 11645–11650 (2017).
13. J. Maes, S. Jacobs, Nature-based solutions for Europe's sustainable development. *Conserv. Lett.* **10**, 121–124 (2017).
14. A. Khatri *et al.*, "BiodiverCities by 2030: Transforming cities' relationship with nature" (Insight report, World Economic Forum (WEF), Alexander von Humboldt Biological Resources Research Institute, AlphaBeta-Access Partnership, Arup International, Cologny/Geneva, Switzerland, 2022).
15. N. Seddon *et al.*, Understanding the value and limits of nature-based solutions to climate change and other global challenges. *Philos. Trans. R. Soc. B Biol. Sci.* **375**, 20190120 (2020).
16. E. Andersson *et al.*, Enabling green and blue infrastructure to improve contributions to human well-being and equity in urban systems. *BioScience* **69**, 566–574 (2019).
17. D. Dodman *et al.*, "Cities, settlements and key infrastructure" in *Climate Change 2022: Impacts, Adaptation and Vulnerability, Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, H.-O. Pörtner *et al.*, Eds. (Cambridge University Press, 2022), pp. 907–1040.
18. C. Parmesan *et al.*, "IPCC AR6 WGII cross-chapter box NATURAL|Nature-based solutions for climate change. Mitigation and adaptation" in *Climate Change 2022: Impacts, Adaptation, and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* (Cambridge University Press, 2022), pp. 209–303.
19. E. Brondizio, S. Diaz, J. Settele, H. T. Ngo, "*Global Assessment Report on Biodiversity and Ecosystem Services of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services*" (Zenodo, 2019).
20. World Health Organization, "Urban green space interventions and health: A review of impact and effectiveness" (Full report, World Health Organization (WHO), Copenhagen, Denmark, 2017).
21. A. Ossola, B. B. Lin, Making nature-based solutions climate-ready for the 50 °C world. *Environ. Sci. Policy* **123**, 151–159 (2021).

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22. N. Rao *et al.*, Cultivating sustainable and healthy cities: A systematic literature review of the outcomes of urban and peri-urban agriculture. *Sustain. Cities Soc.* **85**, 104063 (2022).
23. C. M. Raymond *et al.*, A framework for assessing and implementing the co-benefits of nature-based solutions in urban areas. *Environ. Sci. Policy* **77**, 15–24 (2017).
24. H. Dorst, A. van der Jagt, R. Raven, H. Runhaar, Urban greening through nature-based solutions–Key characteristics of an emerging concept. *Sustain. Cities Soc.* **49**, 101620 (2019).
25. L. Li, A. Cheshmehzangi, F. K. S. Chan, C. D. Ives, Mapping the research landscape of nature-based solutions in urbanism. *Sustain. Switz.* **13**, 3876 (2021).
26. H. I. Hanson, B. Wickenberg, J. Alkan Olsson, Working on the boundaries–How do science use and interpret the nature-based solution concept? *Land Use Policy* **90**, 104302 (2020).
27. P. Hamel, L. Tan, Blue-green infrastructure for flood and water quality management in Southeast Asia: Evidence and knowledge gaps. *Environ. Manage.* **69**, 699–718 (2022).
28. L. Khirfan, N. Mohtat, M. Peck, A systematic literature review and content analysis combination to "shed some light" on stream daylighting (Deculverting). *Water Secur.* **10**, 100067 (2020).
29. K. Krauze, I. Wagner, From classical water–ecosystem theories to nature-based solutions–Contextualizing nature-based solutions for sustainable city. *Sci. Total Environ.* **655**, 697–706 (2019).
30. J. Sahani *et al.*, Hydro-meteorological risk assessment methods and management by nature-based solutions. *Sci. Total Environ.* **696**, 133936 (2019).
31. S. E. Sarabi, Q. Han, A. G. L. Romme, B. de Vries, L. Wendling, Key enablers of and barriers to the uptake and implementation of nature-based solutions in urban settings: A review. *Resources* **8**, 121 (2019).
32. I. Vera-Puerto *et al.*, Proposal of competencies for engineering education to develop water infrastructure based on "Nature-Based Solutions" in the urban context. *J. Clean. Prod.* **265**, 121717 (2020).
33. A. A. Zuniga-Teran, A. K. Gerlak, A. D. Elder, A. Tam, The unjust distribution of urban green infrastructure is just the tip of the iceberg: A systematic review of place-based studies. *Environ. Sci. Policy* **126**, 234–245 (2021).
34. C. J. Veerkamp *et al.*, A review of studies assessing ecosystem services provided by urban green and blue infrastructure. *Ecosyst. Serv.* **52**, 101367 (2021).
35. X. Kong, X. Zhang, C. Xu, R. J. Hauer, Review on urban forests and trees as nature-based solutions over 5 years. *Forests* **12**, 1453 (2021).
36. S. Stroud, J. Peacock, C. Hassall, Vegetation-based ecosystem service delivery in urban landscapes: A systematic review. *Basic Appl. Ecol.* **61**, 82–101 (2022).
37. E. K. Nassary, B. H. Msomba, W. E. Masele, P. M. Ndaki, C. A. Kahangwa, Exploring urban green packages as part of nature-based Solutions for climate change adaptation measures in rapidly growing cities of the Global South. *J. Environ. Manage.* **310**, 114786 (2022).
38. P. N. Carvalho *et al.*, Nature-based solutions addressing the water-energy-food nexus: Review of theoretical concepts and urban case studies. *J. Clean. Prod.* **338**, 130652 (2022).
39. J. Parker, G. D. Simpson, J. E. Miller, Nature-based solutions forming urban intervention approaches to anthropogenic climate change: A quantitative literature review. *Sustain. Switz.* **12**, 7439 (2020).
40. K. Berthon, F. Thomas, S. Bekessy, The role of 'nativeness' in urban greening to support animal biodiversity. *Landsc. Urban Plan.* **205**, 103959 (2021).
41. P. M. L. Anderson, P. J. O'Farrell, An ecological view of the history of the City of Cape Town. *Ecol. Soc.* **17**, 28 (2012).
42. E. H. Roy *et al.*, "Summary for policymakers of the thematic assessment of invasive alien species and their control of the Intergovernmental Science–Policy Platform on Biodiversity and Ecosystem Services" (IPBES, Bonn, Germany, 2023).
43. H. J. Baker, M. G. Hutchins, J. D. Miller, How robust is the evidence for beneficial hydrological effects of urban tree planting? *Hydrol. Sci. J.* **66**, 1306–1320 (2021).
44. J. Babí Almenar *et al.*, Nexus between nature-based solutions, ecosystem services and urban challenges. *Land Use Policy* **100**, 104898 (2021).
45. E. Brink *et al.*, Cascades of green: A review of ecosystem-based adaptation in urban areas. *Glob. Environ. Change* **36**, 111–123 (2016).
46. D. T. de Souza, P. H. C. Torres, Greening and just cities: Elements for fostering a south-north dialogue based on a systematic literature review. *Front. Sustain. Cities* **3**, 669944 (2021).
47. J. Dick *et al.*, How are nature based solutions contributing to priority societal challenges surrounding human well-being in the United Kingdom: A systematic map protocol. *Environ. Evid.* **8**, 1–11 (2019).
48. V. Ferreira, A. P. Barreira, L. Loures, D. Antunes, T. Panagopoulos, Stakeholders' engagement on nature-based solutions: A systematic literature review. *Sustain. Switz.* **12**, 640 (2020).
49. C. Ordóñez Barona *et al.*, Trends in urban forestry research in Latin America & the Caribbean: A systematic literature review and synthesis. *Urban For. Urban Green.* **47**, 126544 (2020).
50. L. P. Romero-Duque, J. M. Trilleras, F. Castellarini, S. Quijas, Ecosystem services in urban ecological infrastructure of Latin America and the Caribbean: How do they contribute to urban planning? *Sci. Total Environ.* **728**, 138780 (2020).
51. C. Wamsler *et al.*, Operationalizing ecosystem-based adaptation: Harnessing ecosystem services to buffer communities against climate change. *Ecol. Soc.* **21**, 31 (2016).
52. B. Wickenberg, K. McCormick, J. A. Olsson, Advancing the implementation of nature-based solutions in cities: A review of frameworks. *Environ. Sci. Policy* **125**, 44–53 (2021).
53. A. A. Zuniga-Teran *et al.*, Challenges of mainstreaming green infrastructure in built environment professions. *J. Environ. Plan. Manag.* **63**, 710–732 (2020).
54. J. J. Cousins, Justice in nature-based solutions: Research and pathways. *Ecol. Econ.* **180**, 106874 (2021).
55. M. Pineda-Pinto, N. Frantzeskaki, C. A. Nygaard, The potential of nature-based solutions to deliver ecologically just cities: Lessons for research and urban planning from a systematic literature review. *Ambio* **51**, 167–182 (2022).
56. D. L. Badiu, A. Nita, C. I. Iojă, M. R. Niță, Disentangling the connections: A network analysis of approaches to urban green infrastructure. *Urban For. Urban Green.* **41**, 211–220 (2019).
57. A. Callaghan *et al.*, The impact of green spaces on mental health in urban settings: A scoping review. *J. Ment. Health* **30**, 1–15 (2020).
58. X. Chen *et al.*, Research challenges for cultural ecosystem services and public health in (peri-)urban environments. *Sci. Total Environ.* **651**, 2118–2129 (2019).
59. N. Kabisch, H. Korn, J. Stadler, A. Bonn, "Nature-based solutions to climate change adaptation in urban areas–Linkages between science, policy and practice" in *Nature-Based Solutions to Climate Change Adaptation in Urban Areas: Linkages between Science, Policy and Practice, Theory and Practice of Urban Sustainability Transitions*, N. Kabisch, H. Korn, J. Stadler, A. Bonn, Eds. (Springer International Publishing, 2017), pp. 1–11.
60. S. K. Ostoić, F. Salbitano, S. Borelli, A. Verlič, Urban forest research in the Mediterranean: A systematic review. *Urban For. Urban Green.* **31**, 185–196 (2018).
61. I. Säumel, S. E. Reddy, T. Wachtel, Edible city solutions–One step further to foster social resilience through enhanced socio-cultural ecosystem services in cities. *Sustainability* **11**, 972 (2019).
62. A. Sharifi, M. Pathak, C. Joshi, B.-J. He, A systematic review of the health co-benefits of urban climate change adaptation. *Sustain. Cities Soc.* **74**, 103190 (2021).
63. M. Artmann, K. Sartison, The role of urban agriculture as a nature-based solution: A review for developing a systemic assessment framework. *Sustain. Switz.* **10**, 1937 (2018).
64. R. Aerts, O. Honnay, A. Van Nieuwenhuyse, Biodiversity and human health: Mechanisms and evidence of the positive health effects of diversity in nature and green spaces. *Br. Med. Bull.* **127**, 5–22 (2018).
65. N. Kirsop-Taylor, D. Russel, A. Jensen, Urban governance and policy mixes for nature-based solutions and integrated water policy. *J. Environ. Policy Plan.* **24**, 498–512 (2022).
66. V. Venkataramanan *et al.*, Knowledge, attitudes, intentions, and behavior related to green infrastructure for flood management: A systematic literature review. *Sci. Total Environ.* **720**, 137606 (2020).
67. M. Ignatieva, D. Haase, D. Dushkova, A. Haase, Lawns in cities: From a globalised urban green space phenomenon to sustainable nature-based solutions. *Land* **9**, 73 (2020).
68. A. Tiwary, U. Vilhar, M. Zhiyanski, V. Stojanovski, L. Dinca, Management of nature-based goods and services provisioning from the urban common: A pan-European perspective. *Urban Ecosyst.* **23**, 645–657 (2020).
69. H. Toxopeus, F. Polzin, Reviewing financing barriers and strategies for urban nature-based solutions. *J. Environ. Manage.* **289**, 112371 (2021).
70. ICLEI CBC, "Working with formal and informal governance structures: ICLEI Africa's learnings" in *The Value of Urban Natural Assets when Planning for Resilient African Cities–Handbook 4* (ICLEI CBC, Cape Town, South Africa, 2019).
71. R. A. Bellezoni, F. Meng, P. He, K. C. Seto, Understanding and conceptualizing how urban green and blue infrastructure affects the food, water, and energy nexus: A synthesis of the literature. *J. Clean. Prod.* **289** (2021).
72. N. B. Grimm, E. M. Cook, R. L. Hale, D. M. Iwaniec, "A broader framing of ecosystem services in cities: Benefits and challenges of built, natural or hybrid system function" in *The Routledge Handbook of Urbanization and Global Environmental Change* (Routledge, 2015).
73. T. McPhearson *et al.*, A social-ecological-technological systems framework for urban ecosystem services. *One Earth* **5**, 505–518 (2022).
74. T. McPhearson *et al.*, Advancing urban ecology toward a science of cities. *BioScience* **66**, 198–212 (2016).
75. A. Dumitru, N. Frantzeskaki, M. Collier, Identifying principles for the design of robust impact evaluation frameworks for nature-based solutions in cities. *Environ. Sci. Policy* **112**, 107–116 (2020).
76. B. B. Lin *et al.*, Integrating solutions to adapt cities for climate change. *Lancet Planet. Health* **5**, e479–e486 (2021).
77. M. Brindal, R. Stringer, Water scarcity and urban forests: Science and public policy lessons from a decade of drought in adelaide, Australia. *Arboric. Urban For.* **39**, 102–108 (2013).
78. T. Elmqvist *et al.*, Sustainability and resilience for transformation in the urban century. *Nat. Sustain.* **2**, 267–273 (2019).
79. T. McPhearson, N. Kabisch, N. Frantzeskaki, "Nature-based solutions for sustainable, resilient, and equitable cities" in *Nature-Based Solutions for Cities*, T. McPhearson, N. Kabisch, N. Frantzeskaki, Eds. (Edward Elgar Publishing, 2023), pp. xviii–11.
80. H. Burley *et al.*, Substantial declines in urban tree habitat predicted under climate change. *Sci. Total Environ.* **685**, 451–462 (2019).
81. S. P. Gajjar, C. Singh, T. Deshpande, Tracing back to move ahead: A review of development pathways that constrain adaptation futures. *Clim. Dev.* **11**, 223–237 (2019).
82. T. McPhearson *et al.*, "Urban ecosystems and biodiversity" in *Climate Change and Cities*, C. Rosenzweig *et al.*, Eds. (Cambridge University Press, ed. 1, 2018), pp. 257–318.
83. A. Bárcena, J. Samaniego, W. Peres Núñez, J. E. Alatorre, "The climate emergency in Latin America and the Caribbean: The path ahead–Resignation or action?" (Tech. Rep. No. 160 (LC/PUB.2019/23-P), Economic Commission for Latin America and the Caribbean (ECLAC), Santiago, Chile, 2020).
84. M. A. Rodriguez-Dominguez, D. Konnerup, H. Brix, C. A. Arias, Constructed wetlands in Latin America and the Caribbean: A review of experiences during the last decade. *Water* **12**, 1744 (2020).
85. C. G. Persch, R. Tassi, B. Minetto, D. G. Allasia, E. Rippel, Assessing the scale dynamics of the rainfall retention of green roofs in a subtropical climate. *J. Environ. Eng.* **147**, 04021054 (2021).
86. ICLEI CBC, "Creating change through on-the-ground implementation: Protecting urban natural assets in sub-Saharan Africa" in *The Value of Urban Natural Assets when Planning for Resilient African Cities–Handbook 10* (ICLEI CBC, Cape Town, South Africa, 2019).
87. I. C. Mell, Establishing the rationale for green infrastructure investment in Indian cities: Is the mainstreaming of urban greening an expanding or diminishing reality? *AIMS Environ. Sci.* **2**, 134–153 (2015).
88. U. M. Hertling, R. A. Lubke, Use of ammophila arenaria for dune stabilization in South Africa and its current distribution–Perceptions and problems. *Environ. Manage.* **24**, 467–482 (1999).
89. P. O'Farrell *et al.*, Towards resilient African cities: Shared challenges and opportunities towards the retention and maintenance of ecological infrastructure. *Glob. Sustain.* **2**, e19 (2019).
90. T. Elmqvist *et al.*, Urban tinkering. *Sustain. Sci.* **13**, 1549–1564 (2018).
91. A. Prigioniero, D. Zuzolo, Ü. Niinemets, C. Guarino, Nature-based solutions as tools for air phytoremediation: A review of the current knowledge and gaps. *Environ. Pollut.* **277**, 116817 (2021).
92. P. L. García-García, L. Ruelas-Monjardín, J. L. Marín-Muñíz, Constructed wetlands: A solution to water quality issues in Mexico? *Water Policy* **18**, 654–669 (2015).
93. N. Banwell, A. S. Gesche, O. R. Vilches, S. Hostettler, Barriers to the implementation of international agreements on the ground: Climate change and resilience building in the Araucanía Region of Chile. *Int. J. Disaster Risk Reduct.* **50**, 101703 (2020).
94. Activa Valdivia, Consorcio Valdivia sustentable. https://activavaldivia.cl/. Accessed 14 November 2022.
95. J. I. M. Restrepo, Moravia como ejemplo de transformación de áreas urbanas degradadas: Tecnologías apropiadas para la restauración integral de cuencas hidrográficas. *NOVA* **9**, 41–52 (2011).
96. L. Xie, H. Bulkeley, "City for biodiversity: The roles of nature-based solutions in European cities" (NATURVATION, 2020).

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97. W. Van Oijstaeijen, S. Van Passel, J. Cools, Urban green infrastructure: A review on valuation toolkits from an urban planning perspective. *J. Environ. Manage.* **267**, 110603 (2020).
98. Z. J. Grabowski, K. Wijsman, C. Tomateo, T. McPhearson, How deep does justice go? Addressing ecological, indigenous, and infrastructural justice through nature-based solutions in New York City. *Environ. Sci. Policy* **138**, 171–181 (2022).
99. J. Nyika, M. O. Dinka, Integrated approaches to nature-based solutions in Africa: Insights from a bibliometric analysis. *Nat. Based Solut.* **2**, 100031 (2022).
100. ICLEI-South Asia, "Urban green growth strategies for Indian cities–Vol. 1" (ICLEI South Asia, New Delhi, India, 2015).
101. Green Highways, Ministry of road transport & highways (2015). https://morth.nic.in/green-highways. Accessed 22 November 2022.
102. S. Mundoli, H. Unnikrishnan, H. Nagendra, The "Sustainable" in smart cities: ignoring the importance of urban ecosystems. *Decision* **44**, 103–120 (2017).
103. D. Rajasekhar, M. D. Babu, R. Manjula, *Decentralised Governance, Development Programmes and Elite Capture* (Springer, 2018).
104. K. P. Dhakal, L. R. Chevalier, Urban stormwater governance: The need for a paradigm shift. *Environ. Manage.* **57**, 1112–1124 (2016).
105. H. Jia, H. Yao, S. L. Yu, Advances in LID BMPs research and practice for urban runoff control in China. *Front. Environ. Sci. Eng.* **7**, 709–720 (2013).
106. Y. Ma, Y. Jiang, S. Swallow, China's sponge city development for urban water resilience and sustainability: A policy discussion. *Sci. Total Environ.* **729**, 139078 (2020).
107. A. Vásquez, E. Giannotti, E. Galdámez, P. Velásquez, C. Devoto, "Green infrastructure planning to tackle climate change in latin american cities" in *Urban Climates in Latin America*, C. Henríquez, H. Romero, Eds. (Springer International Publishing, 2019), pp. 329–354.
108. C. Figueroa Arango, "Guía para la integración de las soluciones baseadas en la naturaleza en la planificación urbana: Primera aproximación para Colombia" (Alexander von Humboldt Stiftung, Ecologic Institute, Instituto de Investigación de Recursos Biológicos Alexander von Humboldt, Berlin, Germany, 2020).
109. T. H. N. Marques, D. Rizzi, V. Ferraz, C. P. Herzog, Soluções baseadas na natureza: Conceituação, aplicabilidade e complexidade no contexto latino-americano, casos do Brasil e Peru. *Rev. LABVERDE* **11**, 12–49 (2021).
110. Z. J. Grabowski, T. McPhearson, A. M. Matsler, P. Groffman, S. T. Pickett, What is green infrastructure? A study of definitions in US city planning. *Front. Ecol. Environ.* **20**, 152–160 (2022).
111. M. Pineda-Pinto *et al.*, Examining ecological justice within the social-ecological-technological system of New York City, USA. *Landsc. Urban Plan.* **215**, 104228 (2021).
112. L. Diep *et al.*, "It won't work here": Lessons for just nature-based stream restoration in the context of urban informality. *Environ. Sci. Policy* **136**, 542–554 (2022).
113. D. H. Locke *et al.*, Residential housing segregation and urban tree canopy in 37 US Cities. *NPJ Urban Sustain.* **1**, 1–9 (2021).
114. W. Zhou *et al.*, Urban tree canopy has greater cooling effects in socially vulnerable communities in the US. *One Earth* **4**, 1764–1775 (2021).
115. I. Anguelovski, J. J. Connolly, M. Garcia-Lamarca, H. Cole, H. Pearsall, New scholarly pathways on green gentrification: What does the urban 'green turn' mean and where is it going? *Prog. Hum. Geogr.* **43**, 1064–1086 (2019).
116. R. Rothstein, *The Color of Law: A Forgotten History of How Our Government Segregated America* (Liveright Publishing Corporation, 2017).
117. S. A. Shapiro, The complexity of regulatory capture: Diagnosis, causality, and remediation. *Roger Williams Uni. Law Rev.* **17**, 221 (2012).
118. The White House, "FACT SHEET: President Biden signs executive order to strengthen America's forests, boost wildfire resilience, and combat global deforestation" (The White House, Washington, D.C., 2022).
119. Y. Sintomer, C. Herzberg, G. Allegretti, A. Röcke, M. L. Alves, "Participatory budgeting worldwide – updated version". *Dialog. Glob.* **25**, 1–93 (2013).
120. M. Collier, Hyperlinked compendium of nature-based solutions projects 2016–2026 (Final, European Commission, DG Research and Innovation, Brussels, Belgium, 2022).
121. N. Faivre, M. Fritz, T. Freitas, B. de Boissezon, S. Vandewoestijne, Nature-based solutions in the EU: Innovating with nature to address social, economic and environmental challenges. *Environ. Res.* **159**, 509–518 (2017).
122. N. Kabisch, N. Frantzeskaki, R. Hansen, Principles for urban nature-based solutions. *Ambio* **51**, 1388–1401 (2022).
123. A. Armstrong, "Mainstreaming nature-based solutions: Social inclusion" (NATURVATION, 2020).
124. R. Calderón-Contreras, L. E. Quiroz-Rosas, Analysing scale, quality and diversity of green infrastructure and the provision of urban Ecosystem Services: A case from Mexico City. *Ecosyst. Serv.* **23**, 127–137 (2017).
125. F. J. Escobedo, N. Clerici, C. L. Staudhammer, G. T. Corzo, Socio-ecological dynamics and inequality in Bogotá, Colombia's public urban forests and their ecosystem services. *Urban For. Urban Green.* **14**, 1040–1053 (2015).
126. L. Diep, D. Dodman, P. Parikh, Green infrastructure in informal settlements through a multiple level perspective. *Water Altern.* **12**, 554–570 (2019).
127. F. Creutzig *et al.*, Upscaling urban data science for global climate solutions. *Glob. Sustain.* **2**, e2 (2019).
128. M. A. Goddard *et al.*, A global horizon scan of the future impacts of robotics and autonomous systems on urban ecosystems. *Nat. Ecol. Evol.* **5**, 219–230 (2021).
129. T. McPhearson, N. Kabisch, N. Frantzeskaki, "Towards mainstreaming nature-based solutions for achieving biodiverse, resilient, and inclusive cities" in *Nature-Based Solutions for Cities*, T. McPhearson, N. Kabisch, N. Frantzeskaki, Eds. (Edward Elgar Publishing, 2023), pp. 363–375.
130. J. Deely *et al.*, Barrier identification framework for the implementation of blue and green infrastructures. *Land Use Policy* **99**, 105108 (2020).
131. G. Warren-Myers, Valuing sustainability in Australia: Implications for the valuation profession. *Pac. Rim Prop. Res. J.* **18**, 163–179 (2012).
132. M. Moglia *et al.*, "Proposed strategy portfolio for the management of rainwater tanks: The South East Queensland case" (Tech. Rep. 75, CSIRO, Hawthorn, Australia, 2012).

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