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Challenges and Opportunities in the Use of Nature-Based Solutions for Urban Adaptation

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Abstract: The concept of nature-based solutions (NbS) has been endorsed by multiple international organizations as one of the priority approaches to address climate-related challenges. These solutions are versatile, and can simultaneously address challenges such as climate impacts, public health, inequality, and the biodiversity crisis, being uniquely suited for urban adaptation. NbS are particularly relevant in the developing world, where strategies should be as self-reliant as possible, reducing the need for technological processes that require expensive and complex maintenance. NbS can also promote political, societal, cultural, and ultimately, systems change. The purpose of this paper is to present a literature review on the use of NbS for urban adaptation, identifying the main opportunities, challenges, and, most specifically, knowledge gaps, which can be addressed in subsequent research. The present paper identifies four types of knowledge gaps that are particularly relevant for the use of NbS for urban adaptation: future climate uncertainty, lack of site-specific technical design criteria, governance strategies, and effectiveness assessment evaluation. To overcome local governments' limitations, specific implementation strategies and structures should be considered, centered on knowledge transfer within a transdisciplinary and participatory framework. These should be developed in partnership with urban planning entities, seeking to consolidate these approaches in policies that support social resilience and institutional capacity. Therefore, urban adaptation should be initiated with pilot projects to simultaneously address the urgency for implementation, while allowing urban planning practices the time to adjust, building capacity at the local level, and filling knowledge gaps through the assessment of effectiveness. The climate-resilience of urban tree species adequate to the future climate was identified as a relevant knowledge gap for the implementation of NbS.

Keywords: climate adaptation; urban adaptation; nature-based solutions; urban planning; green infrastructure; climate governance

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1. Introduction

Climate change is already taking place all over the world [1], with the most significant impacts being rising temperatures, changes in rainfall patterns and an increasing number of extreme weather events [2]. Urban areas are particularly vulnerable due to the concentration of population, infrastructure, and property [1]. The most impacted regions are located in the developing world [2], despite the global north being responsible for approximately 92% of all GHG emissions [3]. The impacts are accelerating, as stated in the latest IPCC report [2], with tipping points being reached and not enough action being taken by governments. While we are facing scenarios of substantial increase in temperatures, even moderate levels of warming can have catastrophic consequences [4]. The biodiversity crisis is interlinked with climate change, manifesting itself in the sixth mass extinction of life on the planet [5].

NbS have been increasingly recommended for urban adaptation and as an alternative to traditional urban infrastructure [6–9]. The term "Nature-based Solutions" was first mentioned in a World Bank report from 2008 [10,11] listing projects addressing the biodiversity and climate crises, with a particular focus on adaptation and vulnerable communities. The International Union for Conservation of Nature (IUCN) describes NbS as actions that protect, sustainably manage, and restore natural or modified ecosystems, while simultaneously providing benefits for human wellbeing and biodiversity [12]. The European Commission (EC) has a broader definition, considering NbS to be solutions that are inspired and supported by nature, which are cost-effective and simultaneously provide environmental, social, and economic benefits while contributing to build resilience [13]. As the concept of NbS is quite recent, substantial knowledge gaps remain, including how to support its relevance for urban areas [1]. There are also barriers to its implementation that must be understood to be overcome. The objective of this review is to contribute to the assessment of the dimension of the challenges, identifying opportunities, barriers, and knowledge gaps in the use of NbS for implementation in an urban context. The applied review methodology is focused on papers published following the creation of the concept of NbS in 2008 to the most relevant papers with a focus centered on NbS and its adaptation in an urban context published since then. Additionally, several reports from relevant organizations with a global impact were consulted, such as the World Bank, to understand how different sectors, organizations and agents are adopting/supporting these solutions.

2. NbS in the Context of Climate Change

To understand the relevance of NbS in the context of climate change, we focus on the following: (a) what are NbS and what distinguishes them from urban greening; (b) which challenges, beyond the climate crisis, can be addressed by these solutions; (c) how relevant can NbS be for urban adaptation; (d) how relevant can these solutions be for vulnerable communities; (e) which challenges and opportunities lie in its transdisciplinary nature; and (f) finally, the different typologies of NbS are identified.

2.1. General Concept and Definitions

NbS can be described as solutions that harness the power of nature to deliver both natural and social benefits [11]. Multiple authors have highlighted the ambiguity of the concept [11,14], and different organizations provide their own definitions. According to the EC, it is an "umbrella" concept [15,16], encompassing a wide range of approaches including, among others, urban green infrastructure, ecosystem-based adaptation, ecosystem-based disaster risk reduction and blue-green infrastructure [15]. NbS include natural, rural, and urban interventions/typologies of land use, such as forests, wetlands, green belts, and parks in and around cities, natural wastewater treatment plants, green roofs, green walls, ecosystem corridors and other green, blue and hybrid infrastructures. These solutions may contribute to urban resilience, alleviate urban flooding risks, avoid losses, and contribute to economic gains, as well as essential social and environmental services [17]. Importantly, NbS promote sustainable solutions to environmental challenges in the long term [18,19].

As a result of being mentioned for the first time in the context of climate change and the biodiversity crisis [10,11,20], NbS are typically associated with them, although they are not restricted to this realm, and can address other issues such as pest management, enhancement of food production or wastewater treatment [14]. One of NbS' main advantages is that they can deliver results for climate mitigation and adaptation simultaneously, which has been emphasized in multiple scientific assessments and reports, namely by the Climate Change and Land Report of the Intergovernmental Panel on Climate Change [1], the Global Adaptation Commission Report [8] and more recently in the Sharm El-Sheikh Implementation Plan [21]. Additionally, their multiple benefits are relatively low cost, as they can achieve a cost–benefit ratio above 100:1 [22]. NbS' versatility makes them a highly valuable approach to what sometimes seems an unsurmountable challenge [7,9,23]. It is important to note that they are not an all-powerful solution, and in the context of mitigation, have a much lower impact than the radical reduction of fossil fuels consumption [24,25].

It is important to distinguish NbS from general greening projects. The literature review by Sowinska-Swierkosz and Garcia (2022) [11] identifies 11 criteria for exclusion of green infrastructure from being considered NbS as follows:

(1) The lack of functioning ecosystems, meaning that NbS must involve natural processes taking place and not only be "inspired by nature", as this can take the form of solar and wind energy or biomimicry.
(2) Being random actions, meaning that NbS must follow clearly defined goals, beneficiaries, and governance systems; actions that do not include a diagnose of social, economic and environment conditions prior to implementation should be excluded. This would exclude, for example, artistic installations using plants.
(3) Not having post-implementation goals, as NbS must be specifically focused on solving existing problems. This would exclude, for example, historical gardens.
(4) Having negative/no impact on biodiversity, which would exclude, for example, monoculture and reduce "greenwashing" strategies.
(5) Having equal benefits to grey infrastructure. This is particularly interesting, as it highlights that NbS must provide added benefits to the alternative, stating that the degree of human intervention cannot be the sole criteria for an intervention. Hybrid solutions are often best suited for urban spaces [25].
(6) Unfair distribution of benefits. NbS must guarantee simultaneously environmental, human well-being and economic benefits without putting one goal above the others.
(7) Being a copy–paste implementation approach. NbS are specific to context, and expertise is required for its design. Solutions can be replicated if adaptive management and design are put in place.
(8) Adopting a top-down model of governance, as NbS requires community participation.
(9) Having a static management approach, meaning that NbS should have adaptive management with innovation throughout its lifespan, being based on the theory of change. Transparency in decision-making is key, including public participation.
(10) Disproportionate financial expenses in terms of benefits, as NbS must be cost-effective.
(11) Point-scale approaches, as NbS imply interactions across social and ecological dimensions at a landscape scale, while having cumulative impacts, and are not meant to be isolated interventions.

The United Nations Organization (UN) is one of NbS' key supporters. NbS have been selected as one of nine key action tracks at the 2019 UN Climate Action Summit, garnering the commitment of more than 20 countries and numerous organizations in unlocking the potential of nature in climate action through the conservation, reforestation, and restoration of ecosystems [26]. Their increased relevance is apparent in the Nationally Determined Contributions (NDCs) submitted to the United Nations Framework Convention on Climate Change (UNFCCC). In 2015, only 66% of the Paris agreement's signatories included NbS in their NDCs [27], a number that rose to 92% in 2021, with NDCs mentioning NbS both in the context of mitigation and adaptation [28].

2.2. The Age of Crises

The world is currently facing a multitude of crises unfolding simultaneously [29,30]. Expanding human activities and population are imposing an unsustainable pressure on nature, resulting in multiple emergencies, namely ecosystem degradation, deforestation, biodiversity loss, and accelerating climate change [31]. Biodiversity is declining at unprecedented levels in human history [32], with one million species currently threatened with extinction [33]. We are also facing social crises, in particular inequality and public health; NbS have the advantage of addressing these challenges as well [16,34].

Interlinkages between the climate change and biodiversity crises were first mentioned in the *Convention on Biological Diversity* in 2009, Technical Expert Group 1 [35], but have since been highlighted as crucial by both the IPCC and IPBES, which stated that it is not possible to address them separately [30]. The increased risks resulting from cascading crises are being recognized at various levels and by multiple organizations, as is the case with the World Economic Forum (WEF). The WEF annual global risks report identifies and categorizes risks according to five categories: (a) economic; (b) environmental; (c) geopolitical; (d) societal; and (e) technological. In 2022, the three biggest risks identified for the next 10 years were environmental, the first being climate action failure, the second extreme weather and the third the biodiversity crisis [36].

While NbS are versatile, their main benefits in urban areas are reducing climate impacts, enhancing conditions for urban biodiversity [37], improving public health and promoting social cohesion and equality [13,38]. Many biodiversity-focused strategies, such as green corridors centered on supporting species migration and increasing core conservation areas, can also have benefits for adaptation [39]. In terms of reducing climate impacts, NbS can assist in microclimatic regulation [40], stormwater runoff management [41], and reduction of sea level rise impact [39]. NbS can promote human wellbeing [8], in terms of both public health and social benefits. Public health is of particular concern, with the World Health Organization [42] highlighting the danger of the climate crisis. The Lancet report on climate change [43] highlights that climate change has a substantial impact on health through increased temperatures, changed rainfall patterns and extreme weather events, which are reversing the progress of hundreds of years in food and water insecurity in the most vulnerable communities of the world. The report adds that climate change is increasing the conditions for the transmission of several waterborne, airborne, foodborne, and vectorborne pathogens, which can lead to the substantial expansion of diseases. The most documented benefits of urban green spaces (regardless of them qualifying as NbS) for public health are in terms of cardiovascular diseases, blood pressure, respiratory diseases, obesity, and diabetes [38,44–46] and air pollution removal, particularly by urban trees [46]. Studies show exposure to nature is beneficial in terms of mental health as well, reducing stress and improving concentration [38,47,48]. The quality of children's lives in dense urban centers has been associated with the provision of outdoor green areas [37]. Urban green spaces also promote physical activity and recreation, which has public health benefits [37]. At a regional scale, NbS can help safeguard water, sanitation, and hygiene (WASH), which have a strong impact on health and cross-sectoral linkages [49]. They can also reduce the risk of zoonotic diseases such as COVID-19, which are often related to the degradation and/or destruction of ecosystems [49]. Recent studies have indeed shown that climate change can increase the number of these diseases, as it may force new species encounters [50]. In terms of social benefits, NbS reduce inequality [22,51], promote social cohesion [38], lower levels of violence [52,53], and add aesthetic values [53]. The aesthetic component has proven to have a positive effect on health merely from the point of scenery [54], with the first study focused on this issue published in 1984 [55]. Urban green spaces have proved to also impact the perceived thermal comfort, beyond effective temperature reduction [56].

2.3. Urban Adaptation

Adaptation to climate change, which is the process of adjusting to current or expected effects in climate [39], is acknowledged to be urgent, as climate change is already taking place all over the world [2]. Climate finance has, however, prioritized mitigation over adaptation [57]. Even though the *Cancun Adaptation Framework* [58] mandated that adaptation receive the same attention as mitigation, recent data suggest the gap between the available funding for adaptation and adaptation needs is widening [59]. Under the *Paris Agreement*, USD 100 billion are to be transferred annually, starting in 2020, from developed to developing nations [60]. Recent reports show this will not be enough, as estimates indicate that, by 2030, adaptation costs in developing countries will range between USD 155 and USD 330 billion annually [59]. Aligned with this concern, the *Glasgow Climate Pact* [61] mentions the need to double by 2025 the funds to be transferred from developed to developing countries specifically for adaptation.

Urban areas are particularly vulnerable to the impacts of climate change [1,39,62]. As they are also overwhelmingly responsible for carbon emissions, *cities are where the battle of* *climate change will largely be won or lost* [63], as stated by the UN Secretary-General at the C40 World Mayors Meeting in 2019. Impacts will be multiple, from loss of infrastructure to, importantly, public health, which is affected by weather patterns, and several related aspects [43], such as reduced labor productivity [25,64]. In terms of heat, due to the high concentration of hard materials, cities can have temperatures up to 8 °C above the surrounding natural or rural areas, an effect known as the urban heat island (UHI) effect [65]. Additionally, recent research has found that cities are warming up 29% faster than rural areas [66], which seems to point to a disproportionate increase of the UHI effect itself. Cities are also where most of the world population is located, with 55% of the world's population currently living in urban areas, a number expected to increase to 68% by 2050 [67]. The developing world is where most of the global urban development will take place, with 90% of the growth expected to come from the American, Asian, and African continents [68]. Urban development causes negative environmental impacts, such as decreasing soil permeability and increasing flood risk, besides the UHI effect [69]. This has a compounding effect when combined with climate change, interlinked pressures, and the degradation of natural areas [1]. Urban adaptation in developing nations is, therefore, of particular concern and must be prioritized [34]. Some parts of the world cannot afford to wait, such as South Asia, estimated to be facing an additional 49 million people pushed into extreme poverty by 2030 [70]. It is one of the most impacted areas of the world: the heatwave of March–April 2022 was made 30 times more likely by climate change [71].

The advantages of NbS for urban adaptation have been confirmed multiple times, reducing climate impacts [72] and providing numerous public health co-benefits [73]. NbS can be of great relevance for urban adaptation in the developing world, as they are highly cost-effective [22], easily implemented, and have lower maintenance costs than the technological alternatives [25]. The relevance of NbS for the Least Developed Countries (LDCs) is even higher, as they have a strong economic dependence on natural resources. The implementation of NbS tends to safeguard existing natural resources, which is crucial to protect communities, as ecosystem degradation exacerbates human exposure to climate impacts, and access to basic resources (food, water, clean water). The UNFCCC highlighted NbS' contribution to climate-resilient landscapes and ecosystems in LDCs in the *LDC 2050 Climate Change Vision* [74]. Research shows that climate finance is not prioritizing NbS in LDCs, even though nature-related activities are mentioned in 45 of the 46 Nationally Determined Contributions (NDCs) of these countries [75]. A recent study showed that between 2014 and 2018, less than 10% of the finance for climate adaptation projects in LDCs went to nature-related projects [76]. NbS can be overlooked in the countries that need them the most, as in Bangladesh, in which 88% of climate adaptation projects are engineered solutions, with only 12% of NbS [8]. This despite engineering solutions having, according to Narayan et al. (2019) [77] in that country, a worse performance than NbS. One example is mangrove forests, which address sea level rise, one of the country's main vulnerabilities, in opposition to seawalls.

2.4. Relevance for Vulnerable Communities

Low-income communities are disproportionately impacted by climate change [2] in terms of public health, with rising temperatures and extreme weather events having immediate public health consequences [78,79]. This is not only due to a reduced adaptive capacity. Low-income communities are frequently located in flood-prone areas with fewer green spaces [80], which reduce the UHI effect and absorb stormwater runoff. Climate change itself will cause the increase in the number of vulnerable people around the world. The World Bank estimates that, if unaddressed, climate change has the potential to push between 68 million and 132 million people into poverty by 2030 [81]. Considering NbS' substantial social benefits, one of these being the potential to address inequalities [13,22], they seem particularly relevant for vulnerable communities and developing nations, as a sustainable, low-regrets approach to be deployed across contexts and communities [22,23]. NbS can play a role in addressing poverty alleviation [22,51] by protecting livelihoods.

According to the Friends of Ecosystem-based Adaptation (FEBA) [49] (2021), NbS can reduce the vulnerability of exposed communities in three different ways: (a) building resilience: as with agroecology, which can contribute to food security, and income; (b) reducing hazards: the preservation and restoration of forests and watersheds reduces the occurrence of floods and landslides; and (c) decreasing exposure: activities such as restoring and expanding mangroves in coastal areas can substantially reduce the exposure of communities to storm surges. The effective solutions provided by NbS can be replicated by exposed communities, which can then lead, own, and promote them [49], increasing their autonomy and resilience.

The largest impact of climate change on extreme poverty by 2030 was identified by the World Bank as being higher food prices [70]. There will be regional variations, with food prices being the main risk in Sub-Saharan Africa and South Asia, and health in East Asia and Pacific, Latin America, and the Caribbean. Adaptation projects to be developed can and should address these threats: in cities, urban farming can play a role in assisting low-income communities to reduce food security risks [70]. Public participation is key. Research has confirmed that, for adaptation to be effective in both the short- and long-run, local vulnerable communities must fully participate in implementing NbS strategies [8,25,82,83]. Vulnerable communities must be included in these and other climate-related decision-making processes [49] and, when possible, should take the lead. Indigenous communities should play an active role in implementation, due to their knowledge of the local natural environment [25].

2.5. Transdisciplinary Dimension

The use of NbS for urban adaptation is inherently transdisciplinary and intersectoral. Transdisciplinarity is one of NbS' main characteristic traits [84–86], particularly in co-creating, co-developing, and co-implementing initiatives to address challenges. The use of natural processes to address societal challenges is not new, being integral to landscape architecture and planning theory, influenced by McHarg's book from 1969 [87], *Design with Nature*. NbS also draw substantial knowledge from urban planning, engineering, and environmental sciences [16,88,89]. For NbS to be implemented, urban planning must adopt a novel approach to urban greening, which can be tested in projects for urban regeneration and expansion [16].

The implementation of NbS requires collaboration across sectors, which can be challenging, especially for local governments in developing countries [49]. Multi-level governance adds complexity to the process. The implementation and management of natural resources is overseen by diverse groups, which results in various co-benefits, including at social levels [49]. Multi-level governance promotes cooperation and preparedness, which are essential in building capacity for addressing climate challenges. While these processes may be useful to prepare local governments to respond to future crises, their implementation in the present may pose challenges, considering the sectoral silos that tend to exist within their structures.

2.6. Typologies of NbS

NbS can be characterized typologically according to (a) the degree of human intervention, (b) the challenges addressed and (c) the landscape type. The first proposal for a typological categorization for NbS, published in 2015 [57], listed three types, according to the degree of human intervention: type 1 involves minimal or no intervention in ecosystems; type 2 relates to actions that aim to establish sustainable and multifunctional ecosystems and landscapes; and type 3 categorizes measures focused on creating new ecosystems or managing existing ones in an intensive way. NbS can also be categorized by the challenges addressed. Identifying the dimension of socioeconomic vulnerability and type of climate impact addressed: (1) reducing exposure; (2) reducing sensitivity; and (3) supporting adaptive capacity [8]. Both the IUCN and the EC categorize NbS according to challenges addressed. The IUCN identifies five areas addressed by NbS: (a) water security, (b) food security, (c) human health, (d) disaster risk reduction and (e) climate change [12]. The EC identifies seven types of NbS according to areas of research and innovation: (a) regeneration and well-being in urban areas; (b) carbon sequestration; (c) coastal resilience; (d) watershed management; (e) ecosystem restoration; (f) insurance of value of ecosystems; and (g) foster sustainable use of matter and energy [19]. There is some overlap between these categories.

Another way of identifying typologies for NbS is by landscape type, as suggested by Skyrydstrup et al. (2022) for managing urban flooding [90]:

1. Sustainable urban drainage systems, which are small green areas such as accessible green roofs, swales and/or rain gardens. These solutions are flexible, requiring little or no space. The typical spatial scale is inferior to 1 ha.
2. City parks, green areas with room for several types of recreation that might contain blue areas, for example, a lake. In the referred research, a city park is 1–50 ha.
3. Nature areas, green areas with room for diverse types of recreation that might contain blue areas; for example, a wetland. Compared to a city park, they are wilder and provide more biodiversity, are larger than 50 ha and are typically adjacent to a city (for example, a forest).
4. Rivers/streams, in which most of the area is water, so there may be a riverbank or flood plain along the river people can access. Typically, only partial sections of the river with urban recreational activity are considered, with a spatial scale of 1–60 ha.

3. Knowledge Gaps

As an emergent field, there is much research to be performed on NbS [91]. Despite drawing increasingly more interest and becoming a subject of research [19,25], many knowledge gaps subsist and have been identified. Kabisch et al. (2016) [1] identify four types of knowledge gaps for NbS: (a) effectiveness; (b)societal relations; (c) design; and (d) implementation. FEBA (2021) [49] identifies the need for data, research, assessment, policy coherence, data and tools that support the integrity of ecosystems and NbS specifically for humanitarian contexts. Assessment is particularly important, as the potential of NbS to deliver benefits has not yet been fully evaluated [8]. *Network Nature*, a resource for NbS funded by the EC and developed jointly by IUCN, ICLEI Europe, BiodivERsA, Oppla and Steinbeis 2i, launched in 2022 a study that identifies 142 knowledge gaps categorized under 27 broad topics [92]. An online survey by *Network Nature* (2021) [92] identified 29 unique knowledge and implementation gaps. The study identifies four types of knowledge gaps in NbS related to: (a) technical design, (b) evaluation, (c) governance and (d) capacity building, as illustrated in Figure 1 and Table 1.

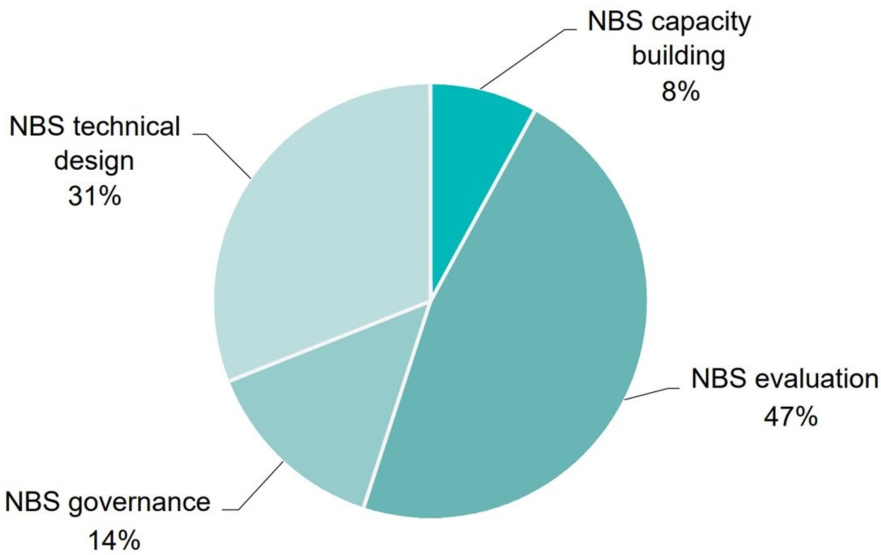

Figure 1. Knowledge gaps identified in the *Network Nature* (2022) desk study.

Table 1. Broad topics of knowledge gaps collected online by *Network Nature* (2022).

Nature of Gaps	Broad Topics of Gaps	%
NBS Technical Design	Relationship between biodiversity, ecosystem functions and ecosystem services	14%
	Biodiversity benefits	14%
	Synergies and trade-offs between goals	7%
	Direct and indirect benefits for climate mitigation	7%
	Social cohesion and environmental justice	3%
	Performance and characteristics of plants	3%
NBS Evaluation	Effectiveness across socio-ecological contexts	14%
	Cost-benefit evaluations	10%
	Effectiveness at different time scales	3%
	Effectiveness at different geographical scales	3%
NBS Capacity Building	Awareness and Capacity Building	31%
	Knowledge Base	3%
NBS Governance	Planning and policy Framework	10%
	Stakeholder engagement	7%

Although types of knowledge gaps differ depending on the author(s), two types of knowledge gaps are consensual: technical design and assessment of effectiveness. Besides the ones specific for NbS, some knowledge gaps are adaptation-related, despite the substantial progress of the past two decades.

Considering the reviewed literature, the present paper identifies four types of knowledge gaps that are particularly relevant for the use of NbS for urban adaptation:

(1) Future climate. There is uncertainty, both in climate science and in policies, regarding the solutions to be adopted by national governments. This leads to ambiguity and to the need for permanently updating estimates. In 2022, the World Meteorological Organization [93] announced that there was a 50% probability that the 1.5 °C of increase above pre-industrial levels (the target of the Paris Agreement for 2100) would be achieved between 2022 and 2026. In 2015, the probability of this occurring was zero. Another example of this uncertainty, a study published in September 2022, revealed that Greenland's glaciers appear to be melting 100 times faster than previously thought [94]. The four representative concentrative pathways (RCPs) allow us to explore future climate scenarios, but it is not certain that one of them (or within their spectrum) will take place. Some climate impacts are clear, but their degree of intensity is yet to be determined by human action, by unknown ecosystem interrelations and feedback loops, and potentially by other unknowns. Some areas of the globe will likely become unlivable due to the wet-bulb temperature [95,96], but which areas will be impacted first, and when? This is key knowledge for purposes of risk management.

As for cities, they will see their climate shifting all over the world. This will be more relevant near the equator, with cities such as Jakarta, Kuala Lumpur, Libreville, Manaus, and Singapore all predicted to experience unprecedented climate conditions by 2050 [97]. In these circumstances, many associated unknowns are likely to occur. Understanding what the climate of the future will be is important to define goals and targets associated with the use of NbS in urban adaptation. Will these strategies be enough to offset the changes in climate? Until when? A time-phased approach may be the best suited to help adjust adaptation projects to the ongoing changes.

(2) Technical design. A substantial part of the technical knowledge required for the implementation of NbS for urban adaptation comes from landscape architecture, urban planning, engineering, and environmental sciences [16,88,89]. However, if the goal is to develop a solution to achieve specific targets within a timeframe, more research is needed. The design approach must be based on evidence, having specific targets associated with NbS' multiple benefits and co-benefits [16], including biodiversity, impacts on social cohesion and environmental justice [92], and on synergies with mitigation [1,92].

The misuse of NbS can lead to maladaptation [25]. There are examples of maladaptation associated with choosing the wrong species, for example, sheltering homes from windstorms using species that are not resilient to windstorms [9]. This knowledge exists today, but there are cases in which it does not. NbS should be resilient to the changing climate in the long-term [9]. As the climate starts shifting in cities all over the world, some native or more commonly planted species in specific cities will no longer be the best suited. New species will need to be planted, the ones that will be resilient to the climate of the future [25,98]. This is more challenging for cities that are predicted to have a future climate that is outside of the current climate domain [97]. NbS are highly contextual, despite being based in general scientific knowledge [99], so there are substantial opportunities for research to be developed at local levels. Studies focused on assessing the resilience of species to future climate conditions must be initiated. This is particularly important for urban trees, as they take time to mature and deliver benefits. Having a life expectancy of 50 years and above, if planted today, they are likely to reach maturity in a changed climate, facing the risk of losing their urban habitat by then.

(3) Governance. The two main knowledge gaps in terms of governance are identifying the most suitable planning and policy frameworks for NbS implementation and procedures in terms of stakeholder engagement [92]. The implementation of NbS can contribute to reduce knowledge gaps, and combining policymaking with scientific research should be encouraged [25]. The benefits of NbS must be accessible to all residents [1]. Some studies point to the fact that the introduction of NbS in urban areas may have negative impacts in terms of equality, contributing to increase costs of property in the areas surrounding the new green interventions, leading to gentrification [100]. Engagements with the communities are crucial to identify potential unintended impacts.

(4) Assessment. The main knowledge gaps in terms of assessments of effectiveness are related to cost–benefit evaluation, effectiveness at different time and geographical scales, and across socio-ecological contexts [92]. The methodology for mapping ecosystem services is not suited for urban adaptation, due to the complexity and coexistence of several types of elements in the urban fabric; as it is challenging, very few studies attempt to transfer values of urban nature [101].

It is important to establish target indicators to assess effectiveness [1]. These will be used in measuring, analyzing, and monitoring impacts [1]. Some knowledge gaps will be addressed by emerging innovations in technology for planning and monitoring of urban greening, which are broadly known as *Internet of Nature* [102]. One such example is the i-tree software [103], which provides information on the benefits of urban trees at four levels: (a) stormwater intercepted; (b) energy conserved; (c) air pollutants removed; and (d) carbon dioxide reduced. These benefits are presented in specific and monetary units for each city annually.

Monitoring should take on a relevant role, as monitoring and assessing NbS pilot projects' effectiveness can contribute to fill relevant knowledge gaps [1,6,49,101].

4. Barriers to Implementation

There is resistance to climate adaptation in general, as efforts to build urban resilience tend to be reactive [104]. Several barriers to the implementation of NbS have been identified by Kabisch et al. (2016) [1]: (a) fear of the unknown, (b) disconnection between short-term and long-term goals, (c) discontinuity between short-term actions and long-term-plans; (d) sectoral silos; and (e) paradigm of growth. In addition, Seddon et al. (2020) [8] identify three types of obstacles to the implementation of NbS: (i) measurement of effectiveness; (ii) mobilizing investment; and (iii) governance challenges.

Considering the reviewed literature, the present paper summarizes five main barriers specific for the implementation of NbS as an urban adaptation approach:

(a) Spatial. Often, NbS require more space than traditional "grey" solutions, particularly for water management; this means they may be competing with other uses for space allocation [69,105]. Other uses, such as urban development projects, tend to have more vested interests behind them, and therefore have a competing advantage for valuable urban land. Public participation may help to shift the power balance from private interests, such as property development, to public interests, such as communal green spaces. It is important to note that not all urban spaces are suitable for NbS, depending on the topography, physical structure and urban density, and projects must be contextualized to the local environment to deliver outcomes for people and the environment [51].

(b) Governance. There are many challenges in initiating climate adaptation projects by municipalities. While some developed nations are promoting NbS adaptation, as is happening in the European Union [92], developing nations often do not have access to the knowledge or resources to do so. Lack of knowledge and capacity, particularly at the city council level, is a strong barrier for NbS implementation. Traditional structures in city governments are based on sectoral silos, which can be a barrier to the implementation of approaches as transdisciplinary and intersectoral as NbS [1]. Governance for NbS in urban adaptation must not only be transdisciplinary and intersectoral, but also systemic, so it can challenging to the capacity of local governments, particularly in developing countries. Strong support from global institutions for design and development is needed, including knowledge tools. Urban planning and policies must be adjusted as well; NbS are seldom implemented if they are not integrated into planning tools and mechanisms [25,106], embedded within viable governance or business implementation models [84]. According to Frantzeskaki, Mahmoud and Morello (2022) [16], for urban planning to integrate NbS, tools and procedures adopting the following principles must be put in place: (1) planning tools must become adaptive and reactive to living materials; (2) the design approach should be based on evidence of the benefits and co-benefits of the NbS adopted; and (3) a collaborative approach to planning and design is essential for the success of NbS implementation.

Governance systems must include local communities for effective action in adaptation to take place, which is recognized in the *Cancun Adaptation Framework* [103]. There is some concern that NbS may fail to account for local voices [25], the risk being higher for non-urban than for urban adaptation projects, as the latter are more participative in nature. Grassroots organizations have manifested some resistance to NbS, perceiving them to be a distraction from impactful action [25,107]. Their concern comes from NbS having been used for purposes of greenwashing [25], as it is easier for governments to promote nature-related activities than to confront the fossil fuels industry and take on renewable energy transition. Full transparency and participation of local communities is important also to address these concerns and to build trust.

(c) Assessment. Policymakers tend to prefer engineering solutions, as they are more easily calculated and quantified than NbS [84]. Research indicates that, for NbS to be implemented, their transformative potential must be recognized as being superior to grey infrastructure [6]. Their benefits compared to the alternatives must be proven, which is not necessarily easy, particularly for co-benefits. The lack of monetary outcomes from the implementation of NbS can be an obstacle to their implementation [101], even though they have been increasingly monetized [100,101]. Addressing this challenge has required special valuation techniques, such as measuring indirect public health benefits by diseases avoided. Despite new types of assessment and monitoring methods being tested, studies show that the existing green infrastructure valuation tools are not being employed in decision-making processes when deciding in grey vs. green infrastructure [101].

(d) Finance. Addressing nature-related issues from a financial point of view can be challenging, not only for governments, as corporations are struggling with knowledge gaps in nature-related finance [108]. Currently, the biggest investor in NbS is the G20, with approximately USD 120 million/year, which mostly goes to domestic projects [109]. In developing countries, which should benefit from global climate finance, the main concern is the lack of funding available [110,111]. Currently, climate finance is supporting NbS for adaptation with USD 3.8–8.7 billion/annually, approximately 0.6–1.4% of the total climate finance in 2018 [109,110]. Considering the urgency of urban adaptation, and that NbS have proven to be a reliable, no-regrets approach, a bigger percentage of climate finance should be allocated to projects in this realm. Most funding organizations, such as the Global Environmental Facility, the Green Climate Fund, and the Adaptation Fund, have supported NbS projects in the past [110]; however, if a specific funding stream is created for urban adaptation using NbS, it can become transformational in terms of supporting a more targeted approach towards action.

(e) Sociocultural. Humans not respecting and properly attributing value to non-human nature is mentioned by some authors as a barrier to the implementation of NbS [112]. Our current paradigm, and what brought us to this age of crises, is one of economic growth, relying heavily on consumerism, and depending on cheap energy [113]. There is currently some support for the need to shift from endless growth to a degrowth model of development [114]. Degrowth [114–116] is a field of research and a social movement that questions the importance of economic growth, primarily because endless growth is not compatible with a world of finite resources; it is an alternative to the sustainable development paradigm, which has failed to produce results [115]. Contemporary social and cultural identities and experiences are so deeply rooted in consumerism and resource exploitation that a change in system seems unattainable. If we are to change the system, we must understand its relevant underlying issues. One such issue is the fact that western civilization is built on the premise that humans and nature are separate [117]. The dominant culture is based on human/nature dualism, a thousand-years-old western-based cultural ideology that sees the human and the mind as part of one category of reason and consciousness, separate from a lower category that comprises the body, the animal, and the pre-human [29,118]. In this *hyperseparation* [29,118], the physical sphere is nothing more than a resource, existing to serve the superior conscious, spiritual and mindful human; nature is devoid of individuality, spirit, conscience, and agency, which belong exclusively to the human. This differs from the view of most Indigenous people, who view themselves and nature as part of the same ecological family, considering that human survival depends on nature [119]. Sustainability in interaction with the natural world is key to most Indigenous communities, as illustrated by the *Seventh Generation Principle*, an Iroquois Confederacy law that states the chief must ensure the land is managed sustainably to provide until the seventh generation into the future [120].

Environmental philosophers have been highlighting the need to change humankind's relationship with nature as a necessary first step to overcome the crises the world is facing. According to Irwin (2010) [113], climate change is a crisis of humanity's illusion of mastery over nature. This human-centric view of the world can create dangerous beliefs, such as humans being ecologically invulnerable. Plumwood (2010) [29] considers that if humankind is to survive as a species, a new origin story is needed, which can help change human's view of the material world and, instead of dominating, start negotiating with the environment. Considering the fast pace of the unravelling of life-support systems [31], the real possibility of societal collapse [25] should be addressed, even if for risk management purposes only [121]. A recent review of *The limits to growth*, from 1972, concluded that the world is almost at the point of no return in terms of societal collapse, with a high likelihood of it taking place before 2040 [122]. Transformative change tackling the root causes of the crises is urgent [31], and a shift towards a philosophical ideal of an ethical participation of humans with nature may be the only option which will allow for a human future to exist [120].

5. Opportunities

Based on the reviewed bibliography, this paper identifies the following main opportunities for the use of NbS in urban adaptation: (a) systems change; (b) social resilience; (c) mitigation and adaptation synergies; and (d) a funding–knowledge support systems nexus.

(a) Systems change. To address the overwhelming challenges of the climate change and biodiversity crises, systems change is required [123]. Systems change seeks the transformation of the *status quo* by altering underlying structures and supporting mechanisms of a system with a series of focused interventions [124]. It is aligned with the concept of *transformational adaptation*, adaptation that is not merely defensive, but that contributes directly to transform society in necessary and beneficial ways, and that simultaneously prevents/mitigates further climate damage [125]. NbS are relevant in this context, working with nature instead of against it, promoting resilience and placing efforts towards a green economy instead of industrialized activities [11]. Recent research is encouraging, showing a correlation in the participation in NbS projects with behavioral change towards more sustainable choices [126]. The role of NbS in supporting systems change seems promising and deserving of further research [25].

(b) Social resilience. The participation of local communities and Indigenous people in implementing NbS can contribute to reduce their vulnerability, including and beyond income-generation. They can build capacity and promote innovation, thereby supporting adaptation [25,83]. Educational programs should be included. NbS are also an opportunity to empower vulnerable communities at a time of great inequality all over the world. Only by leading society away from a resource-extracting paradigm, which is partially responsible for inequality, and towards renewable resources and equality, can they become real solutions [127].

(c) Mitigation and adaptation synergies. NbS can be vital for some parts of the developing world. Substantial areas of *irrecoverable carbon* stored in ecosystems such as peats and mangroves are located near the equator, and, if destroyed, will lead to runaway climate change [128]. This has been identified as a critical international priority in terms of mitigation [128,129]. As mangrove forests can play a substantial role in the adaptation of coastal cities to sea level rise, strong synergies between adaptation and mitigation could be developed. Many cities, particularly in the developing world and in Southeast Asia, could benefit from this combined approach, as it is the region with the largest and most diverse mangrove forests in the world [130].

(d) Funding–knowledge support systems nexus. Funding streams focused on supporting NbS for urban adaptation should be associated with a knowledge support structure to help overcome local governments' limitations, assisting in building institutional capacity. These knowledge support structures could also help map and address existing gaps, assisting with the global knowledge exchange. Synergies should be developed with urban planning departments and entities, as they are the natural change agents and drivers for NbS [16].

6. Conclusions

Urban adaptation is falling behind despite being urgent. Although NbS are far from being able to address the climate crisis on their own, they are a unanimously supported approach for urban adaptation and should be implemented. It is important that this implementation is performed in the context of full-community participation and empowerment for action, promoting awareness, resilience, and innovation. Crucially, for NbS to be successful in the long-term, urban planning policies and the overall approach to urban challenges must be adjusted, which is understandably challenging. Systems change is needed, and NbS can play a role by promoting nature-related opportunities, contributing to steer societies away from a traditionally industrialized model and towards a way of life more connected with the natural world.

Although many knowledge gaps remain, more research is needed, and urban planning policies must be updated, as urban adaptation cannot afford to wait. Pilot projects must be initiated to protect communities, participating in filling existing gaps through knowledge gained during development and assessment of effectiveness, contributing to build capacity at both local and global levels. Beyond physical adaptation to climate impacts, emphasis must also be placed on social resilience and institutional capacity. The lack of capacity by local governments, particularly in developing nations, must be acknowledged and addressed, and alternatives should be explored, such as the creation of external special purpose vehicles. Financing organizations can also play a role in terms of knowledge dissemination, which should include knowledge support systems to overcome local governments' shortcomings, preferably in partnership with urban planning entities. More participatory and interdisciplinary research is needed, detailing insights and challenges of developing, implementing, monitoring, and evaluating pilot projects. This research will assist in scaling up NbS for urban adaptation at local, national, and international levels.

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