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Title

Global mapping of urban nature-based solutions for climate change adaptation

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Abstract

Many cities around the world are experimenting with Nature-based Solutions (NbS) to address the interconnected climate, biodiversity, and society-related challenges they are facing (referred to as the climate-biodiversity-society, or CBS, nexus), by restoring, protecting, and more sustainably managing urban ecosystems. Although the application of urban NbS is flourishing, there is little synthesised evidence clarifying the contribution of NbS in addressing the intertwined CBS challenges and their capacity to encourage transformational change in urban systems worldwide. We map and analyse NbS approaches specifically for climate change adaptation across 216 urban interventions and 130 cities worldwide. Results suggest that current NbS practices are limited in how they may comprehensively address CBS challenges, particularly by accounting for multidimensional forms of climate vulnerability, social justice, the potential for collaboration between public and private sectors, and diverse co-benefits. Data suggest that knowledge and practice are biased towards the Global North, under-representing key CBS challenges in the Global South, particularly in terms of climate hazards and urban ecosystems involved. Our results also point out that further research and practice are required to leverage the transformative potential of urban NbS. We provide recommendations for each of these areas to advance the practice of NbS for transformative urban adaptation within the CBS nexus.

Main text

Nature-based Solutions (NbS) have risen rapidly in the urban climate change adaptation agenda, attracting significant investment as well as academic and political interest worldwide [1–3]. NbS likely account for up to half of all urban climate adaptation measures implemented in the last decade [4,5]. However, their rise is also the subject of much debate. NbS are being promoted by many governments, financial institutions, and international governmental organisations for their ability to potentially address interconnected climate, biodiversity, and social challenges facing cities (referred to as the climate-biodiversity-society, or CBS, nexus) [6–8]. At the same time, the concept of NbS (beyond their application in cities) is challenged by Indigenous and Local Community groups, grassroots organisations, and certain nations (especially in the Global South) for framing it as a "silver bullet" to these joint challenges [9,10] and for downplaying their social justice implications and potential for maladaptive outcomes [3,5,9–12]. In attempting to address these concerns, NbS are now more commonly framed as complementary, rather than alternative, approaches to respond to CBS challenges that must account for local social, ecological, and technical contexts [2,6,9].

Much work has been done in assessing the contribution of NbS to climate change mitigation generally [1,2,6]. However, there are important gaps in knowledge about their role in adaptation in the urban context [4,13–15]. Additionally, much of the analysis of urban NbS is limited to certain sub-sets of NbS [16,17] and regions [18,19], or they tend to provide theoretical framings rather than provide comparable empirical information [20]. Importantly, although critical [21], still yet to be clarified are the patterns of use of urban NbS and their contribution to transformative change across multiple regional contexts worldwide that are yet to be the focus of systematised knowledge [22–24].

To address this gap, we screened 823 NbS projects worldwide sourced from nine secondary databases on climate adaptation actions and NbS. This resulted in the mapping and analysis of 216 individual NbS (interventions, hereafter) across 130 cities in 55 countries (see Supplementary Information 1 (SI1) for the full search, screening, coding, and analysis protocols, and Supplementary Data 1 (SD1) for the coding and analysis protocol. Full database available online at https://doi.org/10.5281/zenodo.7059923[25]). The resulting database allowed us to shed light on two key questions. Firstly, in which ways does current practice on NbS to climate change adaptation address the interconnected climate, biodiversity, and society-related challenges facing cities? And, secondly, is the current practice of NbS helping cities to promote necessary transformational changes to meaningfully address these CBS challenges? Following an exploration of regional trends in urban NbS applications, we analyse ten integral features of NbS grouped into different key CBS challenges they relate to. These include which climate change hazards are addressed and how (hereafter, climate challenges), how ecological features of NbS are leveraged toward urban climate change adaptation outcomes (biodiversity challenges), and finally how NbS are governed and address social justice issues (social challenges). Finally, the transformative capacity of the mapped urban NbS is discussed in terms of their impact on cities in addressing CBS challenges.

[Fig. 1]

A large share of the interventions analysed here are located in (mostly western) Europe (63% of all interventions), followed by the Americas (principally Latin America and the Caribbean), and Africa (primarily sub-Saharan), accounting for 13% in each region. Relatively few cases could be found in global databases for Asia (7%) and Oceania (2%), with the majority in Western Asia and Melanesia (Fig. 1). Our dataset thus has a regional bias towards Europe and South America, as interventions in other regions tend not to focus explicitly on cities or climate adaptation, or were not sufficiently detailed in the available secondary databases we used (see Methods).

Climate challenges addressed by urban NbS

The types of climate hazards addressed, along with the objective of the NbS in reducing socio-economic vulnerability to climate impacts, were taken as key NbS features (grouped under "Climate" in Fig. 2). According to established taxonomies [3,26–28], climate hazards were aggregated into four main categories: (i) intense precipitation (e.g., flooding, soil erosion, landslides) accounting for 81% of interventions, primarily in Europe, (ii) rising temperatures (e.g., heat stress, urban heat island effect, and wildfires) with 59% of interventions, mostly in Europe, (iii) drought, 26%, primarily in Africa and the Americas, and (iv) coastal hazards (e.g., sea level rise, storm surge, and coastal hazards) with 11% of interventions found, more frequently in Africa and Oceania (unless otherwise stated, categories are not mutually exclusive and do not sum to 100%; see "Hazards" in Fig. 2).

[Fig. 2]

Interventions can also be clustered in terms of their objectives in addressing socio-economic vulnerabilities to climate impacts, defined by the Intergovernmental Panel on Climate Change (IPCC) to include three primary aspects [6,29]: (i) reducing exposure to climatic hazards (e.g., by decreasing land area or share of the population that are impacted by flooding, overall seen in 99% of all interventions – "Objectives" in Fig. 2), (ii) supporting the capacity of citizens to enact their own adaptation strategies to hazards (e.g., by implementing early warning systems, overall seen in 36% of interventions), and (iii) reducing sensitivity to climatic hazards (e.g., by reducing the magnitude of the impacts on citizens and their ability to cope with climate-related shocks, seen overall in 17% of interventions- see example in Fig. 3a). A large share of interventions (52%) address only one specific aspect associated with vulnerability, generally connected to reducing exposure to climatic hazards, without addressing sensitivity or adaptive capacity [29].

[Fig. 3]

Biodiversity challenges addressed by urban NbS

Several features help to better describe how and to what extent NbS address urban biodiversity challenges, particularly: (i) which types of NbS approaches and (ii) which types of ecosystems are involved in NbS implementation, (iii) how ecosystems are modified by the interventions, and (iv) which types of species they take into account (grouped under "Biodiversity" in Fig. 2). This framing clarifies the use of the concept of nature in the context of NbS in cities [30].

The broad notion of NbS is evolving as an umbrella term for actions that deal with restoring, protecting, or sustainably managing ecosystems to provide benefits both for biodiversity and people [31,32]. To particularise these differences within our data we aggregated NbS interventions in cities into two broad groups following established typologies [30,33]: (i) interventions associated with "ecosystem-based adaptation" (EbA), generally involving relatively large areas of low-density urbanised land; and (ii) "green and blue infrastructure" (GBI, both under "NBS type" in Fig. 2) generally encompassing smaller areas (although these may form large networks across cities), and typically integrated into the built environment, such as via green roofs/walls [20,30,33]. Though other types of interventions exist under the NbS umbrella [34], these did not emerge from our analysis, see SI1 for further discussion) Overall, GBI approaches are more prevalent (56% of all interventions – see Fig. 3b for an example), especially in Europe, with EbA being used more often in other regions.

The types of ecosystems were aggregated into four main groups ("Ecosystem type" in Fig. 2): (i) terrestrial (lawns/parks, street trees, urban forests, and cultivated lands), (ii) aquatic (in-land wetlands, lakes, and rivers/streams), (iii) coastal (coastal/beaches, coastal wetlands, sea), and (iv) a combination of these categories [15,35]. Terrestrial ecosystems were more common (48% of all interventions), frequently in the form of lawns/parks and street trees, followed by a mix of ecosystems (25%, combining lawns/parks or urban forests with lakes or in-land wetlands, mostly in Europe and the Americas), aquatic ecosystems (21%, mostly rivers/streams and in-land wetlands in Asia and the Americas), and coastal ecosystems (5%, mostly on beaches, often within Oceania and Latin America and the Caribbean).

The main approaches through which NbS interventions involve ecosystems ("Approach" in Fig. 2) are grouped into: (i) ecosystem restoration (45% of all interventions), (ii) ecosystem protection (50%), (iii) ecosystem management (14%), and (iv) novel ecosystems (13% - see Fig. 3c) [15,36]. Few interventions explicitly mention the use of native or climate change adapted species (20% and 2% respectively – "Species" in Fig. 2, and example in Fig. 3d). The latter was used as a proxy for how cities account for the ability of the interventions themselves to adapt to future changing climate conditions [7].

Social challenges addressed by urban NbS

Urban NbS for climate change adaptation involves governance challenges, not least due to potential impacts on social justice. We mapped four governance features (grouped under "Society" in Fig. 2): (i) how current NbS are funded [37], (ii) which actors are tasked with implementing NbS [38], (iii) what broader socio-economic goals they involve (beyond adaptation) [23,38], and (iv) how NbS interventions address issues of social justice.

Sources of funding ("Funding" in Fig. 2) were coded as mostly involving (i) local public funding (e.g., city governments, hereafter "public"), (ii) international institutional funding (e.g., EU programs, climate funds such as from the World Bank, see Fig. 3e for an example) and (iii) private funding (e.g., from private businesses). Funding sources were analysed separately to the actors responsible for implementing the interventions as a way of separating different actors by their roles as funders or implementing parties. Most interventions (80%) received public funding, with much of this ending up in publicly implemented projects (see Fig. 4 for flows among funding sources, implementing actors, and socio-economic goals). Co-funding, typically between local public and international institutional funders, is common (48% of interventions) with private funding being the least common (20% of interventions, but seen more frequently in Europe), and primarily used to fund interventions implemented by public or private (business) actors, with less private funding reaching household or institutionally led interventions overall (see flows between funders and actors in Fig. 4).

[Fig. 4]

Actors responsible for implementing NbS in cities ("Actors" in Fig. 2 for regional distribution, and Fig. 4 for their relationships with Funders and Goals) include (i) local public actors (as described above, 71% of all interventions), (ii) households (e.g., individual households within neighbourhoods, 5% - see Fig. 3f for an example), (iii) private businesses (10%), and (iv) international institutional actors (as described above, 12%).

Tracing the goals of NbS interventions in cities provides insight into the reasons underlying their use and the extent to which they take advantage of their potential to provide multiple socio-economic co-benefits in the urban context[38]. The overall non-climate change-related socio-economic goals (see "Goals" in Fig. 2 for regional distribution, and Fig. 4 for the relationship with Funders and Actors) are categorised as (i) urban development (80% of all interventions, see Fig. 3g for an example), (ii) economic development (e.g., creation of green jobs) (14%), or (iii) legal goals (e.g., complying with or creating new local legal standards or following international laws or covenants, 15%).

Finally, a key challenge faced by NbS for climate adaptation in cities is how they address issues of social justice, for example through green gentrification or other undesirable impacts on the social fabric of cities [39–41]. Although most interventions addressed social justice in some way, they often did not reflect the multidimensional nature of social justice. We evaluated social justice by reference to its three basic dimensions relevant to the design and implementation of NbS [3,42,43]: (i) procedural, relating to how the intervention includes stakeholders in decision-making processes (seen in 81% of all NbS interventions), (ii) recognition, i.e., acknowledgment of special needs of certain stakeholder groups (seen in 28% of interventions), and (iii) 'distributional', i.e., how benefits and costs are distributed across social groups (20% of all interventions; see Box 1 for practical examples of these different forms, and "Social justice" in Fig. 2 for regional distribution). Overall, 53% of the interventions did not consider more than one dimension of social justice. This differed by region, for example, 75% of African NbS interventions included two or more dimensions.

Transformative capacity of current urban NbS practice

There are different approaches to categorise the ways and magnitude with which adaptation actions can trigger necessary changes in cities [44]. Many adopt a tiered approach to place each action along a continuum from shallow to deeper changes in the direction of transformative change [8,24,45]. We adopted this approach as it allows the identification of types of change in a way that is flexible to accommodate the diversity of cities and their diverse contexts [24,44]. Here "change" is understood along three tiers as *incremental* (shallow), i.e., mostly maintaining business-as-usual approaches to adaptation (see Fig. 3h), *reformist* by focusing on addressing underlying drivers of change, but failing to address the problem structurally or systemically (see

Fig. 3i), or *transformative* (deep) by focusing on and substantially changing structures, including institutional ones (norms and rules) (see Methods and Section 4.1.4 of SI1 for further discussion of alternative transformation theories) [24]. While adaptation actions may add up over time to become reformist and even transformational changes (e.g., "radical incrementalism" [46]), we analyse the transformative capacities of NbS under current conditions (rather than potential) future dynamics with the city as a unit of reference [8]. These three levels of change (in terms of potential to achieve them, evidenced by NbS studied [45]) were mapped against the three broad dimensions of cities as social-ecological-technical (SET) systems: (i) social change (e.g., social relationships, networks, and dynamics within them), (ii) ecological change (e.g., ecosystem functions and their distribution), and (iii) technical change (e.g., the built infrastructure of cities and their parts, roads, buildings, etc.) (see Box 1) [47,48].

In general, cities show a higher potential for a deeper degree of transformative change in the ecological dimension (15% of all interventions) over social (11%) or technical dimensions (9%), while the highest proportion of more shallow forms of incremental change was observed in the technical dimension (34% - Fig. 5a). Most NbS interventions are reformist across all three dimensions, concurring with previous studies on non-urban NbS [49] and urban adaptation generally [24]. Here, this was often because of their lack of engagement with a deeper process of social engagement beyond superficial public consultation (social change), their piecemeal approach to improving conditions for urban biodiversity (ecological change), or due to their limited connection to city-wide urban planning rules and norms (technical change) [24,45]. Interventions in the Americas (especially in Latin America and the Caribbean) made up most of the transformative interventions across the three dimensions (social, ecological, and technical), followed by Europe, and with notable degrees of transformative capacity displayed in the ecological dimensions of African cities (Fig. 5b; see Box 1 for examples of transformative change for each SET dimension from data collected).

[Fig. 5]

[Box 1]

Discussion

Combining insights from our two primary research questions on the contribution of NbS towards helping cities address CBS challenges and promote transformative change allows us to synthesise key findings and recommendations for both research and policy to ensure NbS are well-designed and complementary to the broader urban adaptation agenda. Our analysis supports growing calls for the need for careful consideration of how NbS for adaptation in cities are designed, implemented, and governed, to address key deficiencies in current adaptation practice and to move the use of NbS beyond current incremental/reformistic trends [1,2,6,8,9].

What do our results reflect regarding the transformative potential of NbS in cities under the CBS nexus? Overall, the NbS interventions mapped and analysed are characterised by a relatively shallow (incremental and reformistic) capacity to promote change across social, ecological and technological dimensions. Simultaneously they show uneven consideration of interconnected CBS challenges. Our results show a lack of connection of NbS interventions to multidimensional forms of both socio-economic vulnerability (i.e., sensitivity and adaptive capacity [6]) and social justice (i.e., recognition and distribution [12,41]) which are integral to transformative changes for more just and sustainable futures [24,45]. The lack of consideration of non-anthropocentric climate vulnerability of NbS interventions themselves (by not considering species resilient to future climate change [3,5,50]) is an important finding that may constrain the social-ecological transformative potential of NbS by undermining their ability to provide co-benefits into the future [7,50]. Further, although the literature finds the engagement of the private sector to be crucial to unlocking the transformative social, ecological, and technical potential of NbS in cities [37,51], we find little evidence of this. The main responsibility for implementing and funding NbS interventions studied here was left to local public actors and budgets, which are often constrained and subject to shifting priorities, echoing previous findings [18,19]. Relatedly, although NbS are framed both in research and policy spheres as having a high potential to integrate a variety of (non-climate change related) socio-economic goals towards urban transformation [38], our analysis concurs with previous studies noting a lack of uptake of this potential [18] (e.g., green job creation, or solidifying NbS thinking into city planning through legally binding mechanisms).

Other blind spots on transformation emerge in current NbS practice. Contextual factors (e.g., climate, demographics, poverty levels) inform how transformative change can be catalysed within and between cities through knowledge transfer [30,52]. However, inclusive opportunities for knowledge transfer and collaboration rely on the existence of a diverse range of experiences across different urban contexts and their specific challenges under the CBS nexus, and that different cities can learn from and collaborate on [22]. Currently, the literature reports that NbS knowledge transfer is already occurring [52], but mostly centred around landmark, large-scale real estate developments, or around the design of (green) urban parks [18]. Our results reflect a similar bias in NbS practice worldwide towards restorative/novel and terrestrial/infrastructural NbS (particularly GBI through green parks), mostly in the Global North, addressing similar types of climate hazards (intense precipitation and rising temperatures, an acknowledged bias in urban adaptation [4,6,15,18]). However, many cities in the Global South are more often in equatorial climates that are more severely exposed to certain hazards (e.g., rising temperatures) compared to the Global North, or more often face other hazards (e.g., drought, coastal hazards) simultaneously experiencing heightened socio-economic challenges due to rapid urbanisation combined with higher levels of poverty. Other studies have highlighted that these conditions may not favour the same kind of green approaches [23]. This questions the applicability and effectiveness of knowledge transfer of the current practice on NbS described by our data to different contexts as most experimentation is currently occurring under only a specific set of SET conditions and CBS challenges, leaving others without adequate representation [23,53]. The scientific debate around differences among NbS types and their relative applicability and effectiveness across urban contexts facing dire climate change impacts requires more nuance, and thus further work is needed to collect more diverse experiences with NbS across urban contexts and their associated CBS challenges [21,23,54].

Our analysis builds on the growing body of research focused primarily on understanding transformative examples of NbS in cities [55,56]. Our results highlight where and how interventions may fall short of this ambition globally, further breaking open opportunities for reflection on how

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to bridge this gap [11]. Examples of interventions with transformative capacity (or "bright spots" [57]) exist among the NbS interventions that we have mapped. Such NbS illuminate what transformation can look like within social, ecological, and technical dimensions of urban systems. Some promising bright spots include those such as the NbS interventions in the Maldives, which have paid attention to all three forms of social justice studied (uncommon within the database), as well as Durban (South Africa), São Paulo (Brazil) and Hamburg (Germany), given their success in forging transformative capacities across social, ecological, and technical dimensions respectively (see Box 1).

Two key recommendations stem from our analysis to guide future research and policy. First, future research could fill key knowledge gaps that occur across multiple gradients. This includes geographical North-South gaps, and gaps in understanding whether and how cities facing CBS challenges under different social, ecological, and technical conditions to those mapped here may implement NbS effectively and equitably. This could be done by building on and further connecting ongoing efforts to centralise knowledge regionally. Examples include the Urban Nature Atlas focusing initially on Europe [18], and extending later to other regions through participatory approaches [58], or the emerging Kiwa Initiative focusing on NbS in Oceania [59].

Second, urban policies need to engage more deeply with the full range of CBS challenges especially in terms of climate vulnerability experienced both by different social groups and urban ecosystems. This also implies that the full range of potential co-benefits and opportunities for cross-sector cooperation needs to be explored. Together, addressing these gaps could help city planners unlock the transformative capacities that are largely untapped in current NbS practice [22,45]. While already beginning in certain regional contexts [60], enhancing collaboration between science and policy would allow a better understanding of how local contextual factors may favour both the emergence of different types of urban NbS, as well as their potential to promote transformative change [52].

Methods

Between the period of January to June 2021, we systematically mapped 216 nature-based solutions (NbS) to climate change adaptation in urban areas from 55 different countries across all United Nations (UN) regions, collected from nine online databases on climate change adaptation and NbS. This was guided by the systematic mapping standards set by the Collaboration for Environmental Evidence [61]. This process can be summarised as setting the objectives and scope of the mapping, establishing a search and screening process, and finally coding and extracting relevant data from interventions found through these processes. Each of these is outlined below.

Objectives and scope

First, a systematic mapping protocol was established to define the scope of the work presented here (full protocol available in Supplementary Information 1 (SI1)). This protocol defines the key characteristics of interventions eligible for inclusion within the search in terms of their subject, intervention, and outcome (or SIO) [62]. The *subject* defines the relevant population or group to be studied, which here refers to urban areas as defined by the UN Population Division (areas within the defined limits of urban agglomerations, metropolitan areas, or cities proper) [63,64]. The *intervention* then defines the activity that is to be studied, here already implemented NbS (rather than planned or modelled outcomes). The term NbS is used as an umbrella term for numerous types of interventions, but is broadly defined as "… actions to protect, sustainably manage, and restore natural and modified ecosystems that address societal challenges effectively and adaptively, simultaneously providing human well-being and biodiversity benefits" [31]. While numerous other terms have been used to describe what are now more often collectively termed NbS, such as green infrastructure, blue infrastructure, and ecosystem-based adaptation, any intervention meeting the IUCN definition was included regardless of the term used (more information can be found Section 2.1 in SI1, and in the data coding template in Supplementary Data 1 (SD1)) [65]. Finally, the *outcome* frames the motivations or goals pursued through the intervention, here climate change adaptation. Adaptation to climate change was understood as interventions undertaken to address social, economic, and ecological impacts of the following hazards worsened by the ongoing process of climate change:

- coastal hazards (sea level rise, storm surge, and coastal erosion),
- intense precipitation (floods, soil erosion, and landslides),
- drought, and
- rising temperatures (heat stress, urban heat island, wildfires)

See SI1 for a detailed discussion of the SIO [26,27].

Search procedure

The search procedure describes how the overall sample of interventions was collected, upon which the inclusion and exclusion criteria are later applied to produce a set of in-scope interventions for further analysis. The search process involved identifying interventions potentially matching the SIO from a total of nine online databases, spanning from inter-governmental funding organisations, global city-level information sharing platforms on adaptation/NbS projects, as well as national-level funding organisations (Green Climate Fund, Adaptation Fund, International Climate Initiative, World Bank, ClimateADAPT, Oppla, the Panorama Initiative, Urban Climate Change Research Network, and the Equator Initative). Databases were identified from similar reviews on NbS and adaptation conducted without a specific focus on the urban experience, as well as through expert consultation. These kinds of databases, being "grey" sources of information, were selected on the understanding that they are often the most readily available sources of information on implemented on-the-ground NbS from a broad range of geographies and countries [26]. The range of perspectives given by these different databases is also a key strength of the approach taken here as they allow more direct insight into motivations and priorities of interventions according to those who design, fund, and implement them [22]. However, an understanding of the primary intentions in the creation and population of these databases is important to acknowledge potential biases and better interpret our data. Some of the databases used here have been created to report to funding agencies, to showcase NbS as an adaptation strategy or to award local efforts. These differing goals might explain the coverage, quality and quantity of information contained in each database. In Section 3.1 and Table S2 (SI1), we have given further detailed information on each of the databases, including acknowledgement of the use of scientific protocols to collect their information.

To search within these multiple sources for eligible interventions, each having its own internal data structures and search functions, the exact approach taken to searching within each of them had to be adapted following common guidelines. For example, in some databases it was possible to filter and extract results by terms matching exactly to the SIO used in this study, and where this was possible this was done (e.g., to filter by projects involving NbS and adaptation in cities, and directly export to another file format for screening). This was done analogously to how search strings may be applied in reviews of scientific information within repositories of published articles (e.g., Web of Science, Scopus, etc). For others, it was only possible to filter by some or none of the SIO identified, and so different levels of manual effort had to be applied to each database searched. In all cases, the results of all searches were compiled in a single spreadsheet for later screening. The interfaces of all databases consulted were in English, though some could have contained entries in other languages. The mapping was not in principle limited to English language content, and so to ensure the return of non-English entries through searches, local data tags were used that did not depend on the language of individual entries. For a full account of databases consulted and methodological choices made during the search phase, see SI1 (Table S2). Overall, 823 records of interventions were gathered through the search process and were then subject to screening.

Screening process

Screening describes the process of reviewing all search results (823 records, in our case) to verify whether they meet the inclusion and exclusion criteria represented by the SIO identified above. Given the variety of sources consulted, the exact screening process had to be adapted to suit the structure of the individual platforms. In general, screening was a two-step process, where most readily available information was screened in the first instance (e.g., project landing pages), and more in-depth information was then screened as a second step (e.g., detailed project or monitoring and evaluation reports, peer-reviewed publications linked to the entry if available). The first stage of screening was done to identify those interventions that were more clearly in the scope of the search. Where possible, the first stage of screening was aided using data tags either provided by the source if available (e.g., where a project is tagged as being about adaptation) or were applied to the source through a process of web scraping where possible from retrieved intervention URLs using the rvest [66] and dplyr [67] packages in R (version 4.0.3 (2020-10-10)) in RStudio (version 2022.02.3+492). This information was verified manually by the second step and was only used as an aid to interpretation to minimise human error where possible and not as a replacement for manual screening (see SI1, Table S2 for full details of when and how this was done). Where doubts existed as to the eligibility of the intervention, a cautionary approach was taken, and interventions were preliminarily kept for the second stage of review. The second stage then allowed a deeper consideration of all material available through the search to finally ascertain whether the intervention should be included. If the eligibility was still questioned after the second stage, as a sub-step to this stage we conducted a brief Internet search of the name of the intervention as written in the database (i.e., usually in the original language) in addition to the city/country name (to the first 10 results, not limited by language) to seek further information to judge the eligibility of the intervention from reliable sources (e.g., government websites, consultancies or engineering/architect firms involved in the project). If no new information was found, the intervention was excluded. As with the search process, most information screened was available in English. Screening of all non-English entries at both steps was done using online translation tools (Google Translate and cross-checked with DeepL where possible), as were additional Internet searches. This was done to mitigate potential language bias in the retrieval of projects to be included in the sample, with the aim of maximising global representation.

A precautionary approach was applied to interpreting information gathered in both screening steps, as interventions had to explicitly meet inclusion criteria defined by the SIO (e.g., it could not be assumed a given intervention may respond to a climate change hazard-related risk, it had to be specifically stated to be motivated as such). All reasons for exclusion were recorded, and the search and screening results were summarised in the form of a flow diagram, prepared to align with reporting standards set by the Collaboration for Environmental Evidence (SI1, Fig. S1) [68]. Overall, 216 individual interventions were identified from the 823 records screened. In summary, over 90% of all interventions excluded during screening were not urban or explicitly adaptation-focused, principally in regions outside of Europe. The exclusion of most of the remaining interventions was based on a lack of sufficient information to complete the analysis, given that our analysis entailed high informational requirements because of the breadth of data analysed. Overall, 216 individual interventions were identified from the 823 records screened.

Coding and data extraction

Once the 216 individual interventions were collected from the sample through searching and screening, they were analysed and coded according to the kind of information sought by this study to answer our two research questions. Information used to analyse and code interventions included information within the database, for example project descriptions, which contained a varying level of detail. To complement this information where necessary, analysis extended further to any other material attached or linked to the individual entry, for example linked project reports (e.g., monitoring and evaluation reports), peer-reviewed information where available, or other websites from implementers/funders. This was recorded when done ("Further information links used" column in database file, Tab 3). Where this information was still insufficient to conduct the full analysis, further Internet searches were conducted (up to the first 10 results, not limited by language) to find relevant and credible information in the same manner described above for screening. Where results were not in English, online translation tools were used as above (see SI1 for further discussion). This was done to mitigate potential language bias to ensure accurate and credible information was retrieved about all interventions regardless of their geographical location or the language used to describe them.

As discussed in the main section of this paper, these data points centre around the key features of urban NbS in terms of how they address the problem space triangulated by climate change, biodiversity decline, and the social challenges these create in urban areas (referred collectively as the climate-biodiversity-society nexus, or CBS nexus). This concept recognises how each of these issues or nexus points potentially interact in urban environments on numerous levels as they share common drivers and feedback loops. Applied to real-world interventions like urban climate change adaptation, the concept makes visible the different assemblages of ways these nexus points may interact, or not (e.g., climate-biodiversity, climate-society, or biodiversity-society), thereby revealing the kinds of trade-offs that may be encountered through these interventions while further highlighting pathways towards addressing them [7,8].

Within these three categories (climate, biodiversity, and society), there was a total of ten features analysed, each with multiple (often non-exclusive) possible answers, shown in Fig. 2. For example, the ecosystem type variable contained nine different urban ecosystems, of which interventions could involve multiple (e.g., rivers together with parks). Others were mutually exclusive and could only be one of several categories. For example, the type of NbS was aggregated to include ecosystem-based adaptation (EbA) or green/blue infrastructure (GBI) based on previous work highlighting several distinct functional characteristics warranting their mutually exclusive categorisation as unique manifestations of NbS that nonetheless share certain uniting features (see Section 4.1.2 in SI1 for further discussion) [20,30,65]. This collection of features was drawn from a review of current literature on the critical features of NbS within this problem space (i.e., urban climate change adaptation in the CBS nexus). They were included on the basis of their ability to collectively describe current practice on this topic, answering key functional questions on NbS in terms of *how* and *why* are they implemented, *what* kinds of natural or other processes do they rely on, *who* was involved in this process, and *where* are they implemented [6,15,23,30]. These were coded most often in a binary fashion as the presence or absence of a certain attribute.

After establishing what NbS *do* as urban climate change adaptation strategies, it was further necessary to evaluate the magnitude of their impact on CBS dynamics in a way that accounts for the unique nature of cities as social-ecological-technical systems. Here, this was interpreted as the capacity to affect a certain degree of change across the social, ecological, and technical system dimensions of city systems. This accounted for an additional three groups of variables (social, ecological, and technical degree of change). Our chosen approach towards understanding transformative change categorised each intervention as evidencing one of three ascending levels of capacity for change within each city dimension: incremental, reformistic, and transformative. Though there are numerous alternative understandings of transformation[44], this understanding was chosen on the basis of its flexibility to apply to the broad range of city contexts analysed here, combined with its specificity to stratify change across different city dimensions (see Section 4.1.4 of SI1 for further discussion). The classification of an intervention as evidencing a certain capacity for change in each city dimension was done on an interpretive level, taking into account all available information on an intervention emerging from the search and screening process as well as set theory on the topic of transformative adaptation (ranging from mostly self-reported project descriptions within databases to detailed monitoring and evaluation reports or peer-reviewed scientific publications where available, complemented where possible by internet searches described above regarding the search and screening process) [24,45]. For further information on the meanings of all variables, please see Section 4.1 of SI1 (Section 4.1 - Data coding framework) as well as the full data coding template available in SD1 (Tab 1).

Semi-automated data collection

As with screening, coding and data extraction was performed in a hybrid manner using semi-automated techniques. Certain keywords were searched from scraped intervention URLs to automatically pre-fill some data points through web scraping in R version 4.0.3 (2020-10-10) in RStudio (version 2022.02.3+492) using the rvest and dplyr packages [66,67] (e.g., involving climate hazards and ecosystem types). Categorisations made using this process were taken as a suggestion only and were nonetheless checked with source material used to account for errors and over-simplifications. This was done to speed up data collection of certain data points and to minimise human error, though was not a replacement for manual data collection. When this was done, it is indicated in the data coding template supplied in SD1.

Data synthesis

Once all interventions were coded, the results were then synthesised mainly in terms of descriptive statistics. These statistics were used to describe current practice on the use of NbS to urban climate change adaptation as well as answer questions emerging from previous studies while also revealing several gaps in current practice and knowledge on the topic. All data analysis was performed in R version 4.0.3 (2020-10-10) in RStudio (version 2022.02.3+492). Data were visualised using several R libraries, including ggplot2 [69] (Figs. 1, 2, and 5, where Fig. 2 was modified from code used under MIT License (Copyright 2015-2017 Holtz Yan [70])), networkD3 in conjunction with webshot (Fig. 4) [71,72] as well as QGIS (Fig. 3). Box 1 as well as Figs. S1 and S2 were prepared using Microsoft PowerPoint.

Data availability

Data generated or analysed during this study are included in this published article (and its supplementary information files) and online repositories. Information included in this published article includes the systematic mapping protocol (Supplementary Information 1), as well as the coding framework used to analyse interventions (Supplementary Data 1). Information available through online repositories includes the full set of coded interventions, which can be found online at https://doi.org/10.5281/zenodo.7059923. This dataset was establishing from a screening of the following nine online databases: Green Climate Fund, Adaptation Fund, International Climate Initiative, World Bank Portfolio on Nature-based Solutions for Disaster Risk Reduction, ClimateADAPT, Oppla, Panorama Ecosystem-based Adaptation Solutions Database, Urban Climate Change Research Network Case Study Docking Station, Equator Initiative Nature-based Solutions Database.

Code availability

All code used for data analysis and visualisation was made through existing libraries using the R programming language (v4.0.3 2020-10-10) in RStudio (v2022.02.3+492). Relevant R libraries include ggplot2 (v3.3.5, Figs. 1, 2, 4, 5), dplyr (v1.0.5, Figs. 1, 2, 4, 5), and networkD3 (v0.4) in conjunction with webshot (v0.5.2, Fig. 4). Fig. 2 was created using adapted code under MIT License (Copyright 2015-2017 Holtz Yan). The rvest package (v1.0.0) was used for certain parts of the data collection through web scraping as described in the Data synthesis section. The Geographic Information System (GIS) software QGIS (v3.10.11) was used to render Fig. 3. Box 1, Figs. S1 and S2 were prepared using Microsoft Powerpoint (Officer 365).

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Author contribution statement - CRediT

SG: Conceptualization, Methodology, Formal analysis, Investigation, Resources, Data Curation, Writing - Original Draft, Writing - Review & Editing, Visualization – Funding acquisition. **MO:** Conceptualization, Methodology, Formal analysis, Investigation, Writing - Review & Editing. **AJC:** Conceptualization, Methodology, Formal analysis, Writing - Review & Editing. **UP:** Conceptualization, Methodology, Formal analysis, Writing - Review & Editing – Funding acquisition.

Competing Interests statement

The authors declare no competing interests.

Figure Legends/Captions

Fig. 1 Geographical distribution of cities with mapped NbS for climate change adaptation. Countries with no interventions in the database are in grey. More specific information on cities can be found in SD1.

Fig. 2 Regional distribution of ten key NbS features included in the global mapping of interventions in cities. Each feature analysed appears along the curved x-axis, while the y-axis represents its geographical distribution with colour coding for different regions (ratio of the count of feature distribution within the region to the total number of interventions from that region). The values on the y-axis do not necessarily sum to 100%, as they reflect the percentage distribution of each feature in a given region, rather than among all interventions. Actual values can be found in SD1.

Fig. 3 Examples of NbS features (as in Fig. 2) in selected cities that use NbS for climate adaptation. The highlighted features help clarify their definition in the context of urban NbS which may be different to other contexts; city examples were chosen for their ability to exemplify these features. The outline of each tile follows the borders of the country where the example is located, filled by the street level map of the city, and the red marker the precise location (maps are not to scale). Project IDs are provided corresponding to the full data set (available at https://doi.org/10.5281/zenodo.7059923). Map tiles by Stamen Design, under CC BY 3.0. Data by OpenStreetMap, under CC BY SA. Map polygons provided by GADM (https://gadm.org/).

Fig. 4 Connections between regions, funding sources, actors involved, and socio-economic goals (left to right) among mapped NbS.

Fig. 5 Overall distribution of (a) capacity for change per city dimension, and (b) regional breakdown of this distribution per social-ecological-technical dimension.

Box 1 "Bright spots" for just, transformative NbS, including an example of an intervention in Addu City (Maldives) which includes design and implementation features associated with all three dimensions of social justice (something uncommon within the database), as well as local NbS projects in Durban (South Africa), São Paulo (Brazil), and Hamburg (Germany), each displaying transformative potential in the social, ecological, and technical dimensions. The latter NbS cases demonstrate potential for deeper changes across these three dimensions.

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