Solution to what? Global review of nature-based solutions, urban challenges, and outcomes

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In response to multiple societal challenges faced by urban areas, nature-based solutions (NbS) are gaining prominence as means to support sustainable and resilient urban planning. However, NbS are being implemented in cities around the globe without comprehensive evidence on their effectiveness in addressing urban challenges. Based on a systematic mapping methodology, we synthesized 361 scientific publications that investigated the effects of NbS applied in urban contexts worldwide. We mapped and analyzed 547 empirical cases of NbS in 197 cities globally, yielding 799 outcomes. To structure this evidence we developed an urban NbS classification. With the aid of this classification, we analyzed 23 urban challenge categories and 30 outcome domains encompassing biodiversity, health well-being, and regulating ecosystem services. The established linkages between urban challenges, NbS, and their outcomes indicate that specific urban challenges were predominantly addressed through specific sets of intuitively related outcomes and secondary outcomes. Specifically, forests & trees and general parks were commonly used to enhance health and well-being, while grassland and gardens were applied to mitigate biodiversity loss. Furthermore, we show that urban NbS generally yielded overwhelmingly positive effects compared to non-NbS, particularly in relation to microclimate mitigation and mental health outcomes. However, our analysis underscores a notable scarcity of evidence of multifunctional NbS that report multiple outcomes related to biodiversity and well-being simultaneously. In combination, our study provides a foundation for further understanding NbS effectiveness and can inform urban planners and policymakers with measurable evidenced-based targets for the application of NbS.

Keywords: cities, biodiversity, ecosystem services, effectiveness, well-being, systematic map

1 Introduction

Cities worldwide are confronted with increasing environmental, social, and economic challenges that together threaten the resilience and sustainability of urban areas (Bush & Doyon, 2019; Keivani, 2010). These challenges include biodiversity loss, flooding after intense rainfall, the urban heat island effect, air pollution, public health issues, and rising social-economic inequality (Brink et al., 2016; Frantzeskaki et al., 2019; Oke et al., 2021). Global trends of increasing urbanization interacting with climate change are likely to amplify the existing challenges and generate new ones, leading to greater economic, social, and environmental losses in cities (Bazrkar, Zamani, Eslamian, Eslamian, & Dehghan, 2015). Given these growing threats to urban populations, nature-based solutions (NbS) have recently been introduced as integrated and multifunctional solutions to enhance resilience and sustainability (Nesshöver et al., 2017). NbS are most commonly defined as "actions to protect, sustainably manage, and restore natural and modified ecosystems that address societal challenges effectively and adaptively, simultaneously benefiting people and nature" (IUCN, 2020). In urban systems, NbS include, but are not limited to interventions involving the creation of forests, parks, community gardens, and the protection and management of existing ecosystems, such as revegetation of riverbanks.

While NbS have been regarded as an umbrella concept of established approaches including ecosystem services, green infrastructure, and ecosystem-based approaches (Kabisch, Stadler, Korn, & Bonn, 2016), a few factors make NbS an innovative and appealing concept for research and policy. First, compared to ecosystem-based approaches and green infrastructure, NbS target sustainability issues more explicitly with a problem- and objective-oriented approach, which enables decision-makers to find focus and immediacy and provides a common language for actors with different disciplinary backgrounds aiming to address urban sustainability challenges (Dorst, van der Jagt, Raven, & Runhaar, 2019; Kabisch et al., 2016). Moreover, while all four concepts share the common principle of multifunctionality, NbS has biodiversity lying at its core, highlighting the potential to simultaneously provide benefits for people and biodiversity (Key et al., 2022; Nika et al., 2020). Lastly, the focus on the application process of solutions is seen as an important added value to enable its connection to policy and planning (Albert et al., 2019; Coletta et al., 2021; Wang, Huang, Xu, & Wang, 2021).

Given these added values, NbS have become more prominent in urban planning, policy, and research (Seddon et al., 2021). However, the broad framing of NbS and uncertainty about what constitutes an effective NbS hinder its practical adoption (Seddon, 2022). This might lead to misunderstanding and misuse of NbS (Krauze & Wagner, 2019). Examples include the over-reliance on tree planting rather than a wide range of NbS, or simply making the city greener rather than considering societal challenges or potential negative outcomes (Escobedo et al., 2018; Holl & Brancalion, 2020). Evidence is lacking on the effectiveness of NbS, i.e., the specific problems for which NbS are needed, and the outcomes of NbS (Nature editorial, 2017; Seddon et al., 2020). To provide such scientific evidence to facilitate policy makers with measurable evidence-based targets and actions on urban NbS, two key challenges need to be addressed.

First, a holistic assessment of NbS effectiveness by coupling specific NbS to urban challenges and measurable outcomes is currently lacking (Johnson, Kumar, Okano, Dasgupta, & Shivakoti, 2022). NbS effectiveness was previously defined as "the degree to which objectives are achieved and the extent to which targeted problems are solved" (Raymond, Berry, et al., 2017, p. vi) and is commonly communicated through the contribution of NbS to

targeted societal challenges (Cohen-Shacham, Walters, Janzen, & Maginnis, 2016; European Commission, 2015). Numerous efforts have assessed NbS effectiveness related to certain objectives of NbS application, such as climate change or water issues, predominantly at large spatial scales and natural environment (Acreman et al., 2021; Chausson et al., 2020). However, there is a lack of knowledge regarding the contribution of site-specific NbS interventions to address challenges in urban contexts. While several studies have contributed to understanding the role of specific NbS in addressing urban challenges or ecosystem service objectives, they did not clearly evaluate outcomes (Babí Almenar et al., 2021; Castellar et al., 2021; Goodwin, Olazabal, Castro, & Pascual, 2023). Further study linking to measurable outcomes is needed to clarify the particular benefits and co-benefits (Frantzeskaki et al., 2019).

Second, a comprehensive, global evidence-based overview on multiple outcomes of urban NbS concerning both human well-being and biodiversity is lacking. Existing systematic reviews often focused on a limited set of urban NbS types (e.g., forests or green roofs) and specific geographical regions (Johnson et al., 2022), lacking a comprehensive understanding of urban NbS on a global scale. Moreover, existing systematic reviews tend to focus on the outcomes related to particular categories of challenges, mainly climate change adaptation (Chausson et al., 2020), or human health (Kabisch, van den Bosch, & Lafortezza, 2017), with less focus on biodiversity. Additionally, comparative outcomes of NbS, especially the performance against non-NbS alternatives, are less researched (Anderson & Renaud, 2021; Dick, Carruthers-Jones, Carver, Dobel, & Miller, 2020; von Döhren & Haase, 2015). Finally, synthesis on evidence reporting multiple outcomes is lacking and interactions between outcomes have received limited attention (Key et al., 2022).

To address the above-mentioned challenges, we used a systematic mapping methodology (James, Randall, & Haddaway, 2016) to consolidate the scientific evidence on the effects of NbS applied in cities worldwide. We aimed to systematically analyze how urban challenges can be addressed by urban NbS and their outcomes. To achieve this, we 1) studied relations between urban challenges, NbS types and their outcomes, 2) evaluated the performance of NbS compared to non-NbS, and 3) assessed cases reporting multiple outcomes and their interrelationships. To facilitate such analysis, we also developed a classification of urban NbS, to allow comparison among studies and facilitate the transfer of information to support urban policies, strategies, and interventions (Babí Almenar et al., 2021). Through this research, we take important initial steps and provide fundamental knowledge toward better understanding the effectiveness of urban NbS. Our findings contribute to informing urban planning and policy, by offering a consistent NbS classification and insights into which urban challenges can be addressed by NbS, and what kind of corresponding outcomes can be expected.

2. Methods

2.1 Systematic mapping protocol for the review

We applied a systematic mapping protocol to define the scope of our analysis (Appendix A). The protocol documents the question scope, search string, and study selection criteria (Collaboration for Environmental Evidence, 2018). We based our protocol on the Context, Intervention, Outcome, Study type (CIOS) framework, which defines key elements for the inclusion of relevant studies (James et al., 2016). We identified urban areas as the context for our research, i.e. the specific setting where the intervention took place. The intervention refers to implemented NbS. The outcome, i.e. the effects of the intervention, included all

measured and observed effects related to the NbS. Finally, the study type was limited to empirical studies, as our analysis targets applied and evaluated NbS. Moreover, the combined assessment of urban challenges, NbS and outcomes required evidence from context-specific cases that reflect complex decision-making and planning. Hence, modelling studies that solely focused on NbS scenarios without empirical data were excluded.

2.2 Search process

Our search strings were based on the CIOS Context and Intervention elements. For Context, search strings were composed of terms related to urban areas, such as 'urban' and 'city'. For Intervention, a broad set of NbS-related terms was used (Table 1), which go beyond specific definitions. The broad terms were adapted from five IUCN categories of ecosystem-based approaches (Cohen-Shacham et al., 2019), to which we added one category: 'nature-based approaches'. Based on these categories, we formulated an initial list of specific terms, thereby also including terms from existing systematic reviews on NbS (Dick et al., 2020; Nesshöver et al., 2017). To reduce bias, terms that focused on specific issues (e.g., climate, disaster, and flood) or ecosystem types (e.g., forest and sustainable drainage) were not used. Finally, to capture the full breadth of NbS, we reviewed the title and keywords of 119 review papers on NbS (Appendix B). Terms from those papers that overlapped with or substituted NbS were included in our search. Examples include 'nature-inspired solutions', 'sustainable land management', 'green spaces', and 'blue spaces'. All search strings are provided in Appendix A.

Table 1. Terms representing Nature-based Solutions that delineate the scope of the study.

Categories	Nature-based solutions terms identified for searching
Nature-based approaches	Nature-based solutions, nature-based interventions, nature-inspired solutions, nature-based engineering, nature-based rehabilitation, green solutions
Restorative approaches, focus on nature	Ecological restoration, landscape restoration, habitat restoration, land restoration, ecological engineering
Issue-specific ecosystem-related approaches	Ecosystem approach, ecosystem-based approach, ecosystem-based adaptation, ecosystem-based mitigation
Infrastructure related approaches	Natural infrastructure, ecological infrastructure, green infrastructure, blue-green infrastructure, green space, blue space, green and blue space
Management approaches	Sustainable (land) management, best management practice (BMP), natural resource management, ecosystem-based management
Ecosystem protection approaches	Area-based conservation approaches, protected area management

We searched for English language publications listed in the Scopus database, which has a broader and more up-to-date bibliographic coverage than the Web of Science Core Collection. We excluded reviews, proceedings, book chapters, editorials, opinions, and perspectives. We restricted the publication year from 2015 to present, because the notion of NbS has only been adopted widely in academic research since then (Cohen-Shacham et al., 2016; Maes & Jacobs, 2015). The search was finalized on 25th October 2021 and resulted in 7698 peer-reviewed scientific publications (after removing duplicates).

2.3 Screening process

We exported the search results into CADIMA[1], a web tool to document systematic reviews and maps (https://www.cadima.info), in which we first screened the title and abstract, followed by full texts. A series of eligibility and exclusion decisions based on CIOS was consistently applied to determine the relevance of articles (Table 2), among others based on two rounds of internal consistency checks (Section 6.1, Appendix A).

We reviewed any potentially conflicting selection based on each criterion and progressively refined the selection criteria for clarity and consistency. Any doubts about inclusion were discussed among all authors. Details on the excluded articles and reasons for their exclusion are available in Appendix C. Overall, 89% of the articles were excluded in the first stage, mainly because they did not evaluate outcomes of NbS interventions and/or did not yield primary empirical data. The exclusion of articles in the second stage was based on a precise check of the NbS intervention and outcome evaluation, after screening the entire article considered. Ultimately, out of the 7698 articles screened, 691 articles were included and considered for further coding and analysis (Fig. 1).

Table 2. Inclusion and exclusion criteria based on the Context, Intervention, Outcome, and Study type (CIOS) framework. See Table A3 in Appendix A for further details.

CIOS element	Inclusion	Exclusion
Context	Any outdoor environment in urban areas.	Regional, national, and continental context, as well as indoor environment.
Intervention	Implemented NbS. The actions to support or improve natural processes and biodiversity. This includes managing, restoring, or protecting approaches (e.g., revegetation, soil rehabilitation). The presence of specific types of urban nature (e.g., forests, green walls).	Interventions that were defined not by any precise feature but only by general terms (e.g., green area, stormwater management systems). Engineered solutions not employing nature.
Outcome	Studies involve outcomes explicitly related to the effects of NbS interventions (e.g., plant biodiversity, heat reduction).	Studies focused on mechanism/process research and confounding factors (i.e., traffic conditions) without direct evidence on the effects of NbS intervention.
Study type	Studies involve empirical evidence (i.e., studies yielding primary data) with a quantitative or qualitative evaluation of implemented NbS intervention.	Studies on scenario modeling, planning approaches, and conceptual frameworks without providing relevant empirical evidence.

2.4 Data coding strategy

The extraction and coding of evidence from articles were guided by a coding framework with definitions in which we identified each unique combination of NbS intervention and urban context (location) as a separate NbS case study (Appendix D). Due to time constraints and substantial differences in relevance, we selected the 75% most relevant publications of

[1] Our evidence map is accessible on CADIMA, by searching for the title of this article at https://www.cadima.info/index.php/area/evidenceSynthesisDatabase.https://www.cadima.info/index.php/area/evidenceSynthesisDatabase. The screening process outcomes are available there (also included in the Appendix C). Additional details not included there can be found in our protocol (Appendix A).

each publication year for coding (521 out of 691, see Table S1). Relevance was based on the Scopus algorithm, which considers factors such as number of hits, significance of the words, position, etc. (Scopus, n.d.). When identifying individual NbS cases from included articles, a further discussion and interpretation of the scope of urban NbS and outcomes was held. Based on the refined criteria (Table A3, Appendix A), a further 160 publications were removed for coding and evidence mapping (see the list of exclusion with reasons in Appendix C). Ultimately, we considered 361 publications, in which 547 cases were presented.

For each NbS case, we retrieved the following information: 1) geographical location (country, city), 2) urban challenges, 3) NbS, 4) outcomes, and 5) the performance compared to alternative solutions. The coding was performed manually and documented in FileMaker Pro 19. We first recorded the NbS type using the same terms as used by the authors and included a detailed description (see Section 2.5). All the coding categories and their definitions can be found in Appendix D.

To map the urban challenges addressed by NbS, we adapted a typology of 23 urban challenges from existing categories (Babí Almenar et al., 2021; Dumitru & Wendling, 2021). The full list of these categories can be found in Section 3.2, Appendix D. We only recorded an urban challenge if the author(s) stated that it involved an issue that could be mitigated by the studied NbS. We also included a ‘no specific challenges’ category to indicate a disconnection between NbS and urban challenges. We also coded cases reporting multiple urban challenges.

We defined a typology of NbS outcome, using an inductive, bottom-up approach based on the detailed data in our database, i.e. without a pre-determined classification. For each NbS case, we documented all NbS outcomes that had been evaluated using indicators. Domains were based on clusters of similar specific outcomes. For instance, the physical health outcome encompasses outcomes measured by respiratory health conditions, mortality rate, and childhood leukemia incidence. A total of 30 domains were determined (Fig. 3F). The full list of these domains with definitions can be found in Table D1, Appendix D. We categorized these domains into three broad domains: biodiversity, regulating ecosystem services, and health and well-being. None of the outcome domains was found to overlap within or outside the three broad categories.

The performance of NbS was coded based on the comparison of the outcome to a non-NbS comparator (i.e., a control with no intervention). These comparisons were categorized into four distinct groups: control site, before-and-after, green exposure, and simulated non-NbS (see Appendix D for descriptions). When an outcome assessment was based on multiple types of comparisons, it was categorized as a combination. The performance of NbS interventions was recorded as positive, negative, neutral, and mixed effects. Furthermore, we coded the temporal scale related to these effects, differentiating between a cross-sectional effect (i.e., evaluated at a single time point) and an effect over time (i.e., evaluated across various time points) (see Appendix D for detailed definitions).

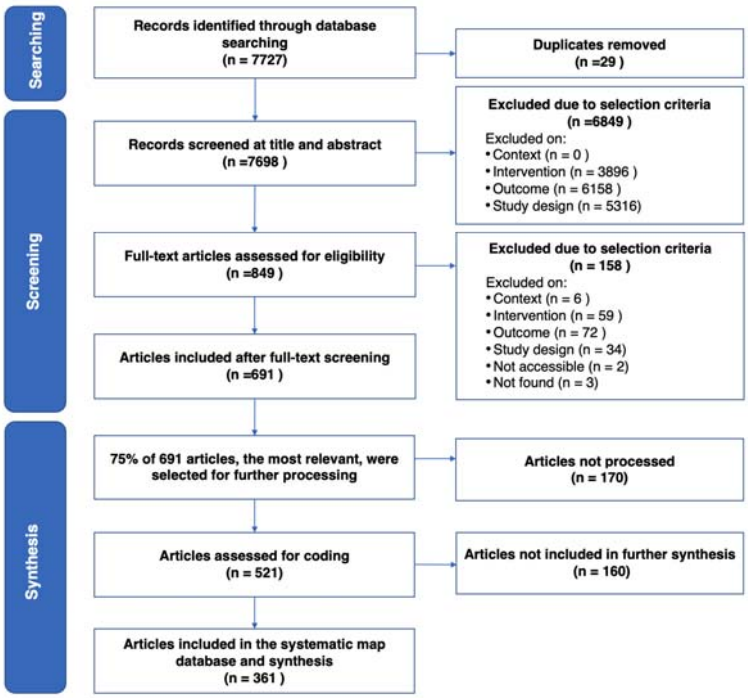


Fig. 1. Overview of the selection process of the peer-reviewed publications included in the systematic map database. Flowchart adapted from ROSES flow diagram for systematic maps (Haddaway, Macura, Whaley, & Pullin, 2017).

2.5 Classification of urban nature-based solutions

A 3-level hierarchical classification of urban NbS was established based on the NbS characteristics of 547 cases (Section 2.4). Building on two categories of urban NbS proposed by Castellar et al. (2021), the first level of our classification involves **NbS units** and **NbS measures**. The fit to this classification was based on our selection criteria of Intervention (Table 2 and Section 2.3). The second and third-level categories were proposed using the same inductive, bottom-up approach as the outcome domains.

NbS units refer to urban spatial units that comprise different elements of natural and built infrastructure. These units are solely based on the physical features (e.g., forms of vegetation), without considering other aspects such as purpose and scale (Castellar et al., 2021). While Castellar's classification considered NbS units as urban green spaces or green technologies (e.g., green roofs), our classification encompasses a broader range of urban spatial units, including all urban natural and semi-natural spaces (e.g., forests, parks, green walls). Next, we consider **NbS measures** as actions to manage, restore, or protect existing urban ecosystems, by applying techniques (e.g., replanting and soil rehabilitation). This is partly in line with the definition of NbS interventions by Castellar et al. (2021). However, in line with NbS units, we considered **NbS measures**, regardless of their purpose, as actions applied to physical components of natural and semi-natural spaces (i.e., an NbS measure always also involves an NbS unit).

In the second and third levels of our classification, we differentiate more notably from the classification of Castellar et al. (2021). These levels further differentiate **NbS units** and **measures**, based on their predominant physical features (Fig. 2). **NbS units** were classified based on three features: **vegetation**, **water**, and **engineered**. In addition, the **hybrid feature** was considered a combination of the three others with no feature dominating, e.g., all types of

parks and gardens. The third level comprises a list of specific types within each of the four features, e.g. forest & trees or grassland within the vegetation feature. This yielded 16 unit types, in addition to 'others' for cases that did not specify the features. The **NbS measures** were differentiated into three featured groups, considering the actions applied to physical components of urban spaces, including **plants, soil, or abiotic components**. The third level consists of a list of specific types of techniques applied to each of these components, resulting in 7 measure types, in addition to 'combined measures' for cases applied a series of measures. A detailed definition of each category is provided in Appendix E.

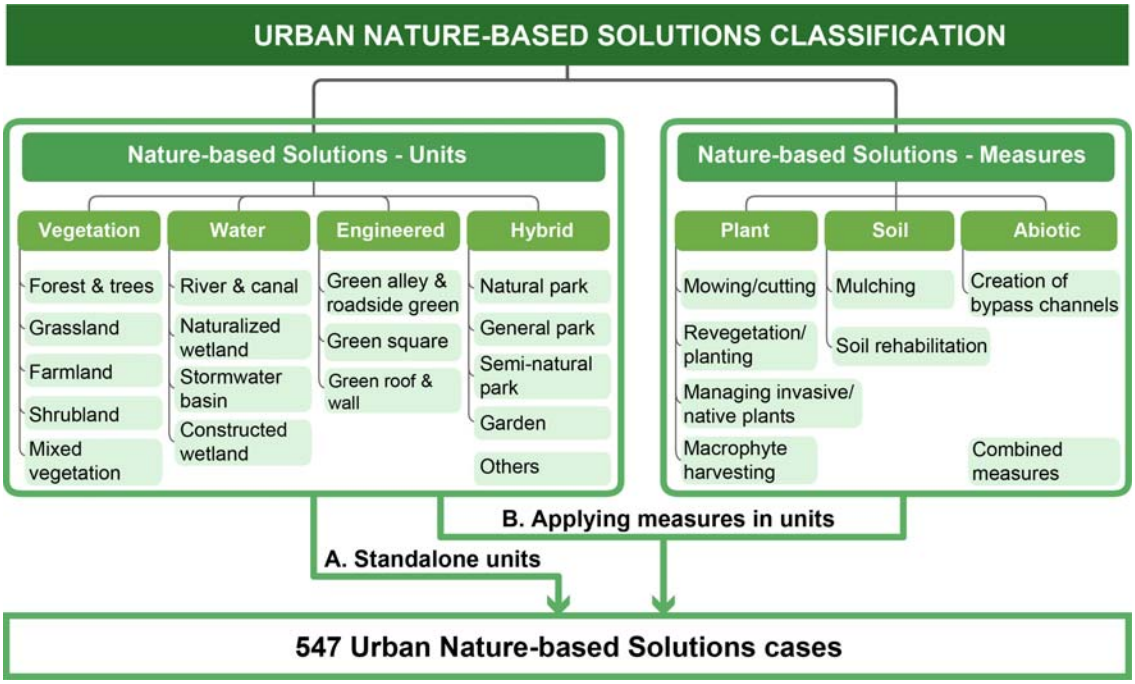


Fig. 2. The classification of urban nature-based solutions used to categorize the cases. Shown are three levels of the classification and the way cases are identified using this classification: 1) categories 'Units' and 'Measures', 2) features, and 3) specific types. Each case is defined either through standalone Units (A) or by applying Measures within these Units (B).

2.6 Data analysis and visualization

We first analyzed the frequency distribution of all 547 cases, including the geographic locations, NbS types, and urban challenges, as well as the distribution of 799 outcomes across defined domains (Section 3.1). Subsequently, to identify the linkages between urban challenges, NbS, and outcomes, Sankey diagrams were created to establish and visualize the number of links between these three elements (Section 3.2). This analysis included only cases of most frequently reported urban challenge categories (reported in over 15 cases) and outcome domains (idem). A total of 462 cases were considered, involving 630 outcomes. The performance of NbS was synthesized considering outcome domains, NbS unit types, comparison types and temporal scales. This analysis involved 370 outcomes assessed using non-NbS comparators, based on 280 cases (Section 3.3). Finally, we analyzed a subset of the data involving 133 cases with multiple outcomes. We first assessed the relationships between outcomes through co-occurrence analysis, establishing a heatmap and network. We also assessed the performance of cases that involved multiple outcomes and compared them to a non-NbS comparator (Section 3.4).

All data analyses were conducted in R (v.4.2.2) with RStudio (v.2022.07.2+576), except the global distribution map (Fig. 3A), which was created using ArcGIS 10.6. For the data visualization, the following R libraries were used: ggplot2 (Figs. 3B-F, 6, and 7A), networkD3 (Figs. 4 and 5), and ggraph (Fig. 7B).

3. Results

3.1 Geographical distribution, nature-based solutions, urban challenges, and outcomes

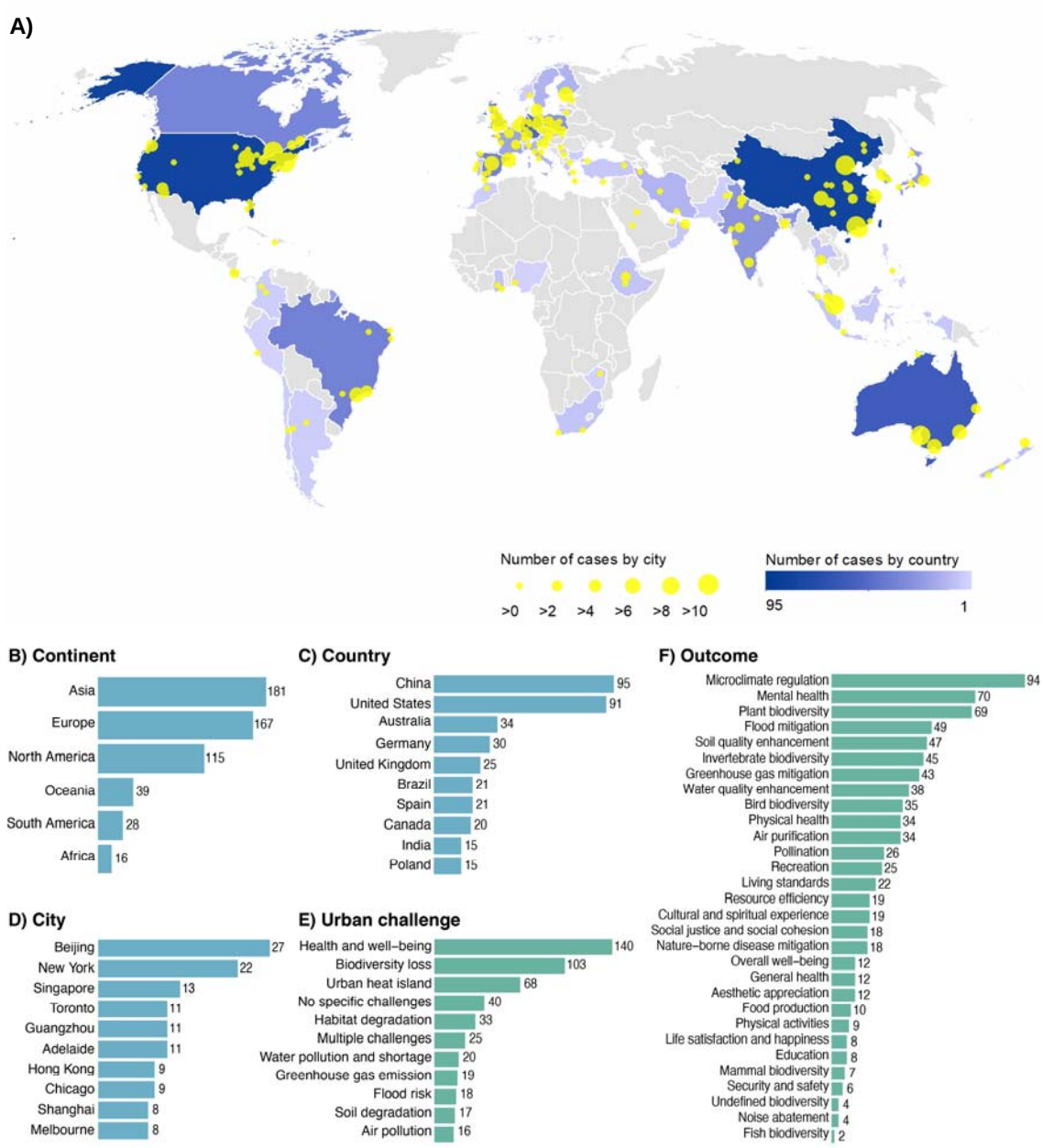


Fig. 3. (A) Geographical distribution of urban nature-based solution cases regarding countries and cities. (B) The number of cases per continent. (C) The 10 countries with the highest number of cases. (D) The 10 cities with the highest number of cases. (E) The 11 most-reported urban challenges with a minimum of 15 cases per challenge. (F) The number of assessments for all 30 outcome domains. See the full list of urban challenges and NbS types in Tables S3-5 in Appendix F.

3.1.1 Geographical distribution

The majority of cases were from Asia, Europe, and North America, together covering 84% of all the cases (Figs. 3A and 3B). Evidence was reported from 56 countries, with China (17%) and USA (16%) providing substantially more cases than other countries (Figs. 3A and 3C). More than half of Asian cases are from China (53%) and 80% of North American cases are from USA.

Evidence was reported from 196 unique cities, and 21 additional cases did not specify the city. A large number of studies was done in Beijing (27), New York (22), and Singapore (13). The top 10 cities together account for 24% of the analyzed cases (Fig. 3D). 99 cities only had a single case.

3.1.2 Nature-based solutions

Our analysis revealed that NbS units serve as the fundamental classification of NbS, while the NbS measures serve as an add-on combined with NbS units. Out of the 547 cases, 89% of cases involved standalone units, while only 11% documented the applied measures within units. Forest & trees were the most studied unit type (16%), followed by semi-natural park and general park (13% each), garden (11%), grassland (10%), and green roof & wall (9%) (Table S3B, Appendix F). In the 62 cases where measures had been documented, most involved a measure involving plants (56%), while a few related to abiotic components (2%). A combination of measures was more frequently observed than any type of a single measure (29%) (Table S4B, Appendix F). Mowing/cutting was the second most reported measure type (28%), which was mainly applied in the grassland unit type (13 out of 16 cases) (Fig. S1B, Appendix G). Combined measures were most related to the river & canal unit type (8 out of 18 cases).

3.1.3 Urban challenges

Overall, 88% of the cases reported just one urban challenge and 5% of the studies reported 2 or 3 different urban challenges. In 7% of the cases, no clear urban challenge was reported. The most often reported urban challenges include health and well-being (26%), biodiversity loss (19%), and urban heat island (12%) (Table S5, Appendix F). 91% of the cases were found to fall within the 11 major challenge categories, each represented by more than 15 cases (Fig. 3E).

3.1.4 Outcomes

We identified 799 outcomes from 547 NbS cases across 30 outcome domains (Fig. 3F), excluding assessments that only provided vaguely defined or unspecific outcomes (e.g., “perceived total environmental impacts”). In general, most outcomes were related to regulating ecosystem service (ES) (44%), followed by health and well-being (32%) and biodiversity (20%) (Table S6). Of the 353 regulating ES outcomes, microclimate regulation (i.e., heat reduction) is most reported (27%), followed by flood mitigation (14%), soil quality enhancement (13%), greenhouse gas mitigation (12%), and water quality enhancement (11%). Of the 255 outcomes of health and well-being, most were related to mental health (27%) and physical health (13%). Very few were related to social well-being outcomes such as aesthetic appreciation, life satisfaction and happiness, and security and safety (around 1% of the total outcomes for each). Out of the 162 biodiversity outcomes, most focused on plants (43%), invertebrates (28%), and birds (22%), while few assessed mammals (4%), undefined biodiversity (2%), and fish (1%).

3.2 Links between urban challenges, nature-based solutions, and outcomes

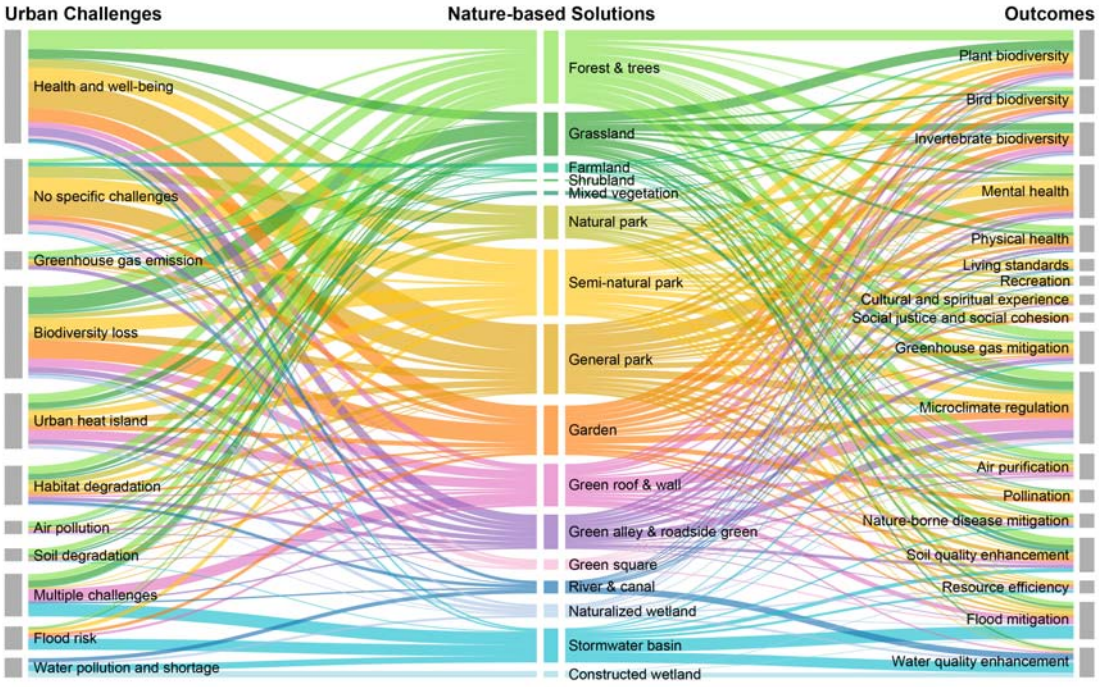


Fig. 4. Sankey diagram relating 16 nature-based solutions (NbS) unit types (middle of the diagram) to the 11 most reported urban challenges (left) and 18 most reported outcome domains (right). The data used in the analysis contains 630 outcomes related to 462 NbS types and urban challenges. The thickness of each band corresponds to the number of cases. NbS types were arranged and color-coded according to features: those in green correspond to the vegetation feature, those in yellow to the hybrid feature, those in purple to the engineered feature, and those in blue to the water feature.

3.2.1 Links between urban challenges, nature-based solutions, and outcomes

Most NbS were linked to all three overarching broad domains of outcomes: health and well-being, regulating ES, and biodiversity. The exceptions were stormwater basins and constructed wetlands, which did not report any biodiversity outcomes, and constructed wetlands, farmlands, shrublands, and mixed vegetation, which did not report any health and well-being outcomes (Table S7).

In general, forests & trees, semi-natural parks, general parks, and grasslands are the NbS types with the highest number of associated urban challenges (Fig. 4). Among NbS with vegetation features, the highest number of links involve forests & trees tackling health and well-being (24), and grasslands tackling biodiversity loss (18). Within NbS with hybrid features, many cases link general parks to health and well-being (33), and gardens to biodiversity loss (23). The most common links among NbS with engineered features involve green roofs & walls tackling urban heat island (12), and green alleys & roadside green tackling health and well-being. Among NbS with water features, stormwater basins were commonly linked to flood risk (14), while constructed wetlands, as well as stormwater basins, tackled water pollution and shortage (8 each). The highest number of links to multiple urban challenges combined were found for stormwater basins (16) and green roofs & walls (14). We also found that the highest number of links to no specific urban challenges was related to different types of parks: semi-natural parks (24), general parks (23), and natural parks (14).

3.2.2 Links between urban challenges and outcomes

Specific linkages between outcomes and urban challenges differ per NbS unit features, with the main differences observed between the water feature and other features (Fig. 5). Notably, health and well-being, biodiversity loss, and the urban heat island, which were the most frequently mentioned urban challenges (Fig. 2D), exhibited the highest numbers of links to outcomes in all terrestrial features, but not for the water feature. Within the 84 links associated with the water feature, water pollution and shortage (36%), and flood risk (12%) showed the highest number of links to outcomes. Moreover, the water feature is the only feature with links to the challenge of water pollution and shortage, while also being the only feature not associated with the challenge of greenhouse gas emission.

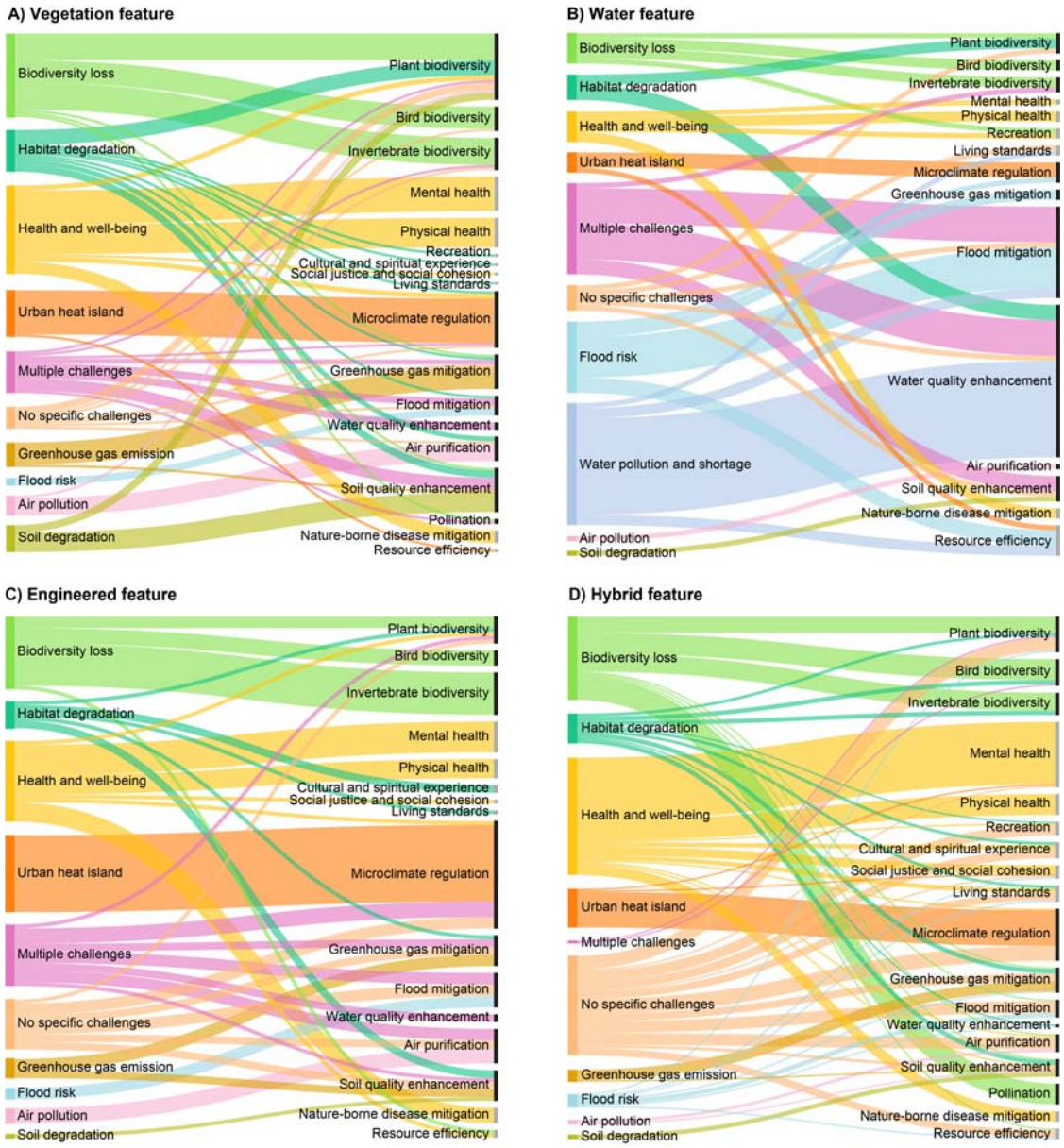


Fig. 5. The linkages between urban challenges (left) and outcomes (right) for 4 features of NbS based on the data from Fig.4: A) Vegetation feature, including 132 urban challenges and 164 outcomes; B) Water feature, including 58 urban challenges and 84 outcomes; C) Engineered feature, including 79 urban challenges and 109 outcomes; and D) Hybrid feature, including 163 urban challenges and 273 outcomes. Outcomes (right) are

arranged by biodiversity (black nodes), health and well-being (grey nodes), regulating ecosystem services (black nodes), and others (grey nodes).

In most cases, each specific urban challenge was linked to the associated outcome that is most intuitive. For instance, the urban heat island challenge was mostly linked to the microclimate regulation outcome (65 of the 69 total links to the urban challenge), greenhouse gas emission was mostly linked to greenhouse gas mitigation (19 of 23 links), and biodiversity loss was most frequently linked to the biodiversity of invertebrates (36 of 115), birds (29) and plants (26). The multifunctionality of NbS was shown by the fact that other outcomes were also linked to a specific urban challenge. These include the links between health and well-being challenge and regulating ES outcomes (e.g., microclimate regulation) (Figs. 5A, 5C, and 5D), as well as biodiversity outcomes (e.g., plant biodiversity), and between biodiversity loss challenge and regulating ES outcomes (e.g., pollination) (Figs. 5A and 5D).

Our analysis shows disconnections between specific outcomes and urban challenges. First, 7% of the cases do not report specific urban challenges, and as a result, 16% of the outcomes have no link to a specific urban challenge (Fig. 5). The majority of disconnections occur within the hybrid feature (67 of 94 links to 'no specific UC' category) (Fig.5). Furthermore, the high proportion of social well-being outcomes lacking a connection to any urban challenge is noteworthy. Among those, recreation (7 out of 12 links missing), cultural and spiritual experience (6 out of 14 missing), and living standards (6 out of 15 missing) have the highest number of links to cases that do not state specific urban challenges. In addition, social well-being outcomes were not connected to the urban challenge of health and well-being. For example, cultural and spiritual experience, living standards, and recreation outcomes provided by vegetation features were only related to the challenge of habitat degradation (Fig. 5A).

3.3 Performance compared to non-nature-based solutions

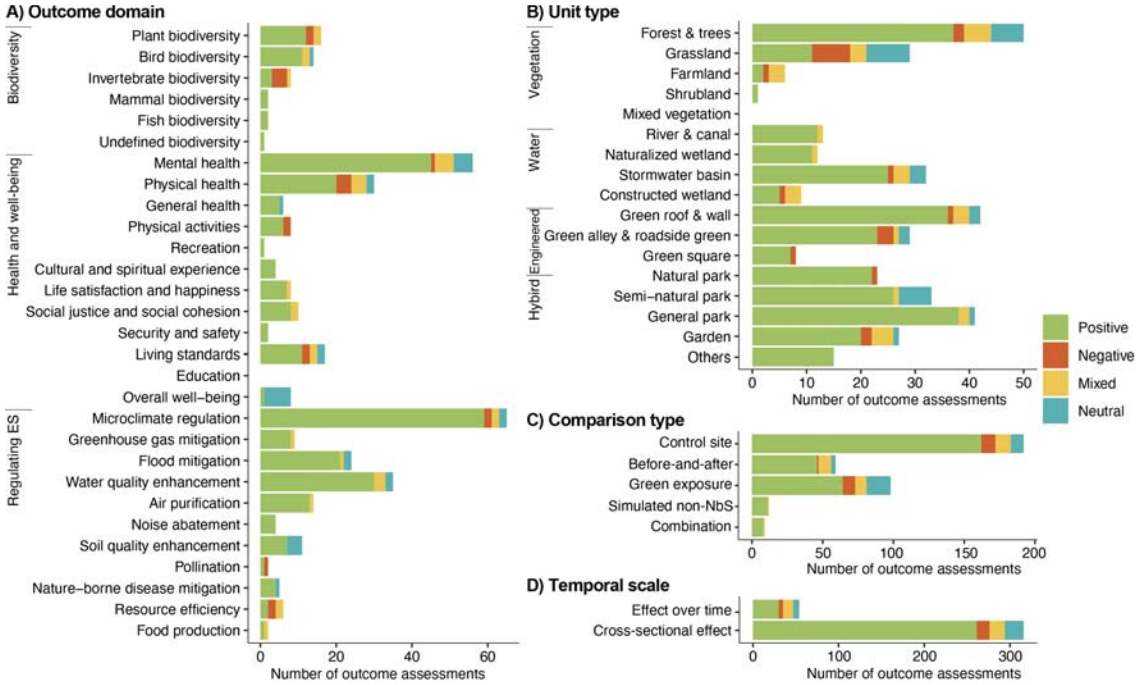


Fig. 6. Performance assessed by comparison to a non-NbS categorized by outcome domain (A), unit type (B), comparison type (C), and temporal scale (D). The analysis was based on 370 outcomes that apply such comparisons.

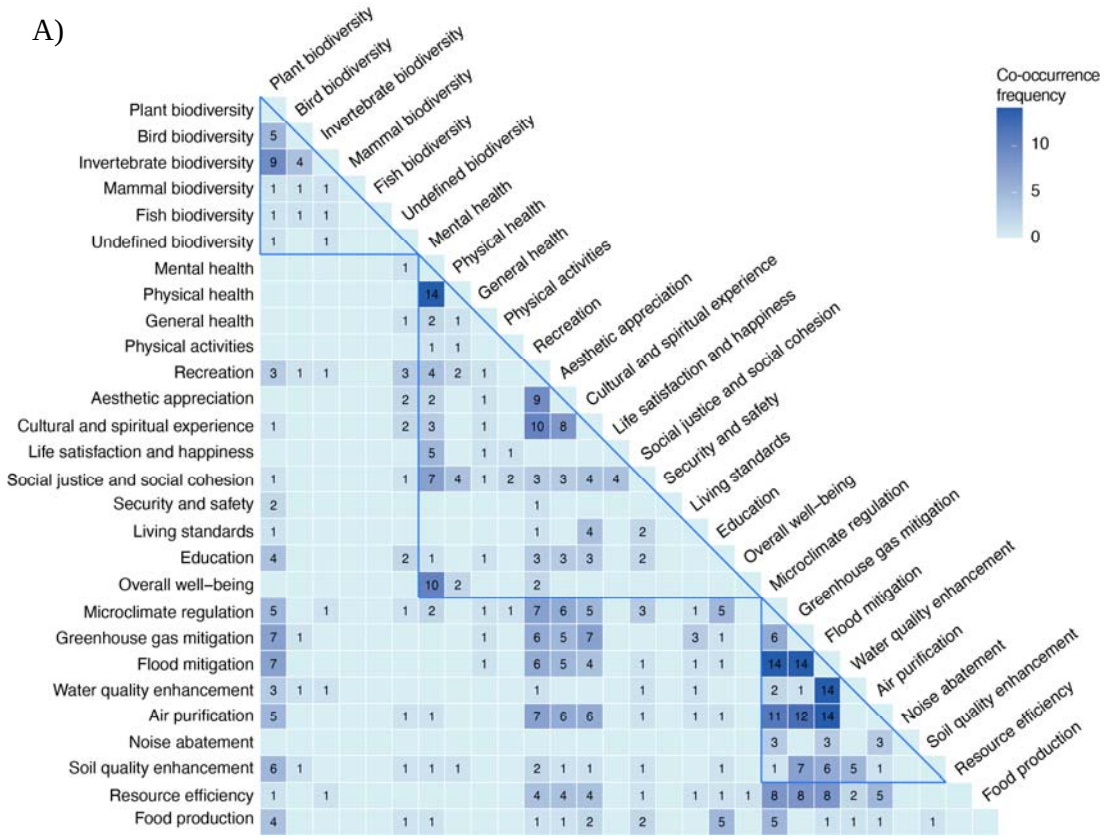
Out of 799 recorded outcomes, 46% were compared to a non-NbS baseline (n=370). Of these 370 outcomes, 79% reported a positive effect, 5% a negative effect, 8% a mixed effect, and 8% a neutral effect. Microclimate mitigation had most outcomes (65), of which 91% were positive (Fig. 6A). Invertebrate biodiversity exhibited the highest proportion of negative effects (50%), of which half related of these effects are attributed to grasslands with the application of mowing or cutting measures. in grasslands. Additionally, 13% of physical health outcomes were negative, all of which were assessed through comparison of green exposure (Figs. 6A and 6C). Comparisons were available for all outcome domains except aesthetic appreciation and education.

Regarding NbS types, natural parks, general parks, rivers & canals, naturalized wetlands and green roofs & walls exhibited a higher proportion of positive effects than the 79% for all outcomes combined, while negative effects were less prevalent in these unit types (all below the 5% for all outcomes combined) (Fig. 6B). The proportion of negative effects reported from grasslands (24%), farmlands (17%), green squares (12%), and green alleys & roadside green (10%) exceeded that of other unit types. Notably, 10 out of 12 positive effects reported from rivers & canals were related to measures taken within this NbS type (Figs. S3 and S4), mostly combined measures (8). Out of 22 negative effects, 5 were associated with measures, primarily linked to mowing/cutting (3).

In terms of the temporal scale of performance, 85% of the 370 reported effects were cross-sectional, while 15% involved effects over time (Fig. 6D). Cross-sectional effects were mostly positive (83%), while effects over time demonstrated comparatively fewer positive effects (56%). A notably high percentage of plant biodiversity outcomes were reported as effects over time (65%) (Fig. S5).

3.4 Evidence of multiple outcomes and co-occurrence analysis of outcomes

A)



B)

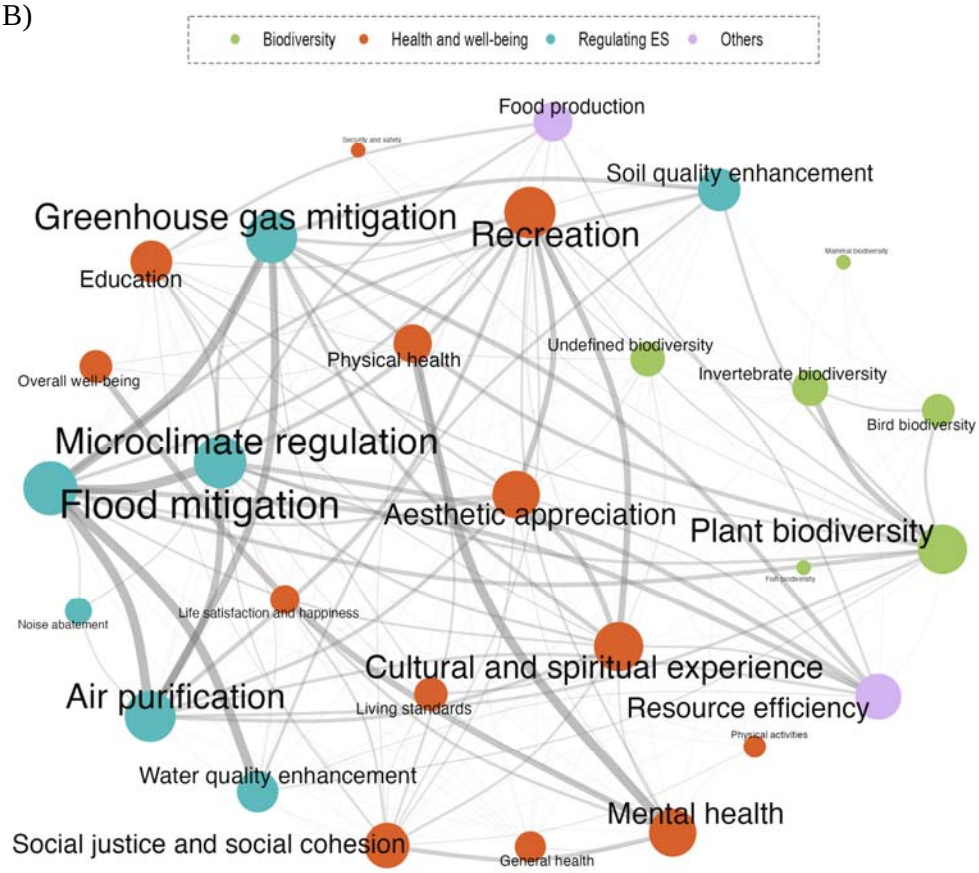


Fig. 7. Analysis of co-occurrence between outcome domains of nature-based solutions. The data includes 387 outcomes generated from 133 cases containing multiple outcomes. The map visualizes the 28 outcome domains that have co-occurrences with other outcomes. Pollination and nature-borne disease mitigation did not show co-occurrences. A) Co-occurrence heatmap. Outcome domains are arranged by the broad domains of biodiversity, health and social well-being, regulating ES, and others. B) Co-occurrence network. The thickness corresponds to the frequencies of the co-occurrence, and the sizes of vertices and texts correspond to the occurrences of outcome domains.

Multiple outcomes were documented in 24% of the NbS cases (133), involving 387 outcomes in total. Among these cases, 59% reported two outcomes and 41% reported three or more outcomes (Table S10). One-third reported outcomes related to more than one broad domain, i.e. health and well-being, regulating ES, or biodiversity. Most cases of multiple outcomes were reported for forests & trees (20), followed by NbS with hybrid features, i.e., semi-natural parks, general parks (each 13), and gardens (12).

The highest frequencies of co-occurrences were found between two outcomes within the same broad domain (Fig. 7A). For instance, flood mitigation was most frequently associated with three other regulating ES: water quality enhancement, microclimate mitigation, and air purification (14 each). Likewise, mental health and physical health co-occurred most often (14). In the co-occurrence network, the outcomes are also mostly grouped according to broad domains (Fig. 7B). In this network, flood mitigation serves as the central node with the highest number of links to other outcomes (200), followed by microclimate regulation (176) and air purification (152). Regulating ES outcomes were frequently associated with health and well-being outcomes, such as high occurrence frequencies between microclimate regulation and recreation, greenhouse gas mitigation and cultural and spiritual experience,

and air purification and aesthetic appreciation (7 each). Of the biodiversity outcomes, only plant biodiversity was highly connected to regulating ES such as greenhouse gas mitigation and flood mitigation (7 each). Few connections were observed between health and well-being outcomes and biodiversity outcomes.

The performance of NbS with multiple outcomes could be evaluated against non-NbS in 47% of the 133 cases (Table S11). Of these cases, 32% provided multiple positive effects, indicating the potential for synergies between NbS outcomes. These cases primarily involved general parks (4) and stormwater basins (3) (see list of these cases in Table S12). General parks were associated with the urban challenge 'health and well-being', by providing multiple benefits such as physical health, mental health, and life satisfaction and happiness. Stormwater basins were related to challenges of water pollution and shortage or flood risk by providing multiple positive effects such as flood mitigation, water quality enhancement, and greenhouse gas mitigation. Only one case indicated a potential trade-off, where a constructed wetland had a positive effect on water quality enhancement (nitrogen removal) and a negative effect on resource efficiency (increasing water consumption).

4. Discussion

Through the combined assessment of NbS types, urban challenges, and outcomes, this study provides a foundation for a more comprehensive understanding of NbS effectiveness in urban areas. To the best of our knowledge, this is the first global systematic mapping that combines these different components of NbS effectiveness. We embarked on this initiative in response to a pressing call for more comprehensive understanding (Johnson et al., 2022).

Our assessment was based on inclusive search terms and criteria, allowing us to look beyond research focusing only on the term 'nature-based solutions'. This offered an overarching perspective on a swiftly developing concept, without disregarding empirical studies in parts of the world or research fields where the concept is called differently. The assessment was conducted on the most relevant 75% of the identified articles after screening (Fig.1). We conducted a quick examination of the excluded 25% of articles, coding continental distribution, urban challenge categories, NbS unit types, and outcome domains. This examination confirmed that processing the complete list of articles would not have had a discernible impact on our findings (see Table A5, Appendix A for detailed comparison results).

Our dataset encompasses a broad range of outcomes related to biodiversity, well-being, and regulating ES, and therefore adding to existing syntheses with more focused perspectives (Chausson et al., 2020; Kabisch et al., 2017; van den Bosch & Ode Sang, 2017). Our broader scope allowed us to explore the multifunctional potential of urban NbS with 132 empirical cases. This facilitated the synthesis of interactions between evaluated NbS outcomes for both biodiversity and human well-being, which contributed to improving the knowledge base on multifunctional NbS.

Our global database contains 547 urban NbS cases located in 197 cities in 56 countries, outlining various NbS types and associated outcomes to address multiple urban challenges. A city-focused NbS database is the first to provide information on NbS effectiveness. Our database thus complements the existing knowledge base by including evidence from 361 scientific papers on NbS evaluation, linking these challenges to NbS outcomes. In this way, our systematic analysis helps policymakers and urban planners with information tailored to their specific interests. For instance, our analysis presents a list of potential urban NbS types

and a range of associated benefits that they can prioritize to address urban challenges or the growing demand for multifunctional NbS.

Here, we first reflect on the urban NbS classification employed in our research. Subsequently, we discuss the key findings of the three aspects related to the effectiveness of urban NbS and provide implications for research and practice.

4.1 Classifying nature-based solutions in the urban context

NbS are defined, classified, and interpreted differently throughout literature (Dorst et al., 2019). During the conceptualization and execution of our study, many iterations and discussions were needed to help interpret and classify different aspects of the NbS concept. Here, we share our key reflections and insights.

The primary point of attention involves the interpretation of what constitutes 'nature-based'. Even though there is no consensus on what constitutes nature (Kotsila et al., 2021), our operationalization was in line with the CBD's definition of an ecosystem, i.e. consisting of various natural elements such as plants, animals, soil, and water, with which they interact (United Nations, 1992). Similar to Castellar et al. (2021), we considered that vegetation plays an important role in characterizing an NbS. The growth of plants embodies a living ecosystem capable of supporting biodiversity, a fundamental tenet to NbS (Key et al., 2022). Following this logic, even bio-engineered solutions that mimic nature, such as permeable pavements, can be defined as NbS, as long as they provide physical space for vegetation to grow.

The second point of attention relates to when nature can be considered an intervention and, importantly, a 'solution'. The IUCN (2020) defines NbS as a solution when it involves actions to protect, sustainably manage and restore ecosystems. Based on this, almost all urban nature would qualify as NbS, since it involves management of green infrastructure in cities (Ferrari et al., 2019). We argue that intentionality is crucial, i.e. NbS involving an intervention to tackle a challenge or achieve a goal in an area. This includes an intentional decision to leave an area untouched. Cities contain informal green spaces and abandoned areas that are neglected or not purposely managed and maintained, e.g. emerging forest patches in abandoned areas and engineered infrastructure with spontaneous plant growth (Huang et al., 2019; Kowarik et al., 2019). However, these 'interventions' can only constitute an NbS if such spaces are managed by 'doing nothing' rather than building in them (Sikorski et al., 2021), and such decisions are coupled with the identified challenges such as preserving biodiversity.

In our classification, both NbS units and measures are presented in an unambiguous way, focusing on physical features regardless of purpose or outcomes. This approach offers a precise and inclusive way for identifying NbS, enabling connections with other aspects of NbS, such as their objectives, to form a more comprehensive understanding of NbS. In our database, each classified NbS type, along with its associated urban challenges can represent a unique solution. For example, green roofs may address urban heat island effects, providing pertinent information for NbS application. Up until now, interventions involving protection, management, and restoration approaches were considered as categories of NbS in existing classifications (Castellar et al., 2021; Eggermont et al., 2015). Yet, these categories have proven challenging to distinguish as separate solutions, or often intangible and hard to apply in urban context, as shown by the near-absence of management approaches in the review of urban NbS literature (Babí Almenar et al., 2021). In our database, the majority of cases involved NbS units without specific management or measures. Only 62 cases (11%) involved

a measure applied to an NbS unit. However, the cases that coupled measures to physical units provide valuable insights for urban planners on how to effectively manage the existing ecosystems. This information holds significance for cities that have limited space for creating new ecosystems.

4.2 Linking outcomes of nature-based solutions to urban challenges

Understanding urban challenges targeted by NbS and the outcomes generated by them is crucial for assessing the effectiveness of NbS. Our results confirm that the majority of cases (507 of 547) explicitly link NbS to specific urban challenges. Cases for which this link was missing mostly related to studies focused on ES assessment and economic valuation (e.g., Chen, Wang, Ni, Zhang, & Xia, 2020; Hoover, Price, & Hopton, 2020). In our dataset, the most frequently reported urban challenges include health and well-being, biodiversity loss, and the urban heat island. We established that tree-based NbS (forests, street trees) and parks most often target health and well-being challenges, whereas grasslands and gardens involve challenges of biodiversity loss. In comparison to a review on urban challenges by Babí Almenar et al. (2021), circular economy and material/resources management were underrepresented in our database, while we do include better coverage of biodiversity loss. Challenges concerning public participation, governance and mobility were lacking in our database, compared to Babí Almenar et al. (2021). These divergences could be attributed to the emphasis of Babí Almenar et al. (2021) on sustainability and resilience, along with their inclusion of grey literature.

Although reported outcomes could often be linked to challenges, their frequencies follow different patterns. The most frequently reported outcomes involve regulating ES, followed by health and well-being and biodiversity. Especially microclimate regulation, mental health, and plant and invertebrate biodiversity were commonly reported outcomes. Although they partly match the key outcomes commonly associated with NbS (Dick et al., 2020; Key et al., 2022), especially well-being outcomes such as safety and security, life satisfaction and happiness, and aesthetic appreciation were underrepresented in our data. Such data is often reported on larger scales (i.e. nation- or citywide) and not in relation to a particular spatial unit. Furthermore, our findings suggest that multiple outcomes were provided by urban NbS to address specific urban challenges. We also note that the NbS cases were limited in terms of interdisciplinary approaches, with few studies measuring outcomes related to biodiversity and human well-being in combination.

Our findings suggest that, aside from human health, other well-being dimensions have not been adequately addressed in empirical studies on established NbS. Within our database, the health and well-being challenge category was primarily focused on human health issues, with few cases addressing other well-being dimensions such as education, social justice and social cohesion, and living standards. Similarly, physical and mental health outcomes dominated the health and well-being domain, in line with Dick et al. (2020). Furthermore, our results reveal that well-being outcomes other than human health are rarely linked to health and well-being challenges, but rather to other challenges, such as flood risk. These well-being outcomes are often included in NbS research as secondary outcomes of NbS, while primarily addressing other challenges. Although well-being dimensions like social justice have been stressed in studies on urban NbS policy, planning, and governance (Haase et al., 2017; Sekulova et al., 2021), solid evidence of the contribution of NbS to improve the living conditions of urban dwellers and foster social inclusiveness is still needed (Haase et al., 2017). To obtain more comprehensive evidence of NbS effectiveness in line with other entries in our database, we advocate for further empirical studies related to implemented NbS that encompass a broader

range of well-being dimensions beyond human health. In addition, the inclusion of empirically grounded studies on preferences and responses to NbS or alternative scenarios (e.g., through surveys) could provide broader insights.

4.3 Assessing the performance of nature-based-solutions

The performance assessment of NbS compared to non-NbS showed that 79% of the outcomes were positive. This suggests that NbS can be effective solutions compared to constructed or engineered solutions, in line with previous literature (Acreman et al., 2021; Chausson et al., 2020; Kabisch et al., 2017). The finding could also be indicative of a tendency to focus primarily on positive effects in academic publications (Mlinarić, Horvat, & Šupak Smolčić, 2017). Furthermore, consistent comparisons for some NbS are challenging, due to the large variation in outcomes considered (Fig. S2). Microclimate regulation and mental health outcomes were often involved in comparative studies (69% of 94 outcomes and 80% of 70 outcomes respectively). Conversely, biodiversity-related, pollination, greenhouse gas mitigation, and soil quality enhancement outcomes were not often included in comparative studies (25% or less of reported outcomes). For the latter topics, the likely explanation is that the non-NbS comparators do not have the necessary biophysical attributes to make useful comparisons. Also education and aesthetic appreciation have no comparative studies. Those topics generally rely on large-scale social surveys rather than city-specific empirical studies. Conducting comparisons of NbS outcomes, while controlling for other variables within the survey, would require additional efforts. To make the outcomes more transferable to urban planners, more comparisons between NbS and non-NbS control are needed, especially for outcomes based on biophysical measurements or related to social well-being.

Our analysis primarily examines general directionality of outcomes summarized by binary situations, i.e., NbS versus non-NbS controls, but does not quantify the outcomes, for which a structured approach investigating the methodology of monitoring and evaluation is needed. In addition, we did not assess spatial and temporal aspects of the NbS and how this related to outcomes (e.g., size, age, or spatial scale of consequences), as this information was often poorly reported in the investigated studies.

For future synthesis research, a focus on quantifying spatial and temporal effects of NbS on outcomes will help improve the granularity of relationships between challenges, NbS, and outcomes (Remme et al., 2024). First, to quantify NbS performance across different spatial scales, further examination of the physical dynamics underlying the delivery pathways of these benefits, such as green exposure, heat fluxes, and water flows, is required (Kumar et al., 2021; Raymond, Berry, et al., 2017). For example, as Hutchins et al. (2021) suggested, the benefits of NbS are substantially scale-dependent, whether it be by the extent of impact (e.g., airshed, water shed) or proximity to receptors (e.g., noise, health).

Further temporal assessment will help urban planners anticipate the time NbS need to become effective (Sowińska-Świerkosz & García, 2021). Our synthesis made the initial step in evaluating the temporal scale of the performance by distinguishing between evaluations at a single snapshot at a specific time and those assessing multiple time points. However, the specific length of time for a particular intervention to become effective is not widely documented in the studies in our database, and in other analyses (Kumar et al., 2021). Information on the established time of interventions is crucial, yet our coding revealed insufficient reporting of this data, similar to Dick et al. (2020). The reported time for an NbS to become effective is closely linked to the post-intervention monitored timeframe. To enhance reporting on the temporal scale, a rigorous framework is needed that incorporates the

monitoring process, including techniques, available data for specific indicators, and time-specific data collection frequencies (Kumar et al., 2021).

Further research is recommended to more comprehensively synthesize potential differences in performance across different NbS units and measures. While we recorded comparisons to other NbS types, further synthesis was hindered by the use of multiple heterogeneous NbS comparators without specifying outcomes for each, as also noted by Dick et al. (2020). A recent review provided a possible approach to generalize the comparative results by focusing on specific pairs of NbS types, such as forest and park (Beute et al., 2023). Their results were mixed due to heterogeneity in NbS characteristics and research design. Quantifying outcomes among different NbS types requires meticulous recording of NbS characteristics, including variations in management regimes and morphology variables such as size, tree coverage and plant composition.

4.4 Multifunctionality of nature-based solutions

To fully assess the effectiveness of NbS, the synergies and trade-offs between their multiple outcomes need to be understood. The evidence base needs to be further developed, although some relevant insights exist. For example, an integrated evaluation has shown that forest plantations as NbS can provide job opportunities, while revitalizing degraded forests and mitigating fragmentation (Lemgruber et al., 2021). Regarding trade-offs, a rooftop farm was implemented as an NbS for ensuring food security in highly dense urban areas, but the life cycle cost increased compared to using a flat roof (Kim et al., 2018). Such evidence is important to understand the interactions between outcomes related to social, ecological, and technical dimensions of complex urban systems underlying the effectiveness of NbS (McPhearson et al., 2022). For example, extensively managed lawns can foster plant species richness but represent high fire risk (Winkler et al., 2021), which shows that management choices in the technical dimension can influence the impacts on ecological and social dimensions. Understanding the interactions can improve urban planning and management choices to maximize synergies and avoid significant trade-offs, to ensure more effective and sustainable NbS (Gómez Martín, Giordano, Pagano, van der Keur, & Máñez Costa, 2020; Raymond, Frantzeskaki, et al., 2017).

The scarcity of studies evaluating the co-occurrence of outcomes across different broad domains highlights the limited involvement of interdisciplinary approaches for NbS evaluation. Data availability to calculate an integral set of indicators is crucial for the integrative evaluation of an NbS project (Sowińska-Świerkosz & García, 2021), but varying technical expertise needed to measure different aspects of outcomes can be a constraint (Key et al., 2022). Therefore, it is unsurprising that we find the highest number of co-occurrences between reported outcomes within single domains, such as mental health and physical health, since they involve overlapping disciplinary expertise. Recent efforts to develop robust NbS evaluation frameworks, integrating selected indicators across multiple outcomes, present a big step forward (Raymond, Frantzeskaki, et al., 2017; Watkin, Ruangpan, Vojinovic, Weesakul, & Torres, 2019). However, further development is essential through more empirical studies that apply these frameworks and facilitate refinement by incorporating site-specific feedback from the field (Colléony & Shwartz, 2019; Watkin et al., 2019). Moreover, more theoretical work is required to elucidate the pathways connecting various types of NbS to multiple outcomes, particularly focusing on the intermediate mechanisms linking NbS characteristics to multiple outcomes (Dumitru, Frantzeskaki, & Collier, 2020).

5. Conclusions

NbS have been increasingly used without systematic scientific evidence of their effectiveness concerning targeted urban challenges. Based on 547 empirical case studies identified from scientific literature studying NbS outcomes in cities worldwide, our systematic assessment links urban challenges, NbS and outcomes.

Our assessments reveal that specific urban challenges, such as microclimate mitigation and biodiversity loss, were predominantly addressed through specific sets of intuitively related outcomes. Well-being dimensions beyond human health, such as social justice and cohesion and living standards, were predominately reported as secondary outcomes to address other challenges, such as flood risk.

Urban NbS generally yielded overwhelmingly positive effects compared to non-NbS. The performance varies depending on the considered types of NbS, comparison design types, and temporal scale of the evaluation. Finally, our analysis underscores a notable scarcity of evidence of NbS that report multiple outcomes related to more than one broad category, i.e. health and well-being, regulating ES, or biodiversity.

The identified linkages, as well as the performance reported in the evidence, show a diverse array of urban NbS portfolios, providing supporting information for urban planners, and policymakers to better understand which NbS type could be more pertinent for targeted urban challenges.

List of Appendix

Appendix A Protocol for the systematic map

Appendix B Titles and keywords of 119 NbS reviews

Appendix C Study inclusion and exclusion results

Appendix D Coding framework and definitions

Appendix E Urban NbS Classification and definitions

Appendix F Supplementary tables

Appendix G Supplementary results and figures

Appendix H Systematic map database

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