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

Meng Li [a, *], Roy P. Remme [a, b], Peter M. van Bodegom [a], Alexander P.E. van Oudenhoven [a]

[a] Institute of Environmental Sciences CML, Leiden University, Einsteinweg 2, 2333 CC Leiden, The Netherlands

[b] Natural Capital Project, Stanford University, Stanford, USA

[*]Corresponding author: Meng Li. Email: m.li@cml.leidenuniv.nl.

Abstract

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 794 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 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 empower 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 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).

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, clarity is needed on how to holistically assess NbS effectiveness. 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). In line with the NbS definition (IUCN, 2020), the effectiveness of NbS is commonly communicated through the extent to which societal challenges are addressed (Cohen-Shacham, Walters, Janzen, & Maginnis, 2016; European Commission, 2015). However, other aspects of effectiveness, such as long-term performance and synergies and trade-offs of NbS outcomes, are still being explored (Sowińska-Świerkosz & García, 2021). Multi-metric indicators have

been suggested as important tools for measuring NbS performance related to diverse societal challenges (Dumitru & Wendling, 2021; Kabisch et al., 2016; Raymond, Berry, et al., 2017). However, most studies assessed the outcomes of NbS related to one given challenge only (Acreman et al., 2021; Chausson et al., 2020; Dick, Carruthers-Jones, Carver, Dobel, & Miller, 2020). A systematic assessment combining urban challenges, NbS types, and outcomes is currently lacking.

Second, a comprehensive, evidence-based overview is lacking on the outcomes of NbS contributions to people and biodiversity in cities. Existing systematic reviews tend to focus on the outcomes related to individual perspectives, such as climate change (Chausson et al., 2020), and human health (Kabisch, van den Bosch, & Lafortezza, 2017), while neglecting biodiversity outcomes. Furthermore, comparative outcomes of NbS, especially the performance against non-NbS alternatives, are less researched (Anderson & Renaud, 2021; Dick et al., 2020; von Döhren & Haase, 2015). Yet, presenting more efficient and cost-effective approaches than traditional engineering approaches is a fundamental idea that is embedded in the NbS concept (Lafortezza, Chen, van den Bosch, & Randrup, 2018). Finally, existing systematic reviews are also focused on a limited set of NbS types, with a predominant focus on landscape-scale NbS in rural or natural environments, rather than the site-specific interventions in an urban context. Key examples of such focused analyses include the mapping of NbS effectiveness in addressing climate impacts (Chausson et al., 2020) and its effectiveness in addressing water issues in Africa (Acreman et al., 2021).

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 its 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 a better understanding of 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 outcomes can be expected.

2. Methods

2.1 Systematic mapping protocol for the review

We applied a systematic mapping protocol (Appendix A) to define the scope of the review work presented here, documenting the question scope, search string, and study selection criteria (Collaboration for Environmental Evidence, 2018). We base 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). The context defines the specific setting in which the intervention will be applied, here urban areas. The intervention itself defines the action to be studied, which here refers to implemented NbS. The term NbS is used as an umbrella term for all interventions fitting the NbS definition by IUCN. The outcome frames the range of the effects of the intervention, referring to all the measured and

observed effects related to NbS. Finally, the study type defines the study designs of scientific literature, which here is confined to empirical studies.

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 terms relating to NbS were used (Table 1). These terms captured global scientific research that applied NbS-related thinking without necessarily using NbS terminology. Six categories of terms were used, adapted from the five categories of ecosystem-based approaches from Cohen-Shacham et al. (2019), to which we added 'nature-based approaches' (Table 1). Based on these categories, we first formulated an initial list of specific terms based on existing NbS systematic reviews (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). Supplementary terms from those papers that overlapped with or substituted NbS were included. 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 published in the Scopus database. We excluded reviews, proceedings, book chapters, editorials, opinions, and perspectives. We restricted the publication year from 2015 to the 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 incorporated 7727 peer-reviewed scientific publications.

2.3 Screening process

We exported search results for screening into CADIMA, a web tool to document systematic reviews and maps (https://www.cadima.info), screening first the title and abstract,

then full texts. A series of eligibility and exclusion decisions based on CIOS was consistently applied to determine the relevance of articles (Table 2).

A conservative approach was applied to ensure that only articles explicitly meeting all inclusion criteria were included. Single reviewer screening was carried out with caution, that is, any unclear decisions were checked with the other co-authors to reach an agreement throughout the process. We reviewed any potentially conflicting selection based on each criterion and progressively refined the selection criteria for clarity and consistency. Details on the excluded articles and the 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 intervention and/or did not yield primary data. The exclusion of articles in the second stage was based on a precise check on the NbS intervention and outcome evaluation, for which the entire article was considered. Ultimately, out of the 7698 articles screened, 691 articles were included for further coding and analysis (Fig. 1).

Table 2. Inclusion and exclusion criteria based on the Context, Intervention, Outcome, and Study type (CIOS) framework, summarized from Table A3 in the protocol.

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 (Appendix D) in which we identified each unique combination of NbS intervention and urban context (location) as a separate NbS case study. Due to time constraints, we randomly selected 75% of 691 publications (521) of each publication year for coding (for study distribution; see Table S1). When identifying individual NbS cases from included articles, a further discussion and interpretation of the scope of urban NbS and outcomes were held. Based on the refined criteria (Table A3, Appendix A), 160 publications were removed for coding and further mapping (see the list of exclusion with reasons in Appendix C). Ultimately, we identified 547 cases from 361 articles.

For each of the NbS cases, 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 author and recorded a detailed description to allow for more detailed categorization (see Section 2.5). All the coding categories and their definitions can be found in Appendix D.

We defined a typology of 30 NbS outcome domains to characterize the contribution of NbS to biodiversity outcomes, ecosystem services, and general human well-being (Figure 2F). For each case, we documented all the outcomes evaluated using indicators. Domains were based on clusters of similar outcomes of NbS. For instance, the physical health outcome encompasses outcomes measured by respiratory health conditions, mortality rate, and childhood leukemia incidence. Additionally, we categorized the identified domains into three overarching broad domains: biodiversity, regulating ecosystem services, and health and well-being.

To map the specific urban challenges that NbS address, we adapted a typology of 23 urban challenges from existing categories (Babí Almenar et al., 2021; Dumitru & Wendling, 2021). We only recorded an urban challenge when the author clearly stated that it was an urban 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 to explore the research focus for NbS multifunctionality (see the full list in Table S5).

To assess the performance of NbS, we employed a non-NbS comparator as a standardized baseline. This comparator includes various conditions that reflect the absence of NbS interventions, for instance, a grey roof was used as a control site to be compared to the performance of a green roof or the performance was compared between before and after access to a forest. The performance of NbS interventions was recorded as positive, negative, neutral, and mixed effects. To explore more possibilities for evaluating the performance of NbS, we also recorded their relative performance compared to other types of NbS. Although about half of the established outcomes involved comparisons to other NbS types, we excluded these comparisons due to the complexity in discerning generalizable trends.

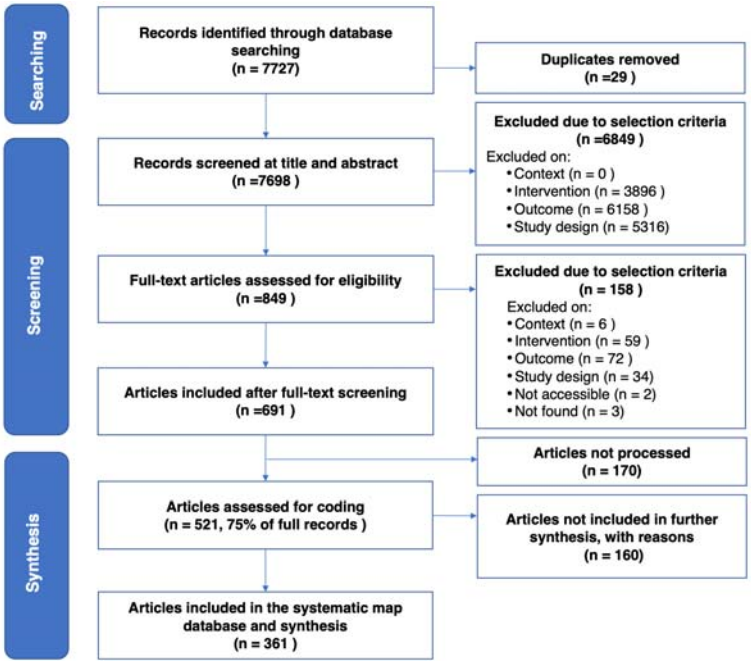


Fig. 1 Overview of the selection process of the peer-reviewed publications included in the systematic map database. Flowchart adapted from ROSES flow diagram for systematic maps (Haddaway, Macura, Whaley, & Pullin, 2017).

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), our classification involves **NbS units** and **NbS measures** on the first level. The fit to this classification was based on our selection criteria of Intervention (Table 2 and Section 2.3).

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), **NbS units** in our classification encompass a broader range of urban spatial units, including all urban natural and semi-natural spaces from the ground to vertical levels (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 what Castellar et al. (2021) defined as NbS interventions. However, we identify **NbS measures** based solely on the physical features of the sites in which measures are applied, rather than the purpose of the action. To avoid confusion, we use the term 'measure' instead of 'intervention', as the latter is used broadly to define broader NbS, and in those definitions, it often includes spatial or ecosystem types in addition to actions. Note that all **NbS measures** were applied in **NbS units**, while the majority of NbS units were standalone, i.e. not involving measures.

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** by their physical features (Fig. 2). Based on the predominant physical characteristics, **NbS units** were classified at the second level in accordance with three features: **vegetation**, **water**, and **engineered**. In addition, we considered the **hybrid feature** as a combination of the three other features with no feature dominating, which for instance includes 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 total, in addition to 'others' for cases that did not specify the features. Similarly, we differentiated **NbS measures** into three featured groups considering the actions are applied to either the **plant, soil, or abiotic** physical components of urban spaces. The third level consists of a list of specific types of techniques applied to each of these components, resulting in 7 measure types in total. A detailed definition of each category and type is provided in Appendix E.

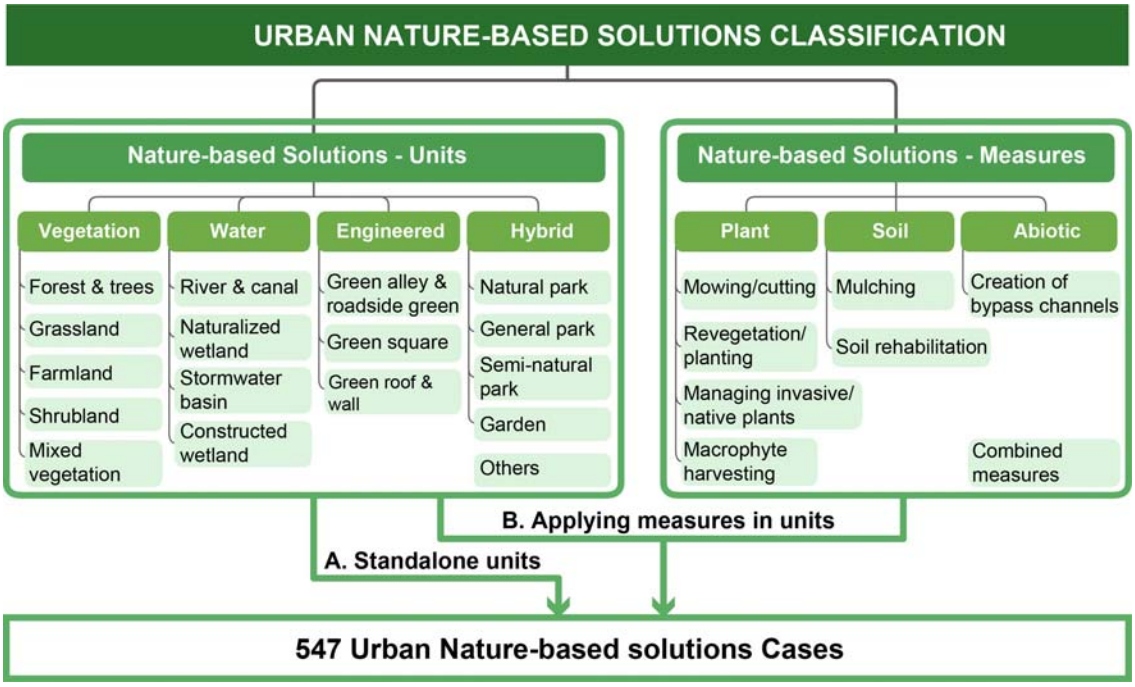


Fig. 2 The classification of urban nature-based solutions used to categorize the cases. Shown are three levels of the classification and the way cases are identified using this classification: 1) categories 'Units' and 'Measures', 2) features, and 3) specific types. Each case is defined either through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

2.6 Data analysis and visualization

We first characterized the data by the frequency distribution of the cases concerning the geographic locations, NbS types, urban challenges, and outcomes (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 involved only cases that mentioned a specific NbS unit type within the most frequently reported urban challenge categories (> 15 cases) and outcome domains (> 15 cases) (462 cases with 630 outcomes). Finally, we analyzed a subset of the data involving cases with multiple outcomes. We first assessed the relationships between outcomes through co-occurrence analysis, establishing a heatmap and network. In this way, we visualized outcome domains that co-occurred with others and established frequencies thereof. We also assessed the performance of those urban NbS 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, several R libraries were used, including ggplot2 (Figs. 3B-F, 6, and 7A and B) and networkD3 (Figs. 4 and 5).

3. Results

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

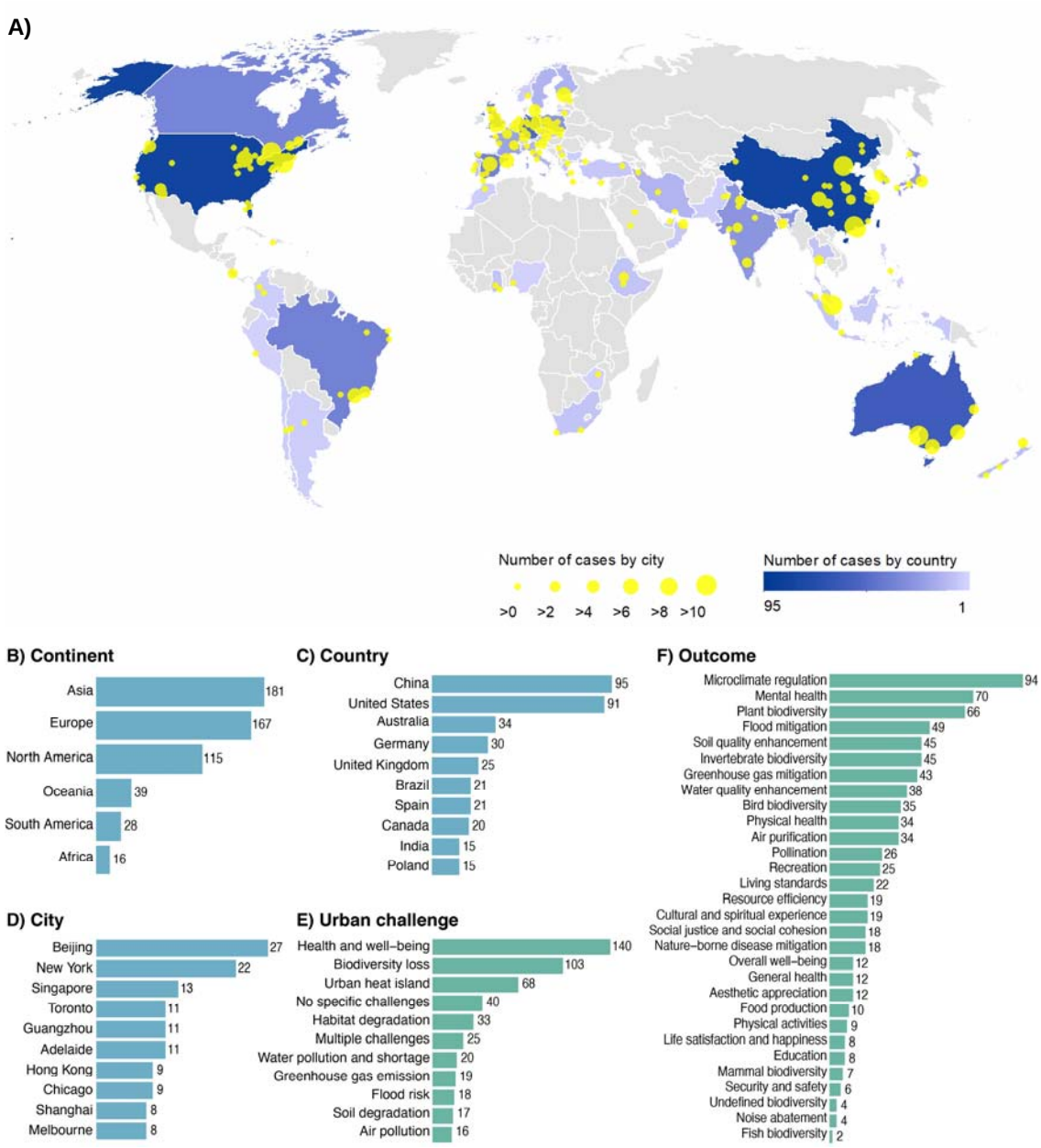


Fig. 3 (A) Geographical distribution of urban nature-based solution cases regarding countries and cities. (B) The number of cases per continent. (C) The 10 countries with the highest number of cases. (D) The 10 cities with the highest number of cases. (E) The 11 most-reported urban challenges with a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

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 the U.S. (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 the U.S.

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 solution types

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 S3). In the 58 cases where measures had been documented, most involved a combination of measures rather than a single type of measure (31%) (Table S4). Combined measures were most related to the river & canal unit type (8). Mowing/cutting was the second most reported measure type (28%, 16), which was mainly applied in the grassland unit type (13) (Fig. S1B).

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%). 91% of the cases were found to fall within the 11 major challenge categories, each represented by more than 15 cases (Fig. 2E).

3.1.4 Outcomes

We identified 794 outcomes from 547 NbS cases across 30 outcome domains (Fig. 2F). 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 351 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 159 biodiversity outcomes, most focused on plants (32%), invertebrates (28%), and birds (22%), while few assessed mammals (4%), undefined biodiversity (3%), and fish (1%).

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

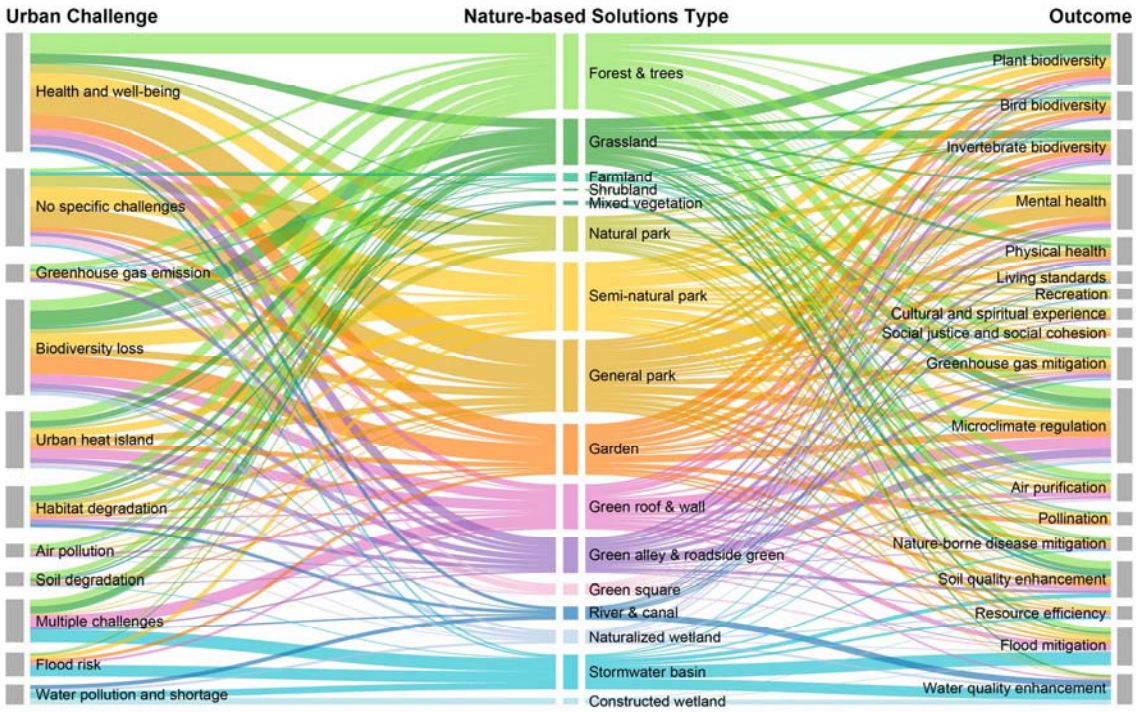


Fig. 4 Sankey diagram relating 16 nature-based solutions (NbS) types (middle of the diagram) to the 11 most reported urban challenges (left) and 18 most reported outcome domains (right). The data used in the analysis contains 630 outcomes related to 462 NbS types and urban challenges. The thickness of 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.

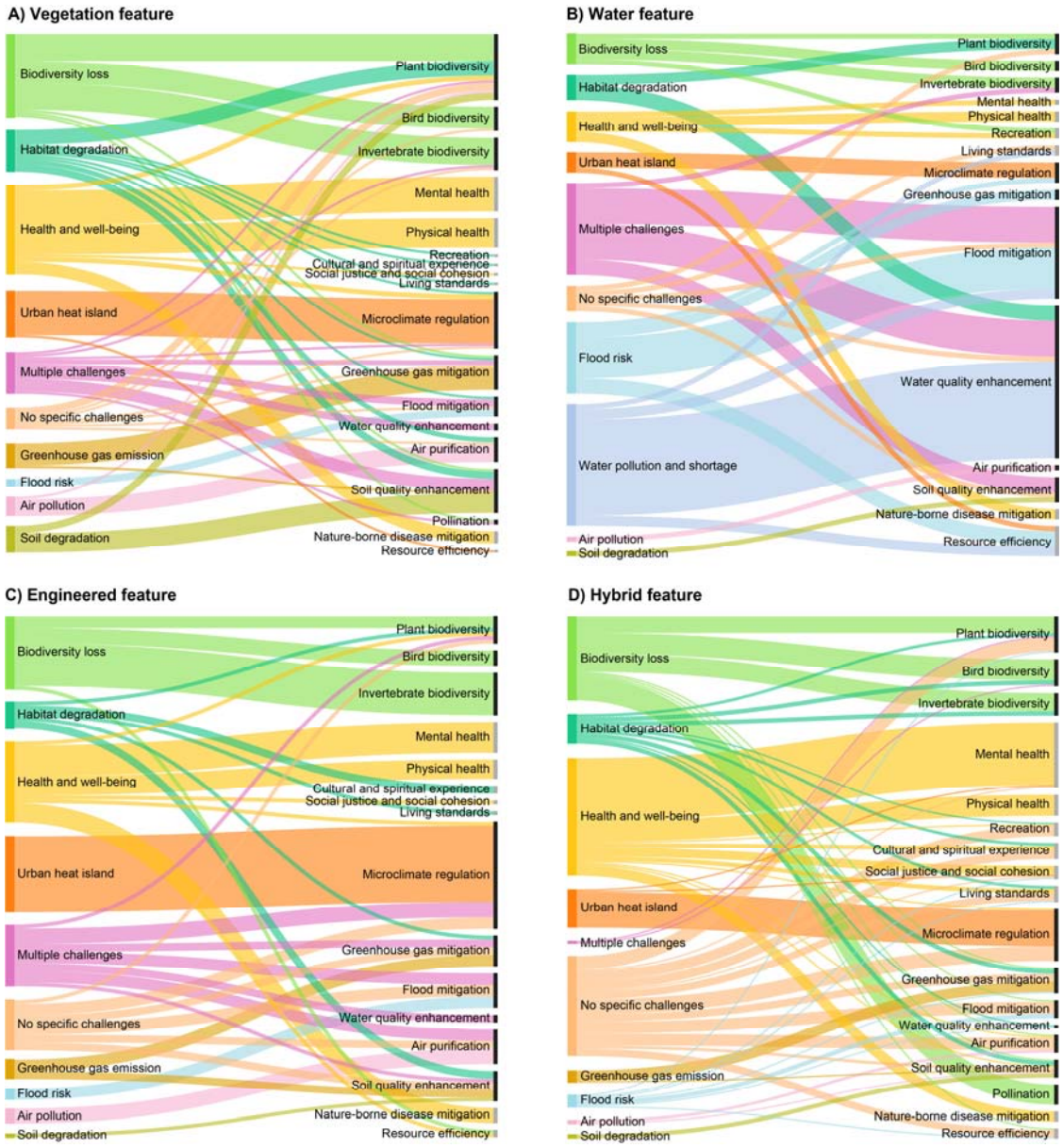


Fig. 5 The linkages between urban challenges (left) and outcomes (right) for 4 features of NbS based on the data from Fig.4: A) Vegetation feature, including 132 urban challenges and 164 outcomes; B) Water feature, including 58 urban challenges and 84 outcomes; C) Engineered feature, including 79 urban 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, C, D), as well as biodiversity outcomes (e.g., plant biodiversity), and between biodiversity loss challenge and regulating ES outcomes (e.g., pollination) (Figs. 5A, D).

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

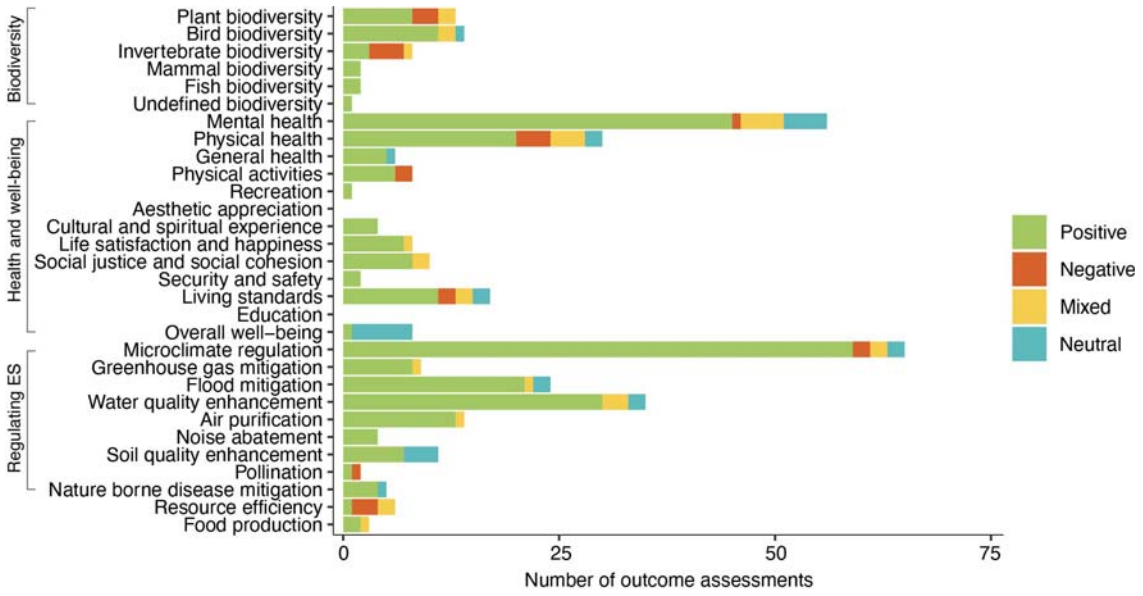


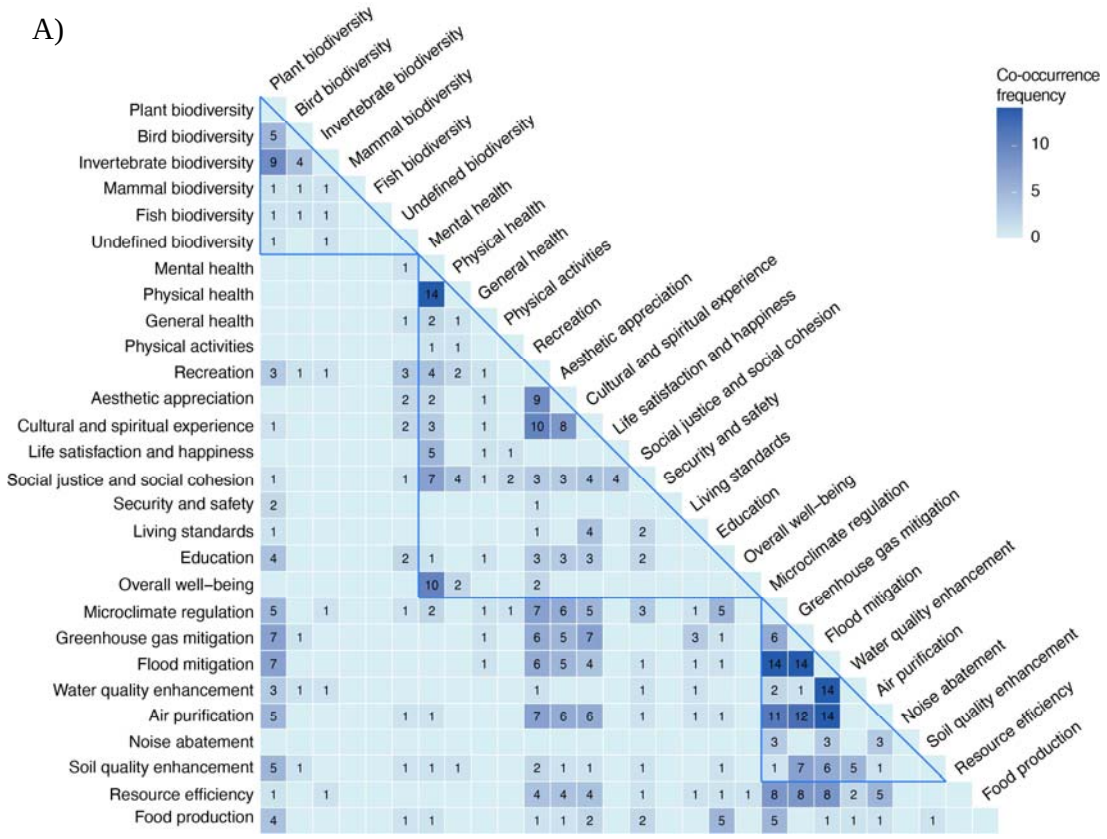
Fig. 6 Performance assessed by comparison to a non-NbS. The analysis was based on 368 outcomes that apply such comparisons.

Of the 794 recorded outcomes, 46% could be compared against that of a non-NbS, such as a green roof versus a grey roof. Comparisons to non-NbS were available for all outcome domains except aesthetic appreciation and education (Fig. 6).Within the reported effects

compared to non-NbS (368 outcomes), 78% of outcomes reported a positive effect, while 6% reported a negative effect, 8% reported a mixed effect and 8% reported a neutral effect. Overall, positive effects were mostly reported in microclimate mitigation (59 out of 287 outcomes), mainly related to green roofs & walls (12), green alleys & roadside green (8), and forest & trees (8). Mental health covered the second most reported positive effects (45), which are mainly related to general parks (12), semi-natural parks (9), and forests & trees (7). Notably, of the reported negative effects (22 outcomes), most were related to invertebrate biodiversity (4) and physical health (4), both mainly associated with grasslands (3 and 2, respectively).

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

A)



B)

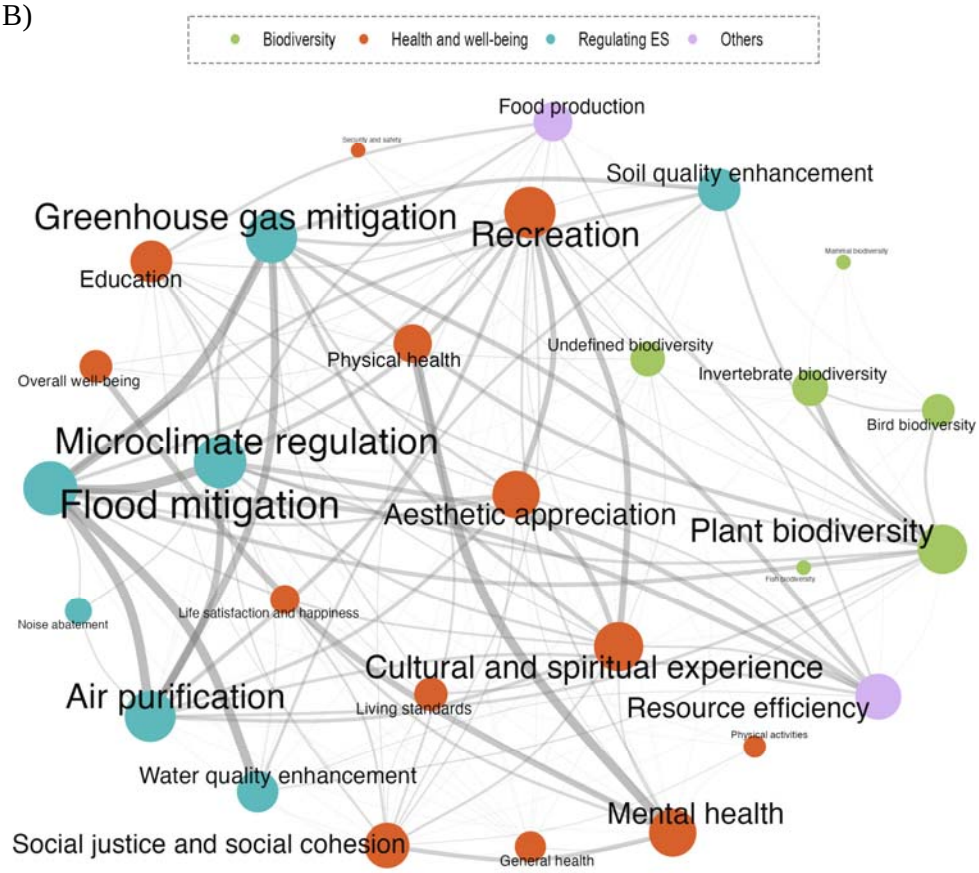


Fig. 7 Analysis of co-occurrence between outcome domains of nature-based solutions. The data includes 385 outcomes generated from 132 cases containing multiple outcomes. The map visualizes the 28 outcome domains that have co-occurrences with other outcomes. Pollination and nature-borne disease mitigation 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 (132), involving 385 outcomes in total. Among these cases, 58% reported two outcomes and 42% reported three or more outcomes. 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 132 cases. 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). 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. To the best of our knowledge, this is the first global systematic mapping that combines these different components of NbS effectiveness.

Our global database contains urban NbS cases located in 197 cities in 56 countries worldwide, albeit with lower representation from particularly Africa and Central America. Our assessment was based on inclusive search terms and criteria, allowing us to look beyond what current research calls 'nature-based solutions'. This offered a generic perspective on a swiftly developing concept, without disregarding empirical studies in parts of the world where the concept is called differently. Compared to existing global NbS databases, we added a large number of NbS empirical case studies (547) that are specific to urban systems. Other global mapping studies, such as Chausson et al. (2020) which contains 293 empirical cases, focus on the natural and rural environments, but not cities. Two major reviews on urban NbS, challenges and ES do not link clearly to outcomes (Babí Almenar et al., 2021; Castellar et al., 2021). We complement this knowledge base by including evidence from 361 scientific papers on NbS evaluation, which go beyond urban challenges by linking these challenges to NbS outcomes.

Our dataset encompasses a broad range of outcomes related to biodiversity, well-being, and regulating ES. Systematic syntheses of NbS have generally focused on only one perspective, for instance climate change adaptation (Chausson et al., 2020; Goodwin, Olazabal, Castro, & Pascual, 2023) and human health (Kabisch et al., 2017; van den Bosch & Ode Sang, 2017). Our study's broader scope allowed us to explore the multifunctional potential of urban NbS. In doing so, we have expanded the evidence base on multifunctional NbS by adding 132 empirical cases with multiple outcomes.

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, practice, and policy.

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. The feature-based classification also suits the assessment of interventions without a clear purpose. Up until now, interventions involving protection, management, and restoration approaches were considered as categories of NbS in existing classifications, including NbS intervention defined by Castellar et al. (2021) and Type 1 and 2 defined by 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. Our assessment illustrated that urban nature-based solutions could be primarily characterized based on their physical feature. 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, coupling measures to physical units in these cases would 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. NbS are commonly communicated either through targeted societal challenges (Cohen-Shacham et al., 2016; European Commission, 2015) or through outcomes provided, often in the context of a broader theme or challenge (Chausson et al., 2020). 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 (Chen et al., 2020; Hoover et al., 2020). In our dataset, the most frequently reported urban challenges include health and well-being, biodiversity loss, and the urban heat island. Another review of urban challenges also identified a significant number of cases related to human health and urban heat island issues, while only a few cases were related to biodiversity loss (Babí Almenar et al., 2021). This divergence could be attributed to their emphasis on sustainability and resilience during their search process. Crucially for policy and urban planning, 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.

Although challenges could often be linked to reported outcomes, 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. This can be explained by the fact that such assessments have a longer tradition than that of NbS. 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 NbS research. 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, we advocate for further empirical studies that encompass a broader range of well-being dimensions beyond human health.

4.3 Assessing the performance of nature-based-solutions

The performance assessment of NbS compared to non-NbS showed that 78% of the outcomes were positive. This suggests that NbS can be effective solutions compared to constructed or engineered solutions (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. S3). 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.

Further research on NbS needs to consider how the performance varies across spatial and temporal scales. First, the performance of NbS needs to be assessed closely related to the relevant spatial scales (Frantzeskaki, 2019; Hutchins et al., 2021). Urban NbS implementation can encompass the micro-level of an individual building, the meso-level of the neighborhood or streets, and the macro-level of the whole city (Raymond, Berry, et al., 2017). The effectiveness of cooling effects would vary depending on whether green roofs are applied at the scale of individual buildings or across an entire city, considering the required thresholds to address the challenge and the spatial extent of NbS impacts (Hutchins et al., 2021). Second, the performance of NbS needs to be assessed between different moments in time. NbS require sufficient time to become effective and generally provide increasing benefits as they mature (Sowińska-Świerkosz & García, 2021). For example, soil rehabilitation measures may take time to effectively enhance forest soil quality (Ward et al., 2021). Likewise, rain gardens may lead to unexpected neighborhood upgrades in the long term (Hagen, Pijawka, Prakash, & Sharma, 2017). Spatial and temporal assessment will help urban planners anticipate the time NbS need to become effective, their potential co-benefits over the long term, as well as the relevant spatial scales at which they contribute. To achieve this, we recommend conducting evidence syntheses that gather information on both spatial and temporal scales of NbS performance.

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, our systematic assessment on linkages between urban challenges, NbS and outcomes contributes to a fundamental understanding of how NbS address urban challenges through its outcomes.

The systematic map also highlights significant gaps in the evidence base. Firstly, there is a noticeable geographic imbalance, with the majority of studies concentrated in Asia, Europe, and North America, while Africa and Central America are underrepresented. Second, well-being dimensions beyond human health, such as social justice and cohesion and living standards, have not received adequate attention in NbS research as initial urban challenges and related outcomes. Third, there is a lack of comparative studies with non-NbS controls, particularly concerning biophysical and social well-being outcomes. Lastly, empirical studies that simultaneously report multiple outcomes to both biodiversity and human well-being are largely lacking. The identified linkages, as well as the highlighted gaps in the evidence, show a diverse array of urban NbS portfolios, enabling scientists, urban planners, and policymakers to understand which NbS type could be more pertinent for targeted urban challenges and what related benefits and co-benefits could be expected. Armed with this knowledge, urban planners and policymakers can make more informed decisions regarding potential solutions that are suitable for addressing specific challenges while minimizing potential trade-offs.

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