

Towards a typology of nature-based solutions for disaster risk reduction

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ABSTRACT

Disaster risk reduction (DRR) is one of the most important societal challenges addressed under the umbrella term nature-based solutions (NbS). One NbS approach that specifically addresses risk reduction is ecosystem-based disaster risk reduction (Eco-DRR). However, there are other approaches, such as integrated fire management or protective forests, which directly aim at reducing the risk of specific natural hazards. Other approaches, such as ecosystem-based adaptation (EbA), do not have DRR as a primary goal, but contribute to it in the form of synergies and co-benefits. Based on a comprehensive literature search of the Scopus database covering all articles published in English during the period 2000–2021, we analyze existing NbS approaches and those which address DRR. In a further step, we select all original research articles ($n = 114$) that refer to NbS for DRR projects or interventions conducted in a specific geographic area and analyze them in terms of (1) approach applied; (2) natural hazards mitigated; (3) ecosystem services for DRR provided; (4) geographic and biophysical site conditions, and (5) measures and techniques used. The analysis forms the basis for developing a typology of NbS for DRR, which we present for discussion. This typology helps scientists, policymakers, planners, and other stakeholders to gain a systematic overview of the NbS for DRR approaches currently addressed in the literature and to advance systematization of these approaches.

1. Introduction

The term nature-based solutions (NbS) was introduced by the World Bank in the late 2000s [1] and was subsequently disseminated and conceptually developed by the International Union for Conservation of Nature (IUCN) to further emphasize the importance of nature in general and biodiversity in particular for climate change mitigation and adaptation [2]. The NbS concept was developed during the UNFCCC negotiations in 2009 and then included in the IUCN Global Programme 2013–2016. At the 2016 World Conservation Congress and General Assembly, IUCN members adopted Resolution WCC-2016-Res-069 [3], which defines NbS as “actions to protect, sustainably manage, and restore natural or modified ecosystems, that address societal challenges effectively and adaptively, simultaneously providing human well-being and biodiversity benefits”.

The European Commission (EC) adopted the concept of NbS for the Horizon 2020 research program [4], and subsequently developed its own definition: “Solutions that are inspired and supported by nature, which are cost-effective, simultaneously provide environmental, social and economic benefits and help build resilience. Such solutions bring more, and more diverse, nature and natural features and processes into cities, landscapes and seascapes, through locally adapted, resource-efficient and systemic interventions” (https://ec.europa.eu/info/research-and-innovation_en). Through the EC initiative, various research programs and research lines emerged, which in turn led to numerous publications related to NbS (Fig. 1) [5]. Amongst others, the European Environment Agency published a report summarizing the findings of current research [6] and the EC [7] published a NbS handbook for practitioners. In 2020, IUCN published the Global Standard for NbS that includes parameters defining NbS and a common framework to

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prevent unanticipated negative outcomes or misuse and help funding agencies, policy makers and other stakeholders assess the effectiveness of interventions [8]. Despite the publication of the standard, acceptance of the term NbS at international level was divided. This changed on the second of March 2022, when the United Nations Environment Assembly adopted a Resolution on Nature-based Solutions for supporting Sustainable Development (UNEP/EA5/L9/REV.1) [9], which defines NbS as "actions to protect, conserve, restore, sustainably use and manage natural or modified terrestrial, freshwater, coastal and marine ecosystems, which address social, economic and environmental challenges effectively and adaptively, while simultaneously providing human well-being, ecosystem services and resilience and biodiversity benefits."

Ever since the introduction of IUCN's definition of NbS, the question of how the term NbS relates to other, already established ecosystem-based concepts, such as ecosystem-based adaptation (EbA) and green infrastructure (GI), arose [10]. Cohen-Shacham et al. [11] define NbS as an umbrella concept that encompasses several approaches that fall into five main categories: restoration, issue-specific, infrastructure, management, and protection. All categories contribute to addressing various societal challenges, human well-being and biodiversity. The authors assign 12 concepts to the five NbS categories. At the same time, they point out that these concepts are examples, so that further concepts could be added, if necessary. In another publication, Cohen-Shacham et al. [12] define eight core principles for the successful implementation of NbS projects or interventions. Both the classification and the principles have been adopted by the IUCN.

Sowińska-Świerkosz & García [13] analyzed 200 papers and 20 definitions of NbS and concluded that the NbS concept is still unclear in terms of its definition and applications. However, they identify four actions that NbS have in common, namely, they "(1) are inspired and powered by nature; (2) address (societal) challenges or resolve problems; (3) provide multiple services/benefits, including biodiversity gain; and (4) are of high effectiveness and economic efficiency." They also define a total of 11 exclusion criteria from the set of NbS.

In the context of NbS for DRR, UNDRR [14] presented a classification that divides NbS into four main categories: according to their main goals: a) climate change adaptation, b) climate change mitigation; c) DRR, and d) environmental management including biodiversity conservation. They too, define NbS as an umbrella concept below which they arrange various approaches derived from the literature that partially match and go beyond those of Cohen-Shacham [11].

With reference to specific natural hazards, Arce-Mojica et al. [15]

identified 13 NbS approaches for mitigating shallow landslides in a global literature review. These include ecological engineering, soil bioengineering, protective forests, bioengineering, ecological restoration and Eco-DRR as the most commonly cited approaches. Debele et al. [16] compiled NbS approaches specific to hydro-meteorological hazards, some of which are very general and do not specifically address DRR, such as ecosystem services and others of which are descriptions of individual measures rather than approaches. However, a total of 14 approaches are directly related to DRR.

For the Eco-DRR approach, or NbS approaches that specifically contribute to natural hazard mitigation, Sudmeier-Rieux et al. [17] undertook a comprehensive global literature review of 529 articles published between 2000 and 2019, demonstrating clear evidence that ecosystems contribute to the mitigation of natural hazards. In their analysis, the authors distinguished between the following ecosystem categories: urban, coastal, mountains, forests, rivers/ wetlands, agro-ecosystems and drylands. The authors also mapped countries and regions where the Eco-DRR interventions and models were implemented. What is largely left open in their analysis, however, is the detailed geographical and biophysical characterization of the types of Eco-DRR projects and models, as well as measures and techniques covered by the literature review.

Given the poorly represented relationships and hierarchies among the various NbS approaches in the literature to date, the objective of this paper is to develop a corresponding typology exclusively on NbS for DRR. As the term NbS has increasingly evolved from a political term to a scientific concept, a more precise and detailed conceptualization is needed. This can help both to address reservations such as those of Nesshöver et al. [18], who suggest that the NbS approach may be too vague and to support the policy process of defining NbS.

Our research was divided into two phases: first, a comprehensive literature review to identify NbS for DRR and second, a process to characterize these approaches in detail. To this end, peer-reviewed articles addressing NbS for DRR between 2000 and 2021 were evaluated with respect to five main criteria: (1) Type of NbS approach employed, (2) natural hazards to be mitigated, (3) ecosystem services for hazard mitigation employed, (4) geographic and biophysical site conditions, and (5) measures and techniques adopted. The second phase consisted of joint development of the typology with all authors of this article in an iterative process. Based on the above phases we propose a typology of NbS for DRR, which we present for discussion.

We believe that such a typology is urgently needed because it

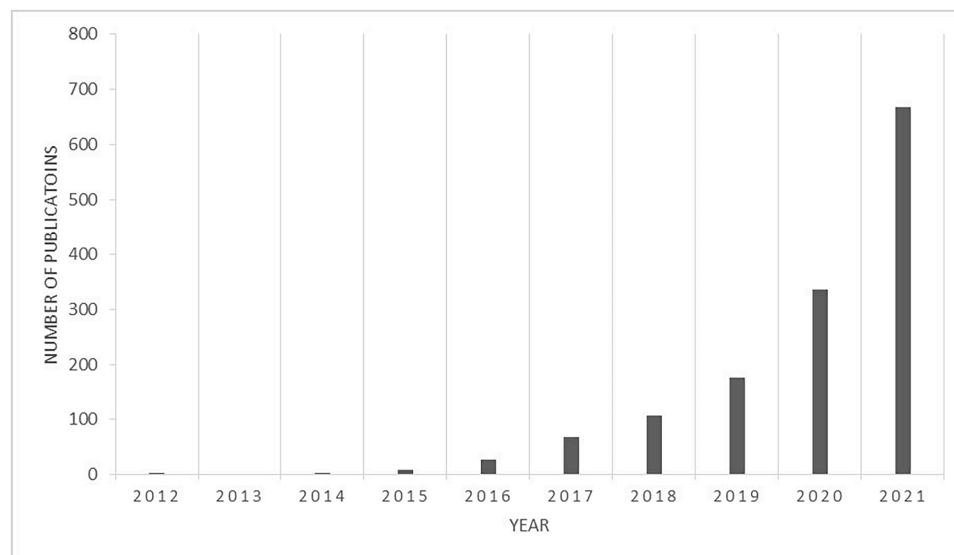


Fig 1. Number of mentions (in title, abstract or keywords) of "Nature-based solutions" in peer-reviewed articles in the Scopus database. Query from 16/12/2022; $n = 1463$.

provides scientists, practitioners and policy makers with an overview of the different NbS approaches for DRR, as well as an important basis for determining which solution might be used in a specific case. In addition, a typology helps to improve coherence and alignment in the mitigation of natural hazards, including in the context of climate adaptation.

2. Methods

In accordance with our objective, we conducted a systematic review of the peer-reviewed English-language literature accessible in the recognized literature database Scopus. The time period chosen was 2000 to 2021, during which the use of ecosystem services to mitigate natural hazards had become increasingly important at the scientific and policy levels, even though, as mentioned, the umbrella term NbS itself did not appear in the literature until 2012. We were interested only in empirical studies related to field research that used NbS for hazard mitigation and DRR in defined geographic areas. Conceptual papers, modeling articles without geographic spatial reference, review articles, and laboratory studies were not included, because we are referring to geographic and ecological site conditions when developing a typology. These are tied to locally implemented NbS. Conceptual work without a site reference as well as review articles and site-independent modeling therefore do not play a role in achieving our objective.

For the systematic literature review, we used the PRISMA (Preferred Reporting Items for Systematic reviews and Meta-Analyses) method to make the flow of information through the different stages of this systematic review transparent [19]. In a first step (identification), we performed a cross-search in title, abstract or keywords with the two terms "nature-based" and "ecosystem-based" (a synonym) on the one side and "hazard(s)" and "disaster(s)" on the other. This way, we identified 361 relevant papers.

As outlined in the introduction, there are numerous NbS approaches that do not necessarily include the key terms "nature-based" or "ecosystem-based" but also have DRR as a goal or at least as a co-benefit and must be included under the umbrella term NbS. We identified four relevant literature studies that compiled such NbS approaches briefly presented in the introduction. These four studies were selected for the following reasons. The study by Cohen-Shaham et al. [11] was the first to systematically review NbS and is accordingly widely cited in the literature. The UNDRR [14] study systematized NbS approaches with a particular focus on the position of DRR-related approaches. The studies by Arce-Mojica et al. [15] and Debele et al. [16] focus specifically on NbS for DRR applications, shallow landslides in the case of Arce-Mojica et al. [15] and hydro-meteorological hazards in the case of Debele et al. [16]. At the time of writing this paper, these were the only articles that explicitly focused on NbS for DRR approaches in relation to specific natural hazards (or groups of hazards). A compilation of all the 35 approaches that are mentioned in these four works can be found in Table 1.

We selected all publications that contained at least one of the 35 NbS approaches listed in the table in Annex 1 combined with the two search terms "hazard(s)" and "disaster(s)" in title, abstract or keywords. This way we were then able to identify another 1563 titles (see Fig. 2).

In the second step (screening) we reviewed all 1924 recorded articles by title and abstract to determine whether they met the following criteria: (a) an empirical study addressing NbS for DRR or hazard mitigation in a specific geographic area and (b) related to one or more natural hazards. After this step, a total of 136 relevant articles remained as a large majority of articles were conceptual, modeling-based and not related to field implementation. The screening process then consisted of forming six groups with 2–3 researchers each, who reviewed the eligible 136 full-text articles. As a result of this review, another 22 papers were eliminated as they either did not focus on a specific geographical area or the natural hazard was not clearly defined.

Following the categories defined in Sudmeier-Rieux et al. [17], the remaining 114 relevant articles were assigned to the following six classes: (1) Urban Ecosystems [13 papers], (2) Coastal Ecosystems [25

papers], (3) Mountain Ecosystems and Forests [42 papers], (4) Drylands [5 papers], (5) Wetlands [14 papers] and (6) Agricultural Ecosystems [15 papers]. The "Economy" and "Multiple Ecosystems" classes, as defined in the paper by Sudmeier-Rieux et al. [17], were not considered, because the focus of this study is on implemented NbS for DRR approaches in a specific geographic area.

The in-depth evaluation of the 114 papers was based on a template with 13 questions related to the five main evaluation criteria mentioned in the introduction section. The template was transferred to Google Forms, an online survey tool with the purpose of facilitating the gathering of information. Table 2 summarizes the main evaluation criteria with the respective purpose of the review, the questions and answer options, the respective scientific references and data sources.

The systematic review provided a detailed overview of which NbS for DRR approaches were implemented: where and in what form and the ecosystem services employed to mitigate various natural hazards. The following section summarizes the key findings of the review. Based on these findings, we propose a typology in Section 4. This typology was developed jointly by all authors of this paper in an iterative process. To this end, several feedback sessions were held to refine and improve the process with each iteration.

3. Results and discussion of literature review

A quantitative analysis of the literature revealed that the terms "ecosystem-based" and "nature-based" were mentioned in 16 and 13 articles, respectively (see Fig. 3). It should be noted that the terms "nature-based" and "ecosystem-based" were often used without further specification. However, "Ecosystem-based" also includes 5 articles that specially refer to ecosystem-based adaptation (EbA).

Among the various specific approaches related to NbS for DRR, agroforestry, green infrastructure, ecological restoration, bioengineering and protective forests were the most frequently mentioned, while several others were mentioned in only one or two articles. It should also be highlighted that the Eco-DRR approach, which explicitly aims at DRR, was mentioned in only four of the articles analyzed. Importantly, only 21 of the 35 approaches listed in Annex 1 appeared in the analyzed articles. This could be because certain approaches were used in practice but the results were not (yet) published as peer-reviewed scientific articles, or because the approaches were described in the literature but have not yet been implemented in practice and thus did not meet the selection criteria of this review.

Based on a detailed analysis of NbS approaches that directly aim at DRR or at least incorporate DRR targets or elements (NbS related to DRR), we propose to group the results into three main categories, as shown in Fig. 4. At the center of the figure are the goal-oriented approaches. In these approaches, a main goal is defined, such as DRR or climate change adaptation (CCA). In the case of DRR, there are three goal-oriented approaches: Eco-DRR, protective forests and integrated fire management. While Eco-DRR is an approach that aims to mitigate all types of natural hazards through ecosystem-based or hybrid solutions, the other two approaches focus on specific natural hazards. The concept of protective forests, which originated in the European Alpine region but exists in similar form in other regions of the world, aims to mitigate mountain hazards, such as avalanches, landslides and rockfall and is based on the slope-stabilizing properties of forests, which can be combined with gray measures such as protective walls and fences [24]. Integrated fire management aims to reduce wildfire risk by integrating ecosystem-based and gray infrastructure and nonstructural measures, such as early warning systems [25,26]. These three approaches can be referred to as NbS for DRR in the strict sense, since DRR is their primary goal, while the approaches described below may have DRR as a subsidiary target or generate additional benefits for DRR. This is the case for the three goal-oriented approaches shown in Fig. 4 in the center below (Environmental management, CCA, climate mitigation). They do not focus on DRR, but can include DRR targets or components. This is

Table 1

Approaches and their categorization under the NbS umbrella concept according to four scientific studies

Source	Cohen-Shacham et al. [11]					UNDRR [14]					Arce et al. [15]	Debele et al. [16]
	Categories					Categories						
Approach ¹⁾	Restoration	Issue-specific	Infrastructure	Management	Protection	CCA ²⁾	CCM ³⁾	DRR ⁴⁾	EM ⁵⁾	n.s. ⁶⁾	SL ⁷⁾	HM ⁸⁾
Area-based conservation												
Bioengineering												
Blue(-green) infrastructure												
Building with nature												
Climate adaptation services												
Climate small agriculture / agroforestry												
Ecological engineering												
Ecological restoration												
Ecosystem approach												
Ecosystem engineering												
Ecosystem-based adaptation												
Ecosystem-based disaster risk reduction												
Ecosystem-based management												
Ecosystem-based mitigation												
Engineering with nature												
Environmental restoration												
Forest landscape restoration												
Green infrastructure												
Integrated coastal zone management												
Integrated fire management												
Integrated water resources management												
Landscape restoration												

(continued on next page)

Table 1 (continued)

Natural capital												
Natural capital accounting												
Natural infrastructure												
Naturalistic engineering												
Protected area management												
Protection forests												
Soil bioengineering												
Sustainable land management												
Urban greening												
Vegetation restoration												
Wetland restoration												
Working with natural processes												
Working with nature												

¹⁾Cohen-Shacham et al. used the term concept instead of approach;

²⁾climate change adaptation;

³⁾climate change mitigation;

⁴⁾disaster risk reduction;

⁵⁾environmental management;

⁶⁾approaches mentioned but not further specified;

⁷⁾approaches for shallow landslides without categorization;

⁸⁾approaches for hydro-meteorological hazards without categorization

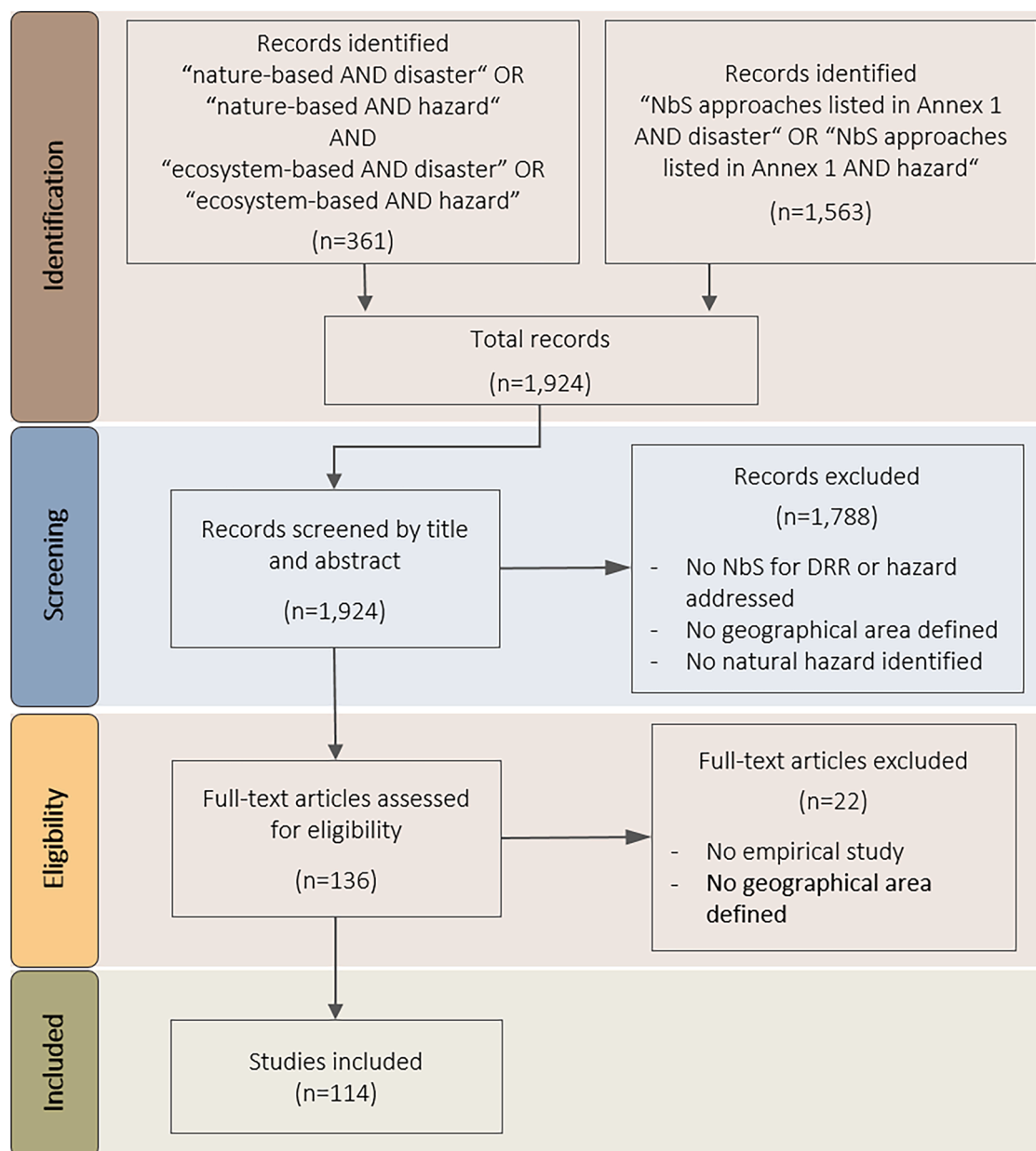


Fig. 2. Flow diagram of the review process using the PRISMA method.

particularly evident in CCA, as climate change often leads to an increase in disaster risk, so EbA projects usually include DRR components.

In addition to the goal-oriented approaches, there are the approaches shown in Fig. 4 on the left, which aim to protect, restore and sustainably use ecosystems. These approaches focus on the ecosystem itself, its services and functions, as well as biodiversity conservation. Ecosystem restoration, conservation and sustainable use contribute to the conservation of biodiversity and the maintenance of supporting and regulating ecosystem services in particular, without focusing on DRR or hazard mitigation. In many cases, however, these approaches include DRR targets or components and create co-benefits for hazard mitigation.

We refer to the approaches on the right side of Fig. 4 as sectoral approaches because they originate from different disciplines, such as engineering or agricultural sciences. By far the largest proportion are environmental engineering approaches that focus on specific ecosystem functions and services. This may involve, for example, the function of tree roots to stabilize slopes, or the dense cover of bunchgrasses to stabilize riverbanks. In addition to technical aspects, the various

approaches differ in that they focus either on vegetation (e.g., green infrastructure), soils (e.g., soil bioengineering), water (e.g., blue infrastructure), or the landscape as a whole (e.g., building with nature). Climate-smart agriculture and agroforestry originate in agricultural sciences, which aim to achieve sustainable land management. DRR or hazard mitigation is often only a secondary objective or a co-benefit of these approaches. In resource economics, approaches have developed that focus on the valuation of natural capital or ecosystem services. Such valuations often include components of DRR and hazard mitigation. Finally, urban greening originates in urban planning, where DRR is considered a co-benefit or one of several objectives.

A closer analysis of types of natural hazards mentioned in articles related to landscape types, shows us that NbS for DRR are most frequently used in mountain and forest ecosystems as well as in coastal ecosystems, followed by agroecosystems, rivers and wetlands, urban landscapes and drylands (Fig. 5). In mountainous regions, the focus is on protection against mass movements, while in coastal regions it is on protection against storms and coastal flooding as well as wave action

Table 2
Overview of the evaluation of scientific publications.

Evaluation criterion	Purpose	Question	Answer options	Reference / data source
(1) NbS approach	Assignment to a specific NbS for DRR approach.	Q1. Which NbS for DRR approach was used?	Options were provided from 35 approaches listed in Annex 1; additional approaches could be added.	As shown in Annex 1
(2) Natural hazard	Indication of the natural hazard(s) that the approach is intended to mitigate.	Q2. What natural hazard(s) is/are mitigated by the implemented approach?	30 different natural hazards in four main categories were indicated (geophysical, meteorological, hydrological, and climatological); one or more could be selected.	Classification of natural hazards according to the EM-DAT database [20]
(3) Ecosystem services for disaster risk reduction / hazard mitigation	Identification of the ecosystem service(s) for disaster risk reduction / hazard mitigation	Q3. Which ecosystem service(s) is/are used to mitigate natural hazards?	Subdivision into two categories: (1) Biophysical buffer with six subcategories: coastal, slope, river, storm, fire, desertification, and (2) Regulating function with three subcategories: heat reduction, fire risk reduction and drought risk reduction. Multiple response options for each subcategory, e.g., for coastal buffer: mangrove belt, coastal bank, coastal dune, coral reef, seagrass meadow, barrier island. Open text fields for supplementary entries.	Own categorization based on ecosystem services and functions cited in the scientific literature related to hazard mitigation.
(4) Geographical and biophysical conditions	Characterization of geographic and biophysical conditions under which the NbS approach was implemented.	Q4. In which country or region was the study conducted?	Open text field for country/region	Country / region as named in the article
		Q5. What are the climatic conditions?	Climatic zones according to the modified Köppen-Geiger climate classification. Classes used: Af (tropical rainforest), Am (tropical monsoon), As/Aw (tropical savanna with dry summer / wet winter), BS (steppe), BW (desert), Cs (Mediterranean), Cw/Cf (temperate with dry winter / no dry season), D (continental), E (polar)	Modified Köppen-Geiger classification by Kottek et al. [21]. ¹⁾
		Q6. In which biome or ecosystem is the study region located?	14 territorial biomes were indicated according to the classification of Olsen et al. [22], as well as three coastal, three marine and artificial ecosystems. Open text fields for supplementary entries.	Olsen et al. [22] biome classification plus coastal/marine and artificial ecosystems.
		Q7. At what altitude was the approach implemented?	Four altitude levels were given: (1) sub-alpine / alpine / nival (>1500 masl), (2) sub-montane / montane (300–1499 masl), (3) lowland (<300 masl outside coastal zone), (4) coastal zone defined as boundary between land and ocean, influenced by marine processes.	According to common altitude zoning in geography and ecology ²⁾
		Q8. In which hydrographic environment was the approach implemented?	Five hydrographic environments were given: glacial, riverine/fluvial, lacustrine, coastal, marine as well as “no specific hydrographic environment.”	According to common classification in hydrology and geomorphology
		Q9. How natural is the implemented ecosystem?	Four classes were given: Natural or near natural; cultivated with several natural elements; cultivated with few natural elements; urbanized or intensively cultivated	According to Rüdiger et al. [23]
		Q10. To what natural geofactors or anthropogenic design do the measures or techniques relate?	Four geofactors and one anthropogenic intervention were given: (1) vegetation-related, (2) soil-related, (3) landscape-related, (4) water-related, (5) urban design-related. Multiple answers were possible, as well as open fields for additions.	Own classification based on the scientific literature
(5) Measures / techniques	Identify and describe the measures or techniques used	Q11. Is it a measure based on traditional knowledge?	Possible answers: yes, no, not clearly provable	No specific reference
		Q12. Is it a hybrid solution combining NbS with engineered infrastructure?	Possible answers: yes, no, not clearly provable	No specific reference
		Q13. How can the measures or techniques be briefly characterized?	Field for free answer with maximum 50 words	No specific reference

including tsunamis. Flood risk reduction is also the main goal in river and wetland ecosystems as well as urban ecosystems, while in agro-ecosystems multiple hazards are addressed. As expected, NbS for DRR approaches in drylands aim to mitigate desertification, sand drift and droughts.

Fig. 6a shows a world map with the countries and the number of NbS interventions for DRR conducted there, as well as the climate zones

where the research was undertaken. Map 6b assigns NbS interventions per biome/ecosystem. Most of the interventions were carried out in Europe, China, USA, Indonesia and other Southeast Asian countries, while very few interventions were conducted in South America and Africa, with the exception of East and Southeast Africa. No studies on the subject were included in our final selection from the large territorial states of Russia and Canada. Most research was conducted in humid

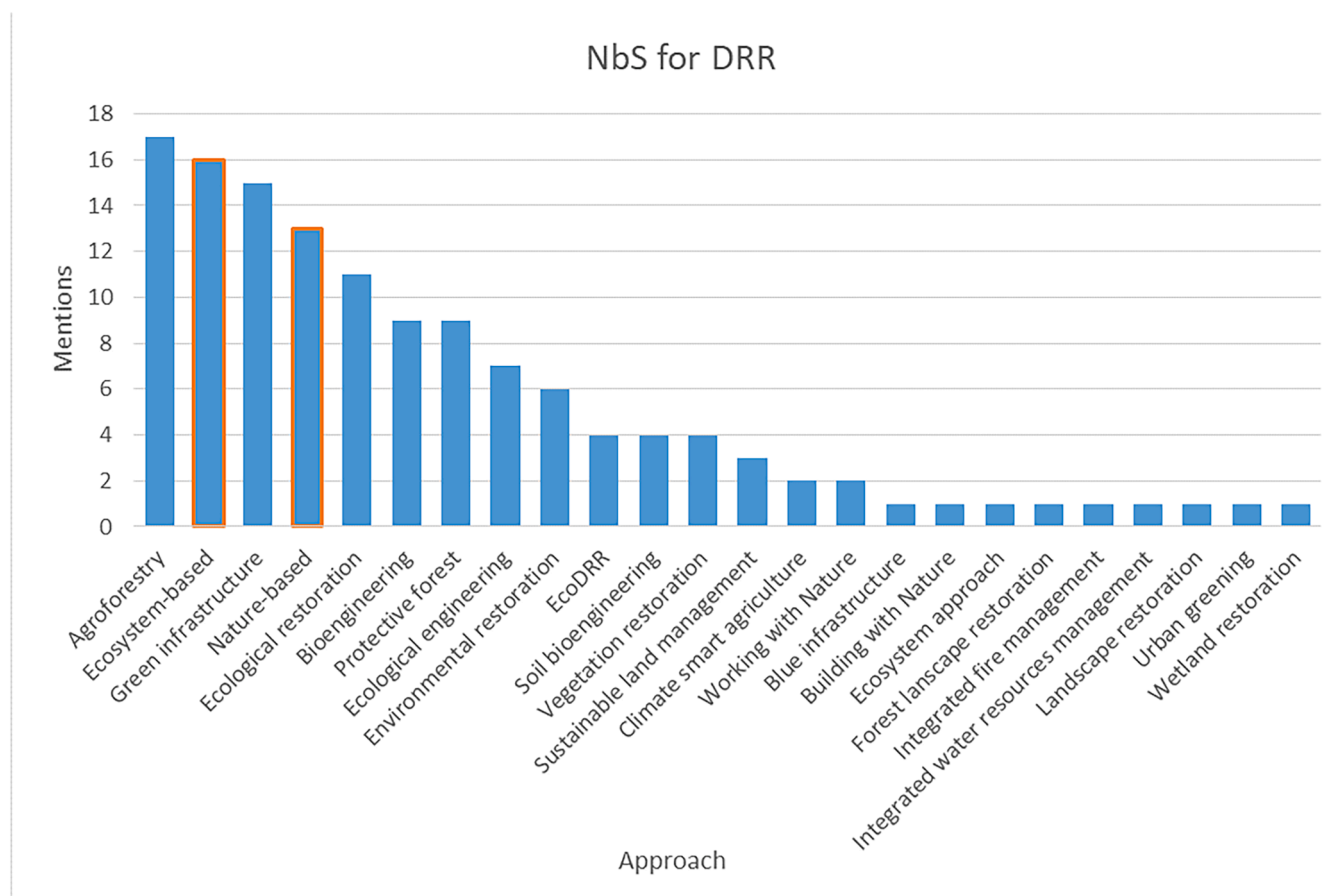


Fig. 3. NbS approaches mentioned in the analyzed scientific literature. Some articles cited multiple approaches, thus the total of 131 exceeds the number of articles analyzed ($n = 114$). The approaches framed in red refer to the search terms "ecosystem-based" and "nature-based" rather than a specific approach. In the literature, the terms "protection forests" and "protective forests" exist, which are summarized here under the term "protective forests".

tropical (Af/Am) and temperate to subtropical (Cf/Cw and Cs) climates, with a few in savanna climates (As/Aw), arid regions (Bs/Bw climates), as well as cold continental and mountain climates (D) and even polar (E) climates. In humid tropical, subtropical, and temperate climates, most of this research relates to the various forest biomes and ecosystems. Another focus is coastal ecosystems, and in particular mangroves. Projects and interventions were conducted at all altitudinal levels, with the highest number of measures implemented in sub-montane to montane areas (51), followed by lowlands (39), coastal (29) and alpine (23).

Table 3 shows the ecosystem functions and services used in implementing NbS. Very often, NbS require use of the ecosystems' biophysical buffer functions to reduce impacts of natural hazards. This is the case in mountain regions, where protective forests safeguard against rockfall, landslides and avalanches [27,28], or in coastal regions, where, for example, mangrove forests, coastal dunes or wetlands buffer the effects of wind and waves [29,30]. The buffer function is also frequently used along rivers, for example in the form of riverine forests, which protect against inundation and bank erosion [31]. Protective forest belts and woody plants are also used in arid lands to protect against advancing desertification and sand drifts [32]. Further buffer functions are listed in Table 3.

In addition to biophysical buffers, which are primarily based on vegetation as a protective shield, there are regulative functions that require the entire ecosystem to be effective. Both flood and drought control, for example, depend not only on vegetation, but also on soil, water bodies and the entire landscape to be effective. Thus, sustainable soil management, which counteracts compaction and promotes a sponge effect, can reduce the risk from flooding and drought, as can the use of side channels or floodplains for retention and appropriate landscaping

[33], for example through terracing [34]. Similar holistic uses of regulatory ecosystem services are also found in fire management [35], erosion control [36], heat island reduction [37], wave surge and reduction [38].

We took a further look at the continuum of NbS approaches that are based on natural or near-natural ecosystems, such as forests or wetlands, to anthropogenic NbS such as parks or green roofs. Here we see that 40.4% of the NbS interventions described in our review were natural or near-natural. Some 19.3% were cultivated ecosystems with several natural elements, such as agroecosystems with tree rows, while another 12.3% were cultivated ecosystems with only a few natural elements. The 15.3% of urbanized or intensively cultivated ecosystems were essentially green urban infrastructure, such as green roofs, green facades and other manmade green structures. In 15.8% of the articles, the level of natural to near-natural could not be specified.

Of the individual measures and techniques implemented, numerous NbS for DRR were related to landscape design, vegetation planting and management and somewhat fewer were soil- water- and urban design-related. A special case is the restoration of coral reefs, which even included animals. Landscape-related measures included for example, the reshaping of riverine landscapes or wetlands for flood protection (e.g., [39]). In most cases, vegetation, water- and soil-related measures were also integrated into landscape design. Landscape design also often played a significant role in mountainous regions, for example in terracing to protect against landslides and avalanches (e.g., [40]). Here too, landscape design was combined with vegetation-related and soil-related measures. An example of this are the protective forests in the European Alps (e.g., [41]). Finally, landscape-related measures were also very important in coastal protection, for example in the

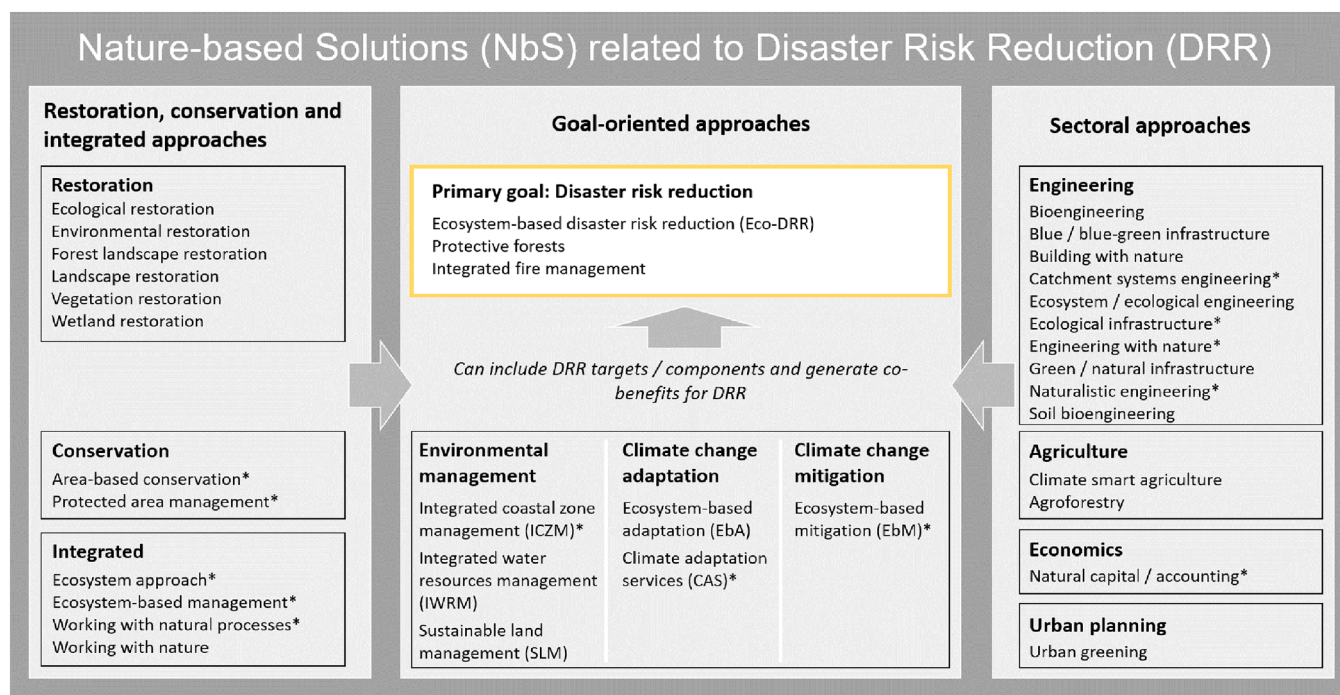


Fig. 4. Categorization of NbS approaches related to DRR. The approaches outlined in orange are NbS for DRR in the narrow sense. The NbS approaches marked with an asterisk are included in the NbS literature, but were not found in the reviewed literature on NbS related to DRR in the Scopus database (compare Fig. 3). Nevertheless, they are listed here because they are mentioned in the NbS literature (see Annex 1) and may generate benefits for DRR.

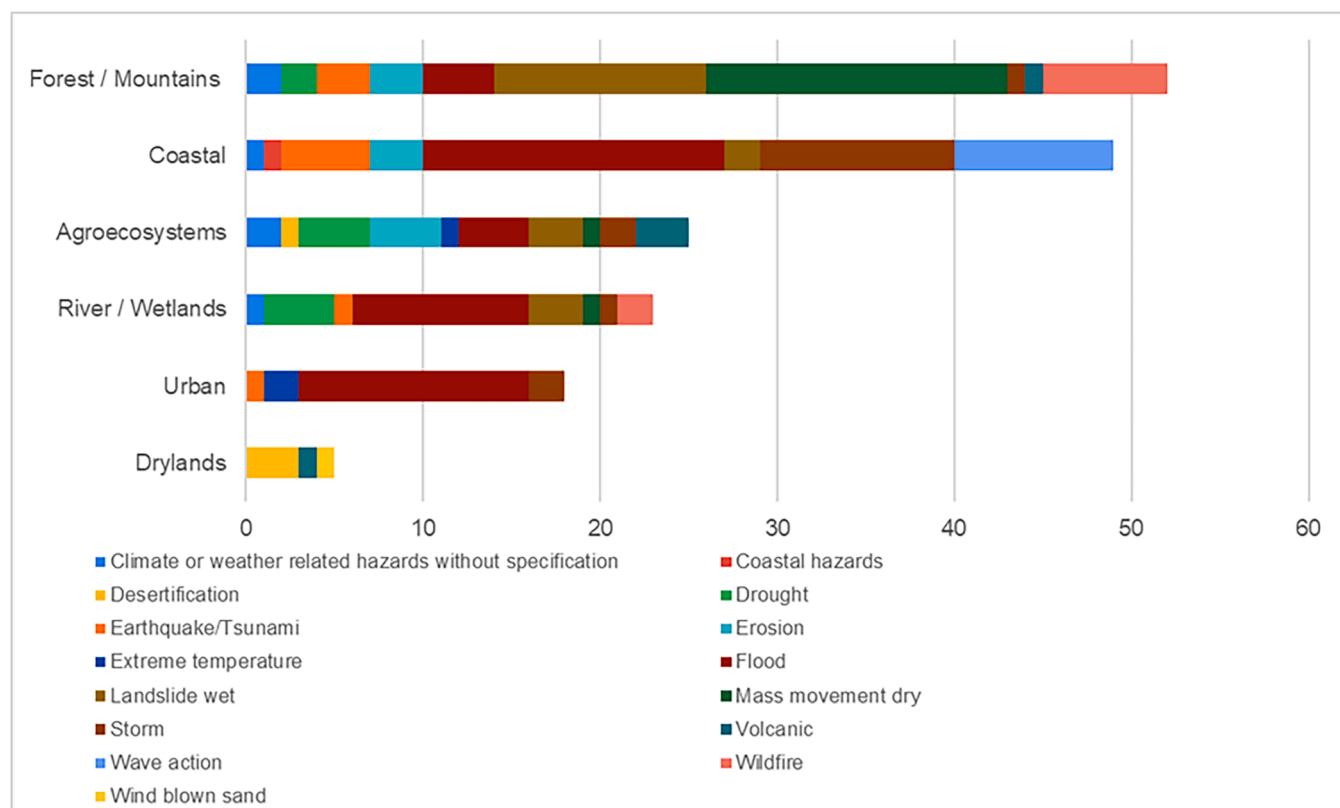


Fig 5. Natural hazards addressed in the reviewed articles in the major landscape units ($n = 114$; multiple hazards could be mentioned in one paper).

conservation or restoration of coastal dunes as buffers against wind and waves or the integrated management of mangroves, where vegetation, water and soil-related measures are also integrated (e.g., [42]).

Especially for landscape-related measures, so-called hybrid solutions that combine green, blue and gray infrastructures were often used. Among the 114 articles evaluated, a total of 41 referred to such hybrid

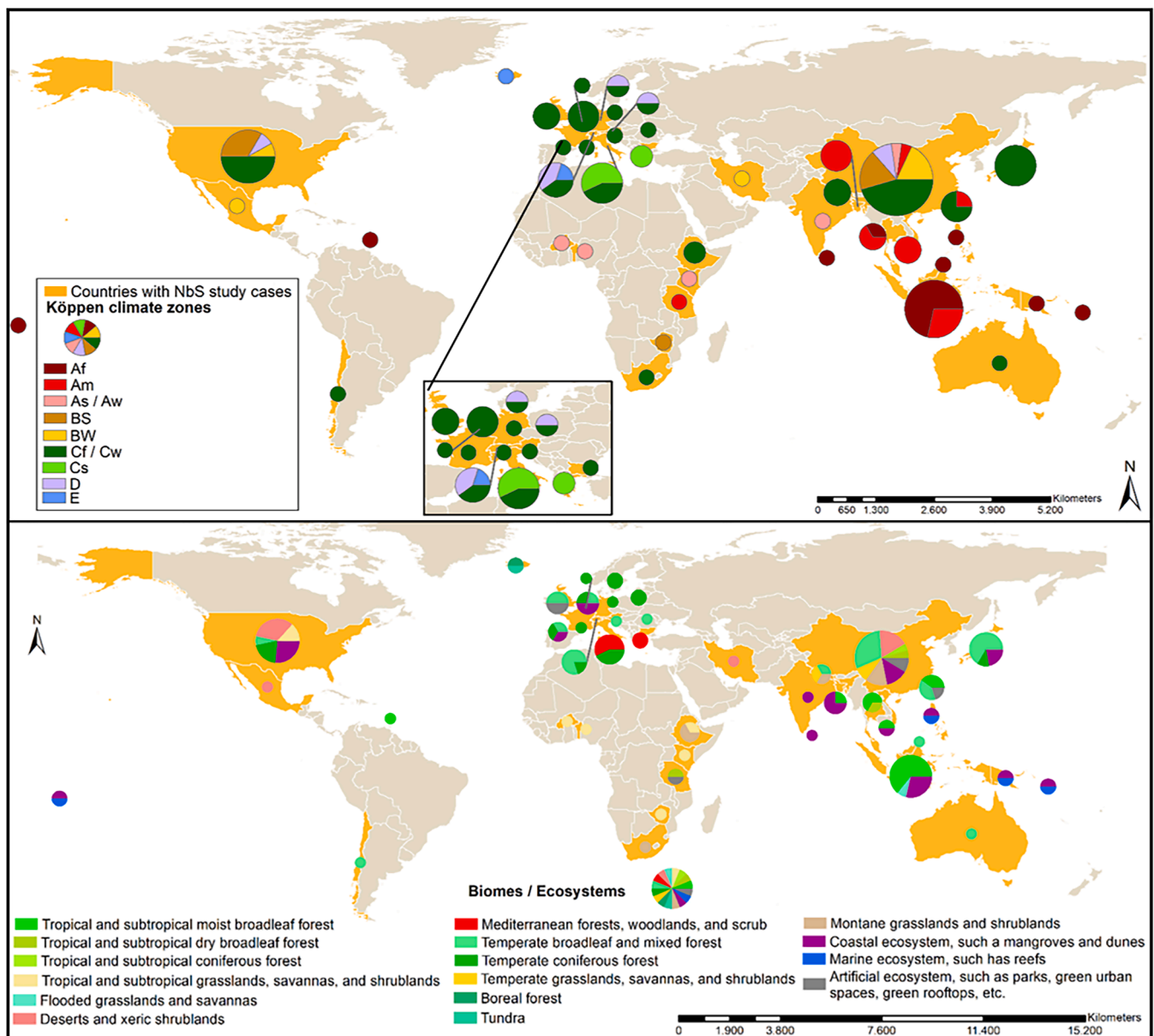


Fig. 6. (a) Countries with NbS for DRR study cases by climatic zones (for definitions of Köppen climate types, see Table 2); (b) biomes or ecosystems in which the studies were conducted; modified from Olsen et al. [22].

measures, while no specification was made for 18 articles. One example of such hybrid solutions was the redesign of river landscapes for flood protection, where, for example, on the one hand, retention areas were created and riverine forests were protected or restored, and on the other hand, hard infrastructure such as levees and protective walls were used. The Room for the River program in the Netherlands, for example, relies on such hybrid solutions [43]. Hybrid solutions were also often found in mountain regions and on coasts. For example, the protective forest concept in the European Alps, can be complemented by hard infrastructure such as protective fences [44], and on coasts, protective vegetation is often combined with dikes or other hard infrastructure (e.g., [45]).

Unlike landscape-related measures, purely vegetation-based measures focused on the protective function of vegetation rather than the ecosystem or landscape as a whole. By far the greatest importance was attached to forests and also forest belts and their buffering and regulating functions. Packages of measures for the protection, rehabilitation and sustainable use of forests were found in all large-scale landscape

units from high mountains to riverine landscapes of the mid mountains and lowlands to the coast and likewise in urban areas. Even in arid areas, they play a role in the form of tree or shrub barriers. Aspects of forest management for protection against natural hazards covered forest structure (density, height, width, spacing, etc.), diversity and age in particular (e.g., [46]).

Soil-related measures were often found under approaches such as soil bioengineering, frequently combined with vegetation and water-related measures. In most cases, the measures were aimed at improving soil quality, especially stability. Soil bioengineering included for instance techniques such as brush layering, palisades, live check dams, fascines and vegetative stone pitching for erosion and landslide control (e.g., [47]). Sometimes the measures were rooted in traditional or local knowledge. Overall, however, only 12 of the 114 articles clearly referred to traditional knowledge, while 59 did not and 43 could not be specified.

Water-related measures were often found in connection with the creation of retention areas for flood protection. These were often hybrid solutions that combined green, blue and gray infrastructure. The

Table 3
Ecosystem functions and services used for hazard mitigation.

ESS functions and services	Counts	Regulating function (ecological)	Counts
Biophysical buffer function			
Vegetated slopes buffer against rockfall, landslides, avalanches	35	Flood regulation	45
Coastal vegetation buffer against storms, waves, storm surges	33	Drought regulation	10
Vegetated river buffer against inundations/floods and riverbank erosion	28	Protection from forest fires	9
Desertification barriers (e.g. green belts)	7	Landslide and erosion control	8
Storm barrier (tree rows and plantations; non-coastal)	2	Heat reduction	2
Wetlands buffer against inundations/floods (inland)	2	Surge and wave reduction	2
Vegetation buffer to minimize tephra-fall impacts	1		
Vegetation gaps and patches as fire barriers	1		

portfolio included, among others, the creation of retention areas, the construction of water reservoirs, the widening of the riverbed, hydrological rehabilitation for peatlands and mangrove areas and the creation of levees (e.g., [48]).

In the area of urban design, a variety of measures were mentioned, often targeting multiple natural hazards, which included flood control, reduction of heat islands through temperature reduction and ventilation, or protection against landslides. In the urban context, green or green-blue infrastructure approaches were widespread (e.g., [49]), including the sponge city concept, originating in China [50]. Measures and techniques mentioned green roofs, green facades, permeable pavements, bioswales, raingardens, parks and others (e.g., [51]).

4. Results and discussion of the proposed typology

The term NbS has been consolidated in the scientific literature over the past 10 years. In various literary sources (e.g., [11],[14]), NbS is defined as an umbrella concept that addresses multiple societal challenges through a host of approaches. We join this view and focus on one of the societal challenges under the NbS umbrella concept: DRR. For this purpose, we have conducted an extensive literature study, which is the basis for the typology presented below.

An important finding of the literature review is that while the notion of NbS in the context of natural hazards has become increasingly established in the literature, there are comparatively few publications dedicated to specific case studies and implementation of measures in defined geographic areas (only 114 papers between 2000 and 2021). Many articles referred to natural hazards, but either focused on other societal challenges than DRR or remain at a conceptual level. A detailed review of the 114 articles showed that from 2000 to 2014, no research article used the term “nature-based solutions”, but rather used approaches that were often established earlier than NbS. These include sustainable land management (SLM), integrated water resources management (IWRM), and integrated fire management (IFM), among others. In our evaluation however, studies using these approaches fall under the umbrella concept NbS. It is only since 2015 that the term NbS has been increasingly used in the literature on natural hazards, but it is often used as a generic term to refer to a specific approach. Therefore, we propose a more specific typology building on the detailed overview presented in Section 3 (Fig. 4) organized by the five attributes of NbS for DRR (Fig. 7). These attributes are described and discussed below.

4.1. Typology attribute 1: NbS approach

We propose a simplified categorization of the approaches for our

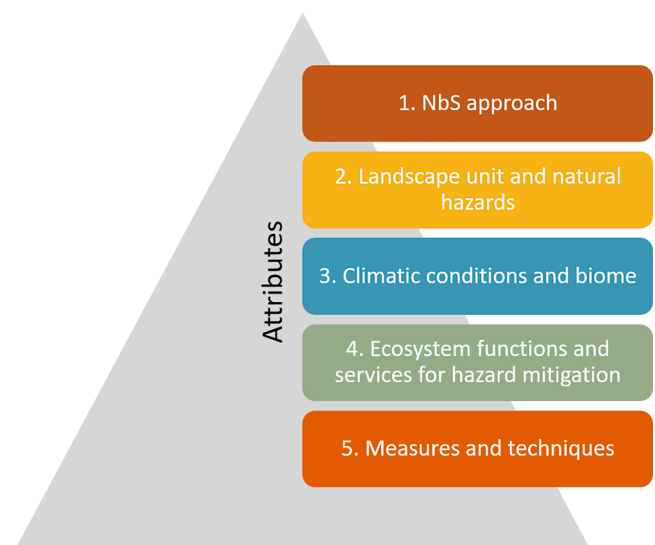


Fig. 7. NbS for DRR typology based on five attributes.

typology (see Fig. 8), whereby the NbS for DRR approach is the first attribute. At the center of the figure are the approaches that have DRR as their main goal – in a strict sense, only these are NbS for DRR approaches. We identified three approaches in the scientific literature where this is the case. Eco-DRR is an overarching concept that encompasses all types of natural hazards. Estrella and Saalismaa [52] define it as “the sustainable management, conservation, and restoration of ecosystems to reduce disaster risk, with the goal of achieving sustainable and resilient development”. This approach is promoted by UN agencies such as UNEP and UNDRR and described in various reports (e.g., [14, 53]). In the scientific literature, Eco-DRR is gradually becoming established. Of particular note is the global literature review “Scientific evidence for ecosystem-based disaster risk reduction” by Sudmeier-Rieux et al. [17], which is based on a review of more than 500 articles. However, the vast majority of the articles evaluated refer to ecosystem functions and services for hazard mitigation without using the term “Eco-DRR”. Moreover, among the articles that explicitly refer to Eco-DRR, there are only a few that have implemented the approach. This is in line with the results of this review, according to which only four research articles refer to implemented Eco-DRR projects. In addition, there are two other NbS for DRR approaches that address specific natural hazards: integrated fire management and protective forests. However, there is only one article in the literature reviewed that addresses NbS in the context of integrated fire management, compared to nine for protective forests (see Fig. 3). Some authors argue that these hazard-specific approaches can be considered as sub-approaches of Eco-DRR (e.g., [17]). It is important to note that the NbS for DRR approaches create co-benefits for other approaches with different goals and targets, such as biodiversity conservation and climate change adaptation (see Fig. 8) [5].

We refer to NbS approaches that do not explicitly aim at DRR but create additional benefits for it or incorporate elements of DRR as ‘NbS for DRR related.’ Based on our literature research, we distinguish three categories, as shown in Fig. 8.

- (1) Goal-oriented non-DRR approaches can be grouped into CCA, climate change mitigation and environmental management approaches, as suggested by UNDRR [14], with related approaches. One of these approaches is EbA, which addresses CCA. Since climate change is usually accompanied by an increased frequency and magnitude of certain natural hazards, aspects of DRR are taken also into account. The situation is similar with IWRM, which considers hydrological hazards such as floods and

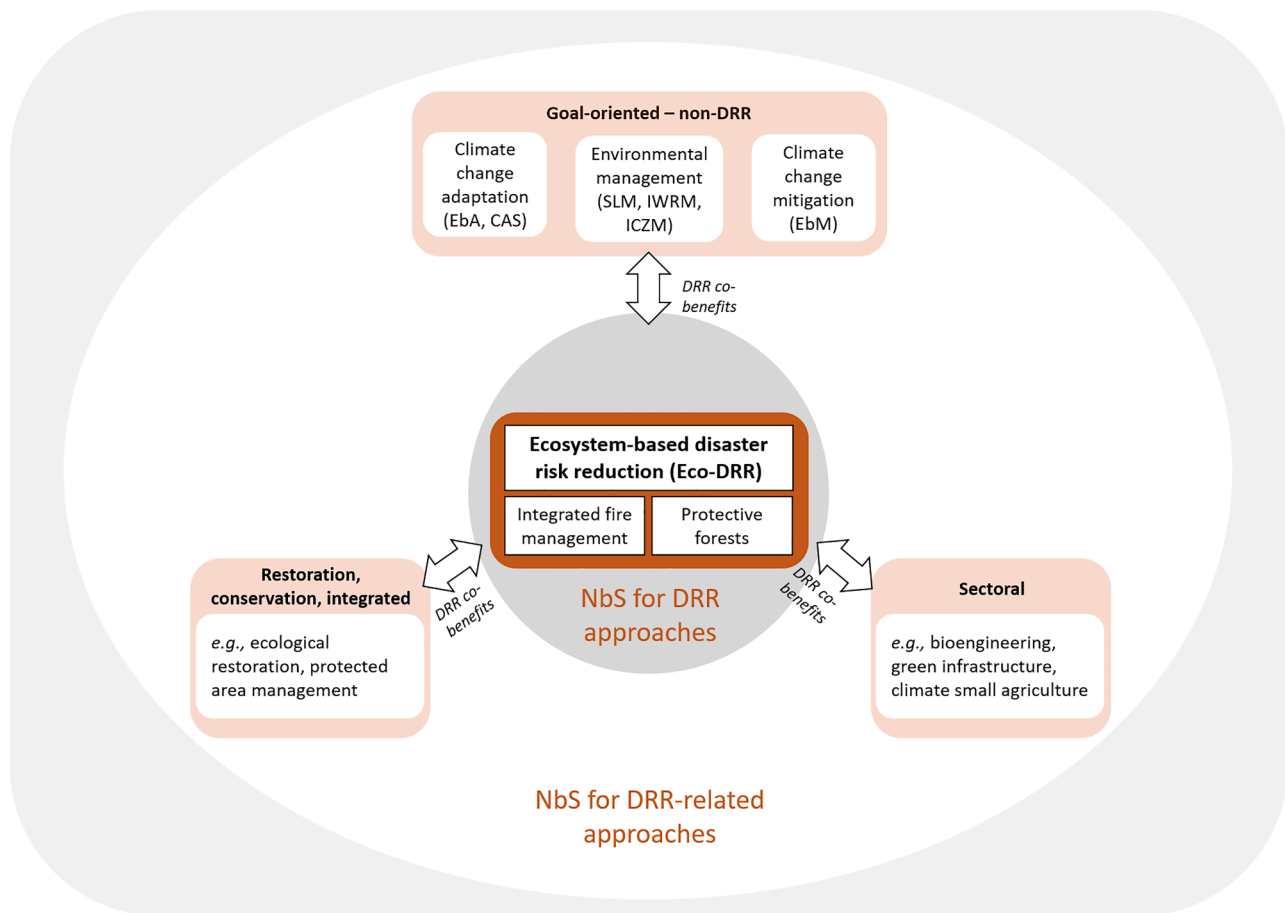


Fig. 8. Typology attribute 1: NbS for DRR and related approaches.

droughts, and with ICZM, which, among others, considers coastal hazards such as storms, storm surges and high waves. This is slightly different with SLM, which was introduced at the 1992 UN Earth Summit in Rio and defined as “the use of land resources, including soils, water, animals and plants, for the production of goods to meet changing human needs, while simultaneously ensuring the long-term productive potential of these resources and the maintenance of their environmental functions” (see: WOCAT [54]). This approach also includes DRR components, but similar to NbS, it can be also viewed as an overarching, holistic approach rather than a target-oriented approach (see the discussion in Walz et al. [5]).

- (2) Restoration, conservation and integrated approaches aim at the protection of biodiversity and the functioning of landscapes and ecosystems. This group includes various approaches, which are listed in detail in Fig. 4. They may contain elements of DRR and generate additional benefits for it, but without explicitly aiming at it.
- (3) The same is true for sectoral approaches, which are anchored in various disciplines, such as engineering, agricultural sciences and urban planning, and are strongly measure-oriented. Soil bioengineering, as one example, aims to improve soil properties. This can be beneficial for erosion control and soil fertility, and are thus also relevant for DRR. In particular, the sectoral approaches agroforestry, green infrastructure, ecological restoration and bioengineering are often used to mitigate natural hazards, as can be seen in Fig. 3.

4.2. Typology attribute 2: landscape unit and related natural hazards

The second attribute of our typology refers to the landscape unit and related frequently occurring natural hazards (see Fig. 8). Estrella & Saalismaa [52] made an initial categorization of four ecosystem groups with related natural hazards: (1) Mountain forests, vegetation on hill-sides, (2) Wetlands, floodplains, (3) Coastal ecosystems (mangroves, saltmarshes, coral reefs, barrier islands, sand dunes) and (4) Drylands. Sudmeier-Rieux et al. [17] based their review on nine categories; besides mountains, rivers/wetlands, coastal, drylands, which are similar to those used by Estrella & Saalismaa [52], they added urban, forests/vegetation, economics, agroecosystems, and multiple ecosystems. In our review, we used these categories, but modified them slightly and omitted the categories economics and multiple ecosystems because they did not meet the requirements of the review. Following our literature review, we now propose the typology based on five main landscape units and a rural-urban gradient as shown in Fig. 9.

The first three main landscape units follow an elevation gradient: (1) high mountains (alpine), (2) low mountains and lowlands, (3) coasts and assign corresponding natural hazards. In the high mountains, these are mainly rockfalls, landslides, avalanches, (torrential) floods and debris flows, which are counteracted with NbS. There are other natural hazards, such as glacier lake outburst floods (GLOFs), that can occur in the high mountains, but have not been addressed in the literature related to NbS for DRR to date. Various climatological and hydro-meteorological natural hazards occur in the low mountains and lowlands, such as floods, droughts, forest fires and storms, which can be mitigated with NbS. In this context, flooding is mostly found in riverine landscapes and wetlands, so they are included under this category and not treated separately, as in Sudmeier-Rieux et al. [17]. For coastal landscapes,

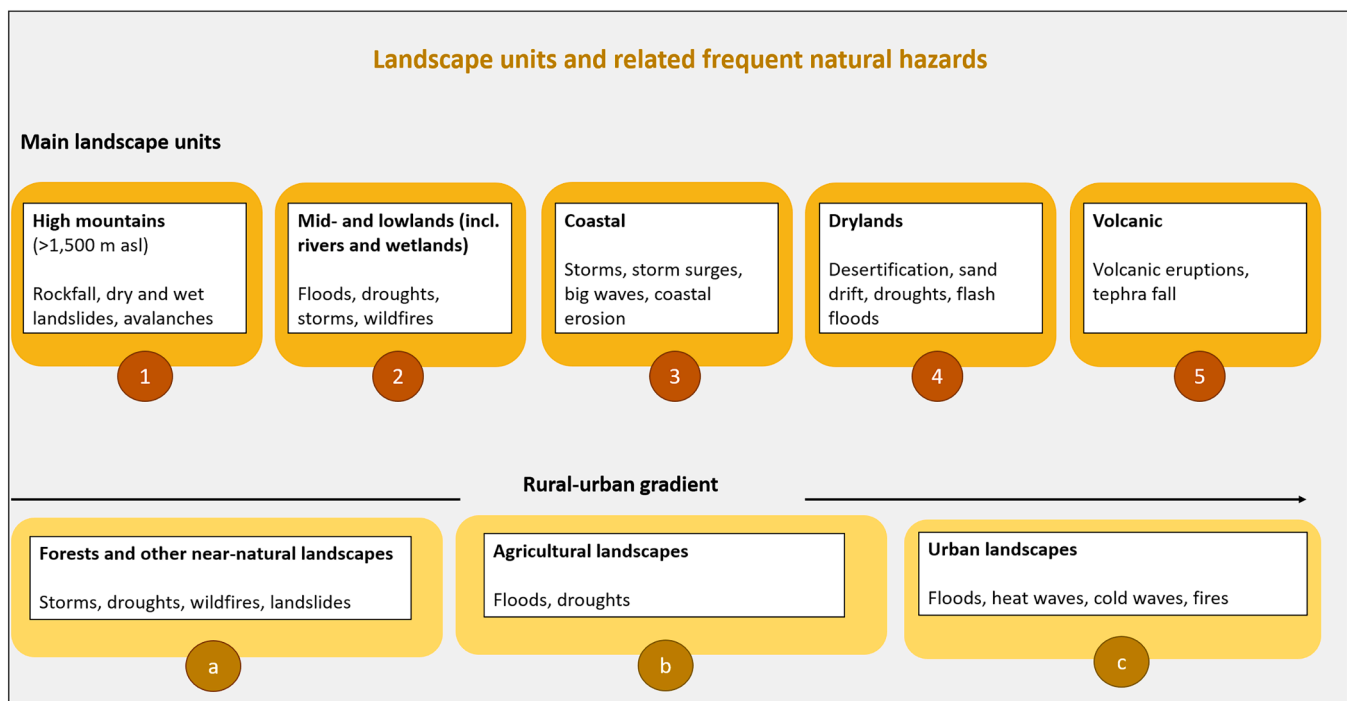


Fig. 9. Typology attribute 2: Landscape units and related natural hazards.

natural hazards include storms (i.e., tropical cyclones such as hurricanes and typhoons), storm surges, coastal erosion, as well as big waves (including tsunamis). In the fourth category, drylands, it is mainly droughts, desertification, and sand drifts/storms that are mitigated with NbS. The fifth category, volcanic landscapes, has not yet been defined as a distinct landscape unit in the NbS literature. Whereas our literature review included mitigation of hazards caused by tephra fall by vegetation.

On a second level, we display a rural-urban gradient from forests and other near-natural landscapes to agricultural landscapes to urban landscapes (subunits a, b and c). The idea behind this is that - independent of the overarching landscape unit - in forest and other near-natural landscapes or ecosystems, NbS interventions are different than in agricultural or urban landscapes. Thus, large-scale protection or rehabilitation measures are often used in forest landscapes, while in agricultural landscapes the focus is on a more sustainable agricultural use, e.g. through agroforestry systems and green-blue infrastructures are used in urban landscapes.

4.3. Typology attribute 3: climatic conditions and biome

The third attribute of our typology refers to the climatic conditions and the biome in which the NbS for DRR intervention is implemented. Climate and the potential natural vegetation significantly determine the success of an NbS intervention. Thus, an NbS intervention should be oriented to the prevailing climatic conditions, but should also take into account climatic extremes, which can lead to increased mortality of planted trees in the case of drought, for example. The potential natural vegetation, which is reflected on a large scale by biomes and ecoregions as their subunit (Olsen et al. [22]), in turn provides information about which plants are adapted to the prevailing climatic conditions and which plant communities and species occur naturally in an area. These should be given special consideration in NbS interventions that include vegetation as a component, such as ecological remediation and restoration.

To characterize climatic conditions and biomes, we propose five groups. In the first group we include the humid to subhumid tropical and

subtropical climates with rainforests, moist forests and monsoon forests as the predominant vegetation, as shown in Fig. 10. The second group encompasses the subtropical subhumid to semiarid climates with dry forests, savannas and Mediterranean forests, woodlands and scrubs as the predominant vegetation. The third group includes the dry climates with deserts and steppes, while the fourth group includes the temperate climatic zone with deciduous and mixed forests. Finally, the fifth group comprises the cold continental and polar climatic zones, in which coniferous forest vegetation (taiga) predominates, followed in the direction of the poles by the treeless cold steppes (tundra). These groups of climatic zones and biomes are useful for general characterization and classification of large-scale site conditions, although more detailed climate and ecosystem data should obviously be relied upon when implementing NbS for DRR interventions.

4.4. Typology attribute 4: ecosystem functions and services for hazard mitigation

Ecosystem functions and services for hazard mitigation is the fourth attribute of our typology. The literature review showed that NbS for DRR interventions use different ecosystem functions and services that aim to mitigate natural hazards. These can be divided into two groups, as shown in Fig. 11: (1) biophysical buffer functions and services, and (2) (ecological) regulation functions and services [52]. We propose this subdivision because there are numerous NbS for DRR interventions that rely primarily on vegetation as protective shields. This applies for example to alpine protective forests as well as mangrove belts [24,30]. On the other hand, there are numerous NbS for DRR interventions that use regulatory functions and services that go beyond a sole buffer function. This applies for example to projects that seek to improve water storage in ecosystems as protection against droughts and floods [33,55]. Furthermore, measures are implemented that increase the water capacity of soils, promote water storage in vegetation and include land unsealing and landscape design that reduces surface runoff, e.g. through terracing [34]. Of course, there are also NbS for DRR interventions that encompass both components. Coastal dunes are a special case, because here not only the vegetation but also the sand dune serves as a protective

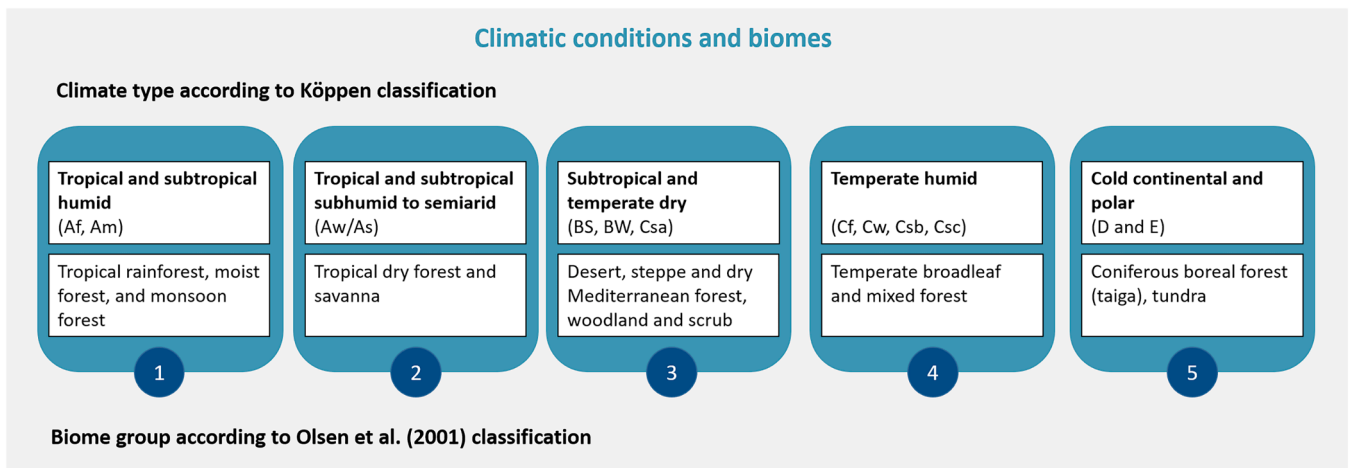


Fig. 10. Typology attribute 3: Climatic conditions and biomes.

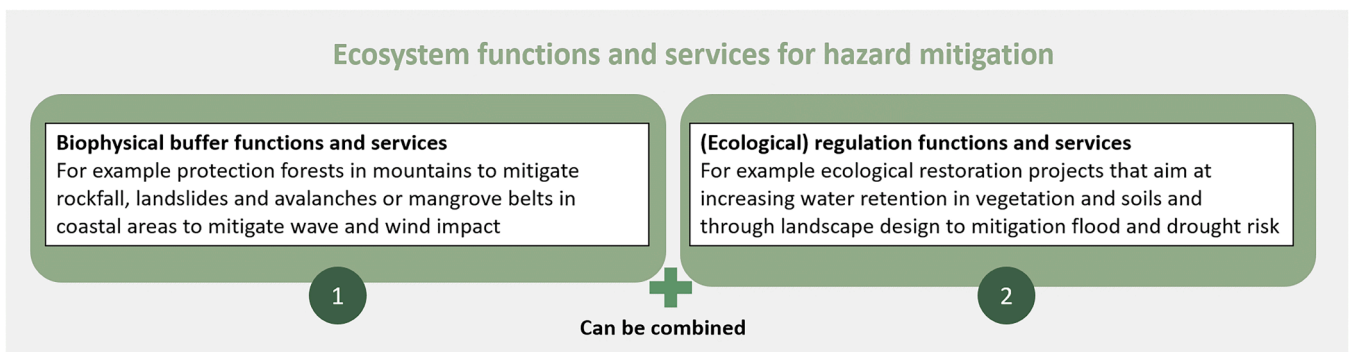


Fig. 11. Typology attribute 4: Ecosystem functions and services.

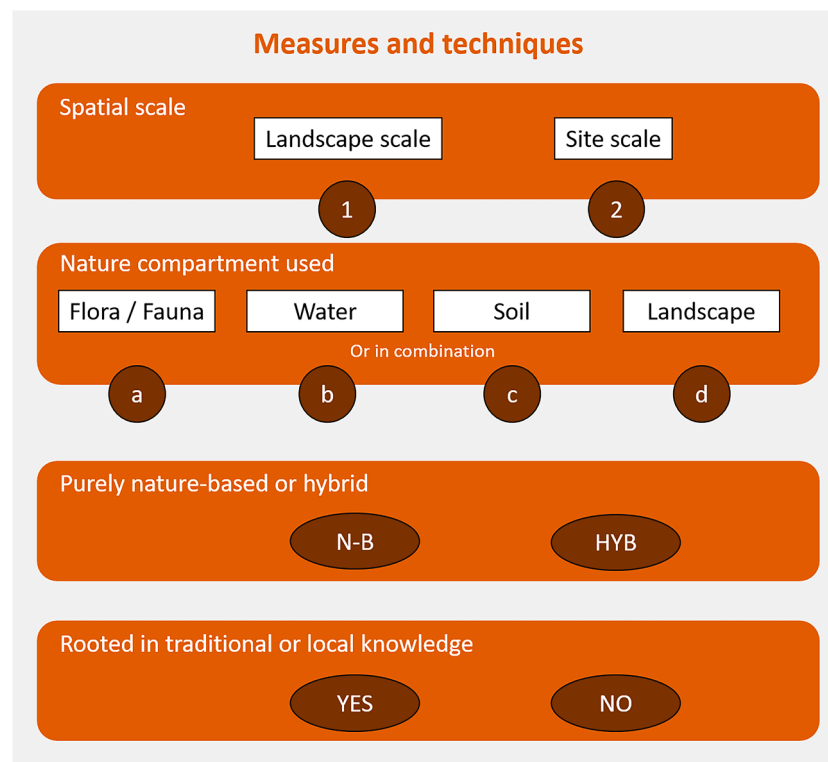


Fig. 12. Typology attribute 5: Measures and techniques.

structure [29]. In our typology, we refrain from a more detailed presentation of individual ecosystem functions and services, as these can vary greatly depending on the particular site conditions and would thus go beyond the scope of an overarching typology.

4.5. Typology attribute 5: measures and techniques

Finally, the fifth attribute of our typology refers to the measures or techniques implemented in NbS for DRR projects. The literature review showed that numerous measures and techniques have been implemented, rooted in different disciplines and related to different natural hazards, site conditions and ecosystem functions and services. Usually, they are described in detail in the research articles. However, this level of detail is too great for a typology, so we limit this review to a few key characteristics of the measures and techniques, as shown in Fig. 12. In a first level, we distinguish between NbS interventions at the landscape level (1) and at the site level (2). Some of the NbS approaches focus by definition exclusively on the landscape level, such as EbA, while others also work on a smaller site level, such as some ecological engineering projects that aim at stabilizing single slopes within a larger landscape.

Regardless of this spatial scale issue, interventions can be further distinguished as using measures and techniques based on flora and/or fauna (a), water (b), soil (c), or landscape design (d), or a combination. Furthermore, NbS for DRR projects can be classified as relying exclusively on green or green-blue measures, or on hybrid measures – i.e., a combination of green or green-blue and gray (engineering-based) infrastructure.

Finally, measures and techniques can be characterized in terms of whether or not they are rooted in traditional or local knowledge. To properly function towards DRR, all these NbS measures need to be accompanied by early warning and preparedness, governance measures, capacity building and other soft measures [53].

5. Conclusions

The objective of this review paper was to develop a typology for the subset of NbS that relate to DRR by conducting a comprehensive literature review of scientific papers which assess NbS for DRR interventions. It also set out to map the geographic distribution of NbS for DRR interventions to highlight gaps for future research. The term "nature-based solutions" can be vague and open to interpretation. A typology can help to clarify the different types of NbS and establish common definitions and terminology, which can improve communication and understanding across different sectors and disciplines. In particular, the five attributes can be used in establishing future NbS projects, or call for proposals by donors by providing a common language upon which future project planning, implementation, monitoring and evaluation can be established. This is especially important when we have complex projects with multiple case studies in different geographic locations with numerous ecosystem and hazard attributes.

The typology and its five attributes are useful for unpacking the complexity of NbS for DRR, while clarifying interactions between various attributes of this approach and similar approaches, such as EbA. The intention is to assist NbS researchers and project developers in establishing clearer boundaries, concepts for more effective project designs and monitoring systems. This is different from standards, which are guidelines that are expected to be followed. Such guidelines are very complementary to the typology developed in this paper when establishing an NbS for DRR intervention.

The number of NbS interventions is increasing exponentially, driven by international policy processes such as the UNFCCC Conference of Parties (COP), where large amounts of funding are pledged by both public and private entities for NbS, but also by government regulations and consumer demand for carbon offsets and sustainable investments. The term NbS is being mainstreamed beyond expectations, for better and for worse, as it is subject to misuse and abuse. It has its proponents and

opponents, with criticisms of being another artifact of Western-dominated ideology favoring nature over human needs and rights [56, 57]. For this reason, certain international bodies and government bodies prefer the term Eco-DRR. We may consider that NbS for DRR and Eco-DRR are thus very similar, whereas NbS for DRR will additionally contain a greater focus on biodiversity as an inherent attribute, whereas for Eco-DRR biodiversity is a co-benefit.

A political review of this debate was beyond the scope of this paper, which instead draws very practical conclusions on the types of attributes that NbS for DRR should include. Most of these attributes should be considered along a spectrum of options notably: whether DRR is the main desired outcome or a co-benefit of the intervention, the type of landscape units and related natural hazards, the type of climatic conditions and biomes, types of ecosystem functions and services related to natural hazards, and measures and techniques of NbS for DRR. The latter can be implemented along various scales, including access to traditional, indigenous or local knowledge as a cross-cutting measure. Furthermore, the review demonstrated that a majority of interventions were natural, or near-natural (e.g. related to restoring or conserving vegetation or buffers such as wetlands and sand dunes). This is an important point to avoid misuse of the term NbS for interventions that have no natural components.

Finally, this review tallied a larger number of papers on montane and forest vegetation, notably from China as compared to the review by Sudmeier-Rieux et al., [17] although overall papers from North America and Europe predominate across all landscape / hazard types. The same geographic gap remains for other countries of Asia, Africa and South America, an important gap considering the number of hazard events already taking place on these continents and forecasted to increase in frequency and magnitude. Whether one uses the term NbS for DRR or Eco-DRR, we believe that this review has contributed to improving our understanding of interventions based on natural attributes to reduce impacts from natural hazards. It should give more confidence and credibility to encourage more investment in research and on-site projects in countries that need it most.

A future goal is to develop a database based on the typology that provides information on a global scale regarding NbS for DRR. Converting the typology into a database can be a useful way to organize and store information about different types of NbS interventions, which can facilitate analysis, decision-making and knowledge sharing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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