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ANALYSIS

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Scientific evidence for ecosystem-based disaster risk reduction

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Ecosystems play a potentially important role in sustainably reducing the risk of disaster events worldwide. Yet, to date, there are few comprehensive studies that summarize the state of knowledge of ecosystem services and functions for disaster risk reduction. This paper builds scientific evidence through a review of 529 English-language articles published between 2000 and 2019. It catalogues the extent of knowledge on, and confidence in, ecosystems in reducing disaster risk. The data demonstrate robust links and cost-effectiveness between certain ecosystems in reducing specific hazards, something that was revealed to be particularly true for the role of vegetation in the stabilization of steep slopes. However, the published research was limited in geographic distribution and scope, with a concentration on urban areas of the Global North, with insufficient relevant research on coastal, dryland and watershed areas, especially in the Global South. Many types of ecosystem can provide sustainable and multifunctional approaches to disaster risk reduction. Yet, if they are to play a greater role, more attention is needed to fill research gaps and develop performance standards.

In many countries, stakeholders are calling for nature-based solutions over grey infrastructure protective measures to reduce the impacts of increasing numbers of hazard events. Examples include using vegetation to stabilize slopes or reducing the impacts of storm surges with sand dunes, mangroves and/or seagrasses[1,2]. However, the potential for ecosystems to attenuate hazards is not well understood or documented[1–3]. This article addresses this knowledge gap by reviewing the English-language peer-reviewed literature published between 2000 and 2019, while also assessing the levels of confidence in the roles various ecosystems play in reducing disaster risk.

The 2004 Indian Ocean tsunami drew the world's attention to the role of ecosystems in disaster risk reduction (DRR). Coastal ecosystems, in particular mangrove forests, were perceived to have protected some coastal communities from the impacts of the tsunami, even though the scientific evidence for this was, and still is, debated[4,5]. This and other devastating events triggered an increase in the number of scientific studies examining the role of ecosystem-based approaches to disaster risk reduction[3] (henceforth Eco-DRR). Disaster risk is usually expressed as the interaction between three factors: hazard, exposure and vulnerability[6]. Eco-DRR is defined as "the sustainable management, conservation and restoration of ecosystems to reduce disaster risk, with the aim to achieve sustainable and resilient development"[3]. More recently, an increasing number of policies, laws and agreements at national and international levels are explicitly addressing ecosystems in their DRR efforts. For instance, the 2030 Agenda for Sustainable Development, the New Urban Agenda, the Sendai Framework for Disaster Risk Reduction (SFDRR 2015–2030) and the European Union, among others, are promoting greater investments in healthy ecosystems to reduce climate and disaster risks[7–9]. However, according to the 2019 Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES)[10], there is still a paucity of knowledge on this topic. Addressing this gap in scientific evidence will be necessary to support policymakers in considering Eco-DRR measures.

Over the past two decades, several studies and reviews have assessed the role of ecosystems and their services in regulating various forms of climatic and geophysical hazards[3–5,11–17]. However, many of these studies were limited to examining the role of individual ecosystems in attenuating specific hazards, while others documented co-benefits, including, among others, clean water, livelihood support, human well-being, temperature regulation and

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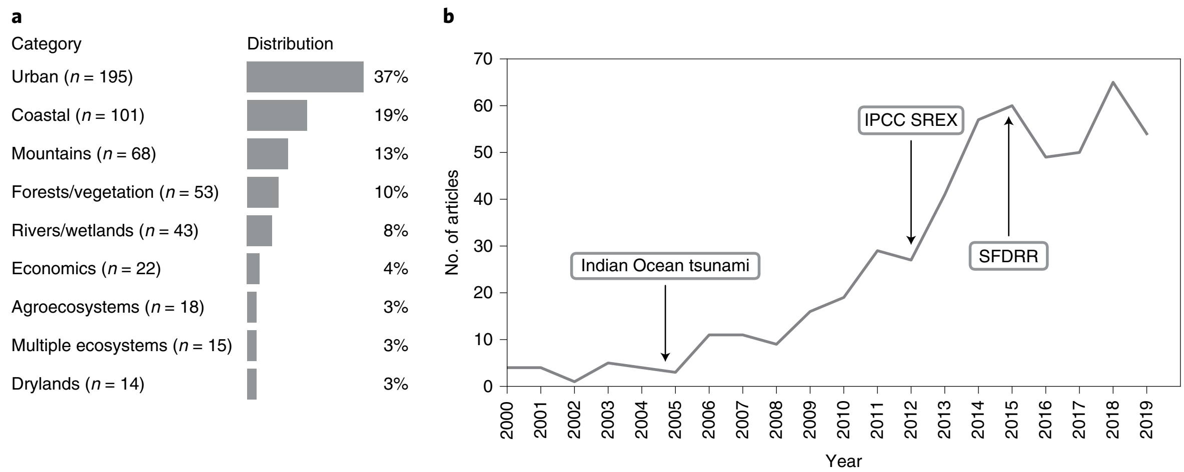


Fig. 1 | Summary of the literature on the role of ecosystems in DRR between 2000 and 2019. a, Distribution of articles reviewed ($n = 529$) by category for the period 2000–2019. **b**, Distribution of articles over the review period from 2000 to 2019, with an increase in articles published on this topic between 2005 and 2019. The research cut-off was September 2019.

carbon sequestration[8,15]. Another set of articles highlighted the economic value of DRR, and compared the costs and benefits of ecosystem-based and engineered solutions (for example, ref. [18]). Finally, a limited number of articles focused on the role of ecosystems in mitigating climate change effects. The most comprehensive of these are Doswald et al.[19], who published a qualitative assessment of ecosystem services for climate change adaptation (CCA), and Ruangpan et al.[20], who focused on hydrometeorological risks.

The aim of this study was to document the evidence base for the role of ecosystem services and/or functions in reducing disaster risks. With this in mind, we carried out a state-of-the-art quantitative analysis of the English-language, peer-reviewed literature examining Eco-DRR, published between January 2000 and September 2019. Few studies on this topic were published before this date. Here, we show the robustness of the evidence and the level of agreement on the role of ecosystems in attenuating 30 types of hazard following a protocol based on the assessment methodology established by the Intergovernmental Panel on Climate Change (IPCC)[21].

Results and discussion

A total of 529 articles covering the role of ecosystem functions and/or services in DRR were analysed for this review. The articles were divided into nine thematic categories, seven of which corresponded to different ecosystem types, while an additional two were cross-cutting: economic-related studies (as related to Eco-DRR) and multiple ecosystems (Fig. 1a). The rationale behind the thematic categories and the criteria for article selection are detailed in the Methods and Supplementary Tables 1 and 2.

The number of articles on the role of ecosystems in reducing disaster risk increased steadily between 2000 and 2019 (Fig. 1b). The greatest increase occurred between 2012 and 2015, a time period that coincides with several milestone events in the Eco-DRR field, including the IPCC Special Report on Extreme Events (SREX) in 2012 (ref. [22]) and the SFDRR 2015–2030 (ref. [7]), both of which placed major emphasis on the role of ecosystems in DRR.

Level of confidence. The level of confidence in ecosystem functions and/or services in attenuating hazards was assessed (Fig. 2) following the IPCC approach (see Methods and Supplementary Table 3)[21]. Overall, the articles reviewed ranged from very high to low-medium levels of confidence that ecosystems play a positive role in attenuating certain types of hazard (Fig. 2a). Five out of the nine categories had, on average, high to very high confidence levels, while one category (agroecosystem) had low-medium confidence. Very high confidence scores were largely derived from economics-based articles, while high confidence scores were attributed to articles examining the role of ecosystems in reducing impacts from mountain hazards, flooding in urban areas, forest fires and/or multiple ecosystems. Medium confidence scores were mostly associated with articles focusing on coastal areas, rivers and wetlands, and drylands, while low-medium scores tended to be associated with agroecosystems.

Economics articles had the highest overall score of confidence, both in terms of levels of robustness of evidence and agreement, as all these papers provided quantitative (monetary) values to assess ecosystem functions and/or services for DRR (for example, refs. [23,24]). In addition, the economics papers demonstrated that ecosystem services and/or functions are cost-effective as well as cost-efficient, particularly with regards to flood mitigation (for example, refs. [25,26]), vegetation cover for slope stabilization and avalanche mitigation (for example, refs. [27,28]), and storm protection of beaches and foredunes (for example, ref. [24]). Articles in the forests/vegetation category demonstrated medium levels of evidence and high levels of agreement, explained by the role that forests and vegetation management have in reducing hazards, particularly wildfires (for example, ref. [29]). Urban- and mountain-related articles were the most prevalent in the area of medium robust evidence with high levels of agreement. Examples of studies with highly robust evidence of ecosystems attenuating urban hazards, mostly flooding, tended to focus on effective green infrastructure designs (for example, green roof tops, permeable sidewalks and constructed wetlands, for example, ref. [30]). The majority of articles in the mountains category were related to the use of various types of vegetation for reducing (mainly shallow) landslides, followed by avalanches and rockfall; these included a number of medium-high robust studies (for example, refs. [14,15,27,28]).

Medium confidence (low robust evidence but high agreement on average) was reported for articles in the coastal category, most likely explained by the greater number of qualitative or descriptive case studies compared with empirical studies. This might be explained by the highly dynamic nature of coasts where attributing protection benefits is difficult due to the large number of variables, such as bathymetry and environmental settings (for example, refs. [11,12]), something that is closely linked to the magnitude of the incoming hazard (for example, ref. [11]). Coastal-related articles with high evidence scores often reported ecosystem functions and/or services

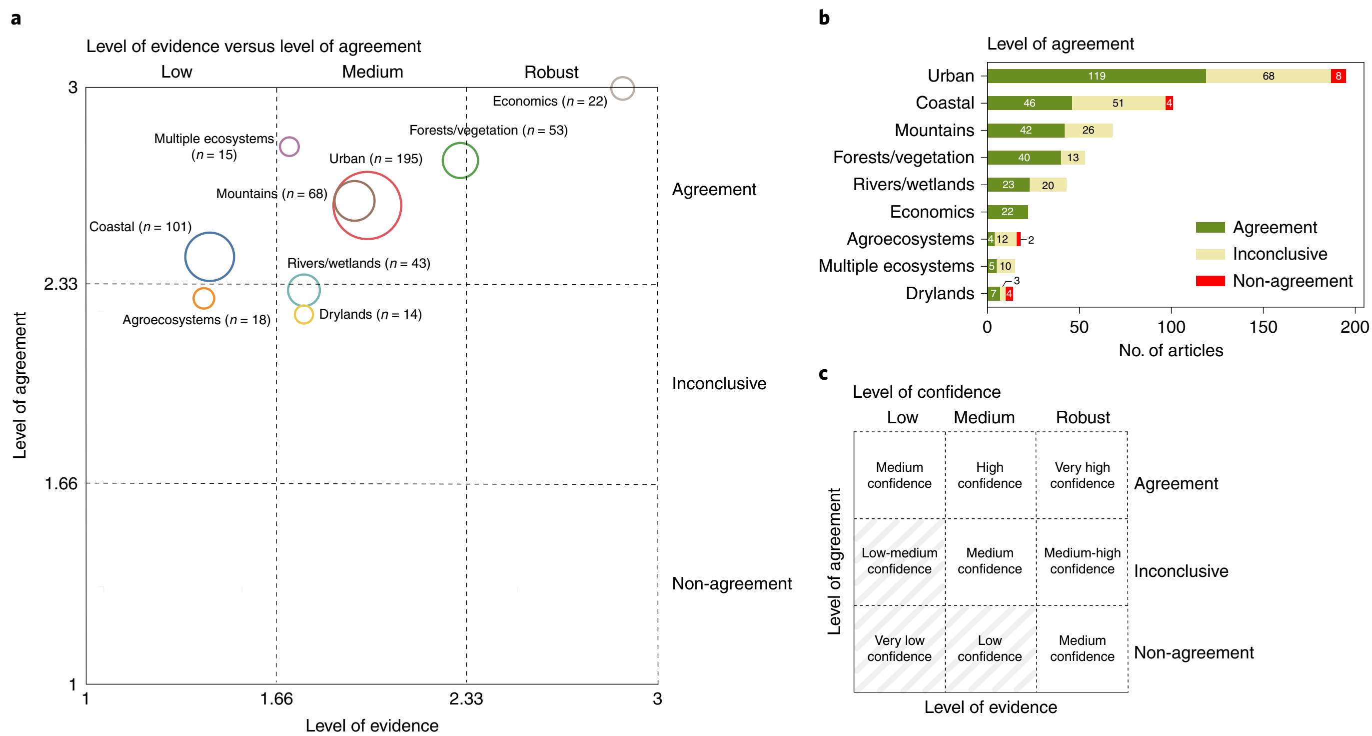


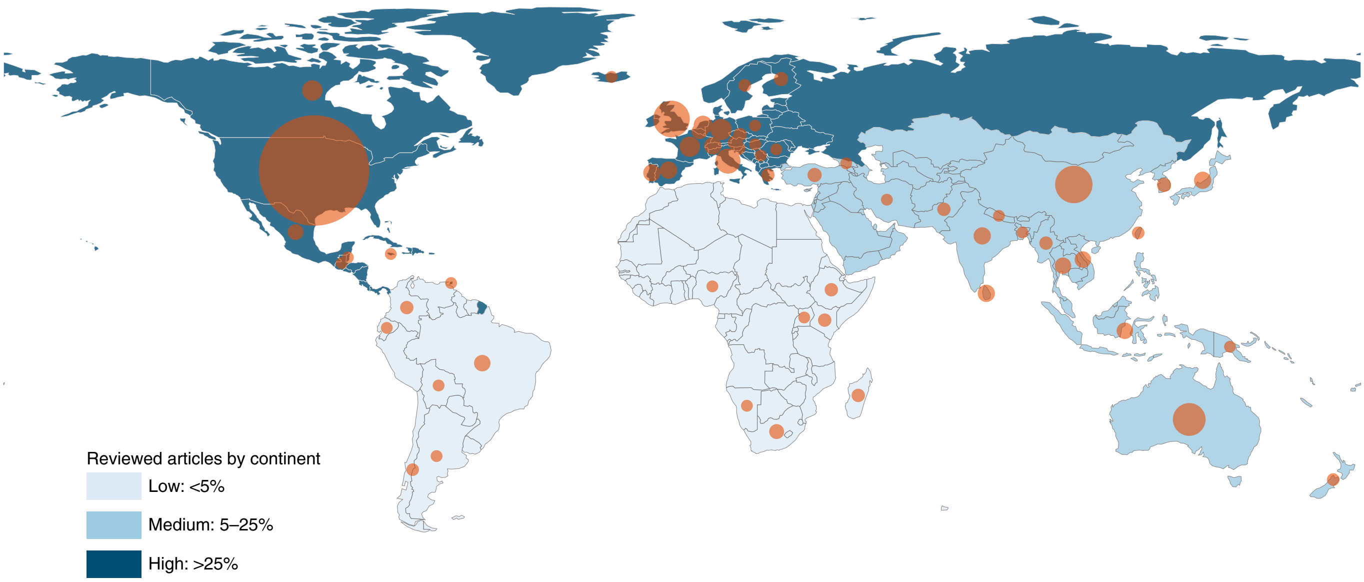
Fig. 2 | Level of confidence in ecosystem functions and/or services in attenuating disaster risks. a, Total average confidence levels. The confidence levels of the reviewed articles are displayed by thematic category based on the IPCC approach (see Methods)[21]. The confidence levels combine a quantitative measure of the robustness of evidence (on a scale from 1 (low) to 3 (high)) and the level of agreement with the statement 'ecosystem functions and/or services attenuate hazards' based on three levels of agreement (level 1, agreement; level 2, inconclusive; level 3, non-agreement). The levels of confidence refer to the confidence that ecosystems play a positive role in attenuating certain types of hazard. **b**, Number of reviewed articles per level of agreement for each thematic group. **c**, Grid showing the levels of confidence based on evidence and agreement. The hatched lines indicate the categories that correspond to low levels of confidence overall.

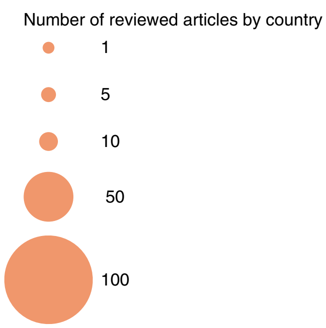
for shoreline stabilization and the protection of coastal populations against storm surges and tsunamis (for example, refs. [13,31]).

The rivers and (freshwater) wetlands articles reflected considerable debate. There was substantial variance between highly robust[32] and less conclusive[33,34] articles that generally agreed on the role of floodplains in reducing flooding risk and the importance of riverine vegetation for riverbank stabilization. Several articles reporting on forest-covered hillslopes and their regulation of above- and below-ground water flows were allocated inconclusive agreement scores. Indeed, flood regulation effectiveness depends on a large range of interdependent metrics, including catchment size, soil porosity and rainfall intensity, and, consequently, no single trend can be deduced (for example, refs. [35,36]). The same applies for other freshwater wetlands, such as peatlands and marshes in the headwaters of river basins, whose functioning depends on similar factors[36]. Medium levels of confidence for the rivers/wetlands category can be explained by the fact that this category covers many wetland typologies, some of which perform strong risk reduction functions while others do not. In addition, such performances are highly variable over time due to environmental dynamics and seasonality. Although several likely robust evidence water management articles have been published, the majority of evidence-based studies on the role of floodplains for reducing flooding were conducted prior to 2000 (for example, ref. [37]) and, therefore, were not captured by our selection criteria.

Only 14 articles were reviewed for the dryland category, which had, on average, a medium level of robustness and inconclusive agreement. However, some papers were highly robust, notably Qi et al.[38], who examined soil and litter water-holding capacities and their influence in reducing drought by maintaining soil groundwater tables. For agroecosystems, the 18 articles reviewed revealed low-medium levels of confidence with low robustness and inconclusive agreement on the role of ecosystems for reducing hazards. It is important to note that although there is a large volume of literature that addresses aspects of DRR in drylands and agroecosystems, this link is rarely explicitly and/or directly made. This could be explained by the fact that disasters in drylands may only become apparent over longer periods of ecosystem degradation. Consequently, these articles were not captured by our review parameters, which focused on arguably more specific and recent terminology (for example, ref. [39]). Hence, while the level of evidence was heterogeneous across the nine categories, the reviewed articles were generally in agreement on the role of ecosystems in DRR. Only a few articles proved inconclusive, while fewer still did not agree that ecosystems played a role in DRR.

Geographic distribution. The geographic distribution of the locations studied in the articles points to North America and Europe as the two regions where most Eco-DRR research was undertaken. In comparison, the Asia and Oceania regions, with the greatest number of impactful disaster events, received relatively little attention (Fig. 3)[40]. Urban studies accounted for the greatest proportion of articles by geographic distribution (for example, 44% of all North America-related studies and 22% for Europe), followed by mountain-related hazards (43% of all studies undertaken in Europe). This skewed geographic distribution coincides with the considerable economic losses associated with disasters in these regions[40]. However, it contrasts starkly with the high number of disaster-related casualties in Asia, Oceania, Africa, Central and South America, and the Caribbean[41]. It also mirrors results from





Reviewed articles per category by continent (*n* = 534)

	North America	Europe	Asia	Oceania	South America	Africa	Other
Urban (*n* = 185)	44%	22%	19%	6%	2%	1%	6%
Coastal (*n* = 103)	25%	26%	26%	5%	3%	2%	13%
Mountains (*n* = 58)	14%	43%	29%	4%	5%	2%	3%
Forests/vegetation (*n* = 53)	29%	11%	13%	11%	17%	6%	13%
Rivers/wetlands (*n* = 50)	24%	34%	20%	6%	6%	4%	6%
Economics (*n* = 32)	9%	47%	22%	6%	3%	13%	
Multiple ecosystems (*n* = 22)	5%	36%	27%	9%	5%	9%	9%
Drylands (*n* = 16)	12%	13%	25%			27%	23%
Agroecosystems (*n* = 15)	13%	27%	27%			27%	6%

Fig. 3 | Geographic distribution of articles reviewed by continent and thematic group. The number of reviewed articles by continent and category ($n = 534$) is greater than the 529 articles reviewed as multiple answers were allowed. North America (28%) was the region with the greatest number of articles, followed by Europe (27%), Asia (22%), Oceania (6%), Africa (5%), South America (4%) and other (8%). The 8% of articles labelled 'other' did not specify a geographic region. The United States was the country where most research was reported (24%), followed by the United Kingdom and China (6% each) and Australia (5%). Papers from Central America and the Caribbean have been included within North America; however, less than 0.5% of the papers came from these regions. Base map open-source data adapted from https://www.naturalearthdata.com/.

other studies that have shown substantial geographic biases in, for example, ecological[42] and urban research[43]. Similarly, ecological and conservation research is not distributed in the biodiversity-rich regions that require it most, such as Oceania[44].

The uneven geographic distribution of Eco-DRR research reflects the well-funded research infrastructure and data availability in North America and Europe. In addition, a focus on English-language and peer-reviewed articles has also likely contributed to this bias. The large number of urban-related articles reflects a greater concentration of risk in urban areas and the growing policy importance of this topic, particularly regarding ecosystem-based solutions to water-related hazards in Europe[9,45] and North America[13]. Hence, the majority of the urban research-related articles focused on niche topics, such as suitable plant species for green roofs and reducing run-off, with DRR often mentioned as an additional benefit (for example, refs. [17,45]). Notably lacking were studies on ecosystem-based measures to mitigate the impacts of drought, a point emphasized by a study examining drought risk reduction in sub-Saharan Africa[39].

Hazards. Overall, 30 different types of hazard were referred to across the articles reviewed. Figure 4 illustrates the most common of these by thematic category. More than one-third of the articles (36%) were related to fluvial and coastal flooding, which, along with storms, are the most frequent triggers of disasters. Of those papers, over half focused on urban environments. Perhaps surprisingly, 15% of the articles examined mountain-related hazards, which generally constitute a smaller proportion of hazard types[40,41]. Urban-related articles mentioned drought and heat island impacts, followed by storms/hurricanes/tropical cyclones. The main gaps in the literature related to the role of ecosystems in attenuating earthquake-related hazards (for example, the reduction of earthquake-triggered landslides by forest cover), as well as the roles of drylands and agroecosystems in DRR.

	All categories (*n* = 807)	Urban (*n* = 264)	Coastal (*n* = 226)	Mountains (*n* = 93)	Forests/vegetation (*n* = 61)	Rivers/wetlands (*n* = 53)	Economics (*n* = 49)	Agroecosystems (*n* = 27)	Multiple ecosystems (*n* = 20)	Drylands (*n* = 14)
Flooding (*n* = 294)	36%	168	35	12	10	42	17	5	5	0
Mountain hazards (*n* = 124)	15%	4	5	78	11	6	6	9	2	3
Storms/hurricanes/tropical cyclones (*n* = 62)	8%	19	40	0	1	0	0	1	1	0
Pollution (*n* = 61)	8%	44	5	0	2	2	6	0	2	0
Drought and heat islands (*n* = 58)	7%	26	2	1	6	2	3	4	4	10
Coastal erosion (*n* = 49)	6%	0	43	0	0	0	6	0	0	0
Tsunamis (*n* = 39)	5%	0	34	0	0	0	1	0	4	X
Wildfires (*n* = 39)	5%	0	1	2	31	1	2	0	1	1
Sea level rise (*n* = 32)	4%	0	32	X	0	0	0	0	0	X
Various coastal hazards (*n* = 30)	4%	0	24	X	0	0	5	0	1	X
Earthquakes (*n* = 11)	1%	0	3	0	0	0	0	8	0	0
Other (*n* = 8)	1%	3	2	0	0	0	3	0	0	0

Fig. 4 | Distribution of the number of hazards mentioned in the 529 articles reviewed. In total, 807 hazards were mentioned in the 529 articles reviewed (multiple answers were allowed). The most-mentioned hazard was flooding (both coastal and fluvial; 36%), especially in urban ecosystems ($n = 168$), followed by mountain-related hazards (landslides, avalanches, rockfall and erosion; 15%) and storms/hurricanes/tropical cyclones (8%). Across thematic categories, urban-related articles mentioned the greatest number of hazards ($n = 264$), followed by coastal ($n = 226$) and mountains ($n = 93$). The crossed-out fields indicate where there was no proven relation between the thematic category and hazard type. The shaded fields indicate the highest values.

Ecosystem services. The ecosystem services mentioned in the articles reviewed were categorized into regulating, provisioning, cultural and supporting services, following the Millennium Ecosystem Assessment approach[46] (Supplementary Figs. 1 and 2). As expected, the majority of articles mentioned regulating services (65%) linked to natural hazards (for example, water run-off, flood mitigation, river and coastal erosion control, landslide mitigation and global climate regulation). DRR goes beyond hazard and exposure reduction to include vulnerability reduction, which is facilitated by the provisioning, supporting and cultural services, or co-benefits, that ecosystems provide (for example, ref. [15]). Studies on provisioning services (19%; for example, water supply, food, fibre and fish), supporting services (9%; for example, soil productivity) and cultural services (6%) were a focus of only a small proportion of Eco-DRR studies. Thus, beyond regulating services, a range of other ecosystem services contribute to Eco-DRR.

Types of method. An assessment of the type of method(s) deployed in the studies revealed that the research was largely based on quantitative methods (42%), with considerably fewer papers employing qualitative methods (27%) and only 17% adopting mixed methods. The remaining 14% were conceptual or descriptive. The results showed that 39% of all articles comprised empirical/field-based measurements, 38% used modelling/simulations and 23% were reviews/meta-analyses.

Limitations. Various limitations were noted in the articles reviewed ($n = 346$). Most of those mentioned were methodological limitations (22%; for example, models were built for use in small areas or relied on a large number of qualitative case studies). An equal number of articles (22%) stated that there were too few validation points, or more research on the links between disturbance and ecosystem response was needed. Meanwhile, 15% identified location- or climate zone-specific limitations (that is, the findings were specific to a certain region or climate zone and were not easily replicated at larger scales or in other geographic locations). The remaining 41% of articles did not mention any limitations. Overall, limitations were attributed to methodological issues and difficulties in conducting research on location- and climate zone-specific ecosystem services and/or functions.

Monitoring. In addition to limitations, different types of monitoring ($n = 389$) over various time periods were identified and classified into three levels according to scale: plant level, ecosystem level and landscape/watershed level. Plant level monitoring included the biological, ecological, physical or chemical characteristics of ecosystems/vegetation for hazard reduction and was identified in 20% of these articles. Monitoring at both ecosystem level (for example, plant diversity for hazard reduction) and landscape/watershed level (for example, land use changes for hazard reduction or monitoring of specific hazard/risk and vegetation interactions over time) were equally represented in 40% of cases each. Thus, the majority of reported monitoring systems were established at the larger ecosystem and landscape/watershed scales.

Reference to the term 'ecosystem-based disaster risk reduction'. We also recorded articles that mentioned the term 'ecosystem-based disaster risk reduction', that is, 'Eco-DRR', or similar terms. While many related terms were noted ($n = 349$), such as 'nature-based solutions', 'working with nature', 'green/natural infrastructure for hazard mitigation', 'designing with nature' and 'integrated flood risk management', only 10% specifically referred to Eco-DRR ($n = 36$). The small number of references to Eco-DRR is not surprising as the field is nascent. Similarly, references to the term 'nature-based solutions' ($n = 27$) began in 2012 and have since increased steadily[15,20].

Recommendations. The most-mentioned recommendation ($n = 606$) across articles (due to multiple responses per article) was the need for improved management systems that integrate risk management, including natural resources management, adaptive management and integrated risk management (23%). Other recommendations called for improved best practices, indicators, models, guidelines and design standards with regards to Eco-DRR, including integrating long-term ecological research, and modelling data in ecosystem services science (18%). This finding is particularly important for global and national policies, which are increasingly recognizing the role of ecosystems in DRR, notably the SFDRR 2015–2030 (ref. [7]).

The way forward

The articles reviewed in this study demonstrate, with high levels of confidence, that ecosystems play a role in reducing disaster risk. This is particularly true for forests and the management of wildfires, the mitigation of flooding in urban areas through the implementation of green design and the use of vegetation on steep slopes to cost-effectively reduce mountain hazards. The role of ecosystems in managing stormwater, where potential monetary losses are high, is also considerably notable[23–25,47]. This study also highlights the multiple services and functions that ecosystems provide in addition to regulating hazards. Provisioning services, for example, contribute to strengthening livelihoods and reducing vulnerability, both of which are important aspects of DRR[48].

The main gaps in the evidence relate to drylands and agroecosystems. However, both categories feature more prominently in the CCA literature[19] because of their potential to attenuate agricultural drought. They are not typically the focus of Eco-DRR literature. Nonetheless, this review reveals that, in drylands, persistent droughts, land degradation and desertification are often slow-onset processes that, overtime, may well lead to disaster. Furthermore, there is ample evidence of how ecosystem-based approaches in areas susceptible to drought can reduce the impacts of climate change[19]. More attention should also be given to evidence-based studies of Eco-DRR, particularly in rapidly growing urban coastal areas and drylands in Asia, Africa, Oceania, Central and South America, and the Caribbean. These are megadiverse regions, where large populations depend on natural resources for protection and livelihoods[49]. Another nascent research field focuses on systems approaches to ecosystem functions and services for DRR[48,50]. These include potential negative ecosystem services, also referred to as 'ecosystem disservices' (for example, trees can become fuel for forest fires and mosquitoes inhabiting wetlands can be vectors for malaria), whereby disservices are essentially caused by human encroachment and best addressed through proper management schemes (for example, integrated fire management). Indeed, including ecosystems in DRR strategies requires an understanding of ecosystem functions and services, respect for the natural world and balance in the approaches employed[50,51].

We strongly recommend that addressing the above-mentioned research gaps and developing performance standards for green infrastructure should be a priority for future research in this field. Such standards are necessary to facilitate the greater uptake and implementation of ecosystem-based approaches by planners and engineers. Green infrastructure approaches can be employed as sustainable alternatives to, or to complement, grey engineering protective measures, or the so-called hybrid approaches to DRR[1,2]. Governments have signed or committed to international framework agreements such as the SFDRR[7] and the Sustainable Development Goals and have, in many cases, formulated national policy commitments recommending ecosystem-based measures for DRR[7,8,46]. There is, therefore, great potential globally, most notably in the Global South, for more evidence-based research to be conducted in this nascent field. To help achieve this, there is a need to strengthen research infrastructure and funding attention, particularly in areas where disaster impacts are most prevalent.

Methods

Review framework. A review protocol[52] (see Screening process) was established to respond to the question "what is the evidence base on the role of ecosystem services and/or functions in reducing disaster risks?". This review question was framed by the following PICOs (population, intervention, comparator and outcome) to help determine the inclusion criteria:

- Population: elements (for example, population and infrastructure) exposed to a natural hazard
- Intervention: ecosystem service, ecosystem function or ecosystem-based interventions
- Comparator: a study comparing an intervention versus no intervention or other type of intervention
- Outcome: reduced hazard impact, reduced risk of impact in terms of hazards, exposure and vulnerability (Supplementary Table 1)

In this study, no comparator was imposed, given we were interested in the state of the evidence base.

Ecosystem functions and services are wide-ranging topics and thus were broken down into seven categories and two cross-cutting groups to allow for a wider spectrum that encompassed economics and multiple ecosystems. In the outcome category, 13 hazards were identified. In terms of interventions, we included ecosystem services, ecosystem functions and services, as well as any articles related to ecosystem management. Because we were interested in the role of ecosystems in reducing impacts, we had no predecided interventions other than the idea that the articles must specifically relate to ecosystems, a property thereof or an aspect of ecosystem management. Economics refers to studies valuing ecosystem services that reduce hazard impact.

Eligibility criteria. Aside from the PICOs, the other filters applied required that those chosen must be peer-reviewed, quantitative articles published in English between January 2000 and September 2019, as few articles were found on this topic before 2000. To keep the search parameters focused on hazards and DRR, and to avoid overlap with an earlier review that focused on the role of ecosystems and climate change[53], this review excluded man-made or technological hazards (for example, eutrophication and oil spills) as well as the topics of climate change and CCA. The research terms did not include the term 'ecosystem disservices' (see The way forward section), as the literature on this topic is very recent, with few references at the time research on this paper was initiated. See Supplementary Tables 1 and 2 for more detail on the inclusion and exclusion criteria.

Search protocol. Two databases were used: Web of Science[54] and Scopus[55]. The grey literature (for example, non-peer-reviewed documents by UN (United Nations) organizations, non-governmental organizations or academics) was excluded because of the difficulty in estimating the quality of the studies and the fact that they rarely document data collection and analysis relevant to this study. The search terms were derived from an iterative process in Web of Science with the aim of providing broad but manageable coverage. We established three sets of terms corresponding to our research objectives:

1. Ecosystem-related (E; three subcategories, $n = 47$), based on Munroe et al.[53]:
   a. Ecosystem services/ecological engineering (E1)
   b. Habitats (E2)
   c. Ecosystem management (E3)
2. Hazard-related (H; four subcategories, $n = 36$), based on the Emergency Events Database (EM-DAT)[56] classification:
   a. Tectonic (H1)
   b. Meteorological (H2)
   c. Hydrological (H3)
   d. Climatological (H4)
3. DRR-related (D; $n = 9$), based on the United Nations Office for Disaster Risk Reduction (UNDRR)[6] terminology: DRR, mitigation, resilience, management, performance, exposure, vulnerability and risk

See Supplementary Tables 4–6 for the full list of search permutations, search terms and search strings.

We ran several permutations of each of the three sets of search terms with individual terms (and wildcard symbols (*) where appropriate) separated by Boolean 'OR' operators. Some sets were combined with 'NOT' (for the exclusions). Each trial was recorded and reviewed for relevance. After an initial search based on these basic permutations, the search protocol was amended. Some terms were subsequently eliminated as they skewed the results and new terms were added (Supplementary Table 4). We then conducted a second search in the Web of Science and Scopus databases using the amended protocol. Three sets of search results were produced: (1) E1 + H + D, (2) E2 + H + D and (3) E3 + H + D.

After title screening, it was decided to discard all the E2 category (habitat) results. These articles were beyond the scope of the research topic (that is, they were mostly related to the impacts of hazards on ecosystems, rather than the role of ecosystem functions and/or services in mitigating hazards and disaster risk). This left 4,284 articles after duplicates were removed ($n = 1{,}824$; Supplementary Fig. 3).

Screening process. A novel method was used for facilitating inclusion and exclusion. The 4,284 articles were tagged into 15 groups using the Zotero tagging function. These groups comprised the nine thematic categories and six other categories that were thematically linked to the question of the review but were likely to contain articles that were outside the scope of the review (for example, climate, geology, health, hydrology/pollution, wildlife and other categories; Supplementary Fig. 3). None of these categories met the criteria regarding the role of ecosystems in attenuating hazards (Supplementary Tables 1 and 2). Each of these 15 thematic categories was analysed by teams of topic specialists. A total of 29 reviewers from 19 different institutions from around the world examined the articles, with some reviewers covering more than one thematic category (Supplementary Table 2). To reduce bias, at least two topic specialists reviewed the articles in each thematic category. The teams for the six potentially 'out-of-scope' categories of articles screened the abstracts and decided whether to include them in one of the nine thematic categories. The teams of reviewers for the nine thematic categories undertook abstract and full-article screening to determine inclusion or exclusion. When discrepancies were found during the review process, reviewers discussed the article and compared notes until a solution was reached.

Coding and data analysis. Bibliographic information was recorded for each retained study. For each article, basic information was retrieved. This included the country of the intervention, the ecosystem service in each thematic category, the hazard investigated, the methodology employed in the study (empirical or field-based, modelling or simulation, or review paper), the limitations in the search methods, the monitoring, the recommendations and the mentions of Eco-DRR. This information allowed for qualitative and quantitative analyses of the evidence pertaining to the role of ecosystem functions and services in reducing hazard impact(s). The articles were examined by thematic group and by hazard to reveal where the evidence was concentrated and to highlight the gaps in evidence that existed.

To gain an overview of the outcome investigated in this review ('ecosystem functions and/or services reduce hazard impact'), we decided to provide an assessment of the robustness of the articles and the level of agreement between articles in each thematic group with regards the goal of the review. This approach, based on the IPCC (Mastandrea et al.)[21], was developed to ensure a common method for establishing expert judgements on our research question in addition to evaluating and communicating the degree of certainty in the findings produced as a result of the assessment process. It had two goals. Firstly, it involved an assessment of the evidence base according to UN-agreed standards, which allows for consistency in the evaluation and communication of uncertainty with the global community of researchers and, secondly, it included an assessment of the evidence base that goes beyond vote counting. Reviewers from each thematic category scored their articles according to robustness, agreement and confidence, and a final weighted average was established for each category.

The assessment process consisted of three steps:

1. Robustness of evidence: reviewers assessed each retained article based on two criteria of robustness:
    a. Robustness of evidence: reflects type, amount and quality.
    b. Consistency of evidence (for example, mechanistic understanding, theory, data, models, expert judgement). Articles were ranked according to three categories: low, medium and robust (Supplementary Table 3).
2. Agreement: reviewers analysed whether articles supported the stipulation that ecosystem services and/or function can attenuate hazards. Reviewers thus categorized articles in each thematic group as follows:
    a. Agreement (reviewers agreed with the above statement).
    b. Inconclusive (reviewers determined that the article did not fully agree with the above statement).
    c. Non-agreement (reviewers determined that the article did not agree with the above statement).
3. Confidence: the third step established the level of confidence, which combined agreement and robustness of evidence for each article. The level of confidence ranges from very low confidence (low evidence/non-agreement) to very high confidence (robust evidence/high agreement). Once reviewers had assessed each article, we tabulated a score of confidence for the entire group of articles based on a weighted mean, based on the number of articles (Fig. 2).

Methodological limitations. While this assessment of the scientific literature established strict search protocols and cross-verification to increase the validity of results and, in turn, reduce bias, several limitations were observed. Firstly, despite using identical permutations, there were inconsistencies in the number of articles produced in each literature search. These varied depending on the day the search was conducted and the institution conducting the search. Secondly, the results were limited in terms of language (only English articles were included), time period (the search was limited to articles published between January 2000 and September 2019) and the fact that only peer-reviewed articles were included (many publications on Eco-DRR exist in the grey literature, for example, UN reports, policy briefs and technical reports, which may occasionally reflect the bias of the organization commissioning the report). In addition, the selection of search terms and a lack of clarity regarding interdisciplinary terms may have inadvertently excluded relevant articles. In summary, articles were excluded for one of four reasons: (1) the article did not meet the criteria of examining ecosystem services and/or functions for attenuating hazards (90% of articles excluded), (2) the article was not peer-reviewed (5% of articles excluded), (3) the article was in a non-English language (3% of articles excluded) and (4) the article was not available online (2% of articles excluded). Meanwhile, the decision to delete all E2 search results (over 30,000 articles that were mainly habitat-related with no relevance to hazard mitigation) may have excluded relevant articles. Finally, although the IPCC[21] approach is widely accepted for the purpose of analysing articles regarding levels of confidence, robustness of evidence and agreement, it is not exempt from criticism. Thus, to reduce possible bias, articles for each thematic category were cross-checked by teams of several reviewers.

Data availability

The data that support the findings of this study are available from the corresponding author upon request, mentioning any restrictions on availability.

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