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Ecosystems for disaster risk reduction: an analysis of the scientific evidence

Introduction

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 for 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 documented¹⁻³. This article addresses this knowledge gap by reviewing the English language peer-reviewed literature between 2000-2019, 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 reduction³ (henceforth Eco-DRR). Disaster risk is usually expressed as the interaction between three factors: hazard, exposure and vulnerability⁶. 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, promote greater investments in healthy ecosystems for reducing climate and disaster risks⁷⁻⁹. 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 are limited to examining the role of individual ecosystems in attenuating specific hazards, while others document co-benefits including, among others, clean water, livelihood support, human well-being, temperature regulation and carbon sequestration^{8, 15}. Another set of articles highlights the economic value of DRR, and compares the costs and benefits of ecosystem-based and engineered solutions (e.g.18). Finally, a limited number of articles focus on the role of ecosystems in mitigating climate change effects. The most comprehensive of these are Doswald et al. (2014),¹⁹ who published a qualitative assessment of ecosystem services for climate change adaptation (CCA) and Ruangpan et al. (2020),²⁰ who focused on hydrometeorological risks.

The aim of this study is to document the evidence-base for the role of ecosystem services and/or functions in reducing disaster risks. In this study we present 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 evidence and level of agreement on the role of ecosystems in attenuating 30 types of hazards following a protocol, based on the assessment methodology established by the Intergovernmental Panel on Climate Change (IPCC).

Results and Discussion

A total of 529 articles covering the role of ecosystem functions and/or services for DRR were analyzed 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. The methods (supplementary materials 1, tables 1 and 2) describe the rationale behind the thematic categories and the criteria for article selection.

The number of articles on the role of ecosystems in reducing disaster risk increased steadily between 2000 and 2019 (Figure 1). The greatest increase occurred between 2012 and 2015, a time period that coincides with several milestone events in the Eco-DRR field, including the Intergovernmental Panel on Climate Change (IPCC) Special Report on Extreme Events (SREX) in 2012²¹ and the SFDRR 2015-2030⁷, both of which placed major emphasis on the role of ecosystems in DRR.

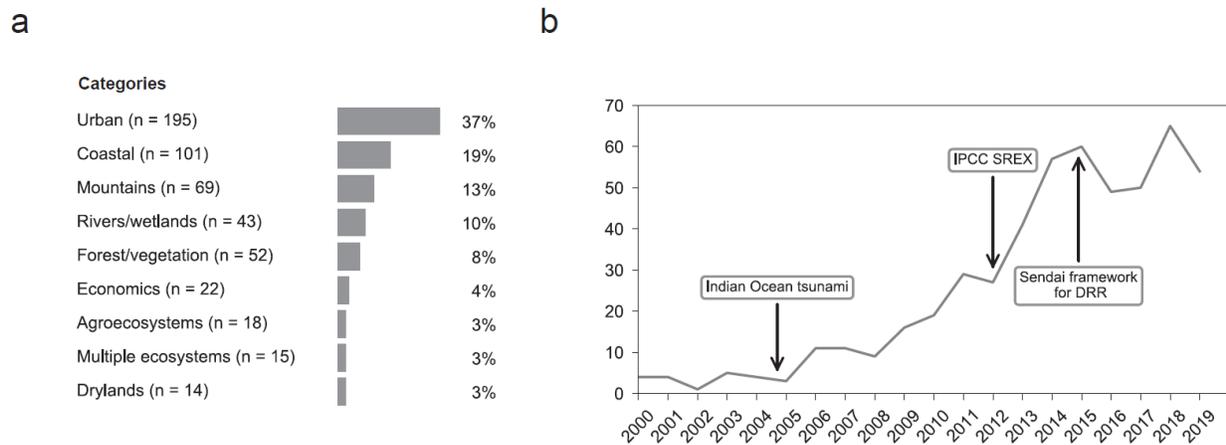


Figure 1a. Distribution of articles reviewed (n=529) by category for the period 2000-2019. **1b.** Distribution of articles over the review period from 2000-2019, with an increase in articles published on this topic between 2005 and 2019. The research cut-off was in September 2019.

Level of confidence

Following the IPCC approach (2012) (see Methods), the level of confidence in ecosystem functions and/or services in attenuating hazards was assessed (Figure 2). Overall, articles reviewed ranged from very high to medium-low levels of confidence that ecosystems play a positive role in attenuating certain types of hazards. Five out of nine categories had, on average, high to very high confidence levels, while one category (agroforestry) 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/wetlands and drylands, while low-medium scores tended to be associated with agroecosystems.

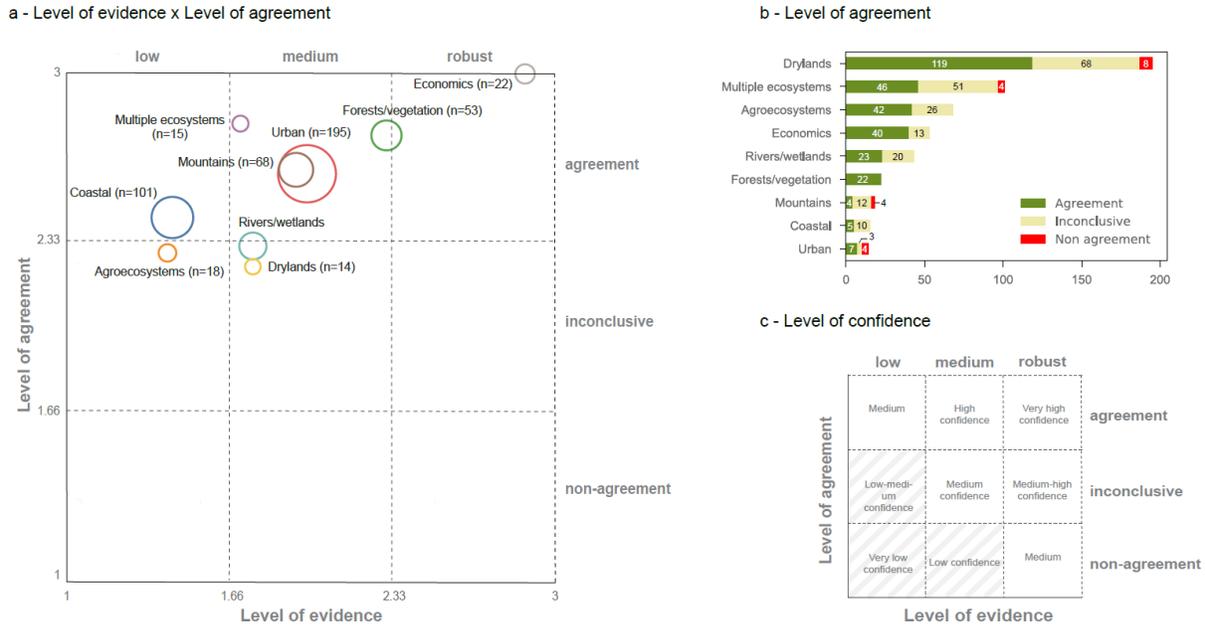


Figure 2a: Total average confidence levels. Reviewed articles are displayed by thematic category based on the IPCC (2012) approach (see Methods). Confidence levels combined a quantitative measure of the robustness of evidence (on a scale from 1 (low) to 3 (high)) and the level of agreement with the statement ‘ecosystem functions and/or services attenuate hazards’ based on three levels of agreement (1= agreement, 2= inconclusive, 3= non-agreement). Levels of confidence refer to confidence that ecosystems play a positive role in attenuating certain types of hazards. **2b:** Number of reviewed articles by level of agreement per thematic group. **2c:** Levels of confidence based on evidence and agreement.

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 (e.g. 22, 23). 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 (e.g. 24, 25), vegetation cover for slope stabilization and avalanche mitigation (e.g. 26, 27) and storm protection of beaches and foredunes (e.g. 23). 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 (e.g. 28). 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 (e.g. green roof tops, permeable sidewalks, constructed wetlands) (e.g. 29). The majority of articles in the mountains category related to various types of vegetation for reducing (mainly shallow) landslides, followed by avalanches and rockfall; these included a number of medium-to-high robust studies (e.g. 14, 15, 26, 27).

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 versus empirical studies. For the former, one explanation might relate to 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 (e.g. 11, 12), something that is closely linked to the magnitude of the incoming hazard (e.g. 11). Coastal-related articles with high evidence scores often examined ecosystem functions and/or services for shoreline stabilization and the protection of coastal populations against storm surges and tsunamis (e.g. 13, 30).

Rivers and (freshwater) wetlands articles reflected considerable debate. There was significant variance between highly robust³¹ and less conclusive^{32,33} articles that generally agreed on the role of floodplains in reducing flooding risk and the importance of riverine vegetation for riverbank stabilization. Several articles examining 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 (e.g. 34, 35). The same applies for other freshwater wetlands such as peatlands and marshes in the headwaters of river basins, whose functioning depends on similar factors³⁵. Medium levels of confidence for rivers/wetlands 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 (e.g. 36) 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. (2012)³⁷, 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-to-medium levels of 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 on 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 (e.g. 38). 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 (Figure 3)³⁹. Urban studies accounted for the greatest proportion of articles by geographic distribution (e.g. 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 considerable economic losses in these regions³⁹. However, it contrasts starkly with the high number of disaster-related casualties in Asia, Oceania, Africa, Central and South America and the Caribbean.⁴⁰ It also mirrors results from other studies that have shown substantial geographic biases in, for example, ecological⁴¹ and urban research⁴². Similarly, ecological and conservation research is not distributed in the biodiversity-rich regions that require it most, such as Oceania⁴³.

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^{9,44} and North America¹³. Hence, a majority of 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 (e.g. 17, 44). 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 Africa³⁸.

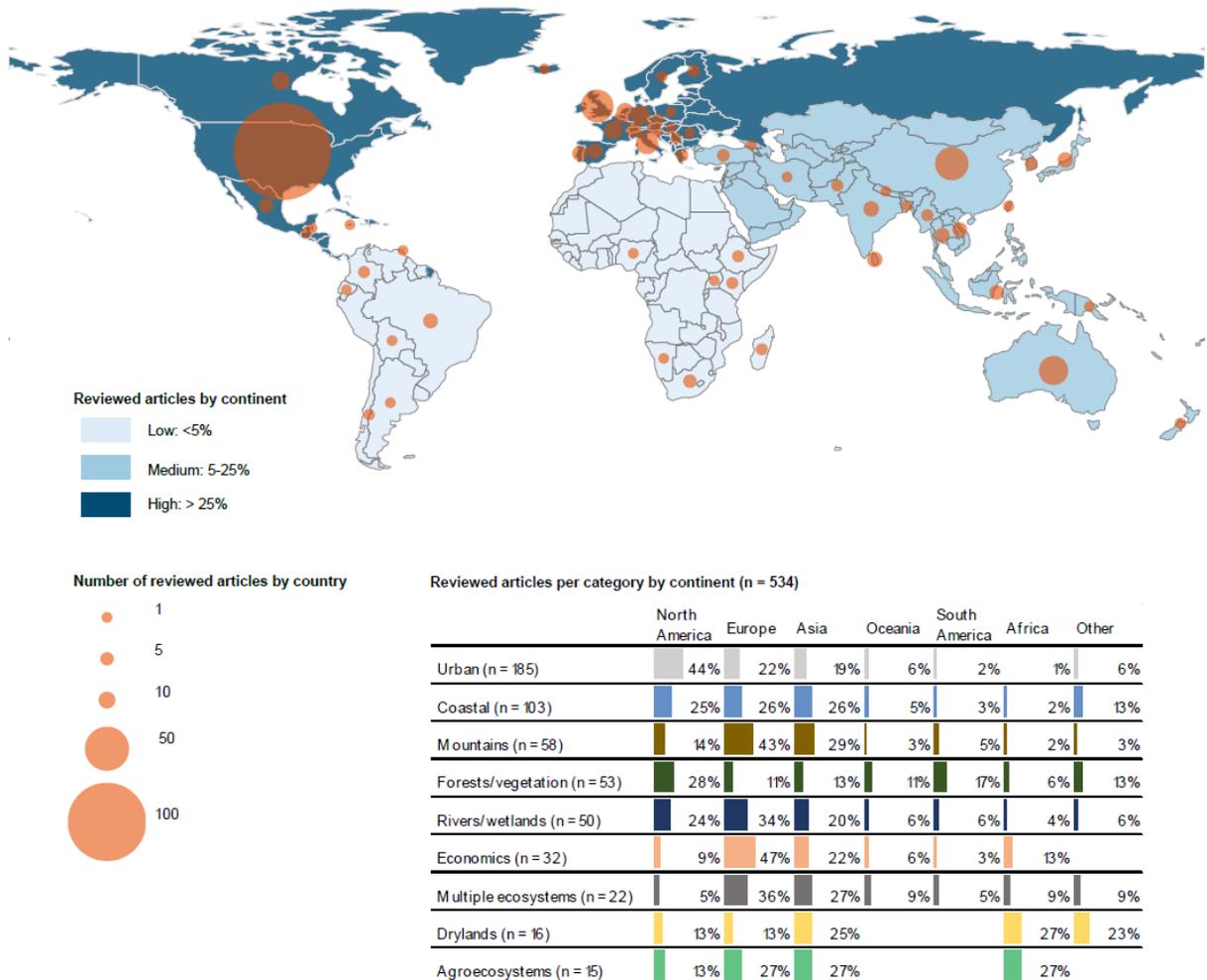


Figure 3. Geographic distribution of articles reviewed by continent and thematic group (n=534). This is greater than the 529 articles reviewed (multiple answers were allowed). North America (28%) was the region with the greatest number of articles, followed by Europe (27%), Asia (22%), South America (8%), Oceania (6%) and Africa (4%). The remaining 8% of articles (labeled “other”) did not specify a geographic region. The United States was the country where most research was reported (24%), followed by the U.K. 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 papers came from these regions. (Base map open source data: <https://www.naturalearthdata.com/>)

Hazards

Overall, 30 different types of hazards 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^{39, 40}. Urban-related articles also mentioned the role of ecosystems in attenuating storms/hurricanes/tropical cyclones and pollution, followed by drought and heat island impacts. The main gaps in the literature related to the role of ecosystems in attenuating earthquake-related hazards (e.g. reduction of earthquake triggered landslides by forest cover), as well as the roles of drylands and agroecosystems in DRR.

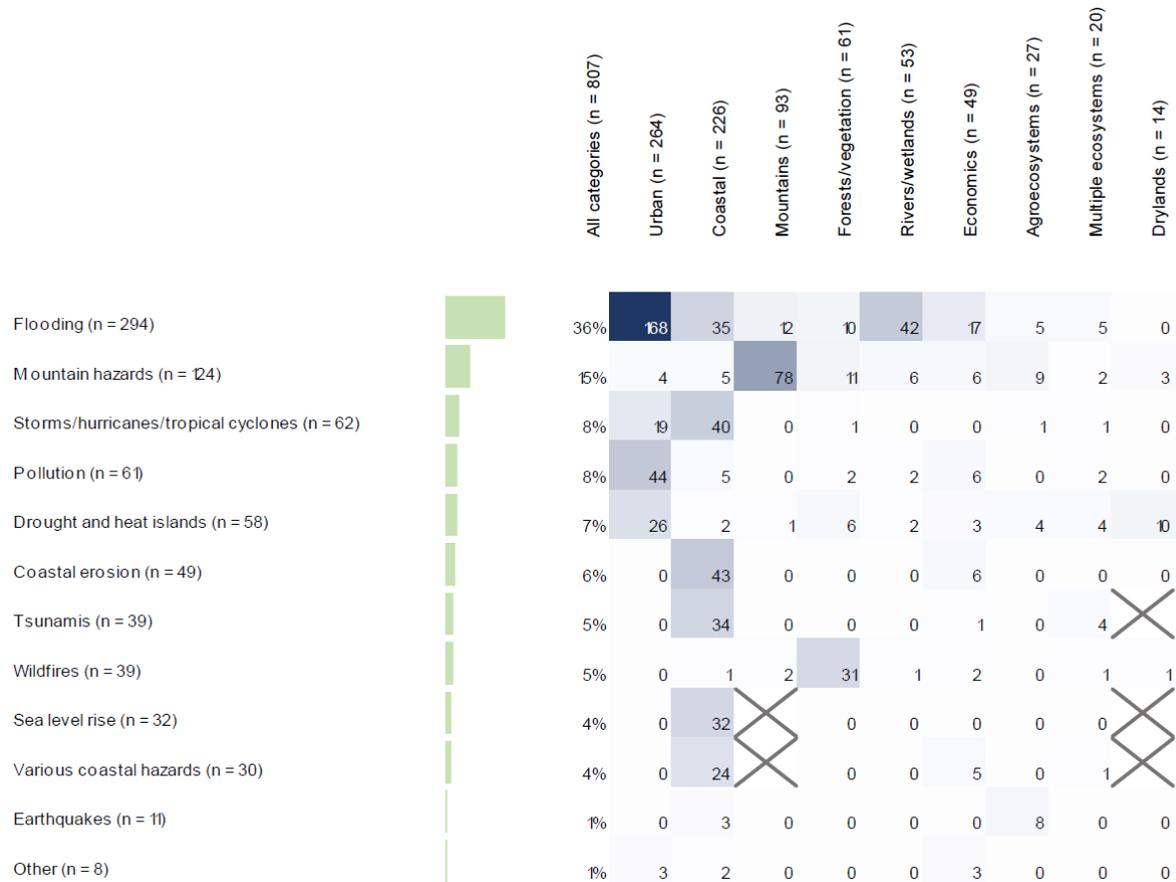


Fig. 4. This figure shows the distribution of the number of hazards mentioned (n=807) in the 529 articles reviewed (multiple answers were allowed). The most commonly mentioned hazard was flooding (both coastal and fluvial) (36%), especially in urban ecosystems (n=168). Second most commonly mentioned were mountain-related hazards (landslides, avalanches, rockfall and erosion) (15%) followed by 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). Crossed out fields indicate where there was no proven relation between the thematic category and hazard type. Shaded fields indicate highest values.

Ecosystem services

Ecosystem services mentioned in articles reviewed were categorized into regulating, provisioning, cultural and supporting services following the Millennium Ecosystem Assessment approach⁴⁵ (supplementary materials Figures 1 and 2). As expected, a majority of articles mentioned regulating services (65%) linked to natural hazards (e.g. 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 (e.g. 15). Studies on provisioning services (19%) (e.g. water supply, food, fiber and fish), supporting services (9%) (e.g. 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 methods

An assessment of the type of method(s) revealed that research was largely based on quantitative methods (42%), while much fewer papers employed qualitative methods (27%) and only 17% of articles adopted mixed methods. The remaining 14% were conceptual or descriptive. Results showed that 39% of all articles comprised empirical/field-based measurements, 39% used modeling/simulations and 23% were reviews/meta-analyses.

Limitations

Various limitations were noted in the articles reviewed (n=346). Most mentioned were methodological limitations (22%) (e.g. 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 (i.e. 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 63% 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 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 (e.g. plant diversity for hazard reduction) and landscape/watershed level (e.g. 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 (Eco-DRR)':

We also recorded whether articles mentioned the term 'ecosystem-based disaster risk reduction', i.e. 'Eco-DRR' or similar terms. While many related terms were noted (n=211), 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 modeling data into 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 2015-2030⁷.

The Way Forward

Reviewed articles demonstrated, with high levels of confidence, that ecosystems play a role in reducing disaster risk. This was particularly true for forests and their management of wildfires, the mitigation of flooding in urban areas through the implementation of green design and using vegetation on steep slopes to cost-effectively reduce mountain

hazards. The role of ecosystems in managing stormwater, where potential monetary losses are high, was also considerably notable^{22-24, 46}. This review also highlighted 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 DRR⁴⁷.

The main gaps in the evidence relate to drylands and agroecosystems. However, both categories feature more prominently in the CCA literature¹⁹ because of their potential to attenuate agricultural drought. They are not typically the focus of Eco-DRR literature. Nonetheless, this review did reveal 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 change¹⁹. 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 & South America and the Caribbean. These are mega-diverse regions, where large populations depend on natural resources for protection and livelihoods⁴⁸. Another nascent research field focuses on systems approaches to ecosystem functions and services for DRR^{47, 49}. These include potential negative ecosystem services, also referred to as ‘ecosystem disservices’ (e.g. 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 (e.g. 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^{49, 50}.

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 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 so-called hybrid approaches to DRR^{1, 2}. Governments have signed international framework agreements such as the SFDRR⁷ and have, in many cases, formulated national policy commitments recommending ecosystem-based measures for DRR,^{7, 8, 45} while seeking to report on other international framework agreements, including the Sustainable Development Goals. 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 protocol¹ (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 (population, infrastructure, etc.) 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 materials, 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 pre-decided 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 PICO, the other filters applied stated 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. In order 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 ², this review excluded man-made or technological hazards (e.g. eutrophication and oil spills) as well as topics of climate change and CCA. These research terms did not include the term 'ecosystem disservices', (see "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 materials, Table 1 and Table 2 for more detail on the inclusion and exclusion criteria.

Search protocol

Two databases were used: Web of Science and Scopus. The grey literature (e.g. non-peer reviewed documents by UN organizations, NGOs 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:

(E) Ecosystem-related (three subcategories) (n=47) based on Munroe et al. (2012) ²:

E1: Ecosystem services/ecological engineering

E2: Habitats

E3: Ecosystem management

(H) Hazard-related (four subcategories) (n=36) based on the EM-DAT ³ classification:

H1: Tectonic

H2: Meteorological

H3: Hydrological

H4: Climatological

(D) DRR-related (n=9) based on the United Nations Office for Disaster Risk Reduction (UNDRR) ⁴ terminology:

Disaster Risk Reduction; Mitigation; Resilience; Management; Performance;

Exposure; Vulnerability; Risk

See Supplementary materials 2, 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 “AND 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 (see Supplementary materials 2, 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 a title screening, it was decided to discard all the E2 category (habitat) results. These articles were beyond the scope of the research topic (i.e. they were mostly related to the impacts of hazards on ecosystems, rather than ecosystem functions and/or services in mitigating hazards and disaster risk). This left 4,284 articles after duplicates were removed (n=1,824) (see Supplementary materials 2, Figure 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 were comprised of 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 (e.g. climate, geology, health, hydrology/pollution, wildlife and other categories) (Supplementary materials 2, Figure 3). None of these categories met the criteria regarding the role of ecosystems in attenuating hazards (see exclusion criteria in Supplementary materials 1, Table 1 and 2). Each of these 15 thematic categories was analyzed by teams of topic specialists. A total of 29 reviewers from 19 different institutions around the world examined the articles, with some reviewers covering more than one thematic category (see Supplementary materials 1, Table 2). In order to reduce bias, at least two topic specialists reviewed the articles in each thematic category. The teams with the seven 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 an 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 to 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 robustness of articles and level of agreement between articles in

each thematic group regarding the goal of the review. This approach, based on IPCC (Mastandrea et al. 2011)⁵, was developed to ensure a common method for establishing expert judgments 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 of 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, quality;
- b. Consistency of evidence (e.g. mechanistic understanding, theory, data, models, expert judgment). Articles were ranked according to three categories: low, medium and robust (Supplementary materials 1, Table 3).

2) Agreement: reviewers analyzed 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 per article reviewed);
- 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 was to establish the level of confidence, which combined agreement and robustness of evidence for each article. 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 (see figure 3 in text body).

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 per literature search. These varied depending on the day the search was conducted and the institution conducting the search. Secondly, 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, e.g. UN reports, policy briefs, 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: a. the article did not meet the criteria of examining ecosystem services and/or functions for attenuating hazards (90% of articles excluded); b. the article was not peer-reviewed (5%); c. the article was in a non-English language (3% of articles excluded); d. 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 ⁵ approach is widely accepted for the purpose of analyzing 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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Statement of individual author contributions

Project administration: KSR

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Data curation: KSR, LS, TAM, YW, BGM, FGR, SS

Formal analysis of thematic category articles reviewed: Urban: SS, FGR, WL, AT, HJ, LN; Coastal: UN, DF, CL; Forests/vegetation: HJB, SG; Economics: MV, LE, JM; Rivers and Wetlands: MvS, PvE, TT, LN; Mountains: CM, TAM; Agroecosystems: PL, YW, MH; Drylands: PL, YW; Multiple ecosystems: KSR, ZS, ND; Out of scope thematic category articles reviewed: Climate-related: KSR, PP; Geology: BGM, TAM; Health: BGM, TAM; Hydrology/pollution: ZS, MH, KSR; Wildlife: SG, HJB

Writing - original draft preparation: KSR, UN, SS, BGM

Writing - review and editing: KSR, SG, HJ, UN, DF, MH, PP, BGM, CL, FGR, SS, MV, LE, CM, HJB, ND, JM, ZS, YW, PL, TAM, LS, MvS, WL

Visualization: LS, PP, UN, BGM

Competing Interests

The authors declare no competing interests.