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Green infrastructure, nature-based solutions and ecosystem services for seismic resilience: Insight from a systematic review to guide urban policy and planning

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ABSTRACT

Mitigating environmental and climate-related hazards through the implementation of Nature-Based Solutions (NBS) and the development of Green Infrastructure (GI) via spatial planning has emerged as a central objective within contemporary urban resilience strategies. Despite their growing recognition in delivering ecosystem services (ES) for flooding, landslides, and extreme heat reduction, the potential of NBS and GI to address seismic risk remains largely under-investigated. This systematic literature review critically examines the current state of knowledge regarding the roles of NBS, GI and ES in mitigating seismic hazards and strengthening the resilience of urban environments.

By analysing studies from Scopus and Web of Science, we identify the direct and indirect benefits of these approaches, such as the mitigation of cascading effects and the increase of community resilience, which may contribute to reduced seismic vulnerability. The findings reveal a critical need for empirical studies on their direct impact in seismic contexts, technical guidance for implementation, and integrative urban planning strategies. Our review highlights the potential of GI and NBS to complement traditional seismic risk reduction methods and offers directions for future research on their application in urban resilience frameworks.

1. Introduction

1.1. Disaster risk: context and challenges

Natural hazards, including earthquakes, floods, and storms, have increased in frequency and severity over recent decades (CRED, 2025). According to the United Nations Office for Disaster Risk Reduction (UNDRR), such events have affected approximately 1.7 billion people globally in the last decade alone (UNDRR, 2015). Whether of natural or anthropogenic origin, these disasters are becoming increasingly complex and extreme, largely due to the compounding effects of climate change, rapid urbanisation and evolving land-use patterns. This growing trend poses a substantial challenge to the achievement of the Sustainable Development Goals (SDGs) set out in the 2030 Agenda, as it generates far-reaching economic, social, and environmental consequences (De Genaro Chiroli et al., 2023). Addressing these challenges requires integrated policy frameworks that support sustainable development while reducing vulnerability to diverse hazards (Wouda Kuipers & Korwatanasakul, 2024).

Traditionally, disaster risk has been conceptualised as the result of three interrelated components: *hazard, exposure*, and *vulnerability* (Alcántara-Ayala et al., 2023; UNDRR, 2017a). While this tripartite framework remains conceptually stable, recent research has highlighted significant changes in the way its individual components are understood, particularly in relation to the intensification of extreme events and their increasingly nonlinear impacts (Leal de Moraes & Santos Lacerda, 2024). In this regard, the hazard component, previously interpreted as an intrinsic property of natural phenomena (Blaikie et al., 2004), is now increasingly recognised as the outcome of dynamic and reciprocal interactions between natural processes and anthropogenic pressures.

This evolving perspective highlights the intrinsic interdependence between hazards and the specific contextual conditions of place, including local socio-ecological systems, development trajectories, adaptive capacities, and resilience mechanisms (Freddi et al., 2021; Oliver-Smith, 2022).

In this context, the Sendai Framework for Disaster Risk Reduction 2015–2030 (SFDRR) serves as a foundational reference for guiding disaster risk policy and action (Hofmann, 2021). The SFDRR not only

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Abbreviations

NBS	nature-based solutions
GI	green infrastructure
ES	ecosystem services
OSs	open spaces
Eco-DRR	ecosystem-based disaster risk reduction
SFDRR	Sendai Framework of disaster risk reduction
QTA	Qualitative Thematic Analysis

calls for targeted interventions to reduce underlying risk drivers but also underscores the centrality of governance and integrated management (UNDRR, 2015). By advancing a holistic approach, the framework promotes enhanced preparedness and more effective response mechanisms, while encouraging the adoption of multi-hazard planning strategies tailored to the resilience of both communities and territories (UNDRR, 2016).

Developing and implementing such multi-hazard strategies requires a nuanced understanding of risk components, not only in their static definitions but in relation to the dynamic characteristics of disaster events –such as onset speed, duration, spatial extent, and cascading impacts– which influence damage severity and societal disruption (UNDRR, 2023; Zuccaro et al., 2018). Furthermore, even when the physical intensity of events is comparable, the differential outcomes are shaped by contextual variables such as governance capacity, socioeconomic structure, and ecological conditions (UNDRR, 2025).

Despite increasing awareness of the need for integrated approaches to multi-hazard risk reduction, existing planning and mitigation efforts remain fragmented and sector-specific (Senevirathne et al., 2024). Such fragmentation stems partly from the high level of technical specialisation of individual risks, and partly from the absence of standardised methodological frameworks and operational guidance (Owolabi & Sajjad, 2023) that facilitate convergence across risk types applied (Gallina et al., 2016). However, this is particularly problematic in the case of cascading disasters, where primary events (e.g., earthquakes) can trigger secondary hazards (e.g., landslides, soil liquefaction, flooding, fire, infrastructure failure) with compounding effects (Nones & Pescaroli, 2016).

1.2. Integrating ecosystem-based approaches in DRR

In response to the growing complexity of disaster risks and the need for integrated multi-hazard strategies, ecosystem-based approaches have gained increasing recognition as vital for Disaster Risk Reduction (DRR). The Ecosystem-based approach to Disaster Risk Reduction (Eco-DRR) has been mainstreamed as an operational implementation of the Sendai Framework for Disaster Risk Reduction 2015–2030 (Faivre et al., 2018), which explicitly promotes the employment of such ecosystem-based strategies to strengthen resilience and reduce disaster risk (Estrella & Saalismaa, 2013).

Over the past decade, this paradigm has been widely endorsed through key international and regional policy instruments. Notably, the European Commission has advanced the integration of ecosystem-based strategies to support climate adaptation and sustainable development, enhancing the resilience of urban, rural, and natural landscapes (Sharifi, 2018). The 2013 European Union Green Infrastructure Strategy (European Commission, 2013) highlighted the role of GI in enhancing urban resilience, while both the 2015 Paris Agreement (United Nations, 2015a) and the Sustainable Development Goals (SDGs) (United Nations, 2015b) underscored the importance of NBS in climate adaptation. Collectively, these frameworks promote a shift from sector-specific and reactive disaster responses toward integrated, preventive strategies that recognize the value of healthy ecosystems in providing multiple societal benefits.

Within this policy context, Nature-Based Solutions (NBS) represent the overarching conceptual framework through which ecosystem-based approaches are operationalised. NBS encompass a range of strategies that leverage natural processes to address societal challenges, including climate adaptation and disaster risk reduction, in a sustainable and cost-effective manner (Faivre et al., 2017; Koren & Rus, 2019). Green Infrastructure (GI) and Eco-DRR can be understood as two complementary and more specific approaches within this broader NBS framework, both relying on the provision of Ecosystem Services (ES) to reduce disaster risk. Specifically, GI refers to a strategically planned network of natural and semi-natural areas designed to deliver a wide range of environmental, social, and economic benefits, including flood regulation, air quality improvement, and biodiversity conservation, and climate regulation (United Nations, 2015b). Eco-DRR, in turn, focuses on the explicit application of ecosystem-based approaches to reduce disaster risk across different hazard contexts, while Ecosystem Services (ES) provide the conceptual and analytical framework that links these approaches by describing the contributions of ecosystems to human well-being, commonly classified into provisioning, regulating, supporting, and cultural services (CICES, 2018; MEA, 2005).

These concepts are not only theoretically aligned but also practically interdependent. While GI and Eco-DRR do not directly modify the probability of hazard occurrence, they influence the conditions that shape vulnerability, exposure, and cascading impacts, primarily through the delivery of regulating, provisioning, and cultural ecosystem services. In this sense, GI and Eco-DRR operate as spatial and functional expressions of NBS within planning and risk governance frameworks (Khan et al., 2023; Nehren et al., 2023; Renaud et al., 2013).

Since the publication of the IUCN report in 2016, NBS have been widely recognised as an umbrella concept encompassing more specific approaches such as GI and Eco-DRR (Nehren et al., 2023). In spatial planning, these relationships have been further clarified and operationalised through a range of integrative frameworks that connect ecological functionality with urban resilience and disaster governance. Notably, Ronchi et al. (2020) propose a coherent model in which GI functions as the strategic planning infrastructure for ES delivery, while NBS represent the operational design interventions through which GI objectives are implemented. This conceptual framework has facilitated the integration of natural processes into both urban and rural contexts, thereby fostering long-term resilience and sustainable development.

In this perspective, Eco-DRR acts as a bridging framework that links ecosystem-based spatial planning strategies with the objective of the Sendai Framework, fostering cross-sectoral and multi-scale approaches to sustainability and risk reduction.

Recent policy developments, including the adoption of the Nature Restoration Law (European Commission, 2024), further reinforced this alignment by positioning ecosystem restoration as a key instrument for disaster risk management.

Consequently, embedding GI development and NBS deployment within spatial planning can play a pivotal role in addressing multiple environmental risks simultaneously (Conti et al., 2021). In this regard, the relationship between ecosystem-based strategies and disaster risk should be understood as dynamic and process-based, rather than static or hazard-specific. GI, NBS, and ES do not directly alter the probability of a hazard occurring; instead, they influence the conditions that shape vulnerability, exposure and the potential for cascading impacts. For instance, ecological structures such as wetlands, forests, and strategically designed open spaces can reduce susceptibility to secondary effects, facilitate evacuation and emergency organisation, and support social and ecological recovery in the aftermath of a disturbance. The interaction between these domains therefore lies in their capacity to act across preparedness, response and recovery phases, moderating the systemic behaviour of risk rather than addressing single hazards in isolation.

Practical applications such as floodplain restoration, wetland conservation, and afforestation help manage flood risks and improve water retention (Renaud et al., 2016). Likewise, urban green spaces and vegetated corridors regulate microclimates, reducing heat stress, while reforestation and slope stabilization minimise soil erosion and ground instability in landslide-prone areas (Lin et al., 2014; Mukherjee et al., 2022). These benefits suggest that both GI and NBS can serve as a central element in truly integrated risk management strategies, capable of addressing multiple environmental and societal challenges and overlapping risks simultaneously and synergistically (IUCN, 2016; Ommer et al., 2022). Beyond their immediate function in hazard mitigation, these solutions are increasingly recognised within urban and regional planning literature for their role in facilitating post-disaster recovery. They contribute not only to ecosystem restoration but also to the psychological recovery of affected populations and the reinforcement of social cohesion, thereby supporting more resilient socio-ecological systems (Anderson & Renaud, 2021; Mabon, 2019).

1.3. Ecosystem-based approaches in seismic risk reduction

Although GI, NBS, and ES have been widely recognised for their effectiveness in addressing natural hazards, their potential contributions to seismic risk reduction remain underexplored (French et al., 2019; Jeong et al., 2021; Renaud et al., 2013; Sebesvari et al., 2019).

This gap is particularly relevant given the nature of seismic risk, which – according to the established tripartite model of *hazard, exposure*, and *vulnerability* (Alcántara-Ayala et al., 2023) – features a *hazard* component that is largely uncontrollable and subject to considerable uncertainty, as it involves the probability of damaging ground shaking at a specific location, factoring in intensity, frequency, and ground motion characteristics. In contrast, *vulnerability* and *exposure* are more amenable to targeted interventions and reducing either can significantly lower the overall impact of seismic events (Rus et al., 2018; Viña et al., 2011).

Moreover, seismic risk is still often addressed in isolation, rather than within a broader multi-hazard framework (Gill & Malamud, 2014; Hochrainer-Stigler et al., 2023). Yet earthquakes frequently trigger cascading hazards –including tsunamis, landslides, liquefaction, fires, and aftershocks– which amplify the initial damage and create interconnected risk scenarios (Alexander, 2018; Kappes et al., 2012). For instance, seismic activity can destabilise slopes, obstruct transportation networks, compromise critical infrastructure such as dams, leading to catastrophic flooding, and cause widespread fires due to ruptured gas lines and damaged electrical systems (Keefer, 2002; Sutrisno et al., 2022). These cascading and compounding effects highlight the need for a holistic and integrated approach to seismic risk management. Such an approach should extend beyond immediate response to encompass preparedness, recovery, and long-term coordination among diverse stakeholders (Alexander, 2018; Poudel et al., 2022). By addressing both primary and secondary impacts, integrated seismic risk strategies can enhance the resilience of infrastructure, ecosystems, and communities within a wider disaster risk reduction framework (Privitera & La Rosa, 2018; UNDRR, 2020).

Therefore, integrating GI, NBS, and ES in spatial planning and mitigation strategies is crucial to enhance the adaptive and response capacity of communities, infrastructures, and ecosystems (Jaiswal & Wald, 2010; UNDRR, 2020), while offering an important complement to conventional engineering-based solutions. For example, well-designed open spaces can serve as emergency gathering and evacuation areas, while tree root systems contribute to soil stabilization in landslide-prone, earthquake-affected landscapes (French et al., 2019; Koren & Rus, 2019; Russo et al., 2022). Moreover, the presence of accessible and restored green areas can aid social and ecological recovery in the aftermath of an earthquake. These nature-based interventions can reduce both exposure and vulnerability by support post-disaster recovery and enhance long-term socio-ecological resilience (Cattani et al., 2023). Thus, integrating them into seismic risk planning not only aligns with the broader goals of the Sendai Framework but also advance a more holistic and proactive model of disaster risk reduction (UNDRR, 2017b).

Building on the growing recognition of GI, NBS, and ES in supporting seismic resilience, several non-European countries have already demonstrated the practical benefits of integrating ecosystem-based approaches into seismic risk management strategies (Faivre et al., 2018). For instance, Japan has incorporated designated open spaces into its emergency preparedness frameworks, providing safe evacuation zones during seismic events. Similarly, Iran has developed green corridors that help reduce the impact of earthquake-induced landslides (Bastani et al., 2024; Jeong et al., 2021).

By contrast, DRR strategies in Europe remain predominantly focused on engineering-based solutions, including the retrofitting of buildings, the construction of earthquake-resistant infrastructure, and emergency systems (El-Maissi et al., 2022). These approaches often overlook the potential role of GI and NBS in enhancing seismic resilience (De Silva et al., 2022), highlighting a broader lack of integration of such strategies into DRR planning and management frameworks. This gap represents both a challenge and a significant opportunity for the European context. Indeed, expanding the use of nature-based strategies within seismic risk management could offer a complementary and cost-effective alternative to traditional engineering approaches. Such integration holds promise for enhancing resilience in earthquake-prone regions of Southern Europe, including Italy, Greece, Turkey, parts of the Balkans, and the Iberian Peninsula.

To address this gap, this study investigates the potential contributions of GI, NBS and ES to seismic resilience. The research is guided by three key questions:

- How can GI, NBS, and ES contribute to reducing seismic risk and enhancing urban resilience?
- What specific benefits do these approaches provide, and how can they be effectively implemented?
- How can these tools be effectively incorporated into multi-hazard planning frameworks for seismic-risk areas across Europe?

The paper is structured as follows: Section Two details the literature review methodology, including search strategy, screening process, and analytical framework. Section Three presents the results and the key findings, focusing on themes such as the resilience of lifeline infrastructures, mitigation of cascading hazards, impacts on human health and well-being, community engagement, and sustainable development. Section Four highlighting challenges and opportunities for implementing these nature-based strategies in earthquake-prone regions, particularly within Europe, providing key insights and recommendations for integrating ecosystem-based approaches into seismic risk management and urban planning frameworks. Finally, Section Five offers some concluding remarks.

2. Methodology

A systematic literature review was conducted between September and October 2024 to examine the role of GI, NBS, ES in mitigating seismic risk and enhancing resilience within the urban planning and design contexts (Fig. 1).

The concentric and overlapping circles in Fig. 1 illustrate the hierarchical and dynamic relationships among the thematic areas. Spatial Planning provides the overarching framework that encompasses multi-hazard planning, which in turn connects to the operational phases of both pre- and post-disaster measures, including prevention, mitigation, and protection, as well as emergency responses and recovery.

Ecosystem Services (ES) approaches offer a broader conceptual framework that supports urban resilience and adaptive capacity to multiple natural hazards, including earthquakes. Through the implementation of ES-based strategies such as Green Infrastructure (GI) (Benedict & MacMahon, 2002), and their operational development into Nature-based Solutions (NBS), these approaches enhance Disaster Risk

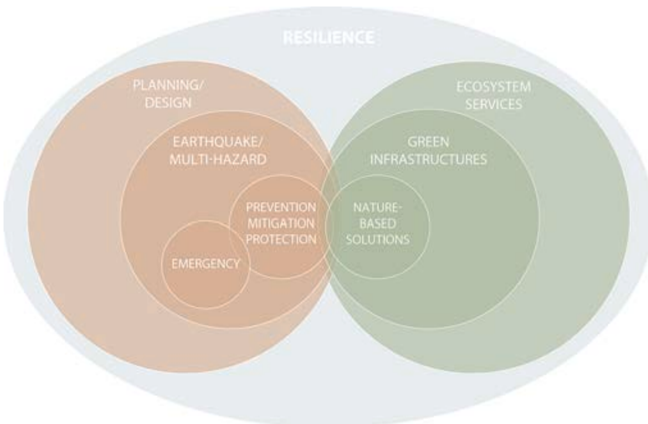

Fig. 1. Interconnecting themes of this literature review.

Reduction (DRR) by integrating ecological, spatial, and socio-technical dimensions within planning and design processes. For example, vegetated slopes and engineered wetlands can reduce the likelihood or severity of earthquake-induced landslides, directly supporting mitigation measures. Urban parks and open green spaces can serve as assembly points or facilitate evacuation, enhancing emergency response and protection strategies. The intersections between multi-hazard planning and ES thus highlight how GI and NBS can strengthen resilience, while planning strategies can optimize the deployment and effectiveness of ecosystem-based interventions across all phases of hazard management.

In accordance with the PRISMA guidelines (https://www.prisma-statement.org/), the aim of the research was to identify recurring themes, approaches, and findings through a combined synthesis of literature, bibliometric and qualitative analysis (Cumpston et al., 2019; Russo et al., 2022), ensuring methodological transparency, rigor, and replicability, while minimizing potential biases (Page et al., 2021; Palermo, 2012; Russo et al., 2022). The systematic literature review search included peer-reviewed journal articles, conference proceedings, and book chapters. Additionally, a complementary grey literature review was conducted to integrate the systematic analysis of peer-reviewed papers retrieved from Scopus and Web of Science. This additional step involved the collection and screening of official documents, policy reports, and institutional publications addressing NBS and risk reduction. The grey literature sample was initially identified through references and contextual information found in the background sections of the articles selected via the systematic review and subsequently expanded through targeted searches on institutional web platforms. Documents such as thesis, preprints, working papers, was not included. Lastly, the review was limited to sources published in the English language.

2.1. Search strategy

The systematic literature search was conducted using the Scopus and Web of Science (WoS) databases, encompassing publications from 1990 to 2024. A structured and iterative search strategy was employed, incorporating Boolean operators to refine and enhance the precision of the results.

Keywords were selected to align with three thematic groups: (i) Risks encompassing earthquake- and seismic-related hazards; (ii) Ecosystem-based tools and approaches, including Green Infrastructure (GI) Nature-Based Solutions (NBS), and Ecosystem Services (ES); and (iii) Application domains, covering urban planning, disaster risk reduction, and resilience strategies. Three successive levels of queries were designed to progressively broaden the scope of the search, ranging from a targeted focus on the direct application of GI, NBS, and ES to seismic risk reduction, to a more comprehensive exploration of interdisciplinary linkages and adjacent risk mitigation approaches:

1) The first query targeted studies explicitly addressing the application of GI, NBS, or ES in the context of seismic risk reduction and resilience.
2) The second query expanded the scope to encompass broader disciplinary contributions, including those addressing seismic risk from diverse methodological or planning perspectives.
3) Given that the consolidation of the terms GI, NBS, and ES has occurred predominantly is relatively recent (European Commission, 2013), the third query was designed to include a wider spectrum of related terminology, such as 'green spaces' and 'natural areas', to capture older and potentially relevant contributions.

The search syntax combined the two main thematic groups (i) Risks and (ii) Natural Solutions using the Boolean operator AND, while variations within each group were captured using OR. The third group, (iii) Application domains, was applied through database filtering options where appropriate. Equivalent search strings were applied in Scopus and Web of Science, with minor syntax adaptations for each database. Table 1 summarizes the keywords used for the systematic search, organized across three levels of specificity (narrow, expanded, broader) to progressively widen the scope of retrieved studies.

2.2. Documents screening and inclusion criteria

A four-stage screening process was adopted to ensure the inclusion of studies most closely aligned with the research objectives. The process was facilitated through the use of Rayyan software, which supported the systematic organisation, review, and exclusion of documents. Due to the substantial number of results retrieved from Query 3, a full manual screening was not feasible. Therefore, a targeted analysis was conducted, focusing on review articles and publications containing the core keywords identified in Phase 2.

In the initial screening stage, titles, abstracts, and keywords have been evaluated to exclude studies unrelated to seismic risk and NBS, GI or ES. Exclusions were made for publication that lacked a direct connection to these domains (classified as 'Wrong study/design') or those focused on unrelated topics such as energy systems, geological surveys, construction materials, or structural engineering, with no relevance to spatial planning or urban design (classified as 'Wrong

Table 1
Keywords used for the systematic search in Scopus and Web of Science, showing thematic groups and query breadth levels (narrow, expanded, broader).

Query no.	Thematic groups						
	(i) Risks			(ii) Ecosystem-based tools and approaches			(iii) Application domains
1 (narrow)	Earthquake*, Seismic, Seism	Risk*, Multi-risk*, Hazard*	Protection, Management, Mitigation, Reduction	Nature-based solutions, Ecosystem services, Green infrastructure			Urban Planning, Urban Strategies, Urban Design
2 (expanded)							all disciplines
3 (broader)				Nature-based solutions, Ecosystem services, Green infrastructure*	Green, Nature	Open Space*, Area*, Solution*	Urban Planning, Urban Strategies, Urban Design

Table 2
Summary of the selection process in relation to evaluation focus and exclusion criteria.

Selection stage	Evaluation focus	Exclusion criteria
Stage 1 Screening of Query 1 and 2 and Review articles of Query 3	Title, abstract, keywords	Wrong study/design Wrong outcome
Stage 2 Screening of 'Included' articles and 'Maybe' articles of Query 1 and 2 and Review articles	Full text	Low or absent correlation of NBS, ES and/or GI with seismic risk resilience
Stage 3 Selected outputs of Query 3, Snowball articles	Title, abstract, keywords	Wrong study/design Wrong outcome
Stage 4 Screening of 'Included' articles and 'Maybe' articles of Query 3	Full text	Low or absent correlation of NBS, ES and/or GI with seismic risk resilience

outcome'). The second stage consisted in a comprehensive full-text review of the preliminary selected studies to assess methodological soundness and thematic alignment. This phase also served to extract emerging themes and keywords to inform the next step.

In the third stage, these keywords and themes guided the identification and selection of additional sources retrieved through Query 3. Additionally, the snowball sampling method was applied, tracing citations from highly relevant studies to capture further qualifying sources.

The final stage involved a secondary full-text review of the remaining studies to validate their inclusion. Table 2 synthetises the overall document screening and inclusion process.

2.3. Analyses

The retrieved literature integrates both bibliometric and qualitative analyses to provide a comprehensive overview of the research landscape.

The bibliometric analysis of the overall results has been carried out with reference to document types, publication trends, geographic distribution, and disciplinary affiliations. Data extraction and refinement were carried out using bibliometric tools provided by Scopus and Web of Science (WoS).

In a second step, a keyword co-occurrence analysis was performed using VOSviewer to identify prevailing thematic patterns and emerging research fronts. Due to their smaller and more thematically focused datasets, the results of Query 1 and Query 2 were analysed jointly, while the broader dataset retrieved through Query 3 was examined separately. To ensure clarity and relevance, each groups' analysis was limited to a maximum of 50 keywords, with a minimum occurrence threshold of 5. Data cleaning was performed by merging variants of similar terms.

In addition to the bibliometric analysis, a Qualitative Thematic Analysis (QTA) was performed through full-text examination of the final selected studies to extract key insights. This process employed a Thematic Analysis Framework (TAF) as described by Braun and Clarke (2006), whereby recurring themes and key terms were systematically identified, coded, and grouped into broader categories. Elements of Qualitative Content Analysis (QCA) (Mayring, 2000) were integrated into the approach to validate and enrich the findings.

The process applied the following steps:

1. Familiarisation with Data: A full-text reading enabled immersion in the dataset and identification of recurring concepts related to GI, NBS, ES and seismic resilience.
2. Category Development: Inductive and deductive coding methods were used to extract relevant themes.
3. Systematic Coding: Each article was systematically examined for content relevance, with key statements classified into predefined analytical categories. This approach ensured that thematic patterns emerged inductively from the literature rather than being imposed arbitrarily, thereby preserving the thematic integrity and conceptual authenticity of the original sources.
4. Searching for Themes: Initial codes were reviewed and grouped into broader thematic categories. This step resulted in the emergence of two overarching themes: 'benefits' of GI, NBS and ES for seismic resilience and 'implementation approaches'.
5. Reviewing and Refining Themes: The coherence and internal consistency of the themes were assessed by comparing data across studies. Adjustments were made to avoid thematic overlaps and ensure that each category was distinct and analytically robust.
6. Defining and Naming Themes: Themes were refined and labelled based on their contribution to understanding the research questions.

Table 3
Overview of the query outcomes.

Query	WoS	Scopus	Total	Duplicates	Total (without dupl.)
Query 1 (narrow)	15	31	46	8	38
Query 2 (expanded)	116	94	210	27	183
Query 3 (broader)	252	1091	1343	81	1262

3. Results

3.1. Overview of the searching and screening process

The systematic literature search yielded a total of 1262 preliminary documents. Specifically, 38 relevant records were identified through Query 1 and 183 through Query 2. Query 3, which used a broader script encompassing the scope of Queries 1 and 2, retrieved 1262 records, corresponding to the total publications considered for the review (Table 3).

In Stage 1, a total of 320 records were screened, including 221 records from Queries 1 and 2, and 99 review articles retrieved through Query 3. At this stage, 282 records were excluded. Stage 2 of the screening process retained 38 documents and excluded 23. In total, 75 records were excluded due to wrong study/design, 212 for irrelevant outcomes and 18 due to a low or absent correlation with the investigation themes. The circular and iterative process between Stages 3 and 4 led to the exclusion of an additional 31 records. Following this rigorous multi-stage review, 19 articles were identified as most relevant for qualitative analysis: 15 from the initial systematic search and 4 through keywords and snowball citation tracking (Fig. 2).

3.2. Findings from the bibliometric assessment

The bibliometric analysis conducted on the total 1262 preliminary documents provided critical insights into the evolution and scope of the scholarly engagement within the field. The results show that most retrieved publications comprise journal articles and conference proceedings, with a comparatively smaller proportion of review articles. Notably, the Scopus database, recognised for its broader indexing criteria and inclusive coverage, yielded a larger number of documents relative to the more selective WoS database (Fig. 3).

Regarding research disciplines, most publications resulting from this literature review are concentrated within the domains of Earth and Planetary Sciences, encompassing geology, hydrology, and climatology, and Engineering/Environmental Sciences, particularly civil engineering and urban planning (Fig. 4). Additionally, notable contributions emerge from the Social Sciences, including sociology and public policy, as well as from the field of Computer Science, especially in areas such as Geographic Information Systems (GIS), remote sensing and machine learning. This distribution underscores the inherently interdisciplinary nature of disaster risk reduction research, which increasingly integrates technical, environmental, and socio-political dimensions to develop

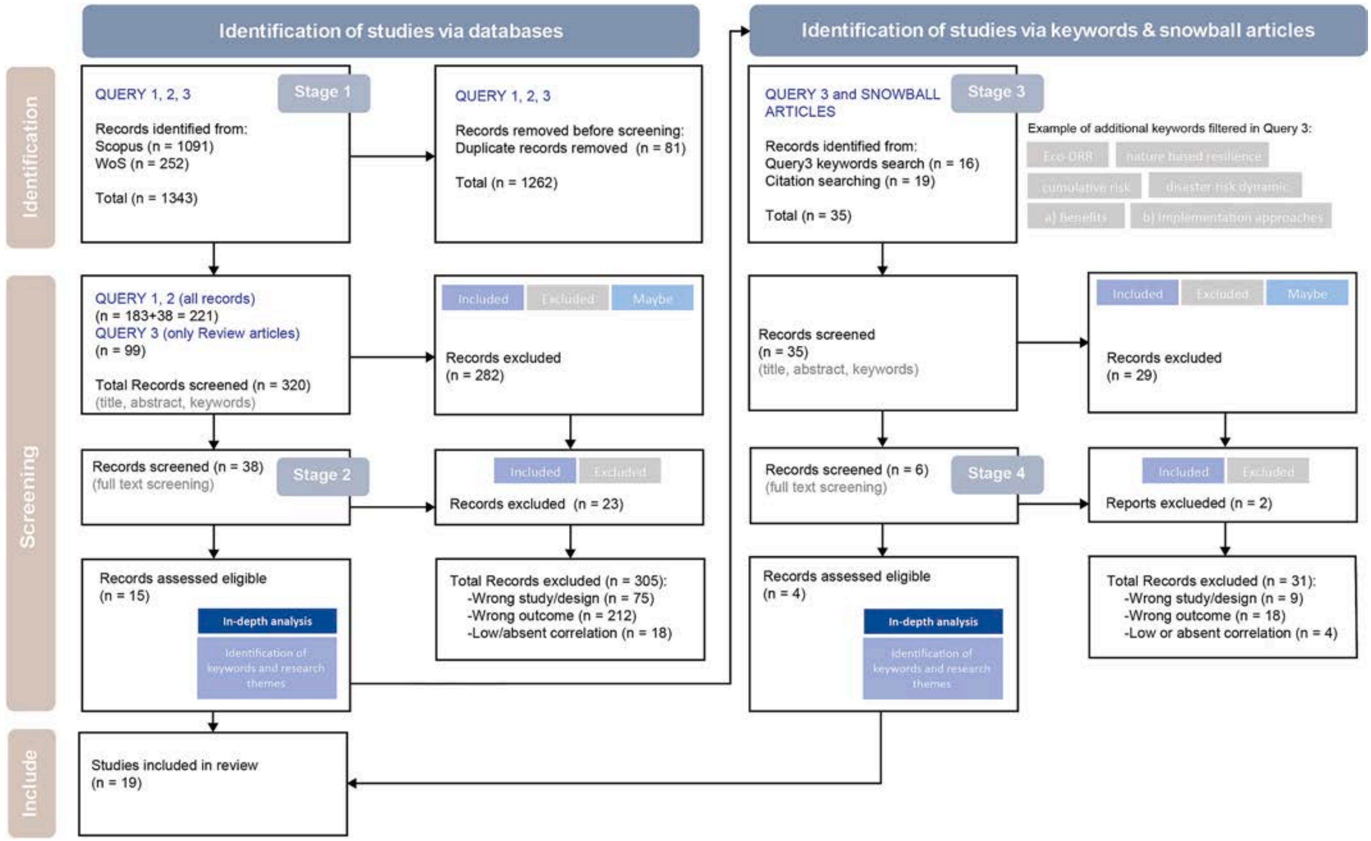

Fig. 2. Adapted PRISMA flow diagram illustrating the screening and selection process used in this systematic review. The diagram was modified by the authors to coherently reflect the process of the present study.

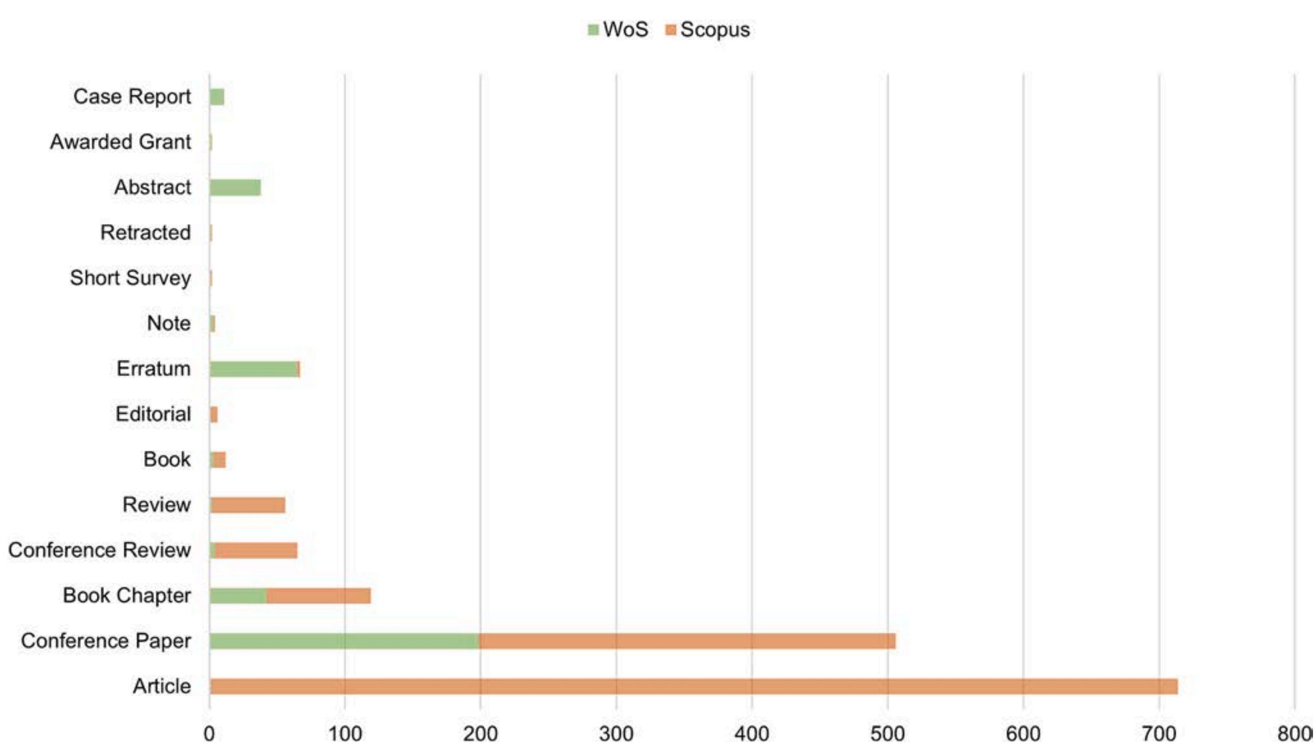

Fig. 3. Outcome of the total 1262 preliminary documents identified by the screening process, divided by type.

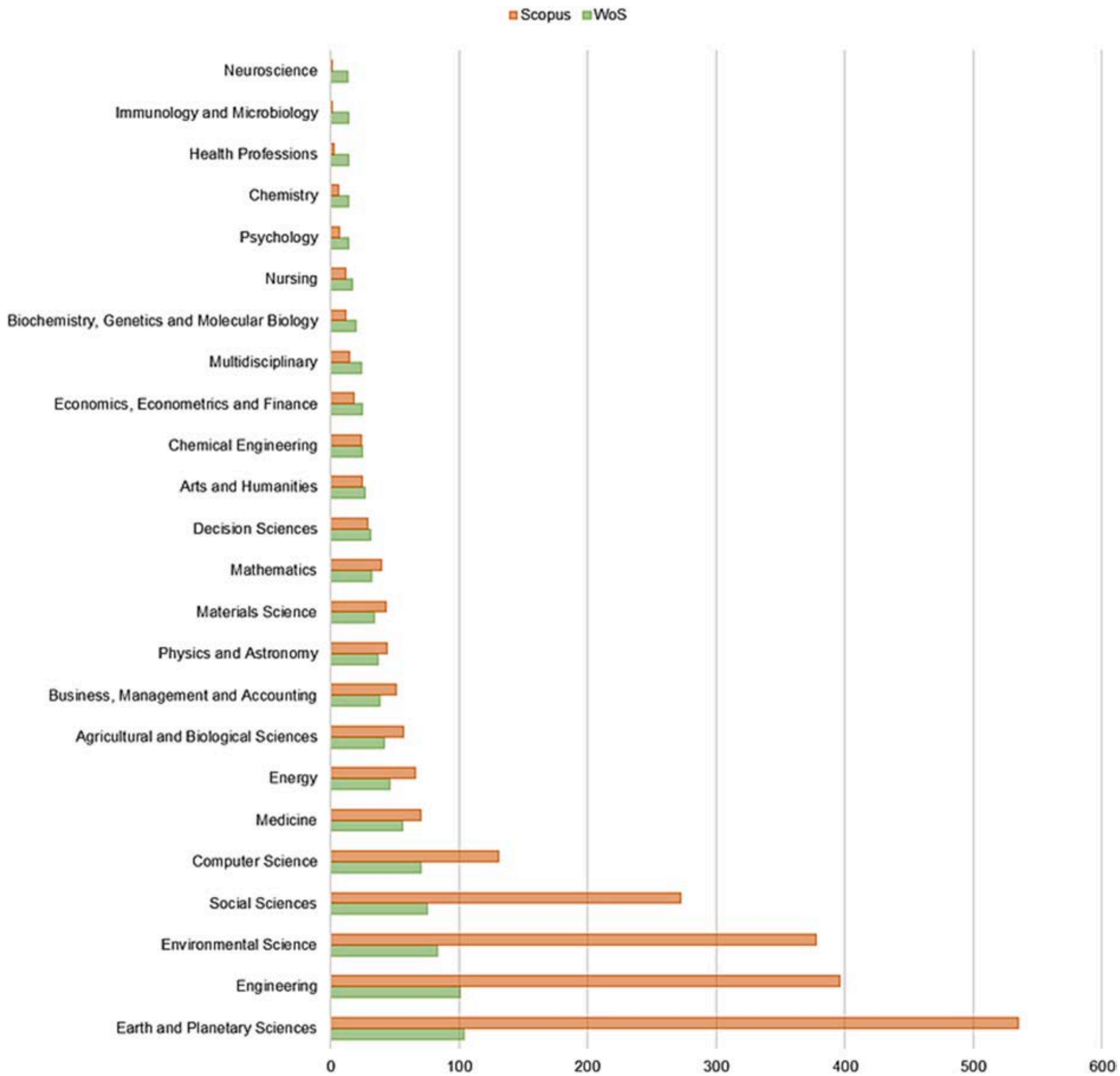

Fig. 4. Distribution of research areas identified through the literature review, organized by Scopus and Web of Science categories.

comprehensive resilience strategies.

The publication trend shows a marked increase after 2000, mirroring not only the general global rise in scientific output but also a growing academic and policy interest in climate change, biodiversity conservation, and ecosystem services (Fig. 5). This upward trajectory reflects the progressive consolidation of green planning and risk resilience paradigms within urban and regional studies, following the diffusion of international sustainability frameworks such as the Millennium Ecosystem Assessment (2005), the Sendai Framework for Disaster Risk Reduction (2015), and the European Green Deal (2019). This growth becomes particularly pronounced after 2015, aligning with the adoption of the Sendai Framework for Disaster Risk Reduction 2015–2030 and a broader institutional shift toward integrating GI, NBS and ES into disaster resilience strategies. While earlier policy milestones, such as the Brundtland Report (1987), the Kyoto Protocol (1997), and the Millennium Development Goals (2000), laid the groundwork for sustainable natural resource management, they did not explicitly endorse nature-based approaches to risk governance. Although the Sendai Framework for Disaster Risk Reduction does not make an explicit reference to NBS, it clearly acknowledges the role of ecosystems and ecosystem-based approaches in disaster risk reduction. This absence is logically consistent with the timing of its development: the SFDRR was elaborated prior to 2015 and formally endorsed in June 2015, whereas the first contemporary and consolidated definitions of NBS were introduced by the European Commission in 2015 and subsequently refined by IUCN in 2016.

Nevertheless, since 2015 the increasing uptake of the Ecosystem-based Disaster Risk Reduction (Eco-DRR) paradigm has clearly influenced scientific output, supporting the implementation of both the Sendai Framework and the 2030 Agenda at multiple governance levels. These dynamics are reflected not only in the quantity of publications, but also in the evolving thematic focus of the literature, an aspect further explored in the following content and keyword-based analyses.

Moreover, the geographic distribution of publications suggests that areas exposed to recurrent or severe seismic hazards tend to foster more active scientific discourse on nature-based risk mitigation strategies (Fig. 6a, b). Particularly, research has been predominantly conducted in regions characterised by elevated seismic activity, including North America, Asia, Oceania, the Middle East, South America, and Southern Europe. Notably, countries such as Japan, Turkey, Italy, Iran, and China have produced a significant body of literature, which may reflect both their high seismic risk profiles and growing institutional engagement with ecosystem-based approaches to risk reduction.

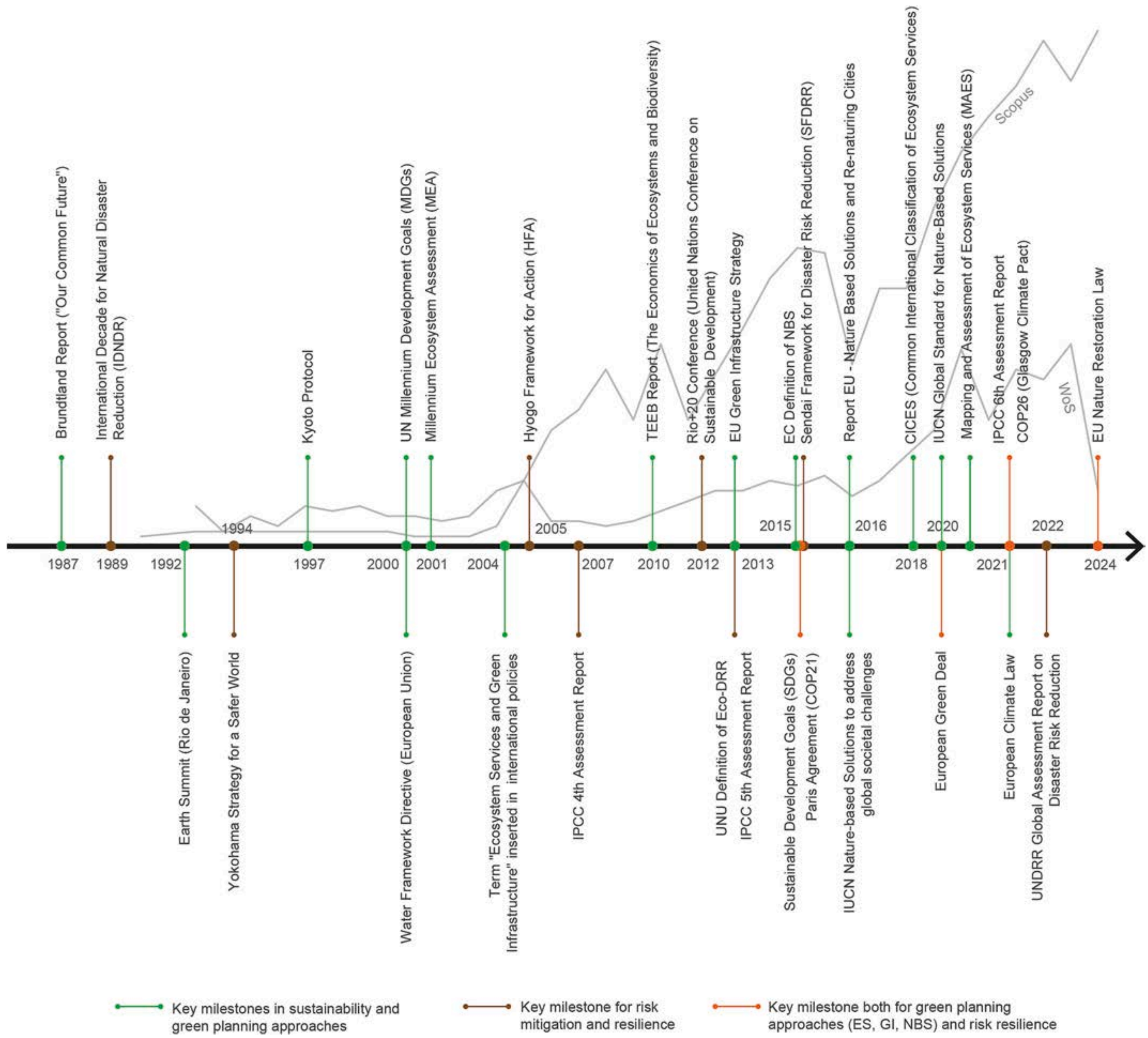

Fig. 5. Distribution of the study outcomes by year in relation to key international events that influences the conceptualization and the implementation of ES, GI and NBS, as well as the advancement of natural hazard mitigation and risk resilience strategies.

The strategic relevance of GI, NBS, and ES within integrated, multi-hazard risk reduction and resilience-building frameworks appears to be further catalysed by the occurrence of major disasters across different hazard types. These include major earthquakes (e.g., Gujarat, India, 2001; Bam, Iran, 2003; Haiti, 2010; Tōhoku, Japan, 2011; Central Italy, 2009 and 2016), devastating tsunamis (e.g., Indian Ocean tsunami, 2004; Japan, 2011). These events have drawn attention to the vulnerabilities created by socio-ecological imbalances and have reinforced the relevance of ecosystem-based approaches in disaster preparedness, response, and recovery.

The comparison between the global distribution of seismicity, as presented in the GEM Seismic Hazard Map (2018), and the geographical origin of the reviewed publications reveals marked discrepancies between risk exposure and research activity. Several high-hazard countries, such as Nepal, Bolivia, Syria, and Mongolia, produce very limited scientific output, whereas economically stronger nations - particularly the United States, China, Japan, and Italy (ranked eighth globally by GDP, The World Bank, 2024) - concentrate most studies, supported by consolidated research systems and established planning and risk management policies.

This imbalance reflects both the stronger engagement of the private sector in research within industrialized countries and the lack of resources and infrastructure in many regions of the Global South, especially Africa, where seismic vulnerability remains high. In some cases, such as Nigeria and Libya, limited research production is linked to private investments in exploratory seismic surveys despite low hazard levels.

In Japan, a long-standing technical and scientific tradition rooted in local knowledge has fostered advanced safety standards and internationally transferable experience, particularly within Eco-DRR and NBS frameworks. Conversely, the Mediterranean region remains underrepresented despite high seismic exposure and valuable cultural landscapes, indicating the need for stronger applied research and governance partnerships. Within this framework, Italy stands out as the European

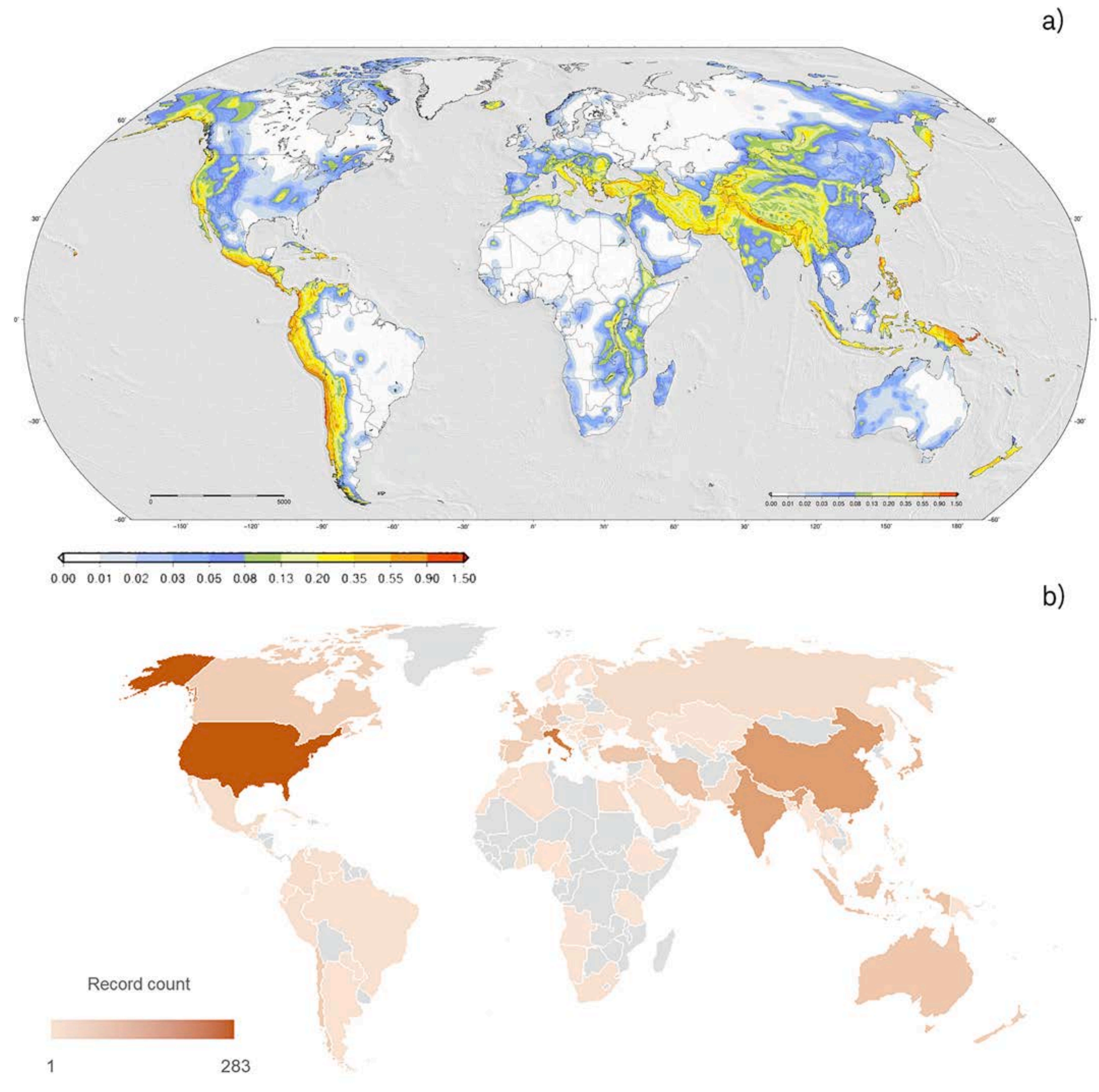

Fig. 6. Comparison between a) global distribution of seismic activity based on the Seismic Hazard Map (2018) Source: Global Earthquake Model GEM https://www.globalquakemodel.org/product/global-seismic-hazard-map and b) distribution of the literature review publications per country.

seismic-prone country with the highest number of publications in this field, reflecting a strong national interest in applied research on the subject.

Future research should support policy development promoting compensation mechanisms and ecosystem-based investments integrated into legal and local governance frameworks, especially in economically weaker regions with limited institutional capacity.

3.2.1. Keyword co-occurrence analysis

The keyword co-occurrence analysis conducted for Queries 1 and 2 identifies key thematic clusters within the current research landscape on earthquakes, highlighting interconnected areas of investigation (Fig. 7). One prominent cluster focuses on the *geophysical and mechanical aspects* of seismic phenomena, including terms such as 'seismology', 'seismic hazard' and 'earthquake magnitude' which reflect a sustained focus on the fundamental science of earthquake generation and hazard assessment, i.e. studies on risk prediction and response. A second major cluster focuses on *disaster resilience* and *environmental sustainability*, highlighting the increasing recognition of the role of ecosystems in risk reduction and community preparedness, as evidenced by terms such as 'ecosystem services', 'resilience' and 'disaster risk reduction'. This reflects a growing interdisciplinary approach within the field of earthquake mitigation research. There is also a rising focus on *data-driven modelling* (DDM), as demonstrated by the frequent co-occurrence of terms such as

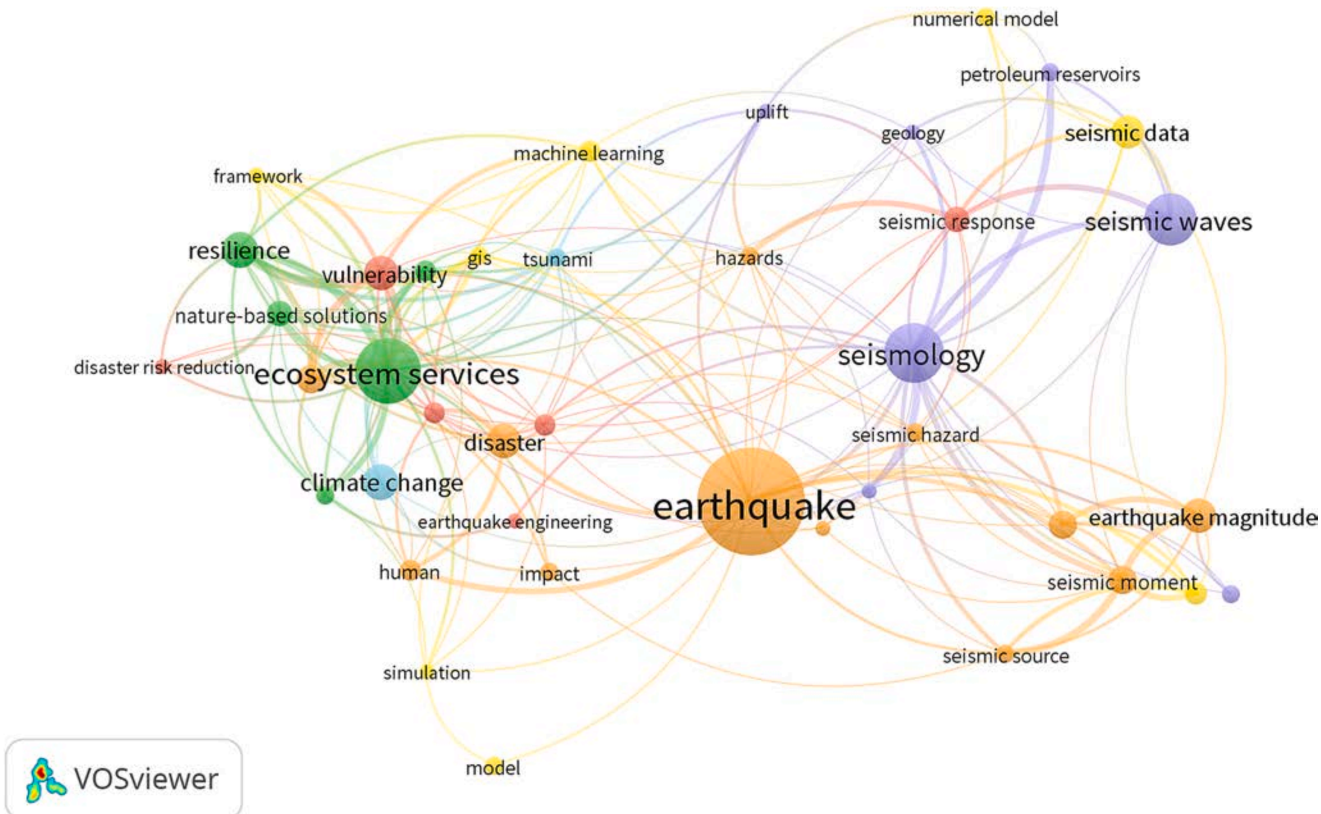

Fig. 7. Keyword co-occurrence of Query 1 and 2. Elaborated with VOSviewer.

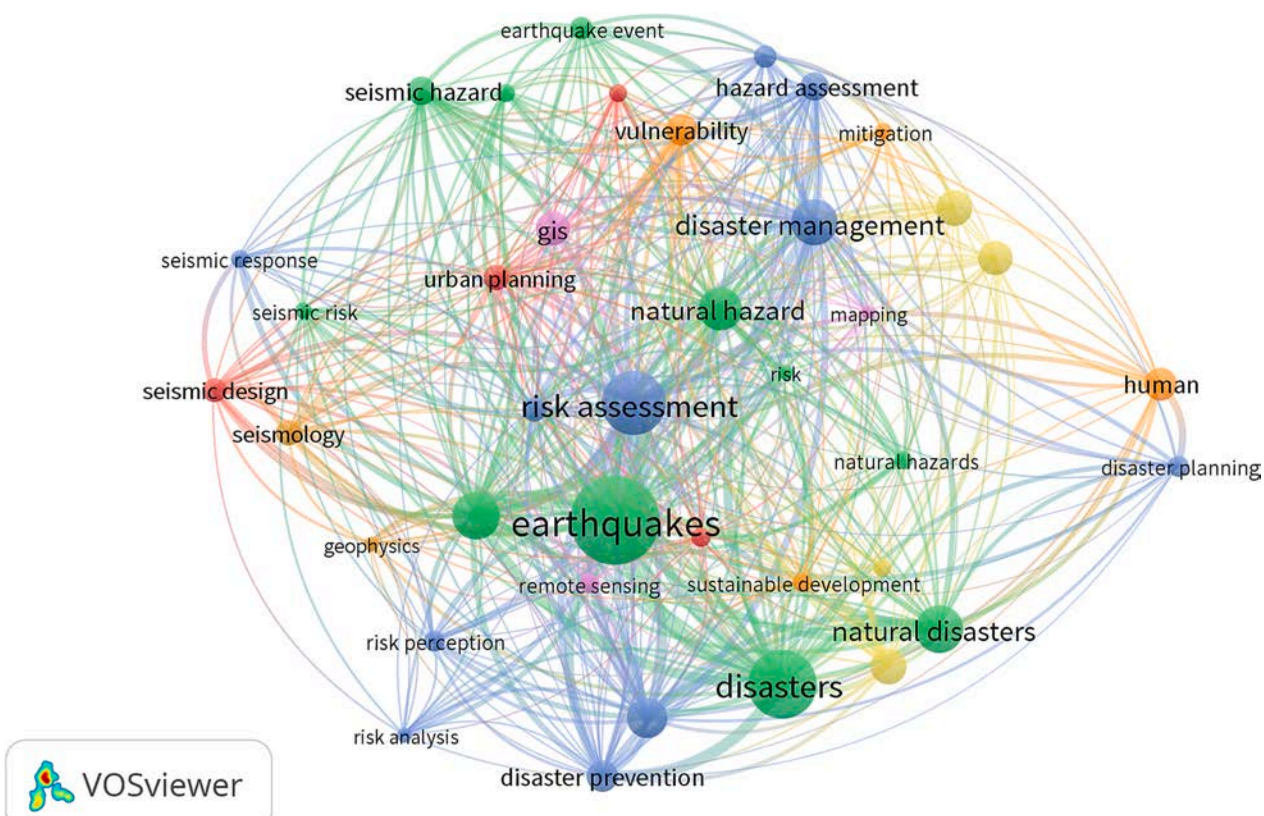

Fig. 8. Keyword co-occurrence of Query 3. Elaborated with VOSviewer.

Table 4
Included articles analysis: geographical distribution of the cases, spatial and risk focus of the articles, and emerging themes in keywords.

No.	Reference	Publ. Type	Country	Spatial focus	Hazard type / risk focus	Temporal focus	Emerging themes in keywords
Systematic review articles							
1	Bastani et al. (2024)	J.A.	Iran	neighbourhood	earthquake	pre-disaster planning, post-disaster response	GI, Essential infrastructures, Land use planning, Environmental adaptation
2	Ergün Konukcu (2023)	B.C.	Turkey	urban districts	earthquake	pre-and post-disaster	DRR, Cascading effects (secondary risks, disaster risk dynamics), Effect on human health in pre- and post-disaster settings, Essential infrastructures, Heritage, Retrofitting
3	Kato and Huang (2021)	J.A.	Japan	regional	multi-risk (particularly flooding)	pre- and post-disaster	Eco-DRR, Flooding, Land use planning, Sustainability, Social-ecological benefits, Protected areas, Forests
4	Khan et al. (2023)	R.A.	/	/	multi-risk (particularly flooding)	pre- and post-disaster prediction & management	Effect on human health in pre- and post-disaster settings
5	Kumagai et al. (2013)	E.	Japan	regional (coast)	earthquake (tsunami & landslide)	pre- and post-disaster	GI, DRR strategies, Natural capital (healthy ecosystems, species and ecosystem services), Protected areas, Cost effective
6	Lanfranconi et al. (2024)	C.P.	Italy, Spain, Netherlands, Latvia	multi-scalar (building, urban, region)	climate change-related risks	pre- and post-disaster	GI, NBS, Innovative sensing technologies, Effect on human health in pre- and post-disaster settings
7	López-Saavedra et al. (2023)	J.A.	Spain	regional (island)	multi-risk (Volcanic eruptions & landslide)	pre- and post-disaster	NBS, Societal safety, Effect on human health in pre- and post-disaster settings, Land use planning, Sustainable development, Education, Protected areas, Cost effective
8	Mabon (2019)) 0	J.A.	Japan	county (8 municipalities)	earthquake (tsunami & nuclear disaster)	post-disaster	Post-disaster recovery planning Social and ecological resilience and benefits, Ecosystem-based adaptation (EBA), Ecosystem-based disaster risk reduction (Eco-DRR), Indirectly: Cascading effects (tsunami and nuclear disaster), Effect on human health in pre- and post-disaster settings 'building back greener', Community building
9	Mukherjee et al. (2022)	J.A.	South Asia (5 cities)	urban	multi-risk	pre- and post-disaster	Nature-based Resilience (NbR), Land use planning, Ecosystem-based Disaster Risk Reduction (Eco-DRR), Blue-Green Infrastructure (BGI), Cascading effects, Effect on human health/well-being in pre- and post-disaster settings, Community building/ participation
10	Rus et al. (2018)	R.A.	/	urban	earthquake (multi-risk)	pre- and post-disaster	Resilience assessment, Urban Open space, Urban system resilience, Qualitative resilience assessment, Quantitative resilience assessment, Effect on human health/well-being in pre- and post-disaster settings, Infrastructures
11	Russo et al. (2022)	R.A.	/	urban	earthquake (multi-risk)	pre- and during disaster	Open spaces (OSs)
12	Salata and Uzelli (2023)	J.A.	Turkey	urban	multi-risk	vulnerability assessment, pre-disaster planning	Soil management/Land use planning, Ecosystem vulnerability, Compensation measures
13	Sutrisno et al. (2022)	C.P.	Indonesia	regional	earthquake (tsunami & landslide)	during and post-disaster	Cascading effects, Infrastructure resilience, Evacuation zone, Land use planning, Forests
14	Viña et al. (2011)	J.A.	China	regional	earthquake (landslide)	pre- and post-disaster	Cascading effects, Land use planning, Protected areas, Forests
15	Zhang et al. (2024)	R.A.	/	urban agglomerations	multi-risk (not only natural hazards)	pre- and post-disaster	Urban ecological risk, Cumulative risks, Effect on human health/well-being in pre- and post-disaster settings, Land use planning
Snowball articles							
16	French et al. (2019)	R.A.	/	/	earthquakes and cascading risks (fire, tsunami, landslides)	pre-disaster planning, post-disaster response & recovery	Open & green spaces (OSs), Cascading effects, Earthquake impacts (physical & social), Lifeline infrastructures, Multifunctionality, Network, Redundancy, Accessibility Evacuation routes, Communication, Multi-scale planning, Grouping OSs with essential facilities, Land use planning & zoning, Seismic micro-zoning for OSs, Design solutions, OSs/green spaces for social resilience, Community engagement & education

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Table 4 (*continued*)

No.	Reference	Publ. Type	Country	Spatial focus	Hazard type / risk focus	Temporal focus	Emerging themes in keywords
17	Renaud et al. (2013)	B.C.	/	/	multi-risk (landslide, fire, flood, avalanche, extreme weather)	DRR and CCA, pre-disaster	Environmental Impact Assessment (EIA) to integrate EBA and Eco-DRR, Environmental Strategic Assessment (ESA) pre- and post-disaster, Gap between Environment and Disaster Risk Reduction policies and governance
18	Renaud et al. (2016)	B.C.	Chap. 4 Czech Republic, Chap.6 Belize, USA, Mexico, Chap.11 Switzerland, Chap. 12 India	regional (mountains, rivers, coasts)	landslides, flooding, costal hazards	DRR and CCA, pre-disaster	Policies & Practices, Integrate Eco-DRR, CCA & EBA, Community Involvement, Cost-Benefit Analysis, Stakeholder Engagement, Co-Benefits, Eco-DRR & CCA Tools GIS Tools, Green/Grey Infrastructure, Forest Landslide Stabilization
19	Nehren et al. (2023)	R.A.	/	/	multi-risk	pre-disaster planning and design solutions	NBS, Social and ecological resilience and benefits, Design and implementation

Note: J.A. journal article; R.A. review article; B.C. book chapter(s); E. editorial; C.P. conference proceedings.

'machine learning', 'numerical model' and 'GIS'. These approaches suggest an emerging emphasis on predictive analytics and spatial modelling to enhance earthquake forecasting and risk assessment capabilities. Overall, the visualization reveals an interconnected research landscape in which traditional seismic science, ecological resilience frameworks, sustainability, computational methods and technologies converge to advance integrated strategies for hazard mitigation and urban resilience.

In the case of Query 3, which encompassed a broader scope, the keyword co-occurrence analysis revealed a more conventional focus on earthquake risk, disaster management, and engineering-based mitigation strategies, with less emphasis on NBS and ES (Fig. 8). While this analysis shares thematic overlap with the previous one, particularly regarding terms such as 'seismic hazard', 'seismic risk' and 'seismology', it shows a notable focus on concepts associated with risk assessment, disaster prevention, and strategic planning. Key terms such as 'disaster management', 'risk perception' and 'human' reflect a governance and policy-oriented perspective, in contrast to the ecological emphasis of the previous analysis. Technological tools such as Geographic Information Systems (GIS) and spatial mapping remain central in both analyses: however, in this context, they are more strongly associated with technical and strategic risk evaluation frameworks.

3.3. *Qualitative thematic analysis (QTA) of the selected studies*

Through the QTA, the final set of 19 studies was synthesised according to publication type, geographical scope, spatial scale, hazard typology, temporal focus of implementation strategies and emerging themes in keywords (Table 4). Although some articles are categorized as "multi-risk", earthquakes were explicitly cited in all selected studies, ensuring consistency with the focus of this review.

This analysis revealed a set of recurring concepts associated with nature-based approaches to risk governance, and points out a growing convergence between NBS, resilience agendas for seismic/multi-risk contexts, and integrated territorial planning. Terms such as *Green Infrastructure* (GI), *Nature-Based Solutions* (NBS), *Ecosystem Services* (ES), *open spaces*, *resilience*, and *disaster risk reduction* collectively point to an interdisciplinary convergence between ecological, spatial, and infrastructural planning. Notably, *'Open Spaces'* (OSs), and '*Green Spaces*' are referenced with varying functions across studies: OSs are often associated with evacuation, assembly, and emergency response functions, whereas Green Spaces typically emphasize ecological, recreational, and well-being benefits (French et al., 2019; Rus et al., 2018; Sutrisno et al., 2022).

While the studies analysed adopt diverse methodological perspectives, they consistently emphasize the multifunctional value of natural systems in both pre-disaster mitigation and post-disaster recovery.

Geographically, most contributions focus on seismic and multi-hazard contexts in urban and regional areas, with several also address rural and peripheral territories, highlighting how localised disasters can trigger cascading effects that impact broader territorial systems.

Ecosystem-based Disaster Risk Reduction (Eco-DRR) and Ecosystem-based Adaptation (EBA) frameworks are frequently cited as structuring references, particularly in multi-risk contexts and in relation to climate-related hazards (Kato & Huang, 2021; Renaud et al., 2013).

Additionally, the QTA enables the synthesis of methodological orientations and thematic priorities emerging from the reviewed studies, structured around two main components:

(i) *approaches and instruments for risk-oriented planning*, including the methodologies, analytical models and conceptual frameworks adopted.
(ii) a *thematic framework* illustrating how nature-based strategies are framed in relation to seismic and multi-hazard contexts (Fig. 10, Table 5).

3.3.1. *Approaches and instruments for risk-oriented planning*

The broad array of tools and methods emerging from the QTA underscores the interdisciplinary character of the research field. These applications are mainly oriented toward the management of multi-hazard scenarios linked to seismic risk, with a specific focus on both pre- and post-disaster response phases.

Several studies employ decision-support techniques such as the Analytic Hierarchy Process (AHP) to assess risk and resilience, as seen in Bastani et al. (2024) and Ergün Konukcu (2023), where criteria are weighted to guide prioritisation. Geospatial analysis and remote sensing technologies are also widely applied: for instance, Khan et al. (2023) use Google Earth Engine (GEE) for disaster risk monitoring, while Lanfranconi et al. (2024) integrate sensor networks, Building Information Modelling (BIM), and Digital Twin platforms for holistic environmental monitoring.

Land use change analysis is often combined with ecosystem-based approaches to address hazard mitigation. Kato and Huang (2021) incorporate Eco-DRR principles into watershed management strategies for flood risk reduction, and López-Saavedra et al. (2023) merge socio-economic data with multi-hazard planning frameworks.

Advanced analytical and modelling techniques also emerge across the corpus. Mabon (2019) applies content analysis and a heuristic coding scheme based on the TEEB framework to evaluate the post-disaster role of green infrastructure. Mukherjee et al. (2022) propose the GeoSM-Nate Framework for risk-sensitive urban planning. Probabilistic fragility curves and social vulnerability indices are employed by Rus et al. (2018) within a quantitative resilience assessment enhanced by the

Table 5
Distribution of the approaches and instruments for risk-oriented planning and thematic framework's dimensions and categories among the 19 selected studies.

no.	Reference	(i) approaches and instruments for risk-oriented planning	(ii) thematic framework							
				Benefits				Implementation approaches		
			Lifeline infrastructures	Mitigation of cascading effects	Human health and well-being	Community building and social cohesion	Sustainable development and environmental co-benefits	Community Participation and co-design	Risk-sensitive Land use planning	Environmental Impact Assessment (EIA)
1	Bastani et al. (2024)	Analytic Hierarchy Process	X						X	
2	Ergün Konukcu (2023)	Megacity Indicator System for Disaster Risk Management (MegaIST) Analytical Hierarchy Process	X	X	X					
3	Kato and Huang (2021)	Land use change analysis Application of Eco-DRR criteria						X	X	
4	Khan et al. (2023)	Detectors/ Sensors Google Earth engine (GEE) Remote sensing Others			X					
5	Kumagai et al. (2013)	/					X	X	X	
6	Lanfranconi et al. (2024)	Sensors (incl. BIM and Digital Twin integrated in holistic monitoring platforms)			X					
7	López-Saavedra et al. (2023)	Integration of societal and economic data with multi-hazardous risk and mitigation plans Spatial and temporal analyses			X	X	X	X	X	
8	Mabon (2019) 0	Content analysis of disaster recovery plans Analysis of how NBS provide a wider suite of benefits post-disaster beyond DRR Heuristic coding scheme TEEB framework		X	X		X	X		
9	Mukherjee et al. (2022)	Nature-Based Resilience Assessment Geospatial Mapping of Natural Ecosystem (GeoSM-Nate) Framework Potential of Nature-Based Resilience Metropolitan		X	X	X	X		X	X

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Table 5 (*continued*)

no.	Reference	(i) approaches and instruments for risk-oriented planning	(ii) thematic framework							
				Benefits				Implementation approaches		
			Lifeline infrastructures	Mitigation of cascading effects	Human health and well-being	Community building and social cohesion	Sustainable development and environmental co-benefits	Community Participation and co-design	Risk-sensitive Land use planning	Environmental Impact Assessment (EIA)
10	Rus et al. (2018)	City Risk Sensitive Quantitative resilience assessment Probabilistic fragility analysis Composite index methodology Social vulnerability index CAPRA holistic risk assessment	X		X					
11	Russo et al. (2022)	Analytical hierarchy process (AHP) Definition of a preliminary OSs risk index							X	
12	Salata and Uzelli (2023)	Analysis of urbanisation trends Land Use Change (LUC) with Urban ATLAS, with Soil Hydraulic Conductibility (SHC) and Active faults map Impact of LUC on SHC	X							
13	Sutrisno et al. (2022)	Spatial multicriteria analysis of land instability Assessment of settlements vulnerability to cascading effects (tsunami, landslide) according to construction type	X	X					X	
14	Viña et al. (2011)	Analysis of satellite imagery and field data		X					X	
15	Zhang et al. (2024)	Environmental risk network Multi-agent modelling System dynamics model Bayesian network		X	X		X		X	
16	French et al. (2019)	/	X	X				X	X	
17	Renaud et al. (2013)	Environmental Impact Assessment (EIA) Environmental Strategic				X		X	X	X

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Table 5 (*continued*)

no.	Reference	(i) approaches and instruments for risk-oriented planning	(ii) thematic framework							
			Benefits					Implementation approaches		
			Lifeline infrastructures	Mitigation of cascading effects	Human health and well-being	Community building and social cohesion	Sustainable development and environmental co-benefits	Community Participation and co-design	Risk-sensitive Land use planning	Environmental Impact Assessment (EIA)
		Assessment (ESA)								
18	Renaud et al. (2016)	Cost Benefit Analysis (CBA) Multi-Criteria Decision Making (MCDM) Economic analysis of stakeholder-defined adaptation scenarios Participatory scenario building, GIS modelling, and economic evaluation InVEST tool Spatial Decision Support System (SDSS) SlideforNET tool Cluster planning approach for Eco-DRR integration		X	X			X		
19	Nehren et al. (2023)	/			X			X		

CAPRA platform.

Several studies further integrate physical-environmental parameters: Salata and Uzelli (2023) combine land use change, soil hydraulic conductivity, and active fault mapping to evaluate the impact of urbanisation on hazard exposure, while Sutrisno et al. (2022) conduct spatial multi-criteria analysis to assess settlement vulnerability to cascading seismic hazards, considering land stability and building typologies.

3.4. Thematic framework

The cross-cutting themes identified in the reviewed studies can be synthesised into the following thematic framework, structured around two analytical dimensions: a) *Benefits* and b) *Implementation approaches*, further classified into five and three categories, respectively: *Lifeline infrastructures, Mitigation of cascading effects, Human health and well-being, Sustainable development and environmental co-benefits, Community building and social cohesion*; and *Community Participation and co-design, Risk-sensitive Land use planning* and *Environmental Impact Assessment (EIA)*. These categories synthesise recurring concepts, strategies and approaches observed in the integration of GI, NBS, and ES within disaster risk reduction and resilience planning (Fig. 9).

a) Benefits

This first dimension addresses the benefits of integrating nature-based strategies in seismic and multi-risk contexts. It encompasses five categories that capture how these approaches contribute to risk reduction, support post-disaster recovery, and promote community sustainability, delivering a wide range of ecological, social, and health-related positive outcomes.

a1 - Resilience of lifeline infrastructures

One of the principal advantages of NBS and GI lies in their capacity to enhance the resilience of critical lifeline infrastructures. These strategies enhance the performance and the functionality of essential services, including water supply, transportation, and communication systems, which are crucial during both emergency response and post-disasters recovery phases. Bastani et al. (2024) and Ergün Konukcu (2023) emphasize that strategically implemented GI elements such as vegetated corridors, and green buffers (e.g. vegetated retention basins, engineered wetlands, and green buffer strips around transport corridors) can contribute significantly to the protection of critical facilities and transportation networks by reducing soil erosion, maintaining slope stability, and buffering seismic shocks. For example, in Mashhad, Iran, vegetated open spaces and green corridors were shown to maintain road accessibility after moderate earthquakes by limiting surface erosion and stabilizing slopes near informal settlements (Bastani et al., 2024). These protective functions are particularly critical in seismic zones, where land degradation or compromised drainage can exacerbate secondary hazards such as landslides and liquefaction and flood-induced road failures, and impede access for emergency response. Furthermore, Rus et al. (2018) and Sutrisno et al. (2022) underscore the importance of incorporating designed earthquake-resistant evacuation routes that integrate multifunctional open spaces and green corridors and highlight the role of GI and OSs as functional redundancies in urban networks. These spaces can provide alternative routes in the event of transportation disruption, serve as temporary shelter sites or community assembly

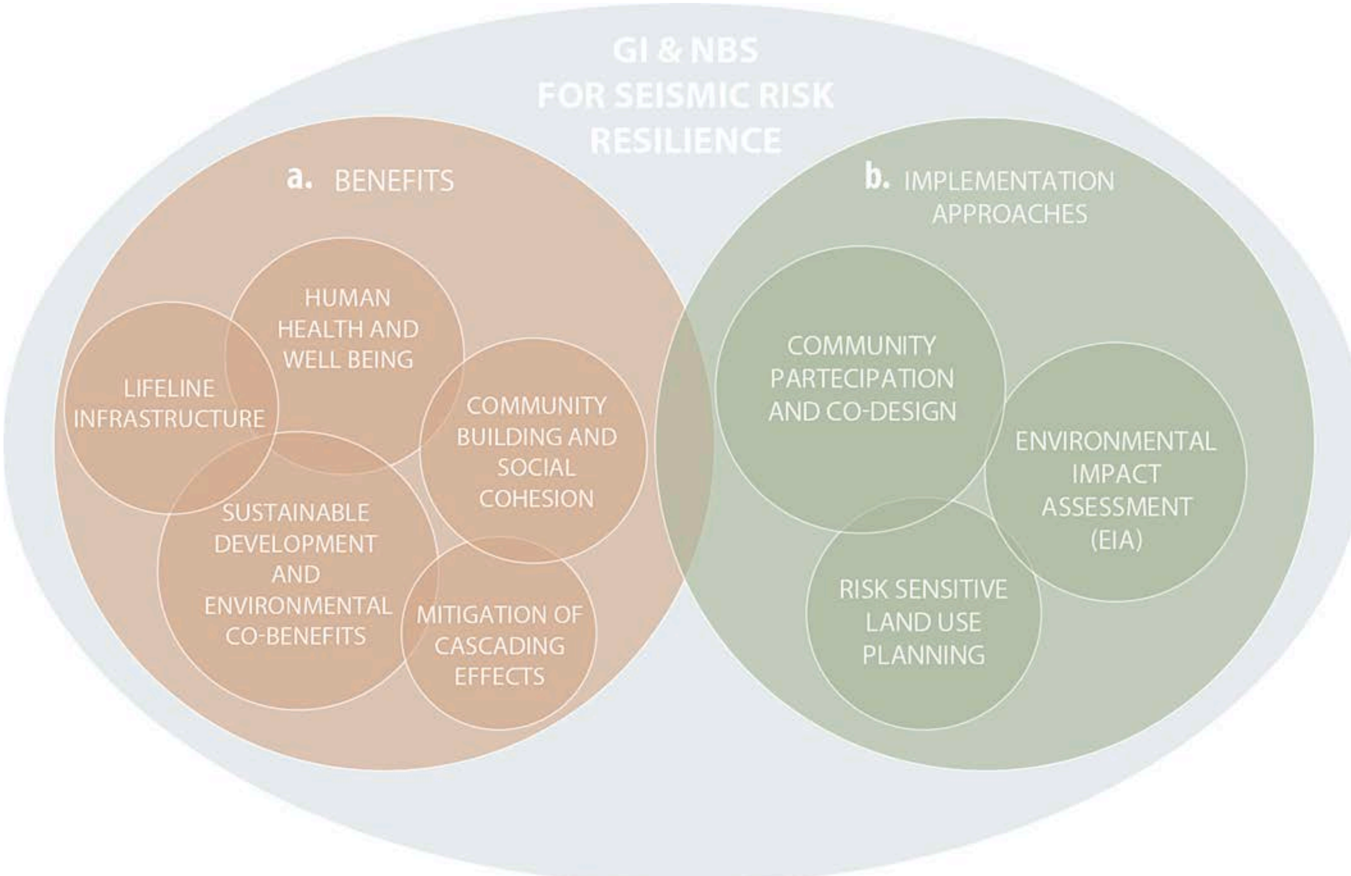

Fig. 9. Synthesis of the thematic framework resulting from the QTA, structured around two overarching analytical dimensions.

areas, and space for building reconstruction in the aftermath of a disaster, improving overall disaster preparedness and recovery. Beyond their immediate protective role, green open spaces contribute a range of ecosystem services - such as stormwater regulation, urban heat mitigation, and microclimate stabilization - which support the broader sustainability and resilience of the urban system, thereby reinforcing long-term disaster preparedness and adaptive capacity.

a2 - Mitigation of cascading effects

Mitigating cascading effects represent a critical function of NBS and GI within seismic risk reduction frameworks. Numerous studies underscore the significance of addressing secondary hazards that are frequently triggered by seismic events, including landslides, fires, and flooding. For instance, Ergün Konukcu (2023) conceptualizes and maps these as 'secondary risks' and 'disaster risk dynamics', while Zhang et al. (2024) describe them as cumulative risks emphasizing the compounded impacts resulting from interconnected disasters. Sutrisno et al. (2022) specifically address how NBS can be used to mitigate cascading disaster-prone areas and infrastructure by implementing interventions such as afforestation and slope stabilization to safeguard vulnerable infrastructure. Several studies also approach these phenomena indirectly. Mabon (2019) examines the cascading effects following the earthquake in Futaba County, where the initial seismic shock triggered both a tsunami and a nuclear disaster, and highlights how the integration of NBS, particularly cultural ES in municipal recovery plans, contributed to restoring community resilience and social cohesion, which can indirectly reduce vulnerability to secondary hazards. In particular, post-disaster green spaces, community gardens, and park restoration provided both ecological buffers and functional gathering spaces, which facilitated emergency coordination and recovery planning. Similarly, Viña et al. (2011) investigate the relationship between seismic activity and subsequent landslides in Wenchuan County, China, demonstrating how forest conservation can reduce landslide risks in post-earthquake scenarios. Mukherjee et al. (2022) further emphasize the interlinked effects of disasters across urban systems, and advocate for a comprehensive multi-hazard, multi-risk perspective in resilience planning, showing how nature-based interventions - such as wetland restoration, green corridors, and urban greening in five South Asian cities - enhanced systemic resilience, reduced urban flooding, and mitigated heat stress amplification in post-earthquake recovery scenarios. Complementing these findings, Kato and Huang (2021) illustrate how land-use scenarios that incorporate wetlands, or green belts can mitigate flood peaks, thereby reducing the potential for secondary hazards in earthquake-prone regions, such as landslides, liquefaction, and fires. They also highlight how restored wetland areas can act as temporary water retention zones following seismic-triggered disruptions to drainage systems.

a3 - Human health and well-being

Disaster events profoundly affect human health and well-being. Several studies reviewed highlight how improving disaster resilience through GI, NBS and ES directly contributes to human well-being, through both physical safety and psychosocial support (pre- and post-disaster). Ergün Konukcu (2023) explores the relationship between urban resilience and quality of life, framing it within broader visions of safe, liveable, eco-sensitive, equitable, inclusive visions and policies. In this context, OSs and GI are identified as crucial assets in mitigating social vulnerability and strengthening community coping capacities. Scholars such as Khan et al. (2023), López-Saavedra et al. (2023), Lanfranconi et al. (2024) and Rus et al. (2018) highlight the contributions of GI and disaster management frameworks to human well-being, underscoring their influence on safety, system efficiency, and the quality of urban living, delivering benefits across social, economic, and ecological domains. Focusing on post-disaster situations, Mabon (2019) advocates for “building back greener” by incorporating ecosystem-based strategies into recovery planning to strengthen both social and ecological resilience. He argues that cultural ES provided by NBS such as opportunities for recreation, education, and aesthetic appreciation (e.g. though community gardens, recreational green spaces, and educational nature trails), may enhance citizen wellbeing, act as spaces for education to enhance preparedness for any future disasters, reducing stress, and contribute to rebuild a sense of place identity by symbolising the rehabilitation of the communities more widely. In a comparable vein, Mukherjee et al. (2022) examine the broader contribution of natural ecosystems to community well-being. They suggest that the development of accessible, aesthetically enriching natural areas - including urban wetlands, green corridors, and multifunctional parks - can support leisure, recreation, and educational activities, which are particularly beneficial for psychosocial resilience both before and after disaster events.

a4 - Community building and social cohesion

Community building is a major benefit of GI, NBS and ES, particularly in fostering social cohesion and participatory disaster risk reduction. Several reviewed studies emphasize that community participation in NBS implementation improves disaster preparedness and local adaptation. Mukherjee et al. (2022) demonstrate how engaging communities in NBS design empower local stakeholders, creating a sense of shared ownership that strengthens social ties and collective capacity to cope with disasters. This social dimension becomes especially pertinent in seismic events, where recovery often depends on the rapid mobilization of community networks and resources. Mabon (2019) also argues that post-disaster recovery should include ecosystem-based approaches that strengthen social ties and rebuild local identity. In Fukushima, for example, community-driven planting and maintenance of green spaces allowed residents to actively participate in recovery, which both rebuilt social cohesion and created functional landscapes for safety, such as open evacuation areas and community assembly spaces. López-Saavedra et al. (2023) and Renaud et al. (2013) further advocate for inclusive risk communication and participatory planning processes, ensuring NBS are co-designed with local populations to maximize local social networks and collective resilience. These approaches not only improve preparedness but also create feedback loops where community engagement strengthens the effectiveness of NBS in mitigating cascading disaster impacts.

a5 - Sustainable development and environmental co-benefits

The integration of GI, NBS and ES not only enhances disaster resilience but also contributes significantly to the advancement of broader sustainable development goals. López-Saavedra et al. (2023) underscore this dual potential by examining volcanic islands in Spain as exemplary contexts where effective risk management strategies - such as reforestation, slope stabilization, and coastal ecosystem restoration - can function as catalysts for sustainable development. They show that these interventions, when planned with local communities, simultaneously reduce landslide and tsunami exposure while supporting agriculture and tourism livelihoods, demonstrating co-benefits beyond disaster mitigation. By integrating NBS into multi-hazard risk planning, these regions can simultaneously reduce risks and support local economies and ecosystems. This integrative approach demonstrates that resilience-oriented planning, when aligned with ecosystem-based principles, can yield co-benefits that extend beyond disaster mitigation to encompass long-term sustainability outcomes, including enhanced biodiversity, soil protection, and livelihood opportunities.

Kumagai et al. (2013) argue that maintaining and expanding protected ecosystems, such as natural parks, serves as a cost-effective strategy for DRR. Over the long term, these ecosystems contribute to sustainable development by safeguarding biodiversity and delivering ecosystem services, including carbon sequestration, water regulation and habitat preservation, that contribute to sustainable development while reducing vulnerability to cascading hazards like floods and landslides. Similarly, Mukherjee et al. (2022) argue that embedding ecological conservation within urban planning strategies through interventions such as urban green corridors, wetland restoration, and multifunctional green space, not only mitigates disaster risks but also supports sustainable growth. This is achieved through the provision of recreational spaces, improved air quality, and fostering community well-being. Zhang et al. (2024) further explore the transition toward resilient regulatory approaches in urban agglomerations that are exposed to ecological risks. Their analysis emphasizes the necessity for urban planning to adopt sustainability-oriented principles by considering cumulative risks and the functional interdependencies of urban systems, ensuring that NBS and GI not only strengthen disaster resilience but also promote long-term sustainable development and systemic urban resilience. The authors advocate for urban systems to recognize their spatial and functional interdependencies and to implement integrative frameworks that align risk governance with long-term sustainable growth strategies, thereby ensuring systemic urban resilience.

b) Implementation Approaches

The second overarching dimension of the identified thematic framework concerns the implementation approaches through which nature-based strategies are operationalised in disaster risk reduction. This dimension reflects the practical pathways, planning processes, governance mechanisms, and design considerations identified in the literature that enable the effective integration of GI, NBS, and ES. Exploring these approaches provides insight into how theory translates into practice and the key factors that shape successful adoption and management of nature-based resilience measures.

b1 - Risk-sensitive Land use planning

Land use planning emerges as a top-down pivotal instrument in the integration of GI and NBS into disaster risk reduction strategies through strategic zoning and conservation of green spaces to serve as seismic buffers. As emphasized by Kumagai et al. (2013) and Mukherjee et al. (2022) the protection and maintenance of natural ecosystems through the designation of protected areas play a fundamental role in mitigating disaster impacts and preserving critical ES. Specifically, Kumagai et al. (2013) highlight that protected areas, when strategically maintained around critical infrastructures and steep slopes, can function as natural seismic buffers, reducing soil instability and limiting secondary hazards such as rockfalls or landslides following earthquakes. Kato and Huang (2021) emphasize the necessity for land use change policies to adhere to risk-sensitive zoning principles, thereby preventing urban encroachment into hazard-prone areas. Particularly, their findings demonstrate that integrating green corridors and riparian buffer zones within urban land use plans helps control downstream flooding and sedimentation after earthquakes, especially in regions where seismic shaking compromises drainage and surface permeability. López-Saavedra et al. (2023) advocate for the systematic integration of hazard-related information into land use planning as a means to reduce risk exposure. Their work on volcanic islands demonstrates how ecosystem-based zoning - such as conserving mangrove belts and restoring volcanic forest slopes - can simultaneously stabilize land, prevent soil erosion triggered by seismic tremors, and sustain livelihoods, effectively embedding NBS into regional planning frameworks.

Salata and Uzelli (2023) highlight the importance of sustainable soil management practices in mitigating the multi-dimensional vulnerabilities of urban environments. They show that neglecting geological and soil characteristics in urban planning, as observed in the case of İzmir (Türkiye), can amplify seismic risk through uneven settlement and ground failure - underscoring the need to integrate soil and vegetation-based stabilization strategies (e.g., slope revegetation, permeable green cover) into land-use regulation. Sutrisno et al. (2022) argue that incorporating hazard mapping into urban planning allows authorities to identify at-risk areas and implement measures such as green buffers and permeable surfaces that reduce flood and landslide risks following seismic events. Their findings emphasize the critical role of land use planning in reducing the vulnerability of cascading disaster-prone areas and infrastructures (e.g. to landslides) utilising the concept of mitigation and adaptation-based spatial planning. Specifically, they propose that post-earthquake reforestation and slope restoration in previously cultivated or deforested areas act as long-term NBS interventions that enhance slope stability and water retention, thereby reducing future seismic and hydrological hazards. Similarly, Bastani et al. (2024) provide an applied example from informal settlements in Mashhad, Iran, where land use planning integrated with green open spaces and vegetation buffers was shown to improve accessibility and reduce seismic vulnerability by providing flexible, low-density zones that can serve as safe gathering areas post-disaster.

b2 - Community Participation and co-design

In terms of how these solutions are operationalised, a significant number of articles underscores the critical role of community participation in the effective implementation of GI, NBS and ES within disaster risk reduction (DRR) frameworks. Engaging local communities in the co-design, planning and implementation of such interventions is widely recognised as essential to ensure their long-term efficacy, contextual relevance, and long-term sustainability. López-Saavedra et al. (2023) call for inclusive risk communication and participatory planning to enhance societal safety. Specifically, their work on volcanic islands in Spain provides concrete examples of how local communities were involved in ecosystem restoration activities, such as the rehabilitation of degraded slopes and forested areas, which both reduced erosion risks and strengthened local capacity to maintain natural buffers against seismic and volcanic hazards. Similarly, Khan et al. (2023) argue that NBS should be co-designed with communities to guarantee that solutions address local vulnerabilities and leverage indigenous knowledge for disaster resilience. They emphasize that incorporating local experience - such as traditional slope management or water retention practices - can improve the design of NBS in earthquake-prone areas by aligning interventions with existing cultural and ecological practices, ensuring their acceptance and maintenance over time. Bastani et al. (2024) and Mukherjee et al. (2022) both illustrate how early and inclusive engagement of diverse local stakeholders, including residents, small businesses, and non-governmental organizations, ensures the alignment of GI and NBS measures with community priorities and values. For instance, Bastani et al. (2024) show that in informal settlements in Mashhad, Iran, participatory upgrading initiatives involving community-led mapping and planning helped identify safe evacuation routes and open spaces that could double as temporary shelters, improving preparedness for seismic emergencies. This co-production of knowledge not only refines technical designs but also reinforces the legitimacy and acceptance of interventions, which is crucial for both flood and seismic risk reduction. Especially, Mukherjee et al. (2022) explicitly call for a paradigmatic shift from conventional top-down DRR models toward new proactive responses with community participation, that leverage emerging technologies to support inclusive governance and culturally relevant communication strategies for building resilience. Their case studies across five South Asian cities illustrate that participatory GIS and community monitoring tools can empower local groups to identify seismic hotspots, prioritize NBS interventions, and track the long-term effectiveness of risk mitigation actions. Particularly, they highlight how participatory models foster adaptive governance systems and empower communities to play a more central role in shaping their risk landscapes. Mabon (2019) reinforces this perspective by demonstrating how post-disaster recovery in Fukushima benefited from community-driven green spaces that contributed not only to ecological restoration but also to rebuilt social networks. In the aftermath of the earthquake and nuclear disaster, residents were actively involved in replanting and maintaining green areas, which served both as symbols of renewal and as physical spaces that supported psychosocial recovery. After a disaster "building back greener" with NBS and ES cultural services may help citizens rebuild a sense of pride and local identity by symbolising the rehabilitation of the communities more widely. This highlights that community participation in NBS design not only strengthens disaster preparedness but also plays a pivotal role in long-term recovery and resilience-building processes following seismic events.

b3 - Environmental Impact Assessment (EIA)

Environmental Impact Assessment (EIA) emerges as a valuable, though underutilised, implementation approach for integrating NBS into seismic risk reduction. Mukherjee et al. (2022) and Renaud et al. (2013) argue that embedding Nature-Based Solutions and multi-risk considerations into Environmental Impact Assessment processes helps prevent less frequent or less visible hazards from being overlooked in favour of more commonly addressed risks such as flooding or heatwaves. Specifically, Mukherjee et al. (2022) highlight that systematic integration of ecosystem-based indicators within EIA frameworks can guide decision-makers to evaluate how proposed projects influence soil stability, water infiltration, and vegetation cover - all of which are critical factors in reducing earthquake-induced landslides and ground failure. In their South Asian case studies, the authors show how incorporating NBS performance metrics into project screening allowed local authorities to prioritize urban greening and slope restoration initiatives that enhance both ecological and seismic resilience. Through systematic evaluation of ecological and social impacts, EIAs can support the selection of projects that deliver co-benefits enhancing biodiversity, human well-being, and resilience to both immediate shocks and cascading hazards. Renaud et al. (2013) further argue that applying EIA as a regulatory entry point for NBS enables the early identification of ecosystem services that can mitigate seismic impacts, for example, by using forested buffers to stabilize slopes in mountainous regions or preserving mangroves and wetlands in coastal zones prone to tsunami inundation following seismic events. This positions EIAs as a potential regulatory lever to align NBS interventions with broader disaster resilience and sustainability goals. However, only a limited number of studies in the reviewed literature explicitly incorporate EIAs in relation to seismic risk, indicating that this approach is not yet mainstreamed. Nonetheless, both Mukherjee et al. (2022) and Renaud et al. (2013) emphasize the need for mandatory EIAs in seismic-prone regions, particularly within infrastructure development, to ensure that NBS elements such as wetlands, vegetated buffers, or urban forests contribute meaningfully to both ecological integrity and disaster mitigation.

4. Discussions

This review explores how ecological approaches and tools such as GI, NBS, and ES are conceptualised and applied in the field of seismic and multi-risk disaster resilience. The combined bibliometric and qualitative thematic analysis reveals a complex and evolving research landscape, in which GI and NBS are increasingly regarded as essential components in the design of targeted risk reduction strategies, particularly in earthquake-prone urban and regional contexts (Ergün Konukcu, 2023; Mabon, 2019; Mukherjee et al., 2022). This aspect reflects a deepening re-conceptualisation of what constitutes effective disaster risk reduction (DRR), particularly in earthquake-prone areas where risk is complex, layered, and often cascading.

The review of the literature emphasizes a critical role of spatial planning in integrating ecosystem-based approaches into seismic risk strategies, highlighting opportunities and current limitations, and reveals key challenges that should be addressed. Firstly, the analysis of the three queries shows that the development of planning and design strategies for risk reduction and mitigation still largely follows a conventional approach. In this framework, environmental and ecosystem-related dimensions are primarily addressed through land use regulation, while the strategic potential of green management and ecological restoration operationalised through targeted tools such as GI, ES, and NBS, remains only marginally explored. This gap is particularly evident in the results of Query 3, where the combination of keywords such as *land use planning* linked to *design action* and *open space/green space/area*, primarily associated with traditional zoning approaches, produced the highest number of results compared to Queries 1 and 2.

Several studies also demonstrate how targeted *land use regulations* and *hazard-sensitive zoning* can effectively reduce ground instability and cascading effects in high-risk areas, confirming the potential of institutionalizing risk-sensitive ecological zoning to help bridge the gap between resilience theory and planning practice, particularly in seismic-prone contexts (Kato & Huang, 2021; Kumagai et al., 2013; Mukherjee et al., 2022; Salata & Uzelli, 2023; Sutrisno et al., 2022). Nevertheless, the capacity to develop context-specific, nature-based risk management strategies - specifically in relation to seismic risk - through the integration of GI and NBS into planning practices, remains limited. Although their role as strategic tools for sustainable urban ecosystem planning is well established, particularly within European policies, NBS and GI continue to be framed primarily in terms of conservation and climate adaptation, rather than as instruments for disaster risk reduction (DRR). This aligns with EU policy key component in ecosystem restoration for climate adaptation such as Nature Restoration Law inside the EU Biodiversity Strategy, where explicit references to DRR remains marginal. Recognising the multifunctional role of ecosystems – not only as ecological assets but also as active components of mitigation strategies - would strengthen the strategic integration of NBS and GI into risk management frameworks at both policy and governance levels, and consequently into spatial planning processes. This would help overcome sectoral fragmentation in local governance and promote integrated risk management, as called for by the Sendai Framework for Disaster Risk Reduction (SFDRR) (Antofie et al., 2025). To achieve this, it becomes essential to: a) strengthen local governance capacities, which could open new pathways for cross-sectoral coordination, investment, and implementation in EU member states where seismic risk is present; b) address the operational gap in multi-risk governance, by developing and testing standardised methodological frameworks that integrate NBS and GI for risk reduction by targeting both the exposure and vulnerability component of risk. These two recommendations pave the way for the experimental integration of Nature-based instruments for Disaster Risk Reduction (DRR) into sector-specific planning frameworks, including Environmental Impact Assessment (EIA), Strategic Environmental Assessment (SEA), and Green or local masterplans.

Concerning these instruments, while the role of EIA clearly emerged from the *Theoretical framework*, the potential contribution of SEA remains comparatively underexplored. Indeed, integrating the two instruments could provide a more comprehensive framework for embedding Eco-DRR principles within formal policy and planning processes, while both operate at the interface between top-down and bottom-up approaches, facilitating the inclusion of local knowledge often neglected in expert-driven planning and thus improving the contextual relevance of mitigation strategies (Arts & Morrison-Saunders, 2004). In the European context, strategically adopting EIA and SEA could offer a structured and legally grounded pathway for incorporating NBS into land-use and urban planning, addressing ecological trade-offs and enhancing resilience outcomes. SEA, in particular, functions at a broader strategic scale, embedding environmental and climate considerations into plans and programs from the earliest stages of decision-making. By aligning spatial, environmental, and socio-economic goals, SEA supports proactive and integrated governance, ensuring that sustainability objectives are pursued alongside development priorities and advancing the shift toward ecosystem-based planning models.

Sectoral instruments such as Green or local masterplans play a

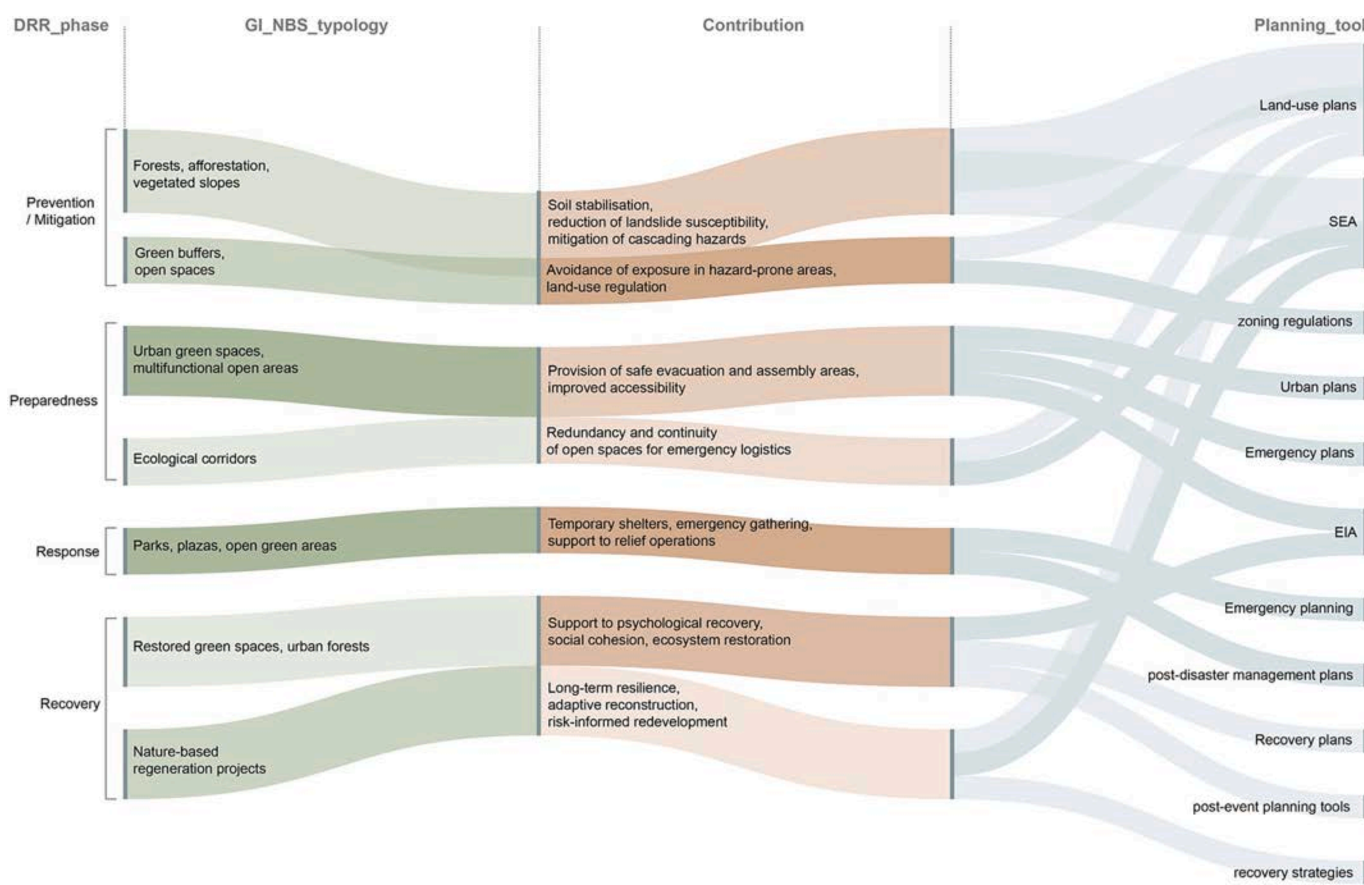

Fig. 10. Relationships between GI and NBS typologies, DRR phases, contributions to seismic resilience, and planning tools. The diagram highlights how GI and NBS support seismic resilience across prevention, preparedness, response, and recovery through ecosystem-based mechanisms, primarily influencing exposure, vulnerability, and post-disaster recovery. The alluvial diagram was performed with RAWGraphs.

crucial role in strategic planning, design, and management of natural resources within urban ecosystems (Di Marino et al., 2019; UNDRR, 2015). These frameworks not only support the integration of risk management considerations but also help assess the long-term feasibility of implementing NBS and GI (Longato et al., 2024). Strengthening cross-sectoral experimentation within planning tools oriented toward environmental management and disaster risk governance (Jeong et al., 2021; Zhang et al., 2024) can foster applied research and the development of standardised yet context-sensitive frameworks for multi-risk governance (Pantaloni et al., 2022). Such an integrated approach enables decision-makers to design strategies that are both scientifically grounded and capable of addressing complex and interconnected risks (Bernardini et al., 2025). Moreover, these planning instruments are fundamental for promoting NBS implementation and developing a long-term vision of GI to be incorporated into urban plans. Integrating multi-hazard evaluation and ecosystem service mapping (UNDRR, 2017b) to guide GI design can provide a methodological basis for embedding NBS in spatial planning for DRR (Fig. 10).

To do so, both regulatory and incentive-based measures should be considered. From a regulatory perspective, introducing prescriptive or prohibitive measures to mitigate secondary earthquake effects in urban green spaces would be particularly effective in transformation areas (UNDRR, 2020). In rural contexts, incentive mechanisms encouraging NBS for hazard mitigation and resilient agriculture (Nicholls et al., 2020) can foster sustainable landscape management, reduce hydrogeological risks, and restore key ecosystem functions such as flood and drought regulation, ultimately helping to prevent land degradation (Nehren et al., 2023).

Moreover, the analysis of the *Benefits* suggests that the implementation of GI and NBS for risk prevention and territorial vulnerability reduction can also bring a wide range of consequent/positive outcomes that enhance the overall quality of life in everyday/non-emergency contexts. GI and NBS are particularly valuable as dual-function interventions, offering both every day and emergency benefits within urban systems exposed to cascading disaster scenarios (Slater & Birchall, 2022). During non-crisis periods, these nature-based strategies enhance urban liveability by providing high-quality public spaces and delivering a wide array of ES including microclimate regulation, biodiversity support, recreational opportunities, and psychological well-being (Mabon, 2019; Mukherjee et al., 2022; Rus et al., 2018). These everyday functions not only enhance urban sustainability and strengthen social cohesion but also generate spatial and cultural benefits that become critical in post-disaster contexts. By maintaining active and inclusive public spaces, green infrastructure supports community identity and continuity, which are essential for recovery and psychological well-being after disruptive events. Moreover, such multifunctional spaces contribute to long-term economic resilience by increasing property values and reducing recovery and reconstruction costs. In this way, green infrastructure and NBS-based strategies can reinforce the economic dimension of DRR, aligning environmental, social, and financial sustainability objectives within urban planning and management.

In the aftermath of seismic events and related cascading hazards such as landslides, fires, or infrastructure failure, these multifunctional open and green spaces can be rapidly repurposed for emergency response, acting as evacuation zones, temporary shelters, staging areas, or locations for emergency services (French et al., 2019; Russo et al., 2022; Sutrisno et al., 2022). Their strategic distribution and accessibility across the urban fabric support effective crisis management and enhance population safety. Furthermore, such spaces play a role in post-disaster ecological and social recovery by enabling ecosystem restoration, offering symbolic and functional settings for community healing, and reinforcing local identity (López-Saavedra et al., 2023; Mabon, 2019; Renaud et al., 2013).

In addition, the role of community engagement, especially in the post-disaster recovery phase, is emphasized as a key factor in strengthening local identities and fostering a more conscious management of the territory and the ES associated.

This confirms that place-based resilience can only be achieved by simultaneously strengthening local communities. Accordingly, investing in initiatives that foster local knowledge and awareness of disaster preparedness and risk management is a fundamental prerequisite for the conscious and effective handling of future emergencies.

Such bottom-up engagement enables communities to proactively manage disaster risks, reinforcing their adaptive capacity while preserving ecological functions. In line with the EU's democratic governance principles under the Aarhus Convention (UNECE, 1998; Wouda Kuipers & Korwatanasakul, 2024), supporting these initiatives through participatory governance helps create multifunctional ecosystems that not only mitigate hazards, but also serve as spaces for cultural identity, social cohesion, and individual well-being, while ultimately fostering more resilient and empowered communities. However, these efforts require stronger institutional support in order to be systematically embedded within risk governance processes.

In response to the conceptual barriers limiting the effective integration of GI, NBS, and ES into seismic risk reduction strategies, we propose the following set of recommendations:

1. Mainstream seismic risk within EU strategies that currently focus on climate and biodiversity, ensuring that NBS are recognised as multi-hazard solutions.
2. Support local implementation through dedicated funding streams, technical toolkits, and capacity-building initiatives.
3. Foster cross-sectoral collaboration, aligning DRR, urban planning, health, and environmental policy through integrative governance models.
4. Expand the scope of EIA and SEA regulations and guidance, incorporating seismic scenarios and ecosystem-based responses.
5. Invest in monitoring and evaluation to document the performance of NBS in real disaster events, thereby strengthening the evidence base for policy and planning.

Lastly, some limitations should be acknowledged. The exclusion of grey literature from the bibliometric search and analysis may have omitted valuable insights from non-academic sources, and the language filter may have biased results toward English-speaking research communities.

Future research should prioritize empirical case studies aimed at assessing the long-term performance of Nature-based Solutions and green infrastructure in multi-hazard contexts. Particular attention should be devoted to exploring socio-economic trade-offs by evaluating post-disaster recovery cost reduction and the potential increase in land and property values. Furthermore, future studies should test the replicability and scalability of successful models across diverse environmental, cultural, and governance contexts, in order to identify transferable frameworks and context-sensitive design principles for disaster-resilient urban planning.

Interdisciplinary collaboration, bridging urban planning, ecology, engineering, and public policy, will be essential to advance integrated and context-sensitive solutions.

5. Conclusions

This systematic review has demonstrated the growing relevance of Green Infrastructure, Nature-Based Solutions and Ecosystem Services in enhancing seismic resilience and supporting disaster risk reduction. The study sought to clarify the role of these applications in mitigating seismic risk, to identify their associated benefits, and to explore implementation strategies. A rigorous methodological framework was applied, combining peer-reviewed literature from Scopus and Web of Science with bibliometric analysis and qualitative synthesis, all structured in accordance with PRISMA guidelines. This approach enabled the identification of thematic trends and methodological advances, while ensuring analytical transparency.

The review reveals increasing academic interest in the integration of GI and NBS within disaster risk frameworks, particularly in seismically active regions such as Japan, Turkey, and Iran.

However, applications targeting seismic risk remain limited when compared to more extensively studied hazards. Key findings emphasize the multifunctional benefits of GI and NBS, including their capacity to mitigate earthquake cascading effects, strengthen community resilience, and contribute to broader environmental and social well-being. Despite this potential, regulatory and empirical gaps remain, particularly in the integration of ecosystem-based approaches within formal planning instruments.

Methodologically, the reviewed studies adopt diverse tools, from geospatial modelling and multi-criteria decision-making to participatory governance mechanisms. These approaches highlight both ecological and socio-economic benefits, including reduced recovery costs and enhanced adaptive capacity. Yet, few studies empirically evaluate the effectiveness of ecosystem-based solutions in seismic contexts, limiting evidence-based guidance for policymakers and practitioners.

Two primary implementation pathways emerged from the literature: top-down regulatory instruments and bottom-up community engagement. Within the top-down framework, land-use planning and Environmental Impact Assessments (EIAs) are recognised as critical mechanisms for institutionalizing GI and NBS within risk governance structures. Nevertheless, their application remains fragmented, highlighting the need for more robust regulatory mandates and operational guidelines to ensure consistent integration. In contrast, bottom-up participatory approaches grounded in local knowledge and emphasizing co-designed interventions, demonstrate strong potential for aligning NBS strategies with community needs and priorities, thereby strengthening long-term resilience and fostering social legitimacy.

Although European research on NBS for seismic risk remains underdeveloped, the region holds significant potential for advancement. Countries in Southern Europe such as Italy, Greece, Turkey, and the Balkans, are particularly well-positioned to benefit from integrating GI and NBS into spatial planning and climate adaptation strategies. The EU Green Deal and Biodiversity Strategy offer supportive policy frameworks for embedding these approaches into national resilience agendas.

By embedding ecological principles into land-use planning and urban governance, GI, NBS and ES can play a pivotal role in enhancing resilience to both seismic and cascading hazards. Moving forward, stronger regulatory frameworks, inclusive governance, and long-term investment in monitoring and evaluation will be critical to mainstreaming such applications within seismic risk reduction strategies.

In this pathway, future directions within the spatial planning and regulatory framework should include, for example, the adoption of targeted methods for monitoring the effectiveness of NBS, and cost–benefit assessments of NBS in seismic-prone areas to evaluate their economic feasibility and long-term capacity to reduce multi-hazard risks while delivering complementary ecosystem benefits. Finally, the integration of design-based, regulatory, and incentive-based instruments should be promoted to foster NBS and GI implementation in urban plans and to update existing regulatory and policy frameworks. As urban regions worldwide face compounding climate and disaster risks, ecosystem-based approaches offer a promising pathway toward more adaptive, equitable, and sustainable urban futures.

CRediT authorship contribution statement

Monica Pantaloni: Writing – review & editing, Supervision, Methodology, Investigation, Conceptualization. **Marta Ducci:** Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation. **Luca Domenella:** Writing – review & editing, Conceptualization. **Giovanni Marinelli:** Validation, Supervision, Funding acquisition, Conceptualization.

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.

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Data availability

Data will be made available on request.

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