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# Geoheritage Degradation Risk Assessment: Methodologies and Insights

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**Abstract:** Over the past 25 years, geoconservation studies and interest in geoheritage have grown significantly. However, the assessment of degradation risks associated with geosites remains less explored. This aspect is crucial for the effective management and conservation of geosites, which face pressure from natural and human factors. In many countries, geosites are at risk of degradation or loss due to the lack of a systematic inventory and inadequate management. Therefore, evaluating and monitoring degradation risks is a priority for the scientific community. Common investigation schemes and approaches for recognizing and preventing threats to geosites are still lacking. This paper presents the first systematic literature review on degradation risk and related terms. Through an extensive search of widely used literature databases, 130 papers were selected and analyzed. The findings highlight a growing focus on quantitative approaches for the assessment of geoheritage degradation risk, with most research conducted at local scales, while identifying climate change as an underexplored yet critical factor. Future priorities include refining spatial and temporal scales, understanding degradation processes, and fostering global collaboration to improve conservation strategies.

**Keywords:** risk of degradation; geoheritage; threats to geosites; vulnerability; fragility

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**Citation:** Vandelli, V.; Selmi, L.; Faccini, F.; Ferrando, A.; Coratza, P. Geoheritage Degradation Risk Assessment: Methodologies and Insights. *Sustainability* **2024**, *16*, 10336. https://doi.org/10.3390/su162310336

Academic Editor: Tommaso Caloiero

Received: 10 October 2024
Revised: 19 November 2024
Accepted: 21 November 2024
Published: 26 November 2024

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## 1. Introduction

Geoheritage is an essential component of the global natural heritage. It encompasses key sites, known as geosites, and objects—such as rocks, minerals, fossils, and landscapes—that have key roles in our understanding of the history of the Earth [1,2]. Due to their scientific, educational, and cultural value, these sites and objects are worthy of protection. The growing global interest in geoheritage and its conservation is reflected in initiatives such as the project of UNESCO International Geoscience and Geoparks Programme on "Geological Heritage Sites", which is managed by the International Union of Geological Sciences (IUGS) [3,4]. However, one aspect of geoheritage that has received comparatively little attention is the assessment of the degradation risks faced by geosites. This topic is, nevertheless, of critical importance, as it provides essential information for the effective management and preservation of these valuable sites. In fact, geoheritage is constantly under pressure due to natural or anthropogenic factors and processes. In numerous contexts, geosites face degradation risk, which could result in their complete loss due to the lack of an inventory and the consequent ineffective management [5]. Research for the evaluation of degradation risk and for monitoring the state of conservation of geosites, therefore, should be a priority for the scientific community. Despite this, few studies have dealt with the concept of geosites' degradation risk, leading to the use of ambiguous terminology, with some of the terms being used interchangeably. Degradation risk is understood as the susceptibility to the deterioration of a geosite. Admittedly, its assessment is fundamental to have an overview of a geosite's state of conservation and to schedule a correct monitoring plan in order to preserve geoheritage relevance and/or restore stable conditions that were lost. As reported by Selmi et al. [5], the concept of fragility and the need for geosites' protection were introduced by Brilha [6], focusing solely on human-induced threats. Subsequent studies have been conducted on this topic (e.g., [7–10]), although they have consistently used different terminology and only partially addressed the factors contributing to degradation risk (cf. [5] and references therein).

Garcia-Ortiz et al. [11] conducted one of the first comprehensive studies focusing on the assessment of degradation risk concerning geoheritage, aiming to establish a unified framework for specialists in geoconservation. Their approach foresaw three main criteria for the degradation risk assessment: fragility, vulnerability, and public use. In a more recent study, Brilha [12] expanded on this concept within geosites' assessment, introducing five degradation risk parameters that encompass both natural and anthropogenic factors. A decade following Garcia-Ortiz's review, it was essential to update the existing knowledge regarding the assessment of degradation risk, serving as a reference for those undertaking similar studies. Indeed, it can be highlighted that the recognition and prevention of threats affecting geosites still lack common investigation schemes and approaches. In this context, this paper presents research aimed at providing the first systematic and updated literature review on degradation risk and related terms. In particular, the research is aimed at (i) understanding how methods of geoheritage degradation risk developed and comparing them; (ii) shedding light on terms related to degradation risk; (iii) laying the groundwork for the implementation of a generalized methodology/approach to assess geoheritage degradation risk. By examining a range of concepts and approaches, we aim to equip those involved in this field with the tools to select or tailor a methodology that best fits their specific case study, while also offering meaningful insights for research focused on geoheritage conservation.

## 2. Materials and Methods

In order to collect and analyze studies dealing with the degradation risk of geoheritage, a literature search was performed in Scopus and Web of Science (WoS) by applying the following research query to "title", "abstract" and "keywords": (sensitivity OR vulnerability OR fragility OR threat*) OR degradation AND risk) AND (geosite* OR geoheritage OR geomorphosite*). All types of documents were considered (e.g., articles, conference papers, book chapters, reviews). The literature search did not have a specific end-date constraint, and all relevant articles indexed in the database as of 19 June 2024, when the research was conducted, were included.

Articles were considered eligible for the review if they (i) addressed the risk of degradation (or vulnerability, fragility, etc.) of geoheritage; (ii) evaluated geoheritage including degradation risk (or similar criteria) in the assessment methodology; or (iii) focused on geoheritage management with attention to degradation risk (or related terms). On the other hand, articles were excluded if they solely discussed the risk or threats faced by visitors/geotourists, as well as articles that marginally cite geoheritage degradation risk (or related terms).

The review was performed in several steps (see Figure 1): (i) Papers were retrieved through Scopus and Web of Science, and they were exported in *csv* and *bibtext* formats, respectively; (ii) the retrieved papers from both literature databases were merged, and duplicate papers were removed using the R-Studio tool bibliometrix (version 4.1.4) [13]; (iii) the papers were then screened and selected according to the above-listed eligibility criteria by title, abstract, and keywords; (iv) selected papers were included in or excluded from the final list after full-text reading; and (v) a check of the completeness of the literature search was performed by consulting Google Scholar and the reference list of the papers selected in the previous step.

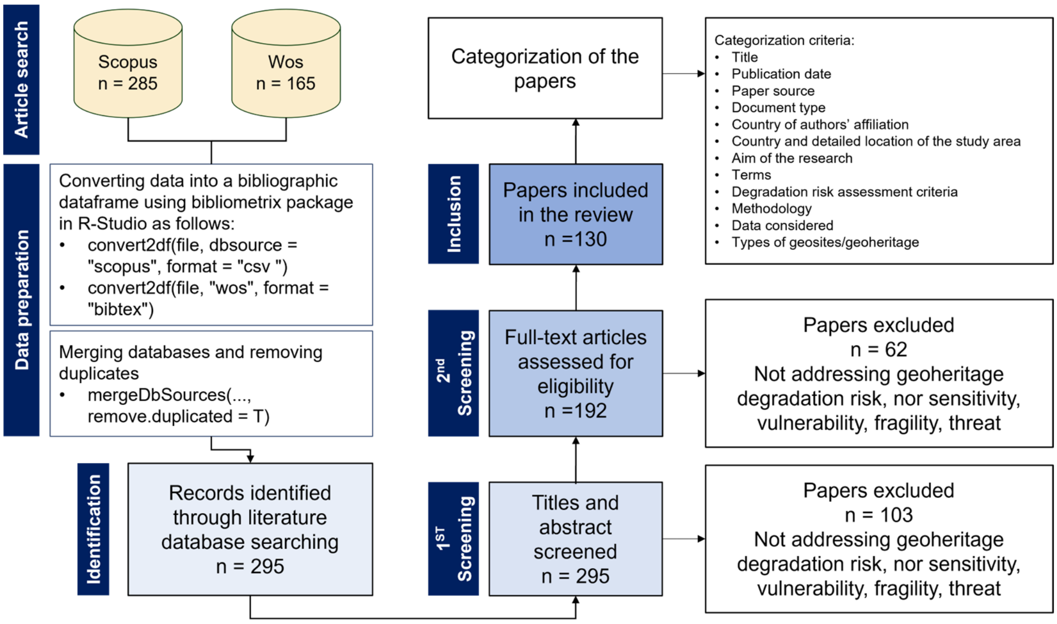


**Figure 1.** Workflow of the literature search on geoheritage degradation risk.

A combined total of 450 papers was sourced, with 285 from Scopus and 165 from WoS. After excluding duplicates (165), 192 papers were deemed eligible based on screening criteria applied to titles and abstracts. The final selection comprised 130 papers, which were catalogued in an Excel sheet (cf. Table S1 in the Supplementary Materials) with detailed information, as outlined below:

- Title
- Publication date
- Paper source (Scopus/WoS)
- Document type (e.g., research article, book chapter, review article)
- Country of authors' affiliation
- Country and detailed location of the study area
- Aim of the research (e.g., inventory, management, assessment, conservation, degradation risk, geotourism, education)
- Terms (e.g., sensitivity, fragility, vulnerability)
- Criteria for the assessment of the degradation risk
- Assessment methodology
- Data considered (e.g., field data, data retrieved from literature, remote sensing data)
- Types of geosites/geoheritage based on the classification by Ruban [14], Ruban and Kuo [15], and Zorina and Silantiev [16].

The papers were analyzed and discussed based on a temporal and spatial perspective (cf. Section 3.1), considering (i) the time distribution referring to the publication year; (ii) the scale of analysis (local, regional, national/federal, global), (iii) the location of the study area, and (iv) the collaboration network among authors based on their country of affiliation.

Concepts and methods related to the degradation risk assessment were also discussed based on information extrapolated from the selected literature (cf. Section 3.2). Additionally, the main threats to geosites were examined and illustrated (cf. Section 3.3), also considering the type of geosites (e.g., geomorphological, paleontological, structural).

## 3. Results and Discussion

A summary and discussion of the principal outputs derived from the literature investigation is provided. Particular emphasis was placed on analyzing the papers according to the aforementioned aspects.

### 3.1. Overview of the Selected Papers

In this subsection, the papers are analyzed and discussed according to the year of publication, the scale of investigation (local, regional, national, or global), the location of the study area, and the collaboration network determined by the authors' countries of affiliation (Figure 2).

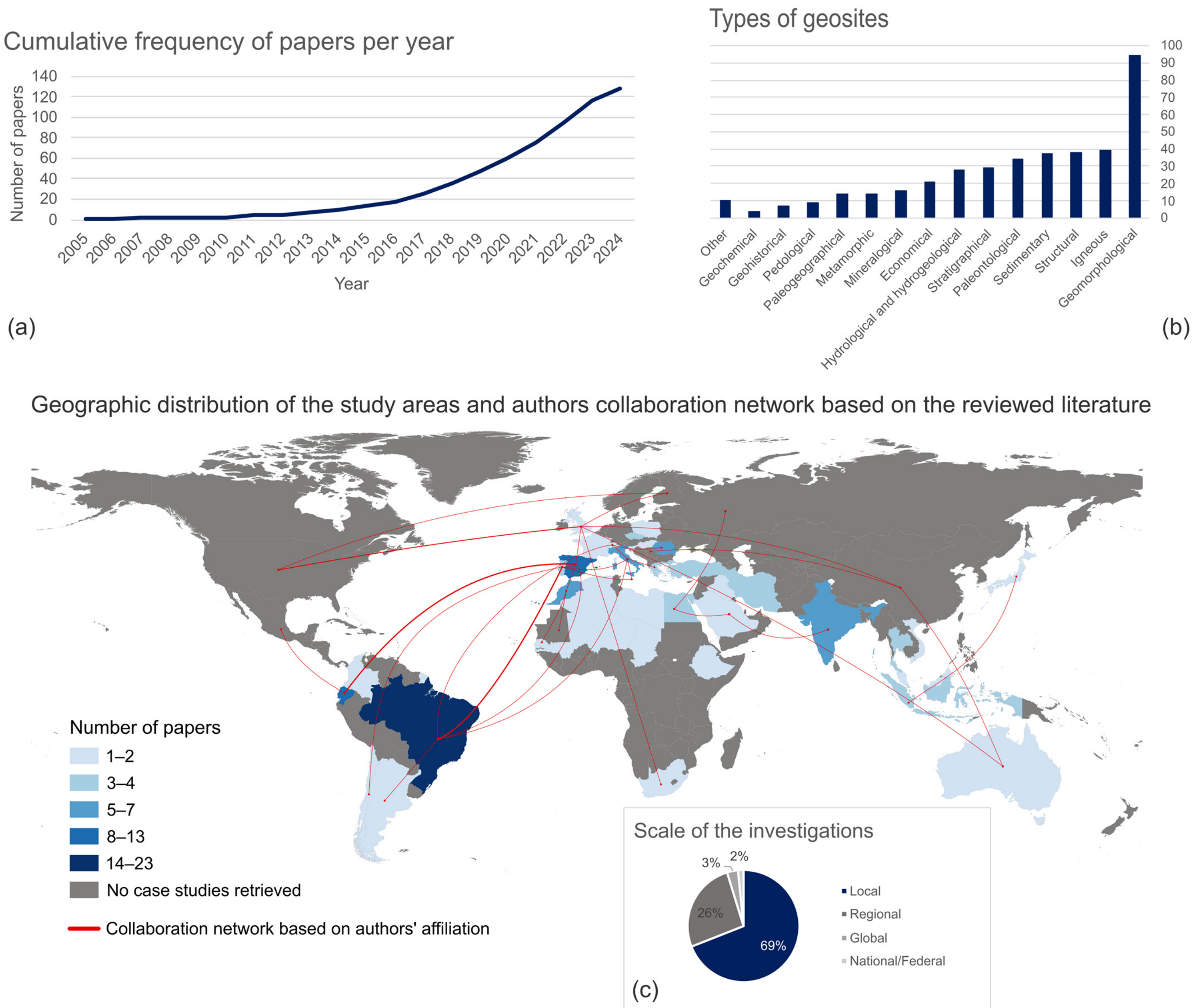


**Figure 2.** Spatial distribution of the study areas and collaboration network among authors in the selected literature. The plots in the frames illustrate (**a**) the cumulative curve of the number of papers published per year, (**b**) the number of papers for each type of geoheritage considered, and (**c**) the spatial scale of the studies in the reviewed literature.

#### 3.1.1. Temporal Distribution of the Reviewed Literature

Regarding the temporal distribution, the available literature on the assessment of degradation risk and related concepts began in 2005, with the first paper identified in our research authored by Bruschi and Cendrero [17]. In their geosite assessment methodology, the authors considered the "State of conservation" of geosites and "Potential threats", which were primarily related to anthropogenic interventions such as the number of inhabitants in the surrounding area and interest in mineral exploitation. Since 2016, there has been a progressive increase in articles on the topic. This rise is likely due to the publication by

Brilha (2016), who integrated the quantitative assessment of degradation risk through a series of indicators and criteria as part of a method for geosite assessment. The maximum number of papers was reached in 2023, with 22 papers. As of 19 June 2024, 12 papers have already been published on the topic, suggesting that by the end of the year, the number of relevant papers will surpass those published in 2023 (Figure 2a). This surge in scientific literature is positive, given the importance of assessing degradation risk related to geoheritage.

#### 3.1.2. Spatial Framework of the Reviewed Literature

Regarding the scale of investigation, most studies were conducted at a local level, focusing primarily on individual case studies (Figure 2c). These case studies were predominantly located in Brazil, which accounted for 23 papers; Spain, with 12 papers; and Ecuador, with 10 papers. India, Italy, and Morocco each contributed seven papers, while Romania had a total of six papers.

This distribution highlights a significant geographic concentration in the literature, with many countries lacking studies on the assessment of geoheritage degradation risk. Expanding the geographic scope of such investigations would provide a more comprehensive understanding of global geoheritage degradation risks and promote more effective conservation strategies worldwide.

As far as local investigations are concerned, study areas corresponded to specific geographic units such as islands (e.g., [18–20]), sectors of mountain ranges (e.g., [21–23]), valleys [24–27], estuaries [28], and sedimentary basins [29–31]. Others corresponded to local administrative units, including municipalities [32–34] and provinces [17,35–37]. Others refer to protected areas such as national parks (e.g., [38–42]) and geoparks [43–47].

Only two studies have been conducted on a national scale. In particular, Mansur et al. [48] propose practical actions for dealing with erosion and other weathering effects, restoring geosites damaged by vandalism, and implementing education projects. Their recommendations are based on various case studies conducted in Brazil, highlighting specific measures for the preservation and management of geosites. Sánchez and Brilha [49] provide a quantitative assessment of impact structures as part of geoheritage in Brazil. Their study systematically evaluates the significance of these features, contributing to the broader understanding and preservation of geoheritage in the region.

Four studies have been conducted at a global scale. Two of them focused on providing guidelines and examples of best practices in geoconservation. Crofts et al. [50] exemplified this by presenting best practices in establishing and managing protected and conserved areas for geoconservation (sensu [51]), including the analysis of the threats affecting geoheritage, and giving examples from around the world. Gordon et al. [52] extended the task regarding geoconservation in protected and conserved areas by presenting a comprehensive framework of strategies for mitigation and adaptation based on evaluating the risk of geosite degradation in the context of climate change. Other research conducted at a global scale includes the one illustrated in the paper by Vasiljević et al. [53], who investigated the geoconservation issue of loess sites in Eurasia, also discussing their threats. Additionally, by considering different geosites across the globe, Hjort et al. [54] explored the role of geodiversity in sustaining ecosystems and biodiversity, also analysing the threats that may affect geodiversity.

Furthermore, the collaboration between authors, based on their affiliations, was investigated. Figure 2 highlights that authors from Brazil and Portugal demonstrate the highest level of collaboration, co-authoring a total of nine papers. This is likely due to their shared history and language, which eases communication and collaboration.

Brazilian researchers exhibit a notably diverse network of collaboration regarding research on geoheritage degradation risk. In addition to their collaboration with Portuguese researchers, they also collaborate with colleagues from Argentina, Italy, Spain, and Switzerland.

Researchers affiliated with the United Kingdom also display a widespread collaborative network. UK researchers have co-authored papers with peers from Australia, China, Finland, Serbia, South Africa, Spain, and the United States, each representing one paper, except for collaborations with the USA, which amount to three papers. This extensive international collaboration highlights the global engagement and influence of UK researchers in the field of geoheritage degradation risk assessment.

Despite these instances of international cooperation, most papers are co-authored by researchers affiliated with the same country. This trend likely reflects the local scale at which most studies are conducted. As stated in the Zumaia Declaration of the IUGS [55], "International collaboration between countries and scientific organizations strengthens the science and best addresses global challenges. Scientific knowledge must be shared and supportive". Furthermore, the Zumaia Declaration also highlights that international collaboration among initiatives related to geodiversity and geoheritage can increase their appreciation, support sustainable educational use, and ensure preservation for society, future generations, and the well-being of our planet.

In this context, it is desirable to increase collaboration between authors from different countries to enhance the impact of research in this field. Such international partnerships could unify efforts and foster a more comprehensive understanding of the best strategies in degradation risk assessment.

### *3.2. Concepts and Methods Related to the Degradation Risk*

In this subsection, the most widely used methodologies for assessing degradation risk, as well as those that offer innovative approaches, are discussed. This analysis is crucial for providing a comprehensive overview of both established and novel methodologies. This discussion aims to support practitioners and researchers who are focused on addressing geoheritage degradation risk, as it offers insights into selecting or adapting a methodology that best suits their specific needs. It is worth mentioning that more than 70% of the reviewed literature addressed the topic of geosite degradation risk by considering a quantitative index-based approach. For a complete list of methods and criteria, please refer to Table S1 in the Supplementary Materials.

As illustrated in the previous section, the first efforts to assess degradation risk in relation to geoheritage date back to the early 2000s. Fuertes-Gutiérrez and Fernández-Martínez [56] provided one of the first comprehensive methodologies for quantitatively assessing degradation risk, considering both fragility and vulnerability. In their previous work, Fuertes-Gutiérrez and Fernández-Martínez [8] defined vulnerability as the risk of degradation due to human activities and fragility as the risk of degradation due to natural processes. Additionally, parameters such as accessibility, dimensions, proximity to human settlements, public influx, and present or potential threats were included in the overall assessment of degradation risk. Many studies have been based on the definitions provided by Fuertes-Gutiérrez and Fernández-Martínez [8,56], including those by García-Ortiz et al. [11], Brilha [12,57], Aoulad-Sidi-Mhend et al. [39], and Ferrando et al. [58]. Since these initial efforts, numerous other methods have been developed. Our literature review identified several predominant methodologies utilized in assessing geoheritage degradation risk (see Figures 3 and 4). The following sections systematically describe and discuss these key methodologies in order of their frequency of application across the reviewed papers.

Additionally, we include a discussion of SWOT analysis (cf. Section 3.2.4), even though it is not specifically designated for studying degradation risk. This method is widely employed across various contexts, e.g., business and project management, public policy, environmental sciences, education, and tourism. More recently, SWOT analysis has been widely applied also to geoheritage management, to identify Strengths, Weaknesses, Opportunities, and Threats associated with geoheritage conservation efforts.

#### 3.2.1. Degradation Risk Assessment Based on Fragility and Vulnerability

Among the numerous papers examined, a significant portion assessed degradation risk using the approach proposed by Brilha [12,57]. Specifically, out of the 128 papers (excluding those authored by Brilha in 2016 and 2018), 52 applied Brilha's methodology (e.g., [59–74]). This methodology incorporated degradation risk as a crucial aspect of geosite assessment. Similar to Fuertes-Gutiérrez and Fernández-Martínez [56], the author describes degradation risk as a synthetic value obtained by considering fragility (an intrinsic feature) and vulnerability (to anthropogenic actions) of the site. In particular, the author considered five criteria, including (i) the deterioration of geological elements related to the site's fragility and vulnerability; (ii) proximity to areas/activities with the potential to cause degradation, (iii) legal protection of the site or control of access (including, for example, fences and entrance fees); (iv) accessibility of the site to the general public, noting that sites with easier access are more likely to suffer damage from visitor misuse compared to those with difficult access; and (v) population density around the site, indicating the number of people living nearby who may cause potential damage (e.g., through vandalism). Each of these five criteria is assigned a score between 1 and 4 (a score of zero can also be assigned), based on four specific indicators for each criterion. Higher values represent greater risks to the geosite. The final degradation risk value is calculated from the weighted sum of the scores assigned to each of the five criteria. The authors also propose classifying degradation risk as low, moderate, or high for management purposes. For further details, refer to Brilha [12,57]. It is possible to argue that the success of this methodology lies in its integration within geosite assessment and its reliance on quite easily available data. For instance, field surveys can provide information on fragility characteristics, while population density data can be easily obtained in most countries. Additionally, the methodology is user-friendly, as the formula for calculating the final degradation risk involves a sum of five parameters. For these characteristics, the methodology developed by Brilha [12,57] is very valuable as a preliminary tool to identify geosites that could be exposed to degradation. It is relatively simple and offers an accessible approach to broadly categorize geosites based on the level of degradation risk affecting them. However, while this approach is effective as a starting point, a more in-depth assessment could benefit from the integration of additional, more specific criteria, adapted to different types of degradation risks and types of geosite. By broadening the assessment criteria, it is possible to gain a more nuanced understanding of degradation processes and the conditions that contribute to them. Over the years, Brilha's methodology has been modified by many authors to tailor the approach to the site's features. Recently, Ech-charay et al. [75] made slight modifications to the criteria of Brilha's methodology, discerning between natural and human impacts, considering (i) natural processes that could lead to geosite degradation (such as erosion, storms, and floods); (ii) the impact of human activities (including illegal excavation and fossil trafficking); (iii) proximity to areas hosting activities that could potentially damage the site (like factories or quarries) or areas with high population density (such as entertainment hubs or major cities); and (iv) the quality of infrastructure networks, as easier accessibility often correlates with higher visitor/tourist traffic, which can lead to damage. However, the scoring system and approach for calculating degradation risk remain consistent with Brilha's method.

#### 3.2.2. IELIG Method and Related Research

Another popular method for assessing degradation risk is the one developed by the Spanish Inventory of Places of Geological Interest (Inventario Español de Lugares de Interés Geológico, IELIG), implemented by the Geological and Mining Institute of Spain (IGME) [42]. This approach defines degradation susceptibility as the ease with which a geological site can degrade based on its size, fragility, and vulnerability (whether natural or anthropogenic). The method evaluates degradation susceptibility (SD) by summing scores assigned to specific parameters related to natural vulnerability (VN) and anthropogenic activities. These activities are further divided into general anthropogenic vulnerability

(VuG), vulnerability due to its proximity to infrastructures (VuI), vulnerability due to mining (VuM), and plunder (VuEX). Unlike Brilha's method (cf. Section 3.2.1), the IELIG method separately assesses the contributions of natural and anthropogenic factors to geosite degradation, considering susceptibility to natural (SDN) and anthropogenic (SDA) degradation. The total of these factors is multiplied by another factor inversely proportional to the site's size (EF) and divided by two.

$$SD = \tfrac{1}{2}\,(SDN + SDA) = \tfrac{1}{2}\,EF \cdot [VN + VuG + VuI + VuM + VuEX] \quad (1)$$

The risk of degradation is then calculated as the product of the geosite's value—whether scientific, educational, or touristic—and its susceptibility to degradation. For a complete description of the method, refer to Carcavilla Urquí et al. [76] and García-Cortés et al. [77,78]. Unlike other methodologies, the IELIG approach offers the distinct advantage of separately estimating the impacts of natural and anthropogenic factors on geosite degradation. By understanding what types of factors contribute most to deterioration, geosite managers can prioritize specific risk reduction actions, more effectively addressing natural or human-induced pressures.

The IELIG method has been extensively applied to various types of geosites, including volcanic, glacial, and hydrological features, in Ecuador [36,42,79–81]. It has also been utilized in the Santa Victoria mountain range in northern Argentina for assessing geomorphological and stratigraphical geosites [22], as well as for waterfall calc tufa and speleothem deposits in the upland plateau of the deccan traps in western India [82].

#### 3.2.3. Degradation Risk Assessment Based on Sensitivity and Public Use

Among the key works on degradation risk assessment, worthy of mention is the research by García-Ortiz et al. [11]. After reviewing the available literature (cf. Section 1), they proposed assessing degradation risk based on two groups of parameters. The first group depends on the geological characteristics of the geosite and is defined as sensitivity, composed of fragility (due to intrinsic factors) and vulnerability (due to natural and anthropic extrinsic factors) as the basis. The second group is related to the public use of the geosite (e.g., accessibility, proximity to roads, inhabitants in the surroundings). In their research, García-Ortiz et al. [11] not only developed a methodology to assess geoheritage degradation risk but also defined specific indicators of alteration (i.e., deterioration indicators) and suggested possible management solutions to prevent or reduce such alteration. This approach inspired several works later on, including the ones by Santos et al. [83] and Selmi et al. [5]. The former considered the assessment of degradation risk of geomorphosites based on scoring and weighting several indicators, namely: legal and indirect protection, access, anthropic vulnerability, natural vulnerability, fragility, use conflicts. Similarly, Selmi et al. [5] quantitatively assessed the degradation risk based on natural vulnerability, anthropogenic vulnerability, and public use. According to Selmi et al. [5], the assessment of the natural vulnerability of geosites is based on two parameters: (i) active processes not responsible for the morphogenesis of the geosite but which may affect it; and (ii) the site's proximity to areas prone to degradation from these active natural processes. Anthropogenic vulnerability is evaluated based on two parameters: economic interest, which considers the potential or actual value of geosites for economic exploitation (such as quarrying and mining), and private interest, which examines the presence of collectible geological assets like fossils and minerals that may be subject to illegal collection or misappropriation. The public use criterion depends on pressures from urban development, susceptibility to vandalism or theft, and lack of protective measures. Similarly to the approach developed by Brilha [12,57], Selmi et al. [5] quantitatively assessed degradation risk by establishing a set of indicators for each criterion, with scores assigned accordingly. The total degradation risk is the sum of these scores, categorized into classes of low, medium, high, and very high values [27,84,85].

The methodology developed by García-Ortiz et al. [11], along with those inspired by this approach, has the advantage of considering a wide spectrum of factors influencing the degradation risk of geosites. This level of detail allows for a more accurate evaluation of the degradation risk, enhancing the ability to prioritize conservation efforts and refine management strategies. However, these methodologies depend on a relatively large amount of data and require detailed information for each geosite, including specific details on geological features, active processes affecting the site, presence of legal protection, and land ownership information. Such data may not always be readily available for all geosites. In remote or less-studied locations, obtaining accurate data can be challenging, potentially affecting the method's accuracy and applicability.

#### 3.2.4. SWOT Analysis

SWOT analysis (Strengths, Weaknesses, Opportunities, and Threats) is a qualitative tool that can be applied for evaluating the management and conservation of geoheritage. In this context, SWOT analysis helps identify both internal strengths and weaknesses, as well as external opportunities and threats, particularly those that could undermine the preservation of geoheritage elements and the sustainability of their exploitation in terms of geotourism. From a broader perspective, SWOT analysis, particularly in the identification of threats, is closely linked to geoheritage degradation risk assessment. This analysis considers various factors, such as the geological and geomorphological context, management practices, geoawareness, and regional economic development [86].

The Threats aspect is crucial in pinpointing external pressures, such as vandalism, waste disposal, and lack of investment in preservation and restoration efforts (e.g., [87,88]). A detailed overview of the main threats to geoheritage identified in the reviewed literature is presented in Section 3.3.

Additionally, SWOT analysis has been employed to evaluate the tourism potential of geosites, incorporating criteria that explore the relationship between social and political context and geoheritage as in Carrion Mero et al. [89]. In the latter paper, the authors not only identified threats directly related to geoheritage integrity but also others, such as competition with other tourist destinations or political and economic instability, which may affect the viability of geotourism development.

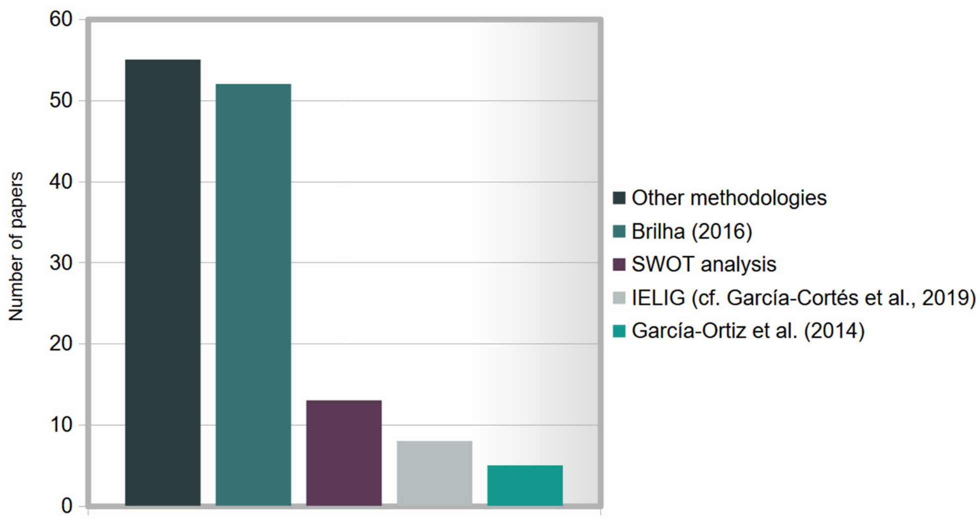


**Figure 3.** Frequency of the main methodological approaches utilized in the literature. The most commonly used methods, listed in order of frequency, include those developed by Brilha [12], García-Cortés et al. [77], García-Ortiz et al. [11]. The total number of papers exceeds the overall count of those included in the review, as several studies employed multiple methodologies.

#### 3.2.5. Other Methods and Approaches

Some authors have attempted to propose new criteria. For example, Bonachea et al. [25] assessed the vulnerability and the degradation risk by combining the intrinsic vulnerability and the external factors. The latter factors are related to anthropic activity and are based on (i) threats due to public use (erosion, waste disposal), (ii) threats due to the development (including infrastructures and buildings), and (iii) plunder risk. To the intrinsic vulnerability and to each of these three criteria, a score is assigned.

The average of the assigned scores provides a final synthetic value, which is the combination of the vulnerability and degradation risk of the site. Worth mentioning is also the pioneering work by Moradipour et al. [35], who implemented a new framework for measuring geosite resilience with respect to the risk of degradation, considering several criteria and indicators related to geological, hydroclimatic, ecological and anthropic features, as well as geotourism development of the site.

An additional insight from our literature review on methods for degradation risk assessment is that these assessments are predominantly based on indirect indicators/criteria/data. In fact, this data is generally gathered through the analysis of existing literature, maps, photographs (including aerial imagery), and qualitative fieldwork observations. Contrasting with these general trends identified in the reviewed literature, Bollati et al. [90] conducted their degradation risk assessment related to the erosion of geomorphosites composed of unconsolidated deposits using direct quantitative dendrogeomorphological and geomorphological analyses. This direct quantitative approach serves to reduce the inherent subjectivity associated with semi-quantitative and qualitative indicators used in traditional assessments. The direct quantitative measurements of the degradation risk can enhance objectivity and ensure the replicability of their assessments, which are crucial aspects for robustly monitoring the conservation status of geosites, particularly amidst ongoing challenges posed by climate change.

One aspect that emerged from our literature review is that despite the increasing attention on geoheritage in relation to climate change (cf. [91]), also in terms of geoconservation [5], only a few studies focus specifically on the impacts of climate change on geosites (e.g., [92]). One notable exception is the work by Gordon et al. [52], who proposed an approach to assess the risk of degradation of geosites due to climate change. Their method considers both the likelihood and severity of impacts on geosite values (see also [93]). Addressing the issues related to climate change is of paramount importance, and these topics should be a priority in future research (Table 1).

**Table 1.** Examples of methodologies and criteria used in the literature for the assessment of the degradation risk and related aspects (e.g., vulnerability, susceptibility). For a complete list of methods and criteria, please refer to the Supplementary Materials.

| Reference | Degradation Risk and Related Aspects | Criteria/Factors Used for the Assessment of Degradation Risk |
|---|---|---|
| Belay and Asrat [94] | Susceptibility to destruction | Natural factors (e.g., drainage systems, lineaments, lithology, topographical parameters) and human-induced factors (roads, railways, irrigation schemes, and settlements) |
| Bonachea et al. [25] | Degradation risk | Threats to public use (erosion/garbage); Current or potential threats from development (infrastructures, buildings); Plunder risk |
| | Vulnerability (Intrinsic vulnerability) | |
| Brilha [12] | Degradation risk | Deterioration of geological elements; Proximity to areas and/or activities with the potential to cause degradation; Legal protection; Accessibility; Population density |
| Datta and Sarkar [95] | Vulnerability | Exposure; Sensitivity; Adaptive capacity |
| Ferrando et al. [58] | Degradation risk | Fragility due to the natural processes that generated the geosite; Fragility linked to natural processes not connected with the geosite's genesis; Vulnerability to anthropic impact |
| Fuertes-Gutiérrez and Fernández-Martínez [8,56] | Degradation risk | Fragility; Vulnerability; Accessibility; Dimensions; Proximity to human settlements; Public influx; Present or potential threats |
| García-Ortiz et al. [11] | Degradation risk | Vulnerability; Fragility; Public use |
| Martínez-Graña et al. [28] | Degradation risk | Susceptibility to natural and anthropic degradation (depending on size, fragility, natural and anthropic vulnerability of the site) |
| Matshusa et al. [96] | Ecological sensitivity | Geoheritage site located within wilderness zone/remote zone/primitive zone/low- or high-intensity leisure zone |
| Moradipour et al. [35] | Resilience | Geological indicators (e.g., lithological resistance, type of geosite); Hydroclimate indicators (e.g., erosion, precipitation, hydroclimatic threats); Ecology indicators (e.g., vegetation density, type of vegetation); Geotourism-related indicators (e.g., tourism infrastructure, number of visitors); Anthropic activity-related indicators (e.g., distance from residential areas, population density) |
| Siqueira et al. [31] | Vulnerability | Site located on a riverbed; Site located on a road or close to a road; Site existing in very fractured rocks; Site subject to frequent visits by tourists; Site close to communities; Site close to an area with mineral extraction activity; Site located on protected property; Site in an area with difficult access; Site located on an animal crossing route |
| Santos et al. [83] | Degradation risk | Legal and indirect protection; Access; Anthropic vulnerability; Natural vulnerability; Fragility; Use conflicts |

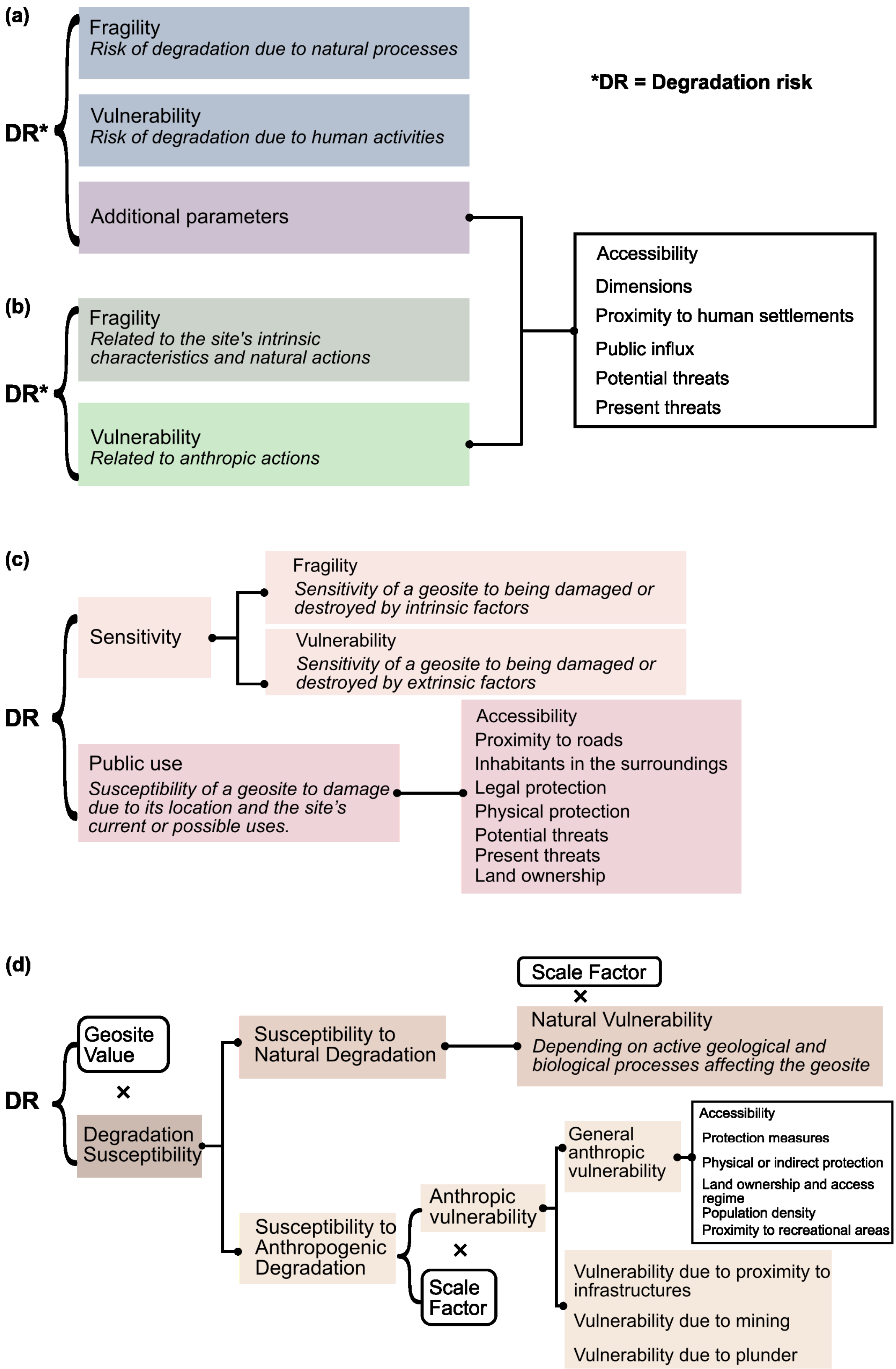


**Figure 4.** Conceptual framework illustrating the key approaches identified in the reviewed literature for assessing the risk of geoheritage degradation: (**a**) Degradation Risk (DR) according to Fuertes-Gutiérrez and Fernández-Martínez [8,56]; (**b**) DR according to Brilha [12]; (**c**) DR according to García-Ortiz et al. [11]; (**d**) DR according to Carcavilla Urquí et al. [76] and García-Cortés et al. [77,78].

### 3.3. Main Threats to Geosites

Some studies within the reviewed literature focused on identifying specific threats to geosites. A noteworthy contribution to this field is the study by Hjort et al. [54], which provides a comprehensive overview of various human-induced threats to geoheritage and geodiversity based on previous research by Gordon and Barron [97], Brooks [98], and Gray [99]. The authors identified a broad range of threats, including: urbanization, construction and energy generation facilities; extractive activities; changes in land use; coastal and fluvial interventions; offshore activities; recreation and geotourism; climate change; sea-level rise; restoration of pits and quarries; irresponsible fossil and mineral collecting. However, not all threats to geoheritage are linked to human activities. For example, Prosser et al. [100], in their review of various threats to different geosites in the British context, identify vegetation encroachment as a significant concern for exposed or extensive geosites.

In this context, considering all the reviewed literature, we identified nine main categories of threats to geosites, which are reported in Table 2. One of the most considered threats is quarrying, mining, and oil exploitation, which can severely impact geosites, and in general geodiversity, altering soils and landscapes, contamination of environmental compartments, and changing the sediment budget, potentially resulting in increased erosion. Sites of geomorphological interest are particularly subject to these types of threats since certain landscapes, especially those with economically valuable rock formations, are at risk from quarrying and extraction. For instance, karst landscapes or unique cliff formations can be destabilized or marred by quarrying. Mineralogical geosites generally host rare or scientifically important mineral deposits, which are often the primary targets for mining. Another significant threat is posed by recreational activities and tourism-related activities, which, besides providing economic benefits and territorial promotion, can lead to physical degradation of geosites (e.g., due to trampling or vandalism). Similarly, urbanization and implementation of engineering projects can lead to the destruction or significant alteration of geodiversity, often through landscape modification, and may lead to its fragmentation. Waste disposal/dumps (both legal and illegal) can severely compromise both the ecological and aesthetic value of geosites. Recreational activities, urbanization and waste disposal all present significant threats to geosites, regardless of their types.

Lack of awareness or lack of interest in geoheritage and geodiversity of both the public and authorities can accelerate the degradation and even lead to the loss of geoheritage and geodiversity, as pointed out by Kubalikova [101]. On the contrary, people who recognize the importance of geoheritage and geodiversity are more likely to take action to protect and preserve them [102,103].

Another considerable threat is posed by active natural geomorphic processes (e.g., wave/fluvial erosion and weathering) that are not involved in the morphogenesis of a geosite and, for this reason, may cause its degradation [5]. However, it is important to note that geosites may hold significance precisely because of the active natural processes that shaped them, resulting in their constant evolution. In such cases, these ongoing processes are generally not seen as contributing to the degradation of the geosite's features [5].

Some of the reviewed papers discussed how agricultural practices can cause damage to landforms and soils. For example, plowing can lead to the levelling of landforms and soil erosion, while the implementation of irrigation systems can alter natural water drainage patterns. Excavation of fossil-bearing rocks can deplete or destroy significant geological and paleontological resources, leading to the loss of scientific and educational value.

Lastly, it is worthy of mention that climate change poses a significant threat to geosites, potentially altering their pristine condition and even leading to their loss. This is largely due to the acceleration of geomorphic processes such as erosion and weathering. Extreme meteo-hydrological events, intensified by ongoing climate change, are expected to particularly affect geosites in exposed and vulnerable locations [91]. For example, geosites along coastal areas are especially exposed to the negative impacts of rising sea levels, which can lead to increased erosion and flooding. In some cases, climate change leads to the gradual reduction or even disappearance of certain processes (e.g., glacial or periglacial processes). This is particularly relevant for active glacial and periglacial geomorphosites, which derive their primary significance from these processes. Within these categories of geomorphosites, a gradual transition occurs from active forms to relict forms, which are subsequently shaped (and degraded) by other processes.

**Table 2.** Threats associated with the types of geosites and relevant references. The types of geosites reported in the table follow the classification used by Ruban [14], Ruban and Kuo [15], Zorina and Silantiev [16].

| Threats | References | Types of Geosites |
| --- | --- | --- |
| Quarrying, mining, and oil exploitation | [21,44,50,53,104–111] | Economical; Geochemical; Geomorphological; Hydrological and hydrogeological; Igneous; Metamorphic; Mineralogical; Stratigraphical; Structural; Paleontological; Paleogeographical; Pedological |
| Recreational activities and tourism-related threats | [21,40,50,53,104,105,107,112–116] | Economical; Geochemical; Geomorphological; Igneous; Metamorphic; Mineralogical; Stratigraphical; Structural; Paleontological; Paleogeographical; Paleontological; Pedological |
| Urbanization and implementation of engineering projects | [21,40,44,50,106–108,110–112] | Economical; Geomorphological; Hydrological and hydrogeological; Mineralogical; Structural; Paleontological; Pedological |
| Waste disposal/dumps (both legal and illegal) | [18,21,53,87,88,104,105,112,117] | Paleontological; Economical; Geochemical; Igneous; Metamorphic; Mineralogical; Stratigraphical; Structural; Paleontological; Paleogeographical |
| Lack of awareness or lack of interest in geoheritage and geodiversity | [44,110,112,118,119] | Geomorphological; Economical; Mineralogical; Paleontological; Pedological; Sedimentary; Stratigraphical; Structural |
| Natural geomorphic processes (e.g., including wave/fluvial erosion and weathering) | [18,53,105,120] | Economical; Geochemical; Geohistorical; Igneous; Metamorphic; Mineralogical; Stratigraphical; Structural; Paleontological; Paleogeographical; Pedological |
| Agricultural practices | [53,111,112] | Geomorphological; Pedological |
| Excavation of fossil-bearing rocks | [50,104,105,110] | Economical; Mineralogical; Stratigraphical; Structural; Paleontological; Paleogeographical |
| Climate change (e.g., including desertification, sea level rise) | [50,107] | Geomorphological; Hydrological and hydrogeological |

## 4. Final Remarks and Conclusions

This study offers the first comprehensive review of the literature addressing degradation risk and associated concepts. By systematically analyzing existing research, it provides a thorough understanding of the various methodologies and frameworks used to assess the risk of geoheritage degradation. This analysis was crucial in exploring both established and novel methodologies to provide a comprehensive overview of current practices and highlight potential advancements in the field.

The reviewed literature on geoheritage degradation risk assessment has shown a significant increase in research efforts since 2016. The majority of studies have been conducted at local scales, with Brazil and Spain being the most studied regions. International collaborations, particularly between Brazil and Portugal, have contributed to the advancement of this field. The methodologies for assessing degradation risk are primarily quantitative index-based approaches, with over 70% of the reviewed literature adopting these methods. Key criteria considered in these assessments include fragility, vulnerability, accessibility, legal protection, and population density around the site. It should be noted that the terms fragility and vulnerability are often used with different meanings in the literature reviewed. Fragility is sometimes defined as the potential for a geosite to deteriorate in relation to intrinsic factors, such as its size and rock strength, and natural processes such as erosion, which may or may not play a role in the genesis of the site. In a narrower sense, some authors use fragility to refer exclusively to intrinsic factors and processes that are directly involved in the formation of the geosite. On the other hand, vulnerability is typically associated with deterioration driven by extrinsic factors. Some studies use it specifically to refer to anthropogenic impacts on a geosite, while others include both anthropogenic and natural factors that are unrelated to the formation of a geosite itself. These different terminologies have to be taken into account when dealing with geoheriatge degradation risk. Beyond the terminology, it is clear that any comprehensive assessment of the risk of degradation of geoheritage must include both intrinsic and extrinsic factors, whether natural or anthropogenic. It is also essential to distinguish between the active processes involved in the genesis of geoheritage features and those unrelated processes that may impact or degrade them. For example, karst processes are an integral part of the formation of karst geoheritage, including, e.g., limestone caves and other karst landforms. However, non-karst processes, such as gravity-induced ones (e.g., landslides) or other mechanical weathering processes, can destabilize or degrade the karst landscape, threatening its integrity. This may raise an ethical question in geoheritage conservation: Preserving these sites often means intervening to prevent natural evolutionary processes that could lead to their alteration or destruction.

Our literature review also highlights climate change as a critical, yet relatively underexplored, factor in geoheritage conservation. Climate change can intensify the degradation of geoheritage, for example, by accelerating erosion, weathering, and other processes, particularly in regions that may face increased frequency of extreme weather events, changes in precipitation patterns, and rising temperatures. Future research should prioritize understanding how climate-induced changes affect various types of geoheritage features, including identifying geosites most at risk, as well as creating common guidelines to mitigate potential damage, shared among the scientific community and stakeholders.

Despite the progress made, there is still a need for increased international collaboration to develop a global understanding of geoheritage degradation risks and enhance conservation strategies worldwide. Based on the results of this literature review and our knowledge of the topic, we believe that, future efforts must focus on defining (i) the spatial scale of analysis, (ii) the temporal scale of the processes involved, (iii) the state of activity of the site, emphasizing the need to establish a time frame for evaluating activity, (iv) the specific processes responsible for both the formation and transformation of the site, and (v) the magnitude and intensity of these processes. A thorough understanding of these elements is crucial for developing accurate and effective strategies to mitigate the risk of geoheritage degradation.

**Supplementary Materials:** The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/su162310336/s1, Table S1. Overview of key characteristics and methodologies used in the assessment of geoheritage degradation risks. This table summarizes the analyzed literature, including details such as title, publication date, source, document type, authors' affiliations, study aims, degradation risk assessment criteria, and methodologies.

**Author Contributions:** Data curation: V.V., L.S. and P.C.; Formal analysis: V.V., L.S. and P.C.; Funding acquisition: P.C.; Investigation: V.V., L.S., F.F., A.F. and P.C.; Methodology: V.V., L.S. and P.C.; Project administration: V.V. and P.C.; Supervision: F.F. and P.C.; Validation: V.V., L.S. and P.C.; Visualization: V.V.; Writing—original draft: V.V., L.S., F.F., A.F. and P.C.; Writing—review and editing: V.V., L.S., F.F., A.F. and P.C. All authors have read and agreed to the published version of the manuscript.

**Funding:** The research was carried out within the framework of the following projects: FAR 2023 program of the Chemical and Geological Science Department of University of Modena and Reggio Emilia (Scientific responsible: Paola Coratza); "Training new generations on geomorphology, geohazards and geoheritage through Virtual Reality Technologies" (GeoVT) under the Erasmus+ Program, Key Action 2: Partnerships for Cooperation (Agreement number: 2021-1SE01-KA220-HED-000032142)—Coordinator: Arjen P. Stroeven (Stockholm University).

**Institutional Review Board Statement:** Not applicable.

**Informed Consent Statement:** Not applicable.

**Data Availability Statement:** This article contains electronic Supplementary Materials available in open access. The supplementary data provide detailed information on the 130 papers analyzed and commented on this review including their categorization based on the following aspects: (i) Title; (ii) Publication date; (iii) Paper source (Scopus/WoS); (iv) Document type; (v) Country of authors' affiliation; (vi) Country and detailed location of the study area; (vii) Aim of the research (e.g., inventory, management, assessment, conservation, degradation risk, geotourism, education); (viii) Terms (e.g., sensitivity, fragility, vulnerability); (ix) Criteria for the assessment of the degradation risk; (x) Assessment methodology; (xi) Data considered; (xii) Types of geosites.

**Conflicts of Interest:** The authors declare no conflicts of interest.

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