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ORIGINAL ARTICLE

A Methodology for Quantitative Assessment of Geosite Degradation Risk

Andrea Ferrando[1] · **Vittoria Vandelli**[1] · **Emmanuel Reynard**[2] · **Francesco Faccini**[3] · **Paola Coratza**[1]

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Abstract
In recent years, many geoconservation studies have focused on the degradation risk of geosites. The identification of threats to geoheritage and the consequent assessment of degradation risk, is fundamental to define any geoconservation strategy. Several methodologies, both qualitative and quantitative, have been proposed in scientific literature to assess the degradation risk of geosites. Most of them revolve around the concepts of "fragility", "vulnerability", "sensitivity" etc., terms that have been used inconsistently over the years. Starting from an evaluation of strenghts and weaknesses of existing methodologies, we propose a new quantitative methodology for the assessment of the degradation risk of geosites. The degradation risk is assessed by means of the following criteria: (i) fragility, which depends on the intrinsic characteristics of the geosite; (ii) natural vulnerability, depending on exstrinsic natural factors, i.e., active natural processes; (iii) anthropogenic vulnerability, depending on exstrinsic anthropogenic factors. The methodology takes into account also the assessment of protection measures, if any, which can be considered measures to mitigate the vulnerability of geosites. Each of these four criteria was assessed by means of a set of indicators, to which numerical scores were attributed. The methodology was tested on 143 geosites belonging to two different study areas: the Liguria region (North-Western Italy), and the Hérens Valley in the Pennine Alps (Valais, Switzerland). The methodology is structured to be easily replicable, also in different geographical-geomorphological contexts, and the results may constitute an important tool for the outlining of effective management and enhancement strategies for geosites.

Keywords Degradation risk · Geoheritage · Geosites · Geoconservation · Vulnerability · Fragility

Introduction

Geoconservation refers to all those actions aimed at preserving and enhancing the geological heritage (Burek and Prosser 2008). According to Prosser et al. (2018), the geoconservation effort is composed of two main phases: (i) conservation needs analysis, in which one has to define the use of the geosite and the threats to which it may be exposed; and (ii) conservation planning and delivery, in which the actual management, conservation and monitoring actions are decided and applied. In the first phase, one of the fundamental requirements to be achieved is the analysis of the degradation risk of the geosite (Wimbledon et al. 2004; Gordon 2019), which is useful to calibrate adequate conservation strategies. One of the main open issues in geoconservation is finding a consensus over the methodology to assess the degradation risk of the geoheritage.

Terms such as 'degradation risk', 'sensitivity', 'fragility', 'vulnerability', 'external threats' applied to geological heritage have been used since the earliest studies in this field (e.g., Sharples 2002; Gray 2004; Brilha 2005 etc.). However, often these terms have not been defined clearly and they have not been used consistently over the years (Carcavilla Urquí et al. 2007; Fuertes-Gutiérrez and Fernández-Martínez 2010). García-Ortiz et al. (2014), in a review of terminology, propose the following definitions. Sensitivity is "geosite's susceptibility to change in its features, i.e., the

✉ Francesco Faccini
faccini@unige.it

[1] Department of Chemical and Geological Sciences, University of Modena and Reggio Emilia, Modena, Italy

[2] Institute of Geography and Sustainability and Interdisciplinary Centre for Mountain Research, University of Lausanne, Lausanne, Switzerland

[3] Department of Earth, Environment and Life Sciences, University of Genoa, Genoa, Italy

likelihood that the geosite's natural characteristics will be modified, damaged or destroyed". Fragility is the "sensitivity of a geosite to being damaged or destroyed by intrinsic factors", and vulnerability is "the sensitivity of a geosite to being damaged or destroyed by extrinsic factors that are natural or anthropic in origin".

Over the years, several methods have been proposed for assessing the risk of degradation. Vandelli et al. (2024) identified four main approaches proposed respectively by (i) Brilha (2016), (ii) the *Inventario Español de Lugares de Interes geológico* (IELIG; García-Cortés and Carcavilla 2009), and (iii) García-Ortiz et al. (2014) and derived works, as well as (iv) SWOT analyses (e.g., Winarno et al. 2019; Carrión-Mero et al. 2024). The first three approaches are quantitative or semi-quantitative, while the latter is qualitative.

The approach proposed by Brilha (2016, 2018) involves a numerical assessment of 5 indicators, the first related to the vulnerability of the site linked to natural factors, the other 4 related to anthropogenic factors and public use of the geosite. The quantitative assessment of degradation risk is proposed within a broader geological heritage assessment method. It is by far the most implemented methodology, often in its original form (e.g., Garcia et al. 2019; Lopes et al. 2019; Zafeiropoulos and Drinia 2021; Duangkrayom et al. 2022; Toma et al. 2022; Akhlidej et al. 2024; Khalaf 2024; Sen et al. 2024), sometimes with small modifications (Dos Santos et al. 2016; Aoulad-Sidi-Mhend et al. 2020; Moradipour et al. 2020; Do Nascimento et al. 2021).

The second approach has been proposed for the Spanish Inventory of Sites of Geological Interest (*Inventario Español de Lugares de Interés Geológico*, IELIG; García-Cortés and Carcavilla 2009; García-Cortés et al. 2019). The first step consists in the calculation of the susceptibility to degradation of the geosites which takes into account the fragility, natural vulnerability and anthropogenic vulnerability due to plunder, mining and public use. The degradation risk is then calculated by multiplying the susceptibility value for the heritage value of the geosite. This method has been used a number of times by various authors with or without modifications (e.g., Carvalhido et al. 2016; Pereira et al. 2019; Carrión-Mero et al. 2024).

The third approach derives from the aforementioned conceptual framework by García-Ortiz et al. (2014). Some of the derived works are based on the quantitative assessment of the fragility, natural and anthropogenic vulnerability and public use of the geosites under consideration, by means of indicators to which scores are given (Santos et al. 2020; Selmi et al. 2022; Ilie and Grecu 2023; Rabelo et al. 2023). Some others instead give qualitative assessment of threats based on the same aforementioned definitions (Fuertes-Gutiérrez et al. 2016; Prosser et al. 2018).

SWOT analysis is a type of qualitative analysis based on the assessment of Strengths, Weaknesses, Opportunities and Threats. It has been applied on geoheritage a number of times (e.g. Kubalíková and Kirchner 2016; Carrión-Mero et al. 2018; Winarno et al. 2019; Datta 2020). In particular, the Threats aspect is related to the identification of factors that could cause the degradation of the geosite (Vandelli et al. 2024; Kubalíková et al. 2025).

In addition to these four main approaches, other methodologies have also been proposed, taking some of their parameters or using entirely original approaches, e.g., the two-level assessment by Kubalíková and Balková (2023) and Kubalikova (2024), or the assessment of the degradation risk related to climate change by Wignall et al. (2018). For a more specific description of these methodologies, see references above and Vandelli et al. (2024).

Each of these methods has its strengths and its weaknesses, that can vary from simplified approaches to the lack of addressing the specificities of certain types of geosites.

The aim of this paper is therefore to propose a new quantitative method for assessing the degradation risk of geosites that could make up for some of the methodological gaps mentioned before. The proposed method could be said to stem from the third approach (García-Ortiz et al. 2014) and has the following characteristics: (a) it is quite simple, so that its application is not excessively cumbersome; (b) it takes into account as many degradation risk factors as possible and the specificities of the different categories of geosites, when these condition the assessment of degradation risk.

The proposed quantitative methodology was then tested on two study areas: Liguria, a coastal region in northern Italy, characterised by a number of environments from the coast to the middle mountains; and the Hérens Valley, an alpine valley in the canton of Valais (Switzerland), characterised by high mountain environments. These two study areas provide a certain diversity of environments and active processes, allowing the method to be tested in different geological and geomorphological contexts.

Materials and Methods

Conceptual Framework

The methodology proposed below takes as its starting point the concepts of 'fragility' and 'vulnerability' as defined by García-Ortiz et al. (2014). Fragility concerns the intrinsic characteristics of the geosite, while vulnerability considers extrinsic factors such as active natural processes or human actions. Based on these definitions, given in the Introduction, an attempt has been made to find quantitative indicators that could best describe them. In this sense, it is comparable to other methods developed in the past (e.g., Selmi et al. 2022).

For almost all categories of geosites, the distinction between intrinsic characteristics (e.g., type, size, substrate) and extrinsic factors (e.g., active natural processes) is straightforward. For geosites of geomorphological interest (i.e. geomorphosites), the issue becomes more complicated. Geomorphosites have three specificities (Reynard 2009; Coratza and Hobléa 2018): (i) the aesthetic dimension; (ii) the dynamic dimension; (iii) the imbrication of scales (Bussard and Reynard 2022). The second one, i.e. the "dynamic dimension" causes some issues in the definition of the fragility of a geomorphosite. In fact, geomorphosites are usually classified as (i) active, when the process that is responsible for their morphogenesis is still active and is still shaping them, and (ii) inactive or passive, when the morphogenetic process is no longer active (Reynard 2009; Coratza et al. 2021).

In the case of active geomorphosites, often their value lies in the current active morphogenetic processes, which constitute therefore an intrinsic feature of the geosite. In most of the cases, the active morphogenetic process does not cause degradation; on the contrary, it builds the landforms considered as geomorphosite and can be, therefore, considered part of the geomorphological heritage itself (Bussard et al. 2025). However, there are some peculiar cases in which the active morphogenetic process can cause degradation of the existing landforms (e.g., earth pyramids shaped and then destroyed by runoff erosion; Bollati et al. 2017). Inactive geosites may be shaped (and degraded) more or less rapidly by current active processes (Komac et al. 2011). In this case, the term of 'evolving passive geosites' has been proposed (Pelfini and Bollati 2014). For evolving passive geosites, current active processes can be considered extrinsic factors of degradation. All this has to be taken into account when assessing the fragility of geomorphosites.

Within anthropogenic vulnerability, the presence of elements of economic or private value in the geosite was considered, but also all the risk factors related to 'public use', which are treated separately by García-Ortiz et al. (2014) and derived methods. In fact, all these risk factors fall under the definition of 'extrinsic factors of anthropogenic origin', so there is no particular reason to separate them.

Instead, those factors related to the protection measures of the site, which are also considered in the methods of Brilha (2016) and García-Cortés and Carcavilla (2009), have been separated. Means of protection are somewhat different from the other anthropogenic factors, as they are essentially measures to reduce anthropogenic vulnerability. For this reason, it was considered appropriate to assess them separately and to compare them later with the anthropogenic vulnerability values obtained. Both physical protective measures (barriers, access control) and immaterial protective measures (laws and regulations) were considered.

In this method, the assessment of natural and anthropogenic vulnerability focuses exclusively on factors that affect the scientific value of a geosite, namely its integrity. Risk factors influencing other geosite values (such as cultural or aesthetic significance, or potential for use) were not considered. This may appear as a methodological limitation, however, including the degradation risk of additional values would overcomplicate the proposed method, as each value would likely require a distinct set of indicators and scoring criteria. Prioritizing the evaluation of factors that threaten geosite integrity is particularly relevant, since any degradation or loss of integrity inevitably affects other associated values as well (Vandelli et al. 2024).

Finally, the concept of degradation risk should be considered in relation to a specific timescale. In fact, the degradation of geosites can happen with extremely different rates, depending on the characteristics of the geoheritage features and the geological and geomorphological context; every geosite is bound to evolve if one considers a long enough period. In similar research contexts, two time scales are generally adopted: the human scale, which is roughly equivalent to the duration of a human lifetime (approximately 100 years), and the historical scale, which spans several generations and is documented by historical sources (Fuertes-Gutiérrez et al. 2013). As processes that unfold over timeframes exceeding a century are difficult to perceive, and consequently complex to monitor and manage effectively, the 100-year timescale was selected within the scope of this methodology.

Description of the Methodology

In this methodology, we propose to describe the degradation risk of geosites by means of three criteria (Fig. 1): fragility (F), natural vulnerability (NV) and anthropogenic vulnerability (AV). Each of them is assessed through several indicators – 5 for fragility, 3 for natural vulnerability and 5 for anthropogenic vulnerability.

In addition to fragility and vulnerability, we propose to assess also the protection measures that have been taken, by means of 3 indicators. Protection measures are taken into account in several procedures for the degradation risk assessment (e.g., Brilha 2016; Selmi et al. 2022). We propose to keep them separated from the other three criteria, because protection measures work to mitigate the degradation risk. Thus, it is useful to assess the 'base' degradation risk, in absence of protection measures, and then to assess the protection measures in a second step.

Each indicator is assigned a score ranging from 1 (value indicating minimum risk of degradation) to 4 (value

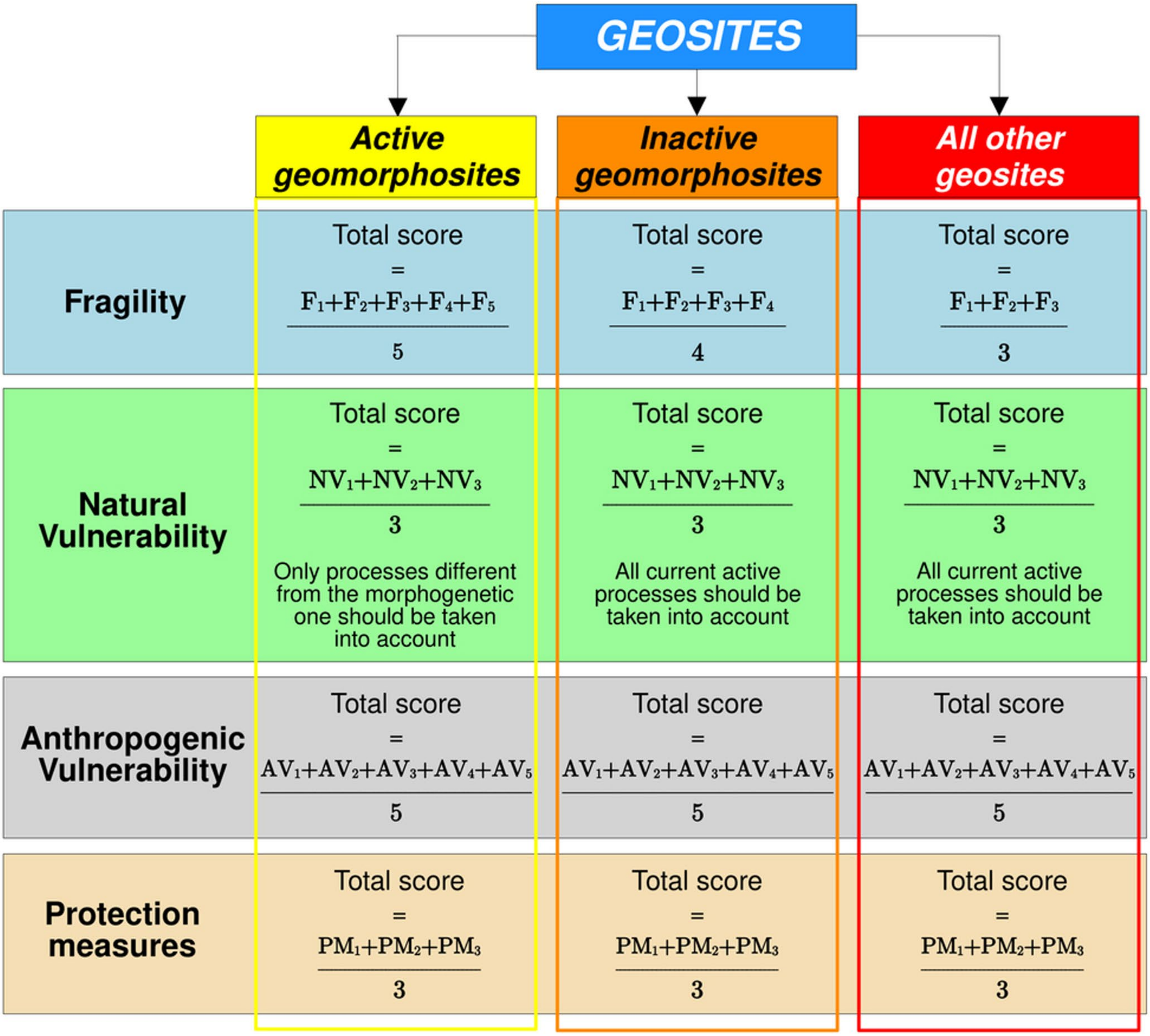

Fig. 1 Scheme of the proposed methodology for degradation risk assessment. The abbreviations (F, NV, PM etc.) refer to the indicators described in Sect. 2.2 (see also Tables 1, 2, 3 and 4)

indicating maximum risk of degradation). An overall score is calculated for each block as the average of the scores obtained for each individual indicator.

Indicators for the Assessment of Fragility (F)

Five indicators were used to assess fragility (Table 1), which refer to intrinsic characteristics of the geosite. The first three are relevant for all types of geosites. The first indicator is the site type according to the Earth Science Conservation Classification (ESCC) (Prosser et al. 2018); three types of sites are distinguished: (i) extensive sites, which contain geological features that are extensive beneath the ground surface, so that removal of material does not cause depletion; (ii) integrity sites, which are all geomorphological sites; and (iii) finite sites, which contain geological features that are limited in extent (e.g., rare fossils, minerals etc.), so that removal cause depletion of the site. The area of the geosite is taken into account, as smaller geosites, such as a lone rock pillar, are inherently more fragile than larger geosites, such as a large karst plateau. Finally, the type of substrate of the geosite is considered, which can range from hard and compact rock, to soft and/or altered rock, to unconsolidated superficial deposits, which represent the highest level of fragility.

Table 1 Description of the indicators for the assessment of fragility (F)

Indicator		Points and descriptions			
		1	2	3	4
F_1	***Site type****(according to* the ESCC)		Extensive sites	Integrity sites (geomorphosites)	Finite sites
F_2	***Area of the geosite***	More than 1 km^2	50.000 m^2 – 1 km ^{2}	5000-50.000.000 m^2	Less than 5000 m^2
F_3	***Substrate***		Hard or fresh rocks	Soft or altered rocks	Superficial deposits
F_4	***Activity and spatial classification****(for geomorphosites only)*	Active geomorphological complex	Active group of landforms	Active single landform	Inactive or relict geomorphosite
F_5	***Geoheritage value loss due to the genetic process*** *(for active geomorphosites only)* *Time scale 100 years*	The genetic process does not cause geoheritage loss	The genetic process can cause mild geoheritage loss	The genetic process can damage parts of the geosite with significant geoheritage loss	The genetic process can cause complete destruction of the geosite

Indicators F_4 and F_5 are relevant only for geomorphosites. Indicator F_4 considers the state of activity and the spatial complexity of the geomorphosite. Inactive geomorphosites are inherently more fragile than active geomorphosite, because their morphogenetic process is not present anymore. Among active geomorphosites, the score is different according to the spatial complexity of the site: single landforms obtain higher scores than geomorphological complexes.

Indicator F_5 is specific to active geomorphosites and concerns the possible loss of geoheritage value due to the action of the genetic process of the geomorphosite itself, taking into account a 100-years time scale. While the genetic process is responsible for the formation of the geomorphosite, and in many cases can be considered the main element of value of the site itself (Bussard et al. 2025), in other cases it can lead to the loss of landforms and other site-specific elements over different time scales (Reynard 2009). In some specific cases (e.g., earth pyramids), the progression of the genetic process activity may lead to the complete destruction of the geosite. On the other hand, for some types of geomorphosites (e.g., badlands), the activity of the genetic process is a prerequisite for the continued existence of the landform - if the process ceases, the gully will be colonised by vegetation and the process will stop. It is therefore important to assess the extent to which the genetic process itself can affect the integrity of the geomorphosite.

Indicators for the Assessment of Natural Vulnerability (NV)

The assessment of NV is essentially based on an evaluation of the extent to which active processes can affect the geomorphosite and lead to a loss of valuable elements, in a 100-years time scale. In the case of geomorphosites, all active processes were considered except the genetic process (which was considered in the vulnerability assessment); for all other categories of geomorphosites, all currently active processes were considered.

Three indicators were considered, shown in Table 2. The first, ‘Geoheritage value loss due to active processes’, is similar to that described in the previous section. Then the continuity of active processes, if any, is assessed, considering a spectrum of categories from continuous to episodic processes over several years. Finally, the third indicator concerns the intensity of active processes.

The last two indicators pose a rather important problem. For the vast majority of the geosites analysed, there are several processes linked to different morphogenetic agents that contribute to the evolution and eventual degradation of the site. Analysing the continuity and intensity of each of them would lead to excessive complexity and unwieldiness of the method. In order to maintain a certain degree of simplicity, it was decided to identify one main process for each site and to carry out the quantitative assessment on this basis.

Table 2 Description of the indicators for the assessment of natural vulnerability (NV)

Indicator		Points and descriptions			
		1	2	3	4
NV_1	***Geoheritage value loss due to active processes*** *Time scale 100 years*	No active processes OR the active process(es) does not cause geoheritage loss	The active process(es) can cause mild geoheritage loss	The active process(es) can damage parts of the geosite with significant geoheritage loss	The active process(es) can cause complete destruction of the geosite
NV_2	***Continuity of active processes***	No active processes	Episodical process on an annual or multiannual basis	Episodical process on a seasonal basis	Continuous process
NV_3	***Intensity of active processes***	No active processes	Low intensity	Medium intensity	High intensity

Indicators for the Assessment of Anthropogenic Vulnerability (AV)

The anthropogenic vulnerability is assessed using five indicators, shown in Table 3. ‘Elements of economic interest’ are generally mineral or stone resources, while ‘elements of private interest’ are mainly minerals or fossils of interest to collectors. With regard to the population density (indicator AV_4), the classes proposed by Brilha (2016) have been used.

For the proximity to potential degrading anthropic activities (indicator AV_5), class thresholds have been taken from Selmi et al. (2022); only the class associated with the highest degradation risk has been modified, increasing the distance threshold from 100 to 250 m make the criterion more conservative. A special case of proximity to potential degrading anthropic activities is that of abandoned quarries. In fact, in this case, the filling of the abandoned quarry, perhaps after its environmental rehabilitation, leads to the complete loss of the geoheritage value of the site. For this reason, quarry geosites should receive the highest score for this indicator.

Indicators for the Assessment of the Protection Measures (PM)

The protection status of the geosite is assessed by means of three other indicators (Table 4): the presence of structures to protect the vulnerable elements of the geosite (indicator PM_1); the presence of a control to access the geosite (e.g., payment of a ticket; indicator PM_2); the presence of legal protection, which is checked if the geosite is located in a protected area or is specifically protected by law (indicator PM_3).

As far as indicator PM_3 is concerned, there is no descriptor for score 1. This is because legal protection is only indirect and not physical protection - however regrettable it may be, a law can always be disregarded, especially if there is no adequate control. Therefore, legal protection cannot be considered on the same level as the physical protections taken into account in indicators PM_1 and PM_2.

Defining Priorities for Intervention

Once the overall scores for F, NV, AV and PM have been obtained, they can be classified in three classes: ‘high’,

Table 3 Description of the indicators for the assessment of anthropogenic vulnerability (AV)

Indicator		Points and descriptions			
		1	2	3	4
AV_1	***Economic and private interest***	No geological elements of economic and/or private interest	One element of economic and/or private interest	Two elements or one rare element of economic and/or private interest	Two or more rare elements of economic and/or private interest
AV_2	***Degradation due to current use***	No degradation from use	Low degradation from use	High degradation of one geological element from use	High degradation of two or more geological elements from use
AV_3	***Accessibility***	Geosite has no direct easy access	Geosite can be accessed by hiking	Geosite can be accessed by easy walking	Geosite can be directly accessed with public or private transport
AV_4	***Population density***	Geosite in a municipality with less than 100 inhab/km^2	Geosite in a municipality with 100–250 inhab/km^2	Geosite in a municipality with more than 250–1000 inhab/km^2	Geosite in a municipality with more than 1000 inhab/km^2
AV_5	***Proximity to potential degrading human activities and infrastructures***	Geosite more than 1 km away from potential degrading activites	Geosite 500 m − 1 km away from potential degrading activites	Geosite 250–500 m away from potential degrading activites	Geosite less than 250 m away from potential degrading activites

Table 4 Description of the indicators for the assessment of the protection measures (PM)

Indicator		Points and descriptions			
		1	2	3	4
PM_1	***Physical protection***	Geosite with physical protection of geological elements and structures for tourists	Geosite with physical protection of geological elements	Geosite with structure for tourists	Geosite not protected
PM_2	***Control of access***	Geosite is in a prohibited area	Payment and check is required to access the geosite	Control of access but no payment required	No control of access
PM_3	***Legal protection***		Geosite is specifically protected	Geosite inside a protected area	Geosite not in a protected area and not specifically protected

'medium' and 'low'. 'High' corresponds to score > 3, 'medium' corresponds to 2 < score < 3 and 'low' corresponds to score < 2. The final step in the methodology is to identify the management priorities, i.e. those sites that require the most urgent intervention in order to preserve their integrity and, more generally, their heritage interest. It is proposed to carry out this assessment by means of three matrices, as illustrated in Fig. 2. The first matrix crosses the values of F and NV and is useful concerning the risk of degradation of natural origin; the second crosses the values of F and AV and is thus related to the risk of degradation of anthropogenic origin; the third crosses the values of AV and PM and is used to find those sites with a high risk of degradation of anthropogenic origin that have not yet been subjected to any protection.

The rationale for this methodological proposal is based on an assessment of what a land manager could realistically do to reduce the risk of degradation of geosites. Fragility, which is linked to the intrinsic characteristics of the site, is not manageable, except in certain exceptional cases (Santucci et al. 2009); rather, it constitutes a "substratum" on which the effects of the same extrinsic process (natural or anthropogenic) can be more or less accentuated. The aspects that can be easily managed are precisely the extrinsic processes on a local scale, whether natural or anthropogenic. It is therefore necessary to identify sites where conditions of high vulnerability – natural or anthropogenic – coexist with high fragility and possibly an absence of existing protection measures.

Study Areas

The method presented in the previous section was tested on two different study areas (Fig. 3): Liguria (Italy), a coastal region characterised by hilly and low mountain environments,

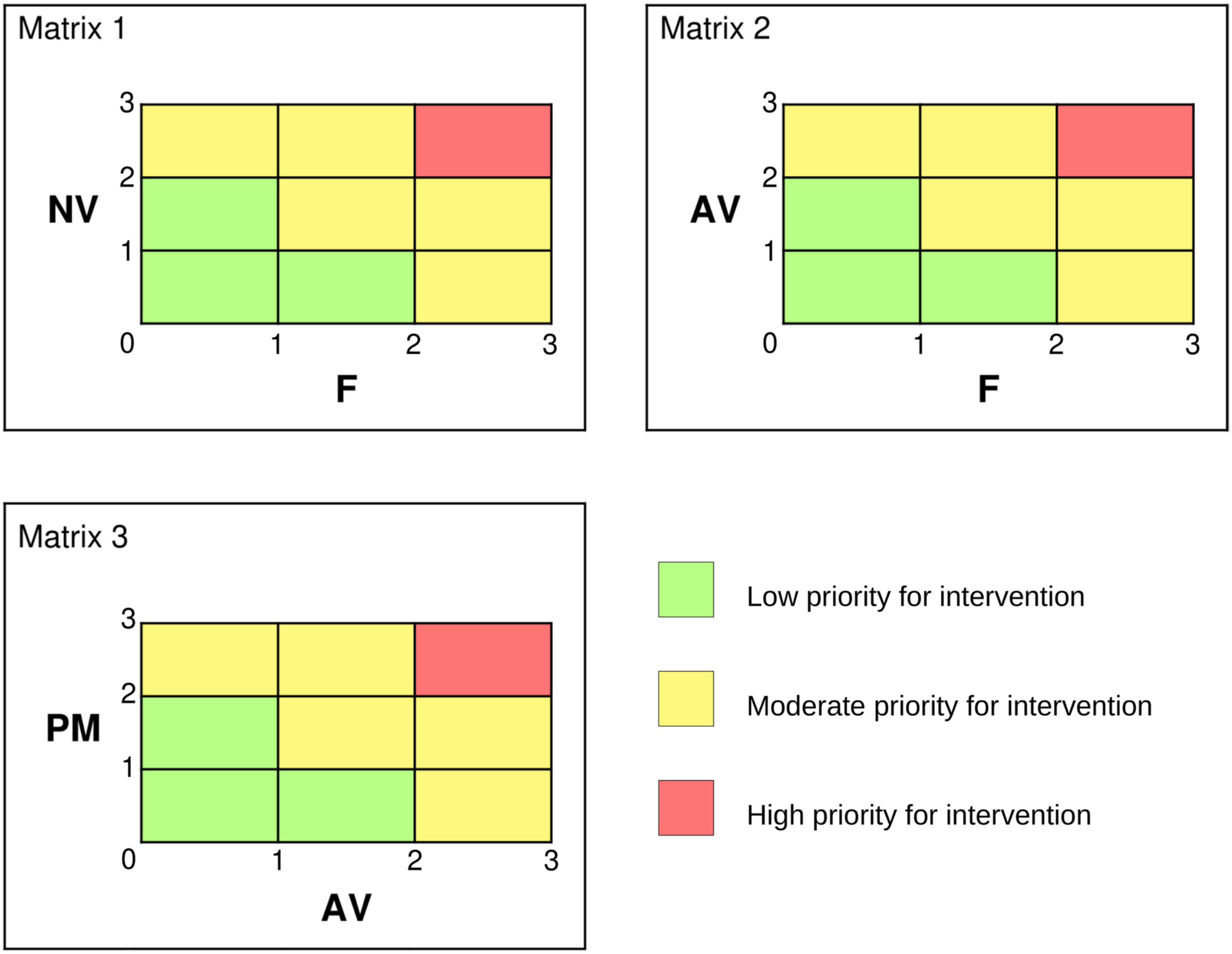

Fig. 2 Matrices for the assessment of the priorities for intervention. *F* fragility, *NV* natural vulnerability, *AV* anthropogenic vulnerability, *PM* protection measures

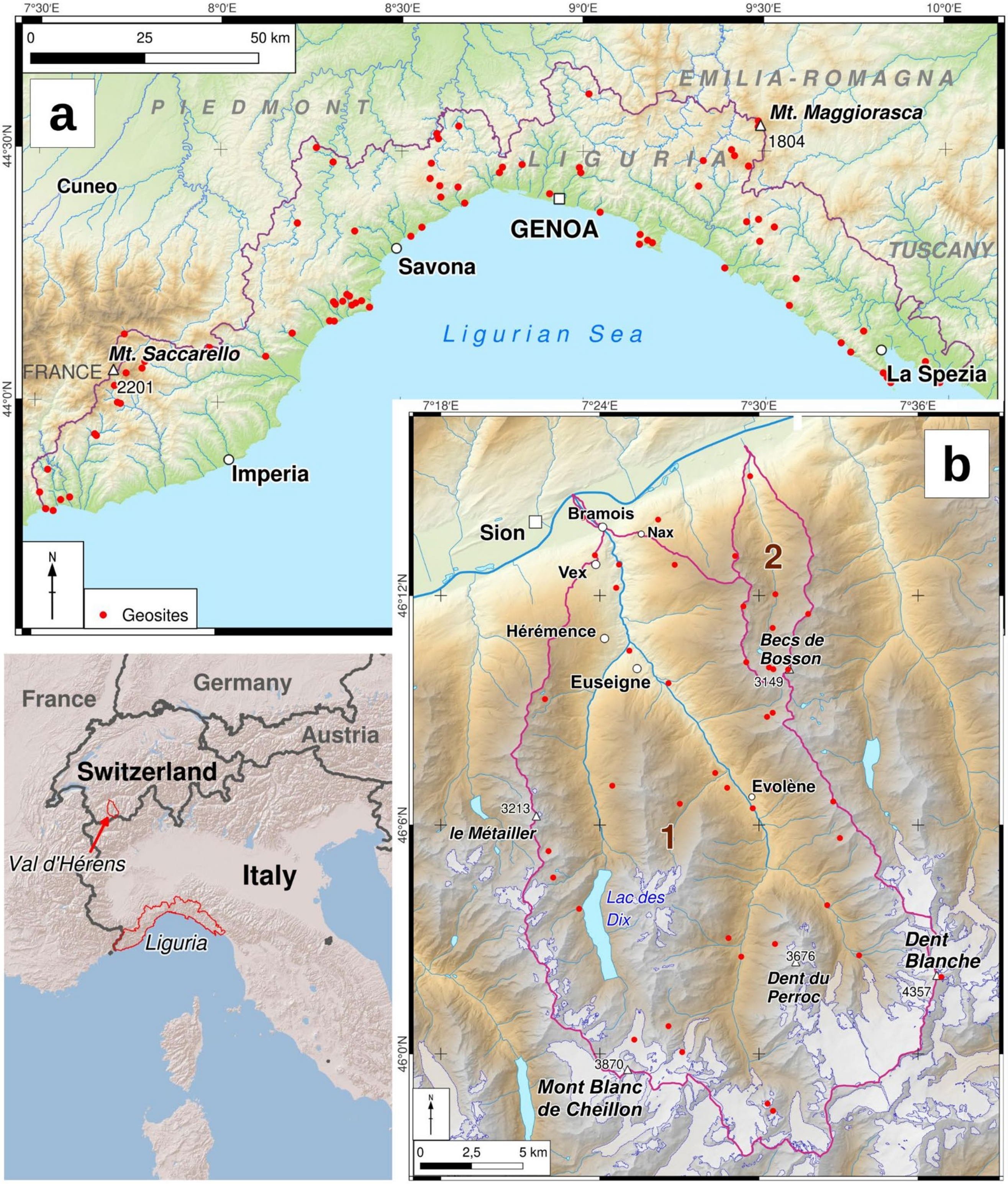

Fig. 3 Geographical setting of the two study areas, with the respective geosites shown as red dots. (**a**) Liguria; (**b**) Hérens valley (1) and Réchy valley (2)

and the Hérens and Réchy valleys, in the canton of Valais (Switzerland), characterised by a high mountain environment. The two study areas thus provide a rather comprehensive spectrum of geological and geomorphological contexts.

Liguria

Liguria (Fig. 3a) is a region in the north-west of Italy, bordering the Italian regions of Piedmont, Emilia-Romagna and Tuscany to the north and the east, and France to the west. To the south, Liguria faces the Ligurian Sea, a subdivision of the Mediterranean Sea. The region is almost entirely mountainous, with an uninterrupted arch-shaped mountain chain consisting of the Ligurian Alps (highest point: Monte Saccarello, 2201 m a.s.l.) and the Ligurian Apennines (highest point: Monte Maggiorasca, 1804 m a.s.l.). The watershed division in the mountain chain is very near to the coastline - in stretches, the distance is less than 5 km. The southern slopes of the Ligurian Alps and Apennines are thus very steep, while the other side is gentler, with long valleys separated by undulating crests. The northern side of the mountain chain drains into the River Po basin, which flows into the Adriatic Sea.

Liguria is characterised by a striking geological diversity, being at the meeting point of two orogens: the Alps and the Apennines, which overlap in what the geologists call the 'Ligurian Knot' (Capponi et al. 2016; Laubscher et al. 1992; Molli et al. 2010). The western part of the region is mostly made of sedimentary and metamorphic rocks belonging to the Alpine tectonic units, both of oceanic and continental origin (Decarlis et al. 2013). In the eastern part of the region, the Apennine tectonic units outcrop, made mostly of oceanic sedimentary rocks and flysch deposits, with occasional ophiolite masses preserving their primary magmatic features (Marroni et al. 2010).

From the geomorphological point of view, Liguria is dominated by gravitational and fluvio-denudational processes in the interior. Coastal processes dominate along the seaside, while small karst areas are present on the discontinuous outcrops of carbonate rocks (Ferrando et al. 2023). Relict periglacial landforms are present on some of the highest mountain massifs (Firpo et al. 2006).

In Liguria, geosites have already been recognised and assessed (Ferrando et al. 2021), and 99 Ligurian geosites are currently included in the National Inventory of Italian Geosites (http://sgi.isprambiente.it/GeositiWeb/default.aspx?ReturnUrl=%2fGeositiWeb%2fricerca_geositi.aspx, accessed on July 2025). These 99 geosites have been taken into account as study cases for the present research. The inventory consists mainly of geomorphosites (59%), but also includes sites of hydrogeological (1%), paleontological (6%), mineralogical-petrographical (14%), pedological (3%), stratigraphical (13%) and geological-structural (5%) interest (Fig. 4).

Hérens Valley

The Hérens valley (Fig. 3b) is located in the canton of Valais, Switzerland, south of the capital Sion. It lies on the northern slope of the Pennine Alps and joins the Rhone valley floor at Bramois, a hamlet of Sion. In just a few kilometres, the valley overcomes a considerable difference in altitude, from Dent Blanche (4357 m a.s.l.) to the 500 m or so of Bramois. The valley is drained by the Borgne river and is divided into two main branches: the Hérens valley proper to the east, which in turn divides into the Arolla and Ferpècle valleys in the upper part, and the Val des Dix (dammed by the Grande Dixence dam) to the west. The study area also includes the small Réchy valley, located immediately east of the Hérens valley, between the latter and the Val d'Anniviers. The Rèche stream has its source on the northern slope of the Becs de Bosson (3149 m a.s.l.) and flows northwards to join the Rhone near the village of Chalais.

The geology of the Hérens valley is quite varied, as it crosses a stack of tectonic units of oceanic and continental origin belonging to the Penninic domain and of continental origin belonging to the Austro-Alpine domain (Marthaler et al. 2008, 2020). The valley has been the subject of numerous studies on the geomorphological setting as a whole (Lambiel et al. 2016), and in particular on the periglacial and glacial landforms, both active and relict (Lambiel 2021 and references therein).

The inventory and assessment of geomorphosites in the Hérens valley has been carried out in the past (Grangier 2013 - unpublished). The inventory is nonetheless mentioned in Reynard et al. (2016) and it has been considered as a case study for this research. The inventory of the Hérens valley thus consists only of geomorphosites, 44 in total. The majority of them are active (61%), while the remaining (39%) are inactive (Fig. 4).

Results

A total of 143 geosites, located between Liguria (Italy) and the Hérens valley (Switzerland) were evaluated according to the methodology explained in Sect. 3. In the following paragraphs, the results are reported separating the risk of natural degradation from the risk of anthropogenic degradation. Case examples from the study areas are shown in Fig. 5.

Fragility (F)

With regard to fragility, the results were classified into three classes: 'high' ($Fr \geq 3$), 'medium' ($2 < Fr < 3$) and 'low' ($Fr \leq 2$). Almost half of the analysed geosites fall into the

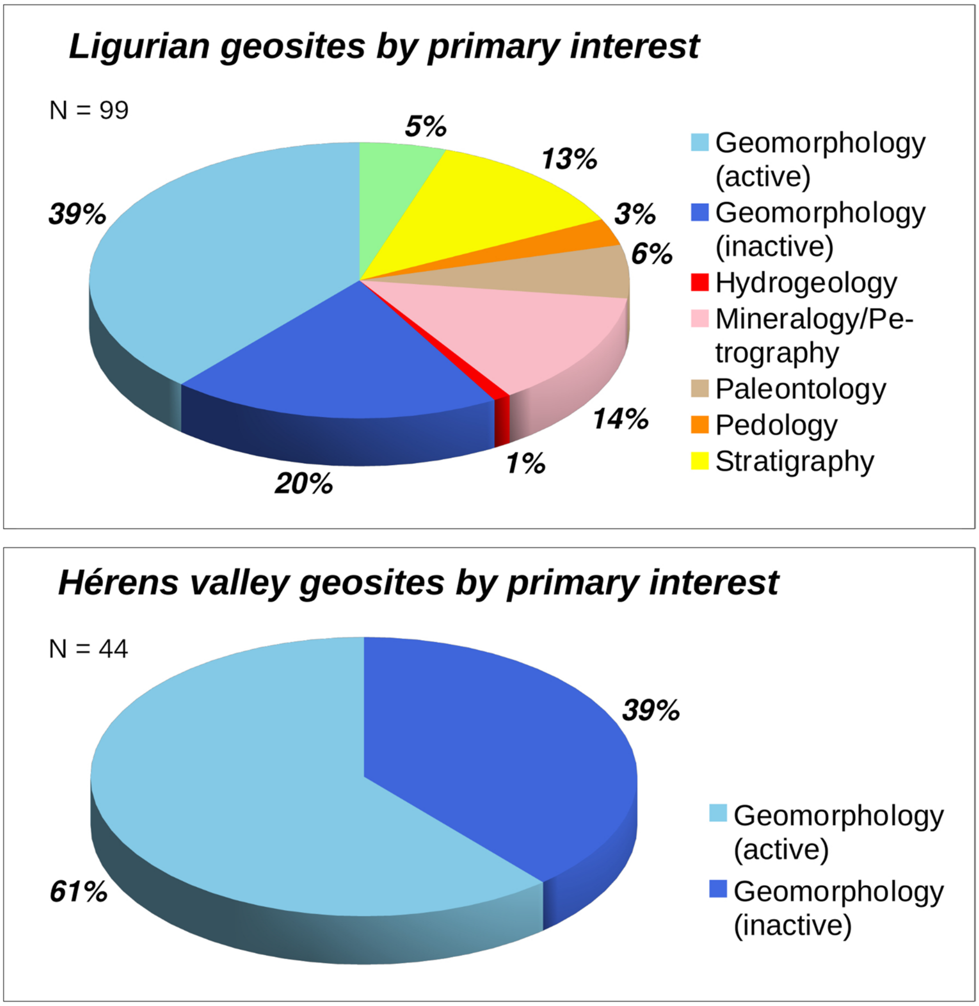

Fig. 4 Geosites in the two study areas, classified by primary interest

'medium' class (48%), followed by the 'high' class (21%), the 'low' class (20%) and the 'very high' class (11%). Thus, almost one third of the geosites analysed fall into the 'high' or 'very high' class of fragility (Fig. 6a).

The breakdown by primary interest class can provide interesting indications as to which categories of geosites are the most fragile (Fig. 6b). As can be seen in Figs. 6b and 100% of geosites of hydrogeological interest and 100% of geosites of soil interest fall into the very high fragility class. For geomorphosites, it is noticeable that the distribution differs between active and inactive sites - active sites tend to have medium to low fragility, while inactive sites are much more skewed towards the high fragility class. Another class of geosites with rather high fragility is that of sites of paleontological interest. In contrast, sites of stratigraphic or geological-structural interest have medium to low fragility.

Natural Vulnerability (NV)

The results for natural vulnerability have been divided into three classes: 'low' ($NV \leq 2$), 'medium' ($2 < NV < 3$) and 'high' ($NV \geq 3$). As far as the distribution of the results is concerned, it is quite homogeneous among the three score classes: each group contains about one third of the analysed geosites (Fig. 6c). The breakdown by primary interest class gives a more precise indication: geosites of paleontological and pedological interest are those with the highest average natural vulnerability, followed by geosites of stratigraphic interest. Geomorphosites have a fairly homogeneous distribution and there are no significant differences between active and inactive sites (Fig. 6d).

Finally, the sites of hydrogeological interest, which were characterised by high fragility, fall entirely into the 'very low' natural vulnerability class.

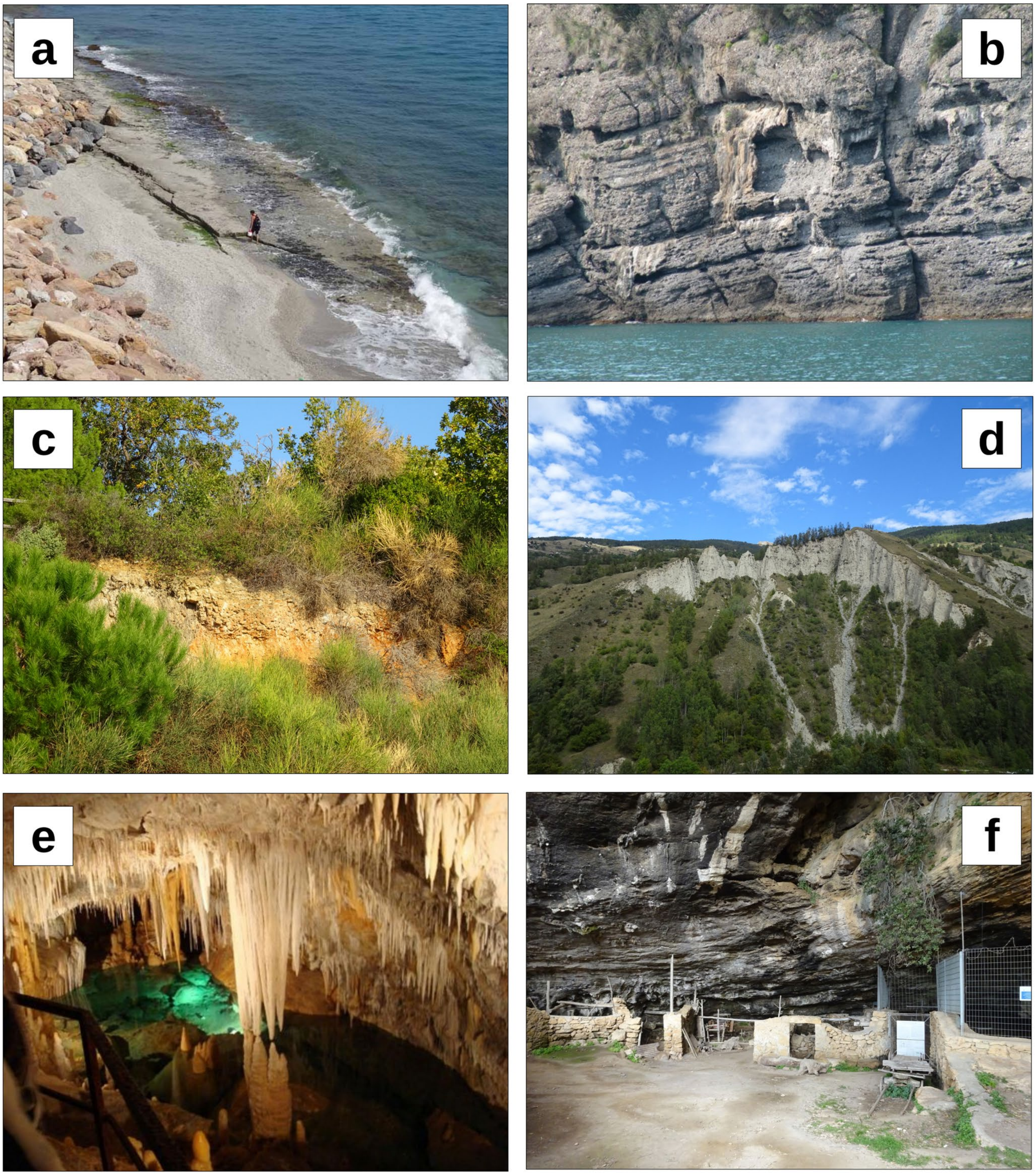

Fig. 5 Examples from the study areas. Fragile geosites: (**a**) Baia dei Saraceni beach rock (Liguria); Geosites with high natural vulnerability: (**b**) Punta Chiappa speleothems (Liguria); (**c**) Celle paleosol (Liguria); Geosites with high anthropogenic vulnerability: (**d**) La Luette earth pyramids (Hérens valley); (**e**) Borgio Verezzi caves (Liguria). Example of protection measures: (**f**) Physical barriers at the Arma delle Manie (Liguria).

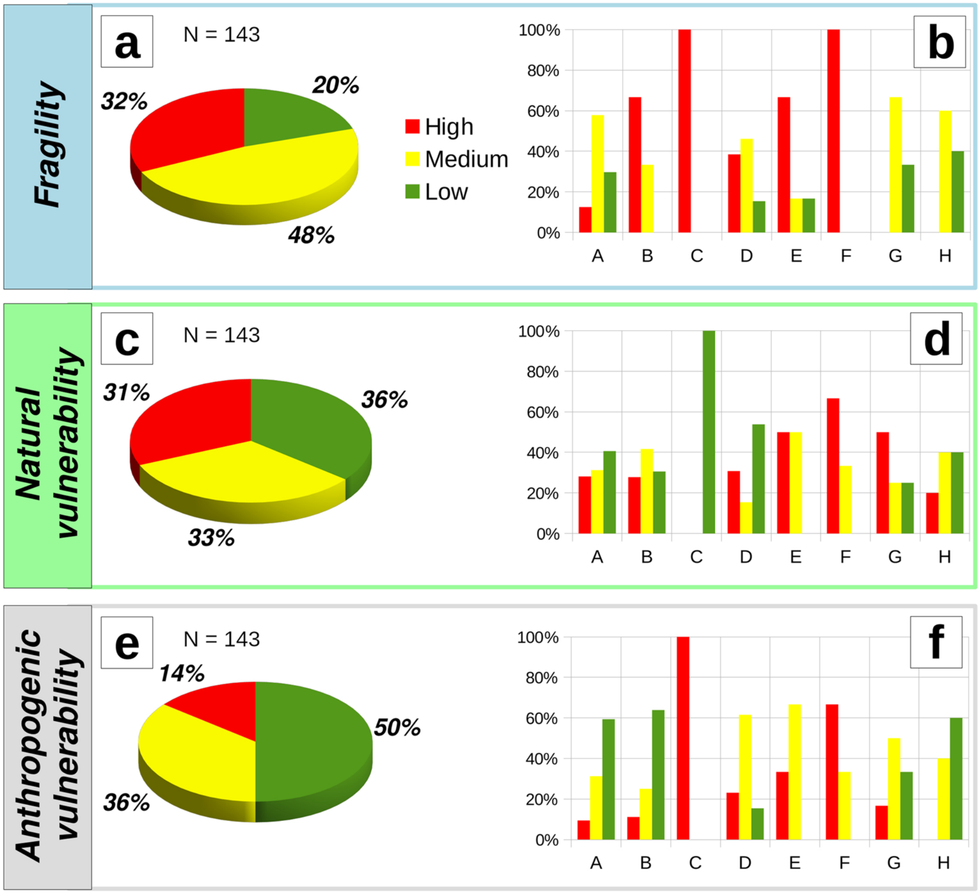

Fig. 6 Results of the quantitative assessment. Diagrams a, c and e show the percentage of geosites falling in the three categories (high, medium and low) for each block. Diagrams b, d and f show the breakdown of these three classes by primary interest of the geosites: A = Geomorphology (active); B = Geomorphology (inactive); C = Hydrogeology; D = Mineralogy and petrography; E = Paleontology; F = Pedology; G = Stratigraphy; H = Structural geology

Anthropogenic Vulnerability (AV)

With regard to the risk of anthropogenic degradation, the scores obtained were also grouped into three classes: 'low' (AV ≤ 2), 'medium' (2 < AV < 3) and 'high' (AV ≥ 3). About half of the geosites fall into the 'low' category, while 36% are in the 'medium' category and only 14% in the 'high' category (Fig. 6e).

As regards the categories of geosites most vulnerable to anthropogenic impact, the breakdown shows that these are geosites of hydrogeological, pedological and paleontological interest. 100% of the geosites of hydrogeological interest fall into the "very high" category; for the pedosites, the percentage of "very high" is just over 60%. Once again, the least vulnerable category is represented by geosites of geological-structural interest (Fig. 6f).

Protection Measures (PM)

The results of the assessment of PM have not been represented in Fig. 6 along with those of F, NV and AV, because they are inherently different – F, NV and AV depend on the local geographical, geological and geomorphological setting of the site, including anthropogenic presence, while PM depend largely on the legal framework and the political context, from the small to the large scale (Reynard 2005).

In the study area, the geosites with structures for the protection of geological features or visitor facilities are represented mostly by tourist caves and mines. The example given in Fig. 5f is the Arma delle Manie, which is a cave protected by fences and walls. Control of access is also present on those sites, including a few geosites falling on private land.

In terms of legal protection, all of the assessed Ligurian geosites receive the lowest score (representing high protection) because of the presence of a specific regional law on geosites (Regional Law No. 39/2009). In the Hérens valley the situation is a bit more fragmented, as only four of the 44 inventoried geosites are included in the Federal Inventory of Swiss Geosites (Reynard et al. 2012). Other geosites are indirectly protected because of their inclusion in other protected federal inventories: examples are the Ar du Tsan peat bog, included in the Federal Inventory of Low Marshes of National Importance, or other sites included in the Federal Inventory of Alluvial Zones of National Importance (e.g., Satarma alluvial zone, Salay alluvial zone).

Priorities for Intervention

Some interesting implications for management can be obtained by combining certain values in charts. Three combinations, displayed in the three charts in Fig. 7, were found to be significant: F vs. NV, F vs. AV and AV vs. PM. The combination of fragility with the two types of vulnerability is important for identifying those geosites that are both fragile and vulnerable. The two types of vulnerability are kept separate because, as mentioned above, they require different types of intervention. Finally, the combination of AV and PM is important to identify those sites that are vulnerable due to anthropogenic factors but not adequately protected. Within these charts, one can identify several cells that correspond to different priorities for intervention; depending on which area the geosite falls into, the urgency to intervene on its management plan can be immediately visualized.

The sites that obtain simultaneously the highest values for F and NV are listed in Table 5, while Table 6 gives the sites that simultaneously obtain the highest values of F, AV, and MP. Thus, the two tables list respectively the sites that have high priority for intervention against the risk of degradation due to natural causes and due to anthropogenic causes. The sites that appear in the two tables are are mostly active or inactive geomorphosites characterized by particular very fragile landforms (e.g.,

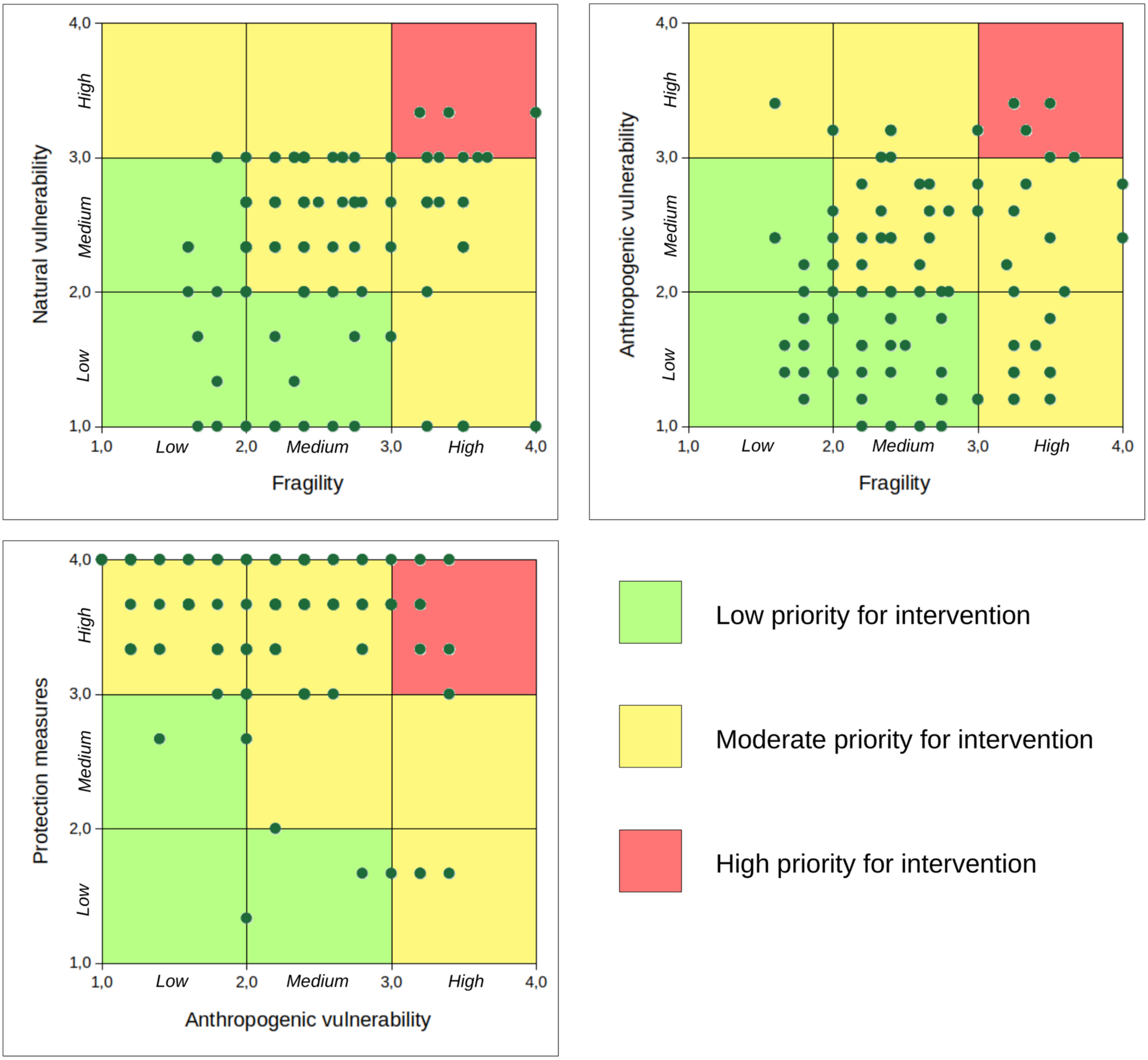

Fig. 7 Chart confronting F, NV, AV and PM of the analysed geosites, represented as green dots in the charts

Table 5 Geosites with the highest priority for natural degradation risk

ID	Name	F	NV
L1	Rio Torsero fossils (Liguria)	3.3	3.0
L9	Baia dei Saraceni beach rock (Liguria)	4.0	3.3
L12	Buco del Prete rock arch (Liguria)	3.4	3.3
L37	Santa Giustina fossils (Liguria)	3.7	3.0
L41	Piana Crixia stone mushroom (Liguria)	3.6	3.0
L44	Arpaia cave (Liguria)	3.2	3.3
L46	Edera cave (Liguria)	3.5	3.0
L64	Celle Ligure plinthitic paleosol (Liguria)	4.0	3.7
L86	Punta Chiappa speleothems (Liguria)	3.2	3.7
H3	Prafleuri anthropic terraces (Hérens valley)	3.3	3.0
H34	Ar du Tsan peat bog (Hérens valley)	3.3	3.0
H35	A Vieille rock glacier (Hérens valley)	3.3	3.0
H41	La Maya (Hérens valley)	3.0	3.0

Table 6 Geosites with the highest priority for anthropogenic degradation risk

ID	Name	F	AV	PM
L1	Rio Torsero fossils (Liguria)	3.3	3.2	3.0
L37	Santa Giustina fossils (Liguria)	3.7	3.0	3.3
L46	Edera cave (Liguria)	3.5	3.0	3.3
L54	Zanairin eclogite blocks (Liguria)	3.0	3.0	3.3
L64	Celle Ligure plinthitic paleosol (Liguria)	4.0	3.2	3.3
L85	Pigna hydrothermal spring (Liguria)	3.7	3.0	3.0
L90	Manie paleosol (Liguria)	3.7	3.2	3.3
H15	La Luette earth pyramids (Hérens valley)	3.0	3.2	3.7

Buco del Prete rock arch; Edera cave; Punta Chiappa speleothems, Fig. 5b) or outcrops (Baia dei Saraceni beach rock; Fig. 5a), paleontological sites (Rio Torsero fossils, Santa Giustina fossils) and pedological sites (Celle Ligure plinthitic paleosol, Fig. 5c; Manie paleosol).

The Baia dei Saraceni beach rock (Fig. 5a) is a very evident example of a site with high F, NV and AV. The fragility is mainly given by the small size of the site and the geomechanical features of the outcrop. The high natural vulnerability is due to the erosive action of waves, while anthropogenic vulnerability derives from both the presence of coastal defences which partly cover the site, and the pressure from tourists resulting from the presence of a very famous beach nearby (the Baia dei Saraceni). Finally, some sites, while not obtaining high values for NV, are vulnerable due to the presence of geomaterials with economic value: for example, the gravel deposits at the site of La Luette earth pyramids (Fig. 5d) are exploited by quarrying activity.

Discussion

The results reported in Sect. 4 have been separated between the 4 criteria (F, NV, AV and PM), as the separate results may give a better indication of the possible problems and vulnerabilities of the geosite than a total score related to the degradation risk. For example, since F is linked to intrinsic characteristics, it may be difficult to intervene effectively on it. For geosites with high NV, interventions could be considered, taking into account the geomorphological context, to mitigate the impact of natural processes that have a degrading effect. The criterion on which it is easiest to intervene is AV, through the implementation of appropriate protection measures or, where necessary, the reinforcement of existing measures.

In general, the method provides a good compromise between ease of use, reliability of results and breadth of application. On the one hand, the large number of indicators ensures that as many as possible of the degradation risk factors that affect geosites are taken into account. On the other hand, the method is applicable to all types of geosites, without neglecting the specificities of some of them. Finally, although the indicators are numerous, they are for the most part easy to implement and assess, with a few exceptions listed below.

The main weakness of this methodology is that, in the absence of quantitative monitoring data, the evaluation of some indicators relies solely on the experience of the evaluator. This is the case for two indicators for NV – i.e., continuity and intensity of active processes – for which the assessment would benefit from the availability of quantitative data. The assessment of AV also suffers from the same problem, especially with regard to the indicator 'Degradation due to current use'. In this case, in addition to monitoring the geomorphological dynamics and physical evolution of the site (Margiotta et al. 2016), it would be useful to monitor the presence of visitors – this may help to see if in some cases there is correlation between the two.

Population density is to some extent a proxy for the number of visitors, but as an indicator it has obvious shortcomings. In this paper and other analogous research (e.g., Brilha 2018), the population density is taken at the municipality level, because this data is available and easy to find. However, it poses some issues. First, this type of data doesn't take into account the variability that can occur inside the municipality itself. Second, the real population density can be highly variable throughout the year: in many tourist centres it increases by up to an order of magnitude during the tourist season – within the context of this research, this is true for many localities in Liguria (Callegari 2003; Candia et al. 2018), but a little bit less for the Hérens valley (Gros-Balthazard et al. 2024). In addition, geosites in areas with very low population density but high visitor numbers may suffer from greater anthropogenic pressure than less visited geosites in areas with high population density (Bertocchi et al. 2021) - especially if the visitor number exceeds the geosite's carrying capacity (Lima et al. 2017).

For these reasons, it is important to monitor the physical development and presence at geosites. Monitoring all 99 geosites in Liguria or all 44 geosites in the Hérens Valley would probably be prohibitively expensive and extremely difficult from a practical point of view. In any case, the results of the assessment presented here can give an indication of the priority sites to be monitored. Monitoring, if carried out over a sufficiently long period of time, can also give indications as to how the geosite is responding not only to anthropogenic pressure but also to climate change (Wignall et al. 2023).

Concerning PM, the proposed indicators only take into account measures that aim to mitigate anthropogenic vulnerability. Protection measures specifically aimed at reducing natural vulnerability or fragility are very rarely taken, either because it is difficult to make them effective, or because geoconservation initiatives are generally aimed at maintaining the naturality of the system as much as possible. Among the 143 assessed geosites, only one has protection measures aimed at reducing its vulnerability and preserving its integrity: the Fungo di Piana Crixia (Liguria; Fig. 8a), near which wooden pilings were posed to reduce runoff on the surrounding scarp. Another case is represented by the Laghi delle Agoraie (Fig. 8b, in which the *status quo* of the geomorphological system is maintained – against the action of natural processes – to preserve the ecosystem. More often, structures aimed at mitigating natural processes are part of management strategies to reduce the geomorphological risk (Figs. 8c, d) – not the natural vulnerability of geosites.

The risk of degradation, as defined in Sect. 3.1 and as assessed in the methodology presented here, relates only to the integrity of the geosite. It does not take into account the possible degradation of other characteristics of the geosite, such as its aesthetic value or accessibility, which are also important from a geological heritage management and enhancement perspective. Some attempts have been made in this direction. For example,

Fig. 8 (**a**) Near the Piana Crixia ‘stone mushroom’ (Liguria), a fragile geosite, wooden structures have been built to reduce runoff along the denudation scarp; (**b**) At the Laghi delle Agoraie geosite (Liguria), the natural geomorphological evolution is prevented to maintain a fragile ecosystem; (**c**) Rockfall nets at the Pointe du Tsaté geosite (Hérens valley); (**d**) The Via Digione landslide urban geosite in the city of Genoa (Liguria) has concrete structures, walls and nets to mitigate the geomorphological risk

Bussard and Reynard (2023) propose a multi-temporal assessment of how the heritage values of some high mountain sites might evolve in response to climate change. However, there is a lack of quantitative or semi-quantitative methods to assess the risk of degradation in relation to other site values.

Finally, within this methodology, there are no indicators directly concerning the issue of climate change. The impact of climate change on geosites has still not been widely studied, with some researchers debating it qualitatively (e.g., Selmi et al. 2022), or others proposing semi-qualitative assessment methodologies (Wignall et al. 2018). In general, the various aspects of climate change can be seen as external forcings that have a non-linear effect on: (i) geomorphological active processes, directly affecting the fragility and natural vulnerability of geosites; (ii) ecosystems, indirectly affecting the natural vulnerability of geosites; (iii) anthropogenic presence and actions, affecting the anthropogenic vulnerability of geosites. Incorporating numerical indicators to quantify the effect of climate change on geosites in a methodology such as the one proposed here could lead to misleading or plain wrong results. One way to work around the issue could be to qualitatively assess the sensitivity of each geosite to climate change separately, then monitor the possible evidence of climate change and adapt the management plan accordingly (Gordon et al. 2022).

Conclusions

The analysis of the degradation risk is a key issue in geoconservation and geoheritage management. That's why, in recent times, many researches dealt with trying to assess degradation risk, with the proposal of several methodologies. In this research a new methodology for the degradation risk assessment has been proposed; the degradation risk is assessed by means of the criteria of fragility, natural vulnerability and anthropogenic vulnerability. In addition to this, protection measures have also been assessed. The methodology has been tested in two different study areas – Liguria (Italy) and the Hérens valley (Valais, Switzerland) – taking into account a total of 143 geosites, and giving consistent results.

The procedure for the quantitative degradation risk assessment combines a certain practicality of use with a precise description of the different risk factors that may affect the geological heritage. It is particularly useful when applied to large inventories of geosites, as it allows the rapid identification of those sites for which possible management interventions should be prioritised – sites that are more fragile, more vulnerable, or that have not been adequately protected. Giving separate scores to each criterion (fragility, natural vulnerability, anthropogenic vulnerability, protection measures) gives precise indications on how to calibrate management measures, highlighting what are the 'weaknesses' of the current status of the geosite. It should be noted that the method is focused on the factors that can affect the integrity of the geosites. Subsequent studies could focus on new methodologies to assess also the factors that affect other values of geosites, such as the aesthetic value, the potential for use or the cultural value.

Based on the results of the assessment, general frameworks of management actions can be proposed. Among the various actions that are proposed and can be undertaken, the most common and generally useful is monitoring. It can be used to provide a more robust quantitative basis for the degradation risk assessment process, as well as to test any direct management actions that are put into practice.

Given that the methodology is designated to highlight management priorities within large inventories of geosites, more specific, site-by-site analyses are required to identify threats to single geosites, and to detail management plans, including management perimeter delineation (Ferrando et al. 2025). Further research will be required to investigate how global changes, and in particular climate change, affects geosites and their fragility and vulnerability.

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Declarations

Competing interests The authors have no competing interests to declare that are relevant to the content of this article.

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