PANGEA ERASMUS +

Assessment of forest fires impacts on geoheritage: the example of Estrela UNESCO Global Geopark

Jéssica Brito Gonçalves

UMinho | 2023

Universidade do Minho
Escola de Ciências

Jéssica Brito Gonçalves

Assessment of forest fires impacts on geoheritage: the example of Estrela UNESCO Global Geopark

julho de 2023

Universidade do Minho
Escola de Ciências

Jéssica Brito Gonçalves

Assessment of forest fires impacts on geoheritage: the example of Estrela UNESCO Global Geopark

Dissertação de Mestrado
Mestrado em Geociências
Ramo Património Geológico e Geoconservação

Trabalho efetuado sob a orientação de
Professor Doutor Paulo Jorge Silva Pereira
Dr. Emanuel de Castro

julho de 2023

Acknowledgements

First, I would like to thank my advisors, Professor Dr. Paulo Jorge Silva Pereira and Emanuel de Castro, for their availability, support and ideas throughout the realization of this dissertation.

I would also like to thank Fábio Loureiro for his time and support, and all the staff at Estrela UNESCO Global Geopark for their kindness and hospitality during my stay and for integrating me into the educational and touristic activities of the geopark.

I am deeply grateful to Erasmus Mundus Joint Master Degree Pangea and the Erasmus+ Programme of the European Union for granting me an Erasmus scholarship and for the unique opportunity to join a program that has provided me with a much learning and valuable experiences. A special thank you to the Vice-Dean in charge of International Relations from the Université de Lille, Professor Dr. Sébastien Clausen, as well as the PANGEA Management Team for their availability, support, and kindness.

I want to thank the professors from the Université de Lille (France), National and Kapodistrian University of Athens (Greece) and Universidade do Minho (Portugal) for the knowledge shared, exchange of ideas, and meaningful discussions during classes.

Additionally, I would like to give my thanks to all of my friends and colleagues from the Pangea Master's program and other university programs who shared this journey with me and further contributed to my personal and professional development.

My appreciation also goes to my family and friends for their encouragement and support throughout my studies. I want to express my gratitude to my grandmothers for whom I have great admiration for always being there for me. A special thank you to my grandmother Necy Alves (*in memoriam*) for always being a source of light and joy. Words cannot express my gratitude to my parents, Angelita Brito Gonçalves and Luis Fernando Alves Gonçalves, for their tireless efforts that allowed me to be where I am today, thank you for always believing in me and supporting my life decisions.

STATEMENT OF INTEGRITY

I hereby declare having conducted this academic work with integrity. I confirm that I have not used plagiarism or any form of undue use of information or falsification of results along the process leading to its elaboration.

I further declare that I have fully acknowledged the Code of Ethical Conduct of the University of Minho.

Avaliação dos impactos de incêndios florestais no património geológico: o exemplo do Estrela Geopark Mundial da UNESCO

RESUMO

Tal como a biodiversidade, a integridade e os valores da geodiversidade são ameaçados pelos incêndios florestais, podendo sofrer danos a escalas muito diversas, desde alterações mineralógicas e texturais a transformações cénicas das paisagens. O tema do risco de degradação do património geológico ainda é pouco explorado, mas de grande relevância para estratégias de gestão e conservação. Uma metodologia para avaliar o risco de degradação de geossítios é proposta e representa uma primeira abordagem prática para identificação de possíveis impactos de incêndios florestais no património geológico. A metodologia foi aplicada ao património geológico do Estrela UNESCO Global Geopark, Portugal, onde um incêndio florestal com uma área total de 24334 hectares, em agosto de 2022, afetou cerca de 15% dos geossítios (22 de 146), incluindo geossítios com elevado valor científico, como o Vale Glaciário do Zêzere. Um total de 20 geossítios foram selecionados (8 geossítios afetados pelo fogo e 12 não afetados) para testar a metodologia de avaliação de degradação (pós-ocorrência) e vulnerabilidade. A avaliação numérica considera dois critérios principais: (1) valor do geossítio, e (2) usos educativos e turísticos. Parâmetros e indicadores foram atribuídos a cada critério bem como diretrizes para a avaliação de cada indicador. Os resultados mostram que o nível de vulnerabilidade máximo obtido é "baixo" sem perda significativa de valor científico, mas impactos nos valores associados (culturais, cénicos, ecológicos) e nos usos educacionais e turísticos foram observados na maioria dos geossítios. A avaliação do risco de degradação foi obtida a partir dos resultados da avaliação de vulnerabilidade combinados com os dados de perigosidade de incêndio florestal no território. Após procedimento de delimitação dos geossítios, foram observados diferentes níveis de risco de degradação para cada geossítio, sendo o nível "médio" de risco de degradação do património geológico por incêndios florestais o máximo valor alcançado. Os dados obtidos correspondem aos resultados expectáveis à partida, uma vez que o património geológico presente na área de estudo é, no geral, menos sensível a degradação pelo fogo devido às características geológicas e tamanho dos geossítios, principalmente caracterizados por granitos e geoformas de grande dimensão. Os resultados podem suportar medidas de gestão no território, e a metodologia proposta mostrou-se uma ferramenta útil que pode ser aplicada em outras áreas e contextos e aprimorar ainda mais o método. Espera-se que os resultados obtidos contribuam para as discussões sobre cartografia do património geológico e métodos de avaliação do risco de degradação de geossítios.

Palavras-chave: incêndios florestais; património geológico; perigo; risco de degradação; vulnerabilidade.

Assessment of forest fires impacts on geoheritage: the example of Estrela UNESCO Global Geopark

ABSTRACT

Just like biodiversity, the integrity and values of geodiversity are threatened by forest fires which can be damaged at very different scales, from mineralogical and textural changes to scenic transformations of landscapes. Geoheritage degradation risk is still a little explored topic but of great relevance for management and conservation strategies. A methodology to assess the risk of degradation of geosites is proposed and represents a first attempt to identify possible impacts of forest fires on geoheritage with a practical approach. The methodology was applied to Estrela UNESCO Global Geopark's geoheritage, Portugal, where a forest fire covering a total area of 24,334 hectares in August 2022 affected about 15% of the geosites (22 out of 146), including geosites with high scientific value, such as the Zêzere Glacial Valley. A total of 20 geosites were selected (8 geosites affected by fire and 12 not affected) to test the validity of an assessment methodology regarding degradation (post-occurrence) and vulnerability. The vulnerability numerical assessment was performed considering two different criteria: (1) geosite value, and (2) educational and touristic uses. Parameters and indicators were assigned to each criterion along with guidelines to support how to assess each indicator. The maximum value of vulnerability obtained is "low", without significant loss of scientific value, but impacts on associated values (cultural, scenic, ecological) and educational and touristic uses were observed in most of the geosites. The degradation risk assessment resulted from the vulnerability assessment combined with the forest fire hazard classification of the territory. After a geosite delimitation procedure, different levels of degradation risk were observed within each geosite limits, with a "medium" degradation risk by forest fires being the highest value. A reduced level of degradation risk was already expected, since the geoheritage in the study area is less likely to be destroyed by fire due to the geological characteristics and size of the geosites (mostly granites and large landfoms). The results can help address proper management procedures in the territory, and the proposed methodology showed to be a useful tool that can be applied to other areas and contexts and further improve the method. It is expected that these results can contribute to the discussions on geoheritage mapping and degradation risk assessment.

Keywords: degradation risk; forest fires; geoheritage; hazard; vulnerability.

Contents

List of Figures

List of Tables

1. Introduction

The interest on the protection of geoheritage (geological heritage) has grown for the last 25 years since the International Conference on the Protection of Geological Heritage held in France, in 1991. Several topics related to geoheritage (geoconservation, geotourism, geoparks) have emerged all around the world, besides a large set of territorial initiatives. Geoconservation initiatives, i.e., policies, methods, and actions, have been developed in many countries, especially in Europe, aiming at conserving geoheritage. Examples of these initiatives include the list of World Heritage Sites (WHS) by UNESCO, the creation of the UNESCO Global Geoparks (UGGp) program based in the Global Geoparks Network (GGN), and the recent selection of the first 100 geological heritage sites worldwide by the International Commission on Geoheritage of the International Union of Geological Sciences (IUGS). In Europe, the European Association for the Conservation of the Geological Heritage (ProGEO), created in 1993, is one of the key organizations that organize various activities (seminars, conferences, and symposia) with the aim of improving knowledge and experience exchanges concerning geoheritage and geoconservation (Reynard and Brilha, 2018).

Although many improvements on geoheritage and geoconservation research have been made in recent years, biodiversity is still the main focus on nature conservation initiatives, especially when considering the impacts from forest fires events. Forests provide large amounts of ecosystem services, including clean water and fertile soils. They help to stabilize the climate, regulate ecosystems, protect the biodiversity, and play a relevant role in the carbon cycle, besides helping to sustainable development. Although forest fires are key to the natural dynamics of some ecosystems, e.g., forest renewal, help in controlling insect and disease damage, or reducing fuel accumulation and therefore future fire intensity, they have caused growing economic, social, and environmental impacts in the last decades, and are also a threat to climate change mitigation due to the release of large amounts of greenhouse gases (IUCN, 2021).

Therefore, forests have been a matter of conservation policy for many years, especially in the face of an increase in the frequency and severity of forest fires in warmer and drier conditions. However, wildfires, or forest fires, have consequences on both biodiversity and geodiversity, but little attention has been paid to their impacts on the latter. This can be explained by the fact that nature conservation policies and studies traditionally consider biological aspects as fragile and vulnerable, while abiotic aspects are seen as stable, static, and free of danger (Ferreira et al., 2019). Although abiotic elements appear robust, the increase in the duration, extent, intensity, and severity of extreme fire events can pose a significant threat to geoheritage from the micro to the macro scale, affecting its associated values, besides direct and indirect impacts to tangible cultural heritage (Figueiredo et al., 2021).

Forest fires need a source of ignition, which can be natural or anthropic. Most of the forest fires are caused by human activities, either accidently or intentionally. According to Calviño-Cancela et al. (2016), wildland-urban interfaces (WUIs) are areas where there is an intense interaction between human activities and wildlife and may affect the risk of ignition and spread of fire (higher ignition risk but lower risk of spread in WUIs). However, many factors are involved in the occurrence and spread of fires, such as the availability of fuel, climatic conditions (e.g., humidity, temperature, and wind), topography, forest management practices, and socio-economic context (EEA, 2021).

In Europe, extreme fire events have been reported in recent years mostly during summer months, especially in the five Mediterranean countries (Portugal, Spain, Italy, Greece, and France - EUMED5 countries), which on average account for around 85 % of the total burnt area in Europe per year. Most of these episodes are driven by severe weather conditions, like the record droughts and heatwaves occurring in the spring and summer of 2017 and 2018, for instance. Besides, the higher risk of ignition in WUIs together with an increase in fuels accumulation in abandoned areas in EUMED countries in previous decades, may contribute to the high number of fires and burnt areas in these countries. Portugal is one of the most affected countries, mainly the north and central region of mainland Portugal (Parente et al., 2018; Costa et al., 2020; EEA, 2021).

The most recent major fire event took place in August 2022 and started in the municipality of Covilhã at *Serra da Estrela*, the highest mountain range in mainland Portugal. This fire event burnt a total area of 24,334 hectares of the Estrela UNESCO Global Geopark, the study area of this work, which affected about 15% of the geosites (22 out of 146) including geosites with high scientific value (e.g., Zêzere Glacial Valley). A quantitative methodology to assess the risk of degradation of geosites by forest fires was developed in this work using different criteria, parameters and indicators combined with a fire hazard assessment from the Nature Conservation and Forests Institute (ICNF, 2020). A geosite delimitation procedure was also developed based on previous studies (Fuertes-Gutiérrez and Fernández-Martínez, 2012; Santos-González and Marcos-Reguero, 2019; Coratza et al., 2021) to help proper management procedures.

The assessment of the risk of degradation of geosites is still a little explored topic but of great relevance for management and conservation strategies. Some studies have been developed on this topic (García-Ortiz et al., 2014; Fuertes-Gutiérrez et al., 2016; Wignall et al., 2018; Selmi et al., 2022) considering a set of different factors (natural and anthropic) that affect the integrity of geosites, but there is still no methodology focusing on the impacts of forest fires on geoheritage. Due to the complexity involved in the occurrence of forest fires and the increase and severity of these events, it is important to develop a methodology that addresses this issue, especially in conserved and protected areas.

Therefore, the main objective of this work was to develop a methodology to assess the risk of degradation of geoheritage by forest fires and its implications to geoconservation and geotourism policies, using Estrela UNESCO Global Geopark as study area. The work included the following steps:

- Test and application of a quantitative methodology in selected geosites to assess the vulnerability of these sites to degradation by forest fires;
- Geosite delimitation and assessment of the risk of degradation of geosites based on their vulnerability and fire hazard information;
- Proposal of management procedures considering the assessment results.

2. State of the Art

2.1Geological Heritage and Geoconservation

Nature conservation has a long history where biodiversity has been the focus of global initiatives over the years. However, the need to conserve relevant elements of the abiotic environment has become the focus of debate in recent years. In this sense, the concept of geodiversity was quickly developed following the recognition that abiotic elements are just as important as biotic elements, and quantitative and qualitative assessments of the variability of abiotic elements have been described in the literature using the term 'geodiversity' (Williams et al., 2020). This term has been defined as "the natural range (diversity) of geological (rocks, minerals, fossils), geomorphological (landforms, topography, physical processes), soil and hydrological features. It includes their assemblages, structures, systems and contributions to landscapes" (Gray, 2013).

Geoconservation is the act of identifying and protecting valuable elements of the abiotic environment (geoheritage), including associated promotional and awareness activities and the recording and rescue of data or specimens from features and sites threatened with loss or damage (García-Ortiz et al., 2014). Geoheritage represents *in situ* occurrences of geodiversity elements with high scientific value (geosites), and also *ex situ* occurrences such as museum collections (geoheritage elements). In addition, geoheritage may also have educational, aesthetic, and cultural values (Brilha, 2016).

Geoconservation initiatives around the world have focused on inventorying elements of geodiversity with the identification of associated values and spectacular examples were listed on registers and inventories of geoheritage, and in geoparks. For example, UNESCO has a list of World Heritage Sites (WHS) that includes geological sites and supports the world program of Geoparks (Mc Keever and Narbonne, 2021). UNESCO Global Geoparks (UGGp) are unified territories where sites with geological significance are managed with a holistic concept of protection, education and sustainable development. At present, there are 195 UNESCO Global Geoparks in 48 countries (UNESCO, 2023). Geoparks play an important role in characterisation, conservation and interpretation of geoheritage (Brilha, 2018) and may provide the vehicle to promote the appreciation of geoheritage by the general public (Williams et al., 2020). In addition, IUGS has recently selected the first 100 geological heritage sites worldwide (IUGS, 2022).

Over the past 30 years, the rapid growth in research and activity across these domains, including geotourism, has increasingly led to an overlap (Figure 1) and much have been done regarding geoconservation initiatives, especially in UNESCO Global Geoparks. However, according to Fuertes-Gutiérrez and Fernández-Martínez (2012), there is still a need of integration of geoheritage as a fundamental parameter in environmental conservation and management which could be achieved by enforcing and standardizing the methodological bases for geoconservation.

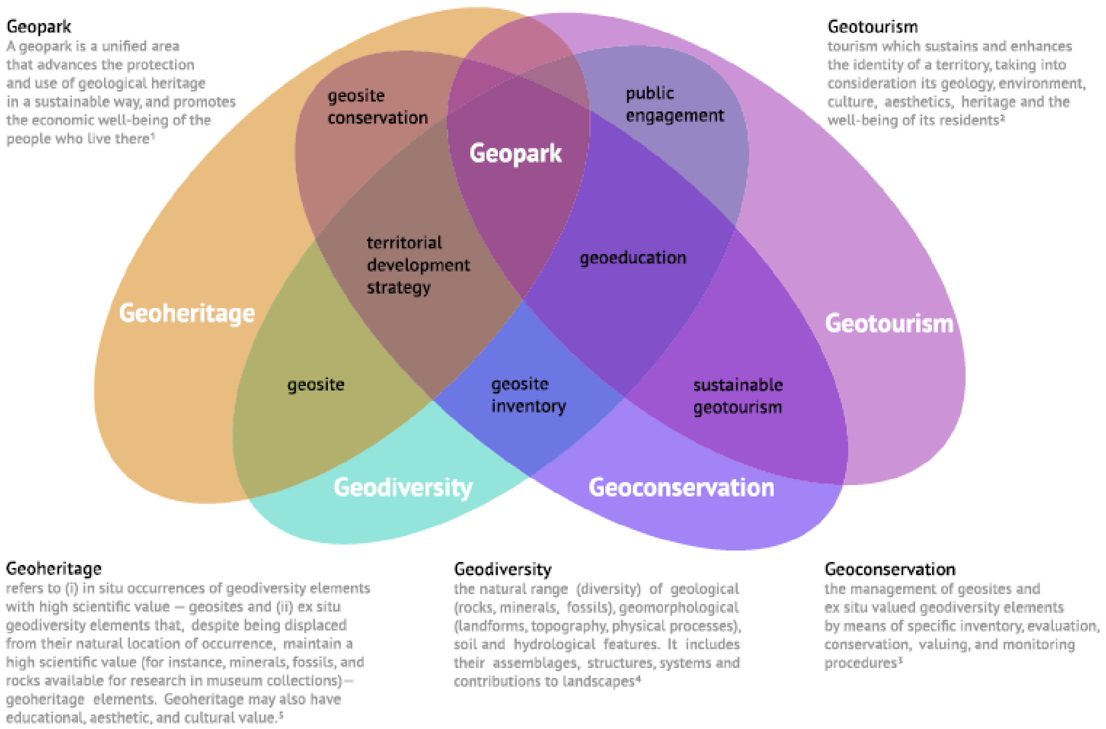


Figure 1: Intersection between the theory and practice domains of geotourism, geoconservation, geodiversity and geoheritage (Williams et al., 2020).

2.2 Review on degradation risk assessment

Geoconservation is now a growing and widespread activity that is well established in the UK, Europe, and many other parts of the world. Several geosites inventorying methods and their potential touristic and educational uses can be found in the literature, mainly applied in areas of UNESCO Global Geoparks and other protected areas. Brilha (2016) included the risk of degradation of geosites as part of the quantitative assessment of an inventory considering criteria such as the possibility of deterioration of geological elements, proximity to areas/activities with potential to cause degradation, legal protection, accessibility, and density of population.

However, assessing the risk of degradation of geosites is still an underexplored topic and the recognition and prevention of threats that affect geosites still lack common approaches and assessment methods applicable to different areas, scales, and contexts (Selmi et al., 2022). Several authors have been addressing this issue (García-Ortiz et al., 2014; Fuertes-Gutiérrez et al., 2016; Wignall et al., 2018; Selmi et al., 2022) focusing on the importance of establishing a standard and generally accepted methodology for assessing the risk of degradation of geosites. According to García-Ortiz et al. (2014), the evaluation of the threats to geoheritage is essential for geoconservation and forms the basis for the management and planning of activities. Additionally, measuring the risk of degradation enables researchers to monitor the changes and the evolution of geosites over time.

The risk of degradation of geosites has been a topic of debate in recent years also in the light of future impacts from climate change, especially in areas of UGGp and WHS. According to Gordon et al. (2022), the site type (e.g., active or relict, finite or extensive) and location (e.g., quarry, river reach or foreshore) are key to identifying many likely pressures on geosites. These pressures or threats will trigger management interventions considering the scientific value of the geosite and other associated values (e.g., touristic, ecological, cultural).

Terms such as sensitivity, fragility, and vulnerability have been used in various publications describing the risk of degradation of geoheritage sites showing different definitions for the terms, and the same concept is sometimes given different names in different papers. García-Ortiz et al. (2014) assessed the risk of degradation of the geosites in La Rioja (Spain) considering only natural criteria (fragility and natural vulnerability) and established a common framework for specialists working on geoconservation issues (Figure 2). For the authors, the parameters involved in the estimation of the risk of degradation are sensitivity, fragility, vulnerability, and public use. Besides, the authors also discuss and define these terms which were adopted in later studies (e.g., Fuertes-Gutiérrez et al., 2016; Selmi et al., 2022) on this topic (Table 1).

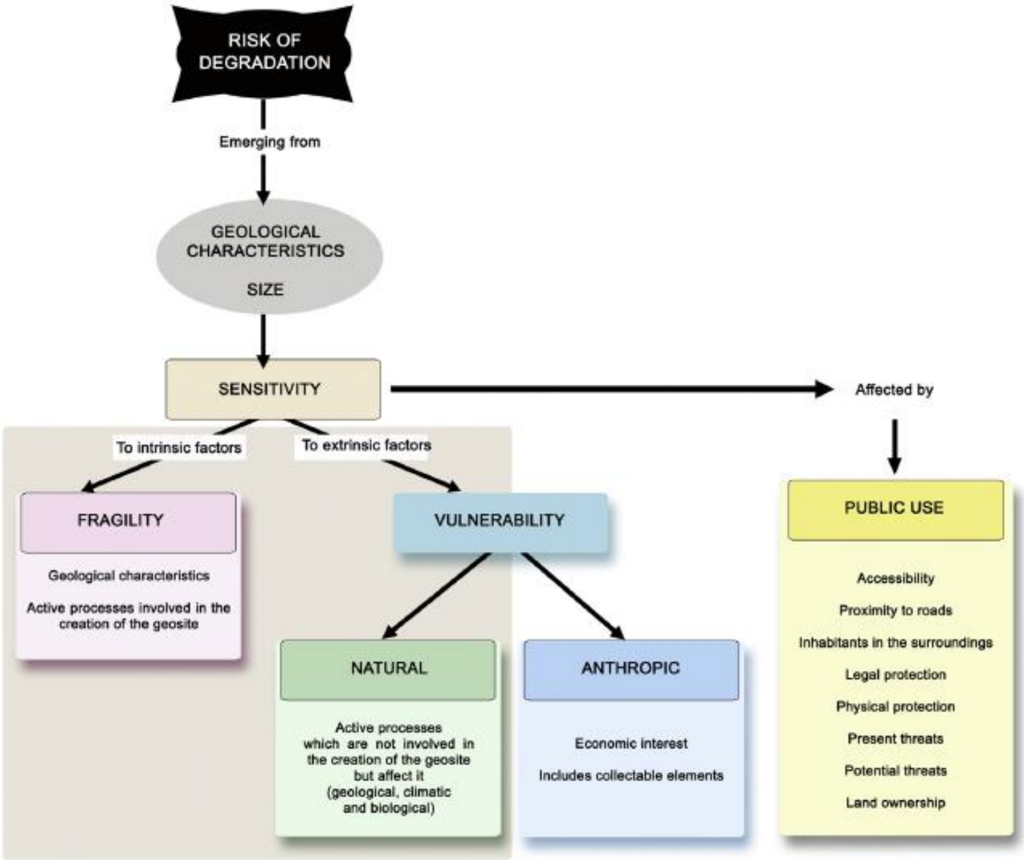


Figure 2: Diagram of the parameters involved in the estimation of the risk of degradation of geoheritage (García-Ortiz et al., 2014).

Table 1: Terms and definitions related to the degradation of geosites, according to Garcia-Ortiz et al. (2014) and modified by Selmi et al. (2022).

Term	Definition
Sensitivity	Geosite's susceptibility to damage or destruction, i.e., the likelihood that the geosite's natural characteristics will be damaged or destroyed.
Natural Vulnerability	The sensitivity of a geosite to be damaged or destroyed by natural processes not involved in its creation.
Anthropogenic Vulnerability	The sensitivity of a geosite to be damaged or destroyed by human activities related to its economic value due to its geological characteristics (mining, quarrying, collection, etc.)
Public Use	The susceptibility of a geosite to be damaged due to its location and its current or possible use (vandalism, no control of access, no physical protection, etc.).
Fragility	The sensibility of a geosite to be damaged by processes involved in its creation and directly related to its geological characteristics.

2.3 Delimitation of geosites

Although there is an increasing number of studies on geoheritage research, these studies have been mainly focused on the definition of the basic concepts, the identification and assessment of geosites and the principles for geoconservation. In many cases, it does not include accurate geosite delimitation (Fuertes-Gutiérrez and Fernández-Martínez, 2012; Santos-González and Marcos-Reguero, 2019).

Geoheritage mapping has recently gained a high level of attention not only in the scientific community but also in the geotouristic context presenting information in an appropriate scale, depending on the geosite characteristics and their size (Santos-González and Marcos-Reguero, 2019; Coratza et al., 2021). In general, thematic maps concerning geosites can be from two different categories depending on the user: (1) maps for the general public, and (2) maps for specialists. The boundaries of the geosites are usually represented in geoheritage maps for specialists (Coratza et al., 2021).

A methodology for mapping geoheritage is thought to be the basis for creating further maps, which are essential for decision making in environmental management, such as zoning of protected areas, the creation of geotourism plans or the protection of geoheritage. The mapping is based on the concept of geosite typology as a parameter, which tries to group types of geosites and thereby to find general and common management principles. Typology gives information on the dimensions of the geosite, the shape and disposition of its features, and its fragility and vulnerability and can be classified as points, sections, areas, and viewpoints. It is a way of identifying how the geological heritage of each location behaves spatially. In general, there is a limit separating punctual features from the other typologies depending on the geosites characteristics (Fuertes-Gutiérrez and Fernández-Martínez, 2012; do Nascimento et al., 2021).

According to Coratza et al. (2021), the choice of the cartographic representation of the geosite as point, polyline or polygon is strictly dependent on both the shape and size of the element, the scale of the map and, consequently, on the aim of the map. In this regard, Santos-González and Marcos-Reguero (2019) stated that the classification in points, lines, and polygons is irrelevant from the point of view of the land manager, who is interested in knowing the precise delimitation of the site regardless its shape and size.

In any case, geosite boundaries is an important factor to consider on geoheritage research especially in the assessment of the degradation risk of geosites, and may rely on the geosite characteristics, location, and area. It helps to determine the possible impacts from natural or anthropic threats and address proper management procedures. For example, a large area geosite such a geomorphological landscape (e.g., a glacial valley), may need different management strategies depending on the site location and threat, than a small area geosite. A possible product of this assessment is a thematic map showing the levels of degradation risk (very low, low, medium, high, very high) for each geosite in a territory (Fuertes-Gutiérrez and Fernández-Martínez, 2012).

2.4 Forest fires

Forest fires (or wildfires) are defined as 'any uncontrolled vegetation fire that requires a decision, or action, regarding suppression' (Forestry Commission, 2014). The use of fire by human species has been known since prehistoric times mainly associated to agricultural activities and the formation of cultural landscapes. However, a greater number of wildfires have been reported in recent decades with longer duration, extension, and severity, which is associated in part with climate change and changing patterns of fire use due to human causes (Figure 3).

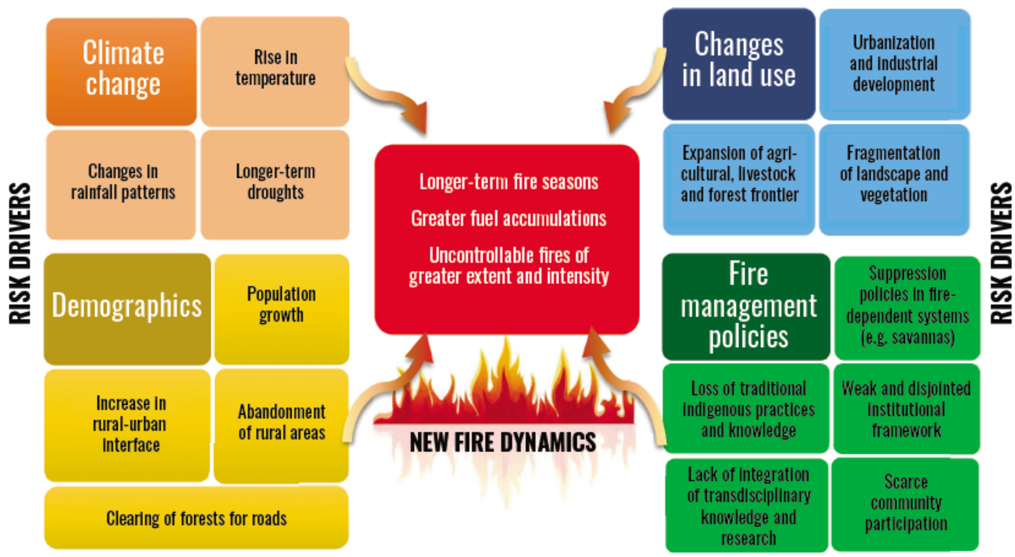


Figure 3: Risk drivers for the incidence of wildfires in the Ibero-American region (Bilbao et al., 2020).

Fire is a natural process, which in some situations can have beneficial ecological effects and contribute to habitat vitality and renewal. Fires are key to the natural dynamics of some ecosystems defining many of their attributes, such as: species composition and abundance; life histories and species adaptations; vegetation growth and regeneration patterns; and also acts as landscape modeling agent. For centuries it has been used as a tool in land and forest management to control vegetation and to maintain important habitats such as heathland. However, fires may cause devastating human and environmental impacts which have caused growing economic, social and environmental impacts in the last decades (Forestry Commission, 2014; Bilbao et al., 2020; Figueiredo et al., 2021).

Although wildfires events are a global problem, they have been reported extensively in Europe and are usually concentrated in the Iberian Peninsula and across Mediterranean Europe. During the second half of the 20th century, Mediterranean Europe has undergone socio-economic changes where the abandonment of rural areas has led to significant changes in traditional land uses of the Mediterranean basin. Less productive regions have been abandoned and reforestation or scrubbing processes have taken place both in Spain and in Portugal. Simultaneously, there was urban expansion into rural areas where there was a concentration of agricultural activities in the most productive areas, increasing urban-forest interface. The higher risk of ignition in these areas combined with an increase in fuels accumulation in abandoned areas in previous decades, may contribute to rise the vulnerability of the landscape in large areas of the Iberian Peninsula (Calviño-Cancela et al., 2016; Ferreira-Leite et al., 2017; Bilbao et al., 2020).

Figure 4 shows the annual burnt area between 1980 and 2020 in Portugal, Spain, Italy, Greece, and France (EUMED5 countries). The burnt area has slightly decreased since 1980, except in Portugal. However, there is large interannual variability, determined strongly by meteorological conditions, such as the very large burnt area in 2017 associated to extreme fire events in Portugal, whereas the burnt area in 2018 was the lowest on record (EEA, 2021).

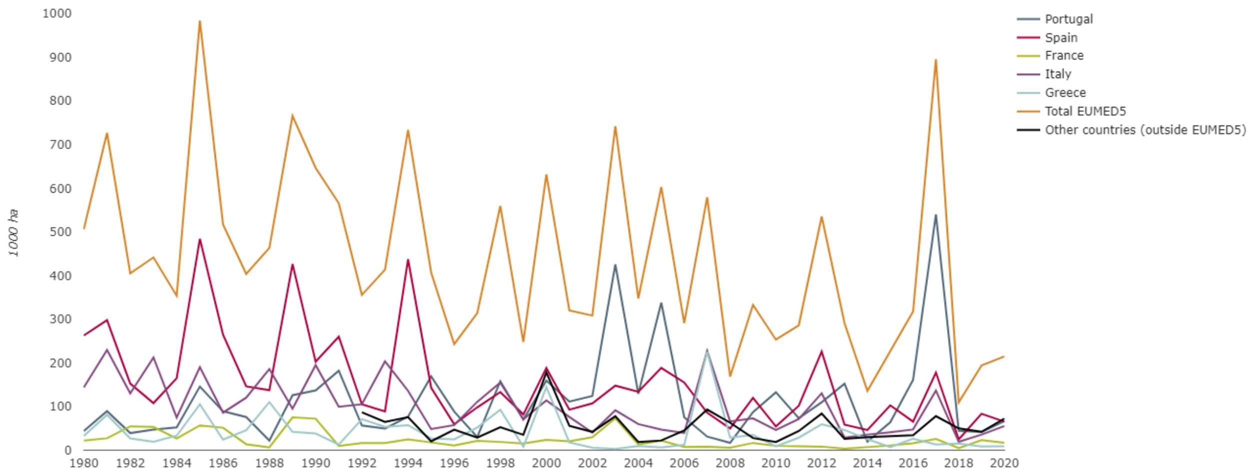


Figure 4: Burnt area in European countries based on EFFIS (European Forest Fire Information System) data. Long time series, starting in 1980, are available for Mediterranean Europe — southern France, Greece, Italy, Portugal and Spain (EUMED5). Source: EEA (2021).

During the summer of 2018, Australia, Greece, North America, Scandinavia (some even within the Arctic Circle) and the United Kingdom experienced unusually destructive wildfires (Turco et al., 2019). Sweden experienced its worst fire seasons ever in 2018 and required international fire-fighting assistance (EEA, 2021). Greece had one of the most severe forest fire events that have occurred in the country over the past decade during the summer of 2021 (27 July to 16 August), not only regarding duration and area, but also intensity. This event resulted in the devastation of an area of more than 3600 Km^2. Forest fire events of similar severity also occurred in other Mediterranean countries during this period (Evelpidou et al., 2021). More recently, a big wildfire event was reported in Portugal during the summer of 2022 which burned a total area of 24,334 hectares (ICNF, 2022).

Both the occurrence and changes in climatic extremes constitute a great concern to fire impacts. Besides, there has been a significant increase of WUI which has caused an increase of society exposure to large wildfires. Projections of wildfire risks are uncertain due to multiple factors including compound events, fire–vegetation interaction and social factors. However, summer droughts and high temperatures seem to be primary determinants of the interannual variability of fires in Southern Europe (Turco et al., 2019), and wildfire risks could increase across all regions of Europe at 1.5°C and 3°C GWL (*medium to high confidence*. IPCC, 2022).

While warm and dry conditions increase the risk of fire, a source of ignition from natural or anthropic causes is also needed. Natural causes are usually related to lighting, volcanic eruptions, earthquakes, and certain types of minerals in the soil that concentrate the sun's rays. Anthropic causes can be associated to accidents (e.g., failure of power lines, use of agricultural machinery); negligence (carelessness in the use of fire for agricultural or livestock purposes, mismanagement of private land); deliberate or intentional (associated with various interests, e.g., deforestation for the expansion of agricultural and livestock land, land tenure conflicts, armed conflicts, etc.); or rekindle and unknown causes. Nonetheless, the great majority of fires have human-related causes (Table 2).

Table 2: Forest fires causes and definitions (modified from Calviño-Cancela et al., 2016).

Category	Definition
Natural	Fires caused by lighting, volcanic eruptions, earthquakes, and certain types of minerals.
Negligence	Fires unintentionally caused by human using fire or glowing objects (e.g., use of fire for agricultural or livestock purposes, mismanagement of private land)

Accidents	Fires unintentionally caused by humans without use of fire, related to railroads, electric power, vehicles, engines, machinery or by army manoeuvres
Deliberate or Intentional	Fires intentionally caused by arsonists or others, usually associated with various interests, e.g., deforestation for the expansion of agricultural and livestock land, land tenure conflicts, armed conflicts, etc.
Rekindle	Restart of fires
Unknown	Fires with unknown causes

2.4.1 Forest fires in Portugal

In the last decades, Europe registered a high number of fires and burnt area with different spatial and temporal trends as the result of human-driven fuel transformations and climate change. Most wildfires in Europe occur in Spring and Summer (known as the 'fire season'). This is because a large volume of ground vegetation (a significant proportion of which may be dry), combined with extended periods of hot or dry weather, increases fire hazard. Fire hazard refers to the chances of a fire starting (ignition risk) and to the probability of fire spreading across the landscape. Despite its smaller land area in comparison with other Mediterranean countries, Portugal is the European country with the highest total number of fires and the second largest total burnt area. Weather and climate variability are the main drivers of the temporal distribution, such as extreme weather (e.g., heatwaves) and drought. However, most wildfires in Portugal are of human origin, which are mostly negligent (accidental and use of fire) or intentional (structural or arson). Spatial distribution of fire ignitions and burnt areas are highly dependent on human and biophysical drivers such as population density, distance to the nearest road, topographic (slope, altitude) and land use/land cover factors (Forestry Commission, 2014; Calviño-Cancela et al., 2016; Parente et al., 2018).

In general, the highest number of fires and burnt area occur in the northern half of the country (Figure 5). The municipalities with the highest number of fires are characterized by high population density, the presence of large urban areas or the traditional use of fire in agroforestry management. On the contrary, the likelihood of having larger burnt areas is greater in low population density areas and in inner country (Parente et al., 2018).

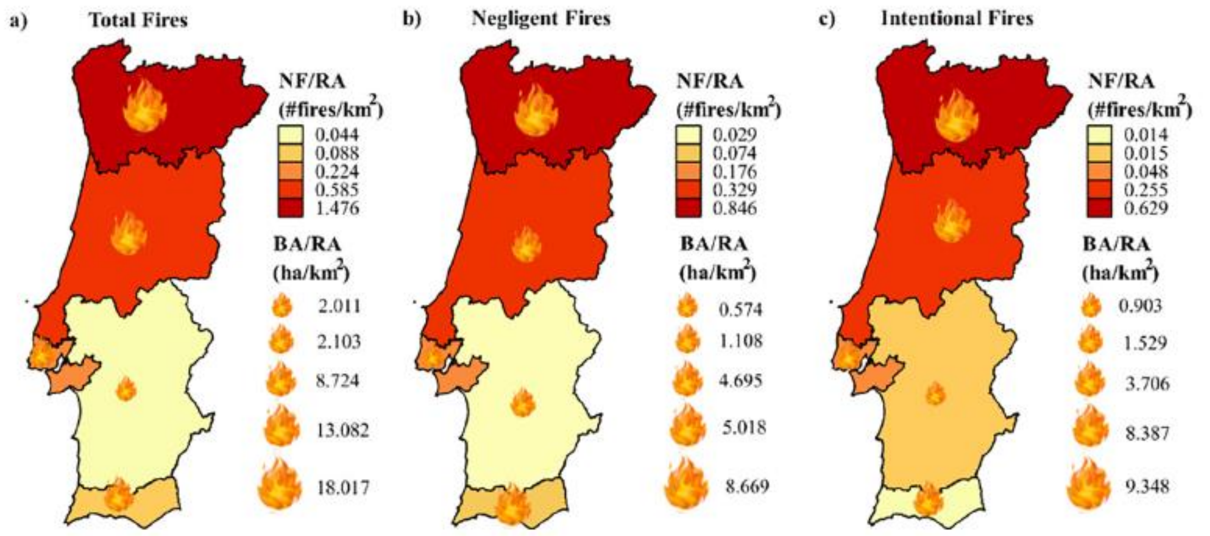


Figure 5: Density of number of fires (NF/RA; number of fires per km2) and burnt area (BA/RA; hectares per km2) in the 5 regions of Continental Portugal (RA) during the 2001–2014 period: Norte (dark red), Centro (light red), Lisbon Metropolitan Area (dark orange), Alentejo (yellow) and Algarve (light orange) (Parente et al., 2018).

According to Köppen-Geiger's climate classification there are two subtypes of Mediterranean climate in Portugal: dry and warm summer (Csb) in the northern part of the country; and dry and hot summer (Csa) in the south. Consequently, these regions present two different predominant vegetation types, namely: Forests (22%) and Scrub and/or herbaceous vegetation associations (30%) in the north region; and Heterogeneous agricultural areas (27%) and Forests (24%) in the south region (Parente et al., 2018).

Certain types of vegetation tend to burn more frequently than others (shrubs or conifers versus deciduous forests or agropastoral systems), also considering the spatial configuration of the vegetation patches that make up the landscape. Analysis of annual data show that the highest percentage of area burned in relation to total forest area in Portugal occurred in areas dominated by shrubs at altitudes above 400 m, located more than one kilometer from roads and with a population density of less than 25 inhabitants per km^2 (Bilbao et al., 2020).

Wildfires in Portugal usually occur during the fire season, as in other European countries, causing human casualties and impacts on the economy and the environment. Examples of big wildfires occurred during the fire season in Portugal in 2017 and 2022. The 2017 wildfire burned a record 500,000 hectares in the country with more than 120 human lives lost. In that year, two particularly tragic events took place before (17–20 June) and after (15–17 October) the official fire season window established by the

Portuguese authorities. The case of October was marked by an unusual meteorological phenomenon (hurricane Ophelia), which caused strong and dry winds in Portugal, together with dry vegetation and soil due to dry and high temperatures throughout 2017, created the conditions for this extreme wildfire event (Turco et al., 2019; Figueiredo et al., 2021).

According to a ICNF report (ICNF, 2022), a total of 9,701 rural fires which resulted in 106,639 hectares of burned area was reported in the period between 1 January and 31 August 2022. When comparing the records from the year 2022 to the ones of the previous 10 years, there were 15% less forest fires and more 36% of burned area relative to the annual average for the period. Fires with a burned area of less than 1 hectare are the most frequent (82% of all forest fires), and 16 fires have occurred with a burned area greater than or equal to 1000 hectares until August 2022. Large fires are considered whenever the total burned area is equal to or greater than 100 hectares. There were 93 fires falling under this category until 31 August 2022, which resulted in 91,046 hectares of burned area, about 85% of the total burned area. The biggest one happened inside the territory of Estrela UNESCO Global Geopark starting on 6 August in the municipality of Covilhã which burned a total area of 24,334 hectares. According to this report, the most frequent causes of forest fires in 2022 are arson - attributable (25%) and burning of forest or agricultural remnants (21%).

3 Study Area: Estrela UNESCO Global Geopark

3.1 General characteristics

Continental Portugal is geographically located between Spain and the Atlantic Ocean with a mainland area of about 90,000km^2. Estrela UNESCO Global Geopark (UGGp) includes the highest mountain range in mainland Portugal (Serra da Estrela), located in the central region of the country. However, the territory of Estrela UGGp has a broader area of 2216 Km^2 including 9 municipalities: Belmonte, Celorico da Beira, Covilhã, Fornos de Algodres, Gouveia, Guarda, Manteigas, Oliveira do Hospital, and Seia (Vieira et al., 2020; 2021). There are currently 146 geological sites inventoried at Estrela UGGp and 22 of them were affected by the fire event of August 2022 (Figure 6).

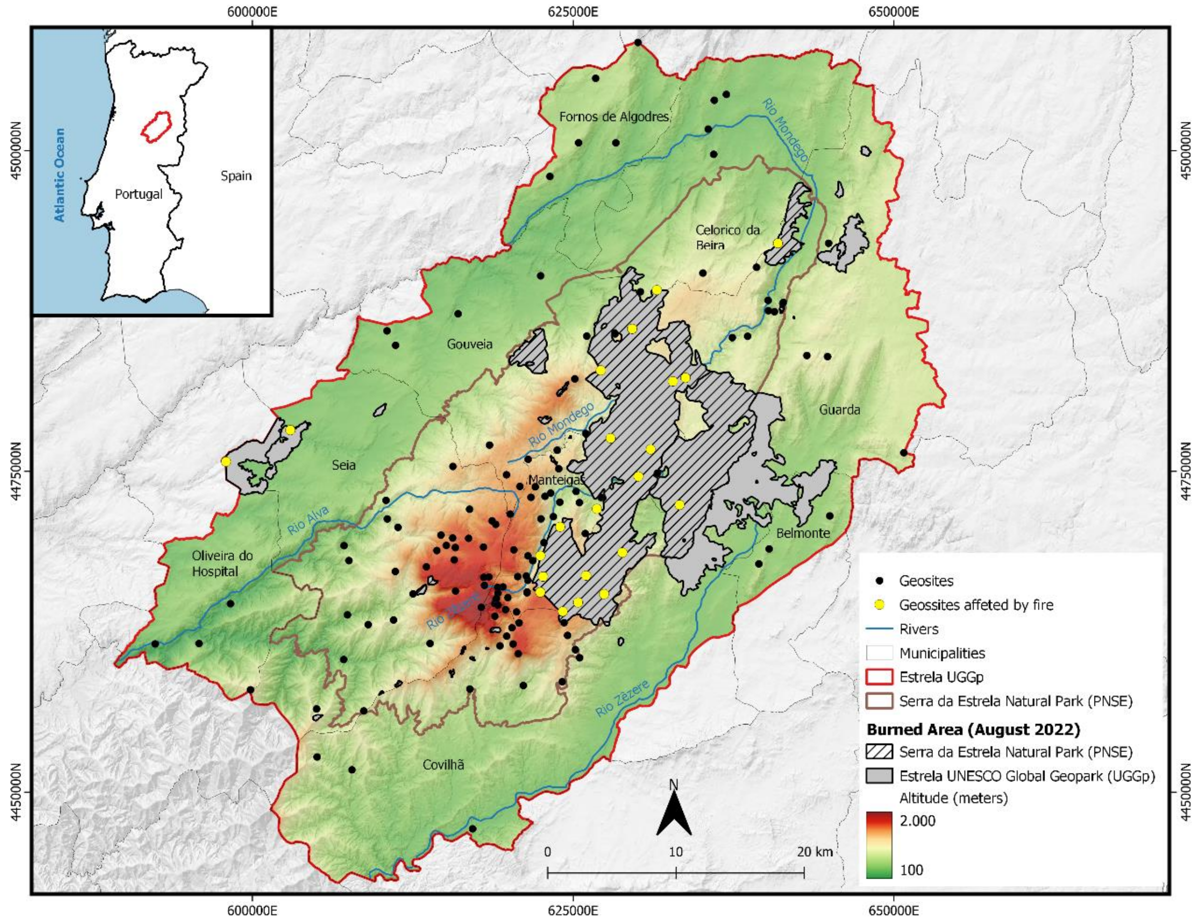


Figure 6: Location of Estrela UNESCO Global Geopark (UGGp) and representation of the burned area caused by the forest fire event of August 2022 and the affected geosites (Projected coordinate system: UTM zone 29N, WGS 84).

The climate in Serra da Estrela is mostly Mediterranean with dry and warm summers, and a wet season from October to May. The mean annual precipitation has values of 2500 mm in the higher parts of the mountain, and 1000 to 1200 mm in the piedmonts. Snow is recorded most frequently in February. The area is characterized by high biodiversity comprising almost one third of the Portuguese flora, which reflects two major European biogeographic regions, the Euro-Siberian and the Mediterranean. The vegetation is today strongly modified by human action, and this interaction is also one reason for the high biodiversity in this area. Geomorphology seems to play a significant role on the vegetation distribution across different spatial scales (POPNSE, 2008).

The Serra da Estrela Natural Park (PNSE) was established in 1976 to preserve its ecological and geomorphological values, but also to support the traditional mountain economy-based population. The territory has an excellent road network facilitating its traditional winter tourism mostly around the summit area at Torre. The PNSE is a central partner of the Estrela UGGp and occupies about 41% of its area, providing legal protection to 102 geosites (Vieira et al., 2020).

The region is affected by a rural abandonment trend since the 1960's with emigration mainly to to France, Germany, Switzerland and Luxembourg, and internal migration to Lisbon Metropolitan Area. The population decline still occurs today with a reduction of about 10,000 inhabitants in the territory from 2011 to 2016. The low population density has led to profound changes in land use, with abandonment of agricultural and grazing lands, which contributes to large burnt areas during fire events, such as the fire event that took place in August 2022 that burned 24,334 hectares of the territory (POPNSE, 2008).

3.2 Geodiversity

Serra da Estrela geodiversity has a long history of over 600 million years with its origins in the Neoproterozoic. It includes one of the several granitic massifs in the central and north-western Iberian Peninsula, although its elevation, tectonic, glacial history and rough relief, make it a rare case (Migoń and Vieira, 2014).

Tectonically, it is located in the Central Iberian Zone (CIZ), a mountain range that extends from Guadarrama, north of Madrid, to Montejunto, northeast of Lisbon, which corresponds to the Variscan Orogen. This large scale orogen is the result from the opening and subsequent closing of the Rheic and Paleothethys oceans. The main geological formations occurring at Serra da Estrela are: Cenozoic deposits, Schist-Greywacke Complex, and Hercynian granites. Serra da Estrela is mostly granitic, where the terrains show well-preserved plateaus and linear tectonically controlled valleys. Most granite types of Serra da Estrela were originated during the Hercynian deformation in the Carboniferous, which was accompanied by metamorphism and synorogenic magmatism. Metasedimentary rocks, mainly schists and greywackes, are also present in areas with deep and sinuous valleys and long ridge-like interfluves, with a dense drainage network. The closing of the Rheic and Palaeothethys oceans originated the Schist-Greywacke Complex Domain and represents the oldest rocks in the territory deposited between the Upper Precambrian and the Lower Cambrian (Figure 7). The Iberian Massif was affected by brittle tectonics at the end of the Variscan orogenesis (Late Permian) which resulted in sinistral (NNE-SSW to ENE-WSW) and dextral (NNW-SSE) lateral strike-slip faults. The evolution of landforms of Serra da Estrela was mainly influenced by the sinistral fault which corresponds to large valley lineaments that cut the mountains today, such as the Unhais da Serra (Alforfa)—Zêzere, or the upper Mondego valleys. These are part of the Vilariça–Bragança Fault Zone (VBFZ), a large fault 250km long that still shows remarkable tectonic activity (Migoń and Vieira, 2014; Vieira et al., 2020; 2021).

Serra da Estrela is predominantly a plateau mountain elongated in the SW-NE direction, being about 45 km long and up to 20 km wide and is the highest mountain in mainland Portugal reaching 1993 meters. The long-term geological evolution influenced the evolution of the landforms of Serra da Estrela where the Alpine tectonic exerted an important control over reactivated Variscan faults. The granitic landscape in this area has evolved under changing environmental conditions and reflects an interplay between climate and tectonics since the Paleogene resulting in the current relief of Estrela UGGp. The planation surfaces at the Summit are remnants from the Paleogene that were uplifted during the Alpine orogeny, possibly in the Middle to Late Miocene, and are mostly represented in granite terrains. Examples of residual relief in these planation surfaces are the Belmonte inselberg at Estrela UGGp and the Monsanto Inselberg at the Naturtejo UGGp further south. The uplift continued during the Quaternary, and local glaciation developed at Serra da Estrela during the Pleistocene, mainly in the last maximum of glaciation, with a plateau ice field covering the upper plateau from the Alto da Torre to Fraga das Penas (Figure 8). Five main valley glaciers radiated from the ice field, in which the Zêzere glacier, ending close to the village of Manteigas, was the one with the greatest extension (about 11 km in extent). The icefield and glaciers occupied 66 km², with about 90 m ice thickness at the Torre Plateau and with ice thickness reaching 340 m at the Zêzere glacier (Migoń and Vieira, 2014; Vieira et al., 2020).

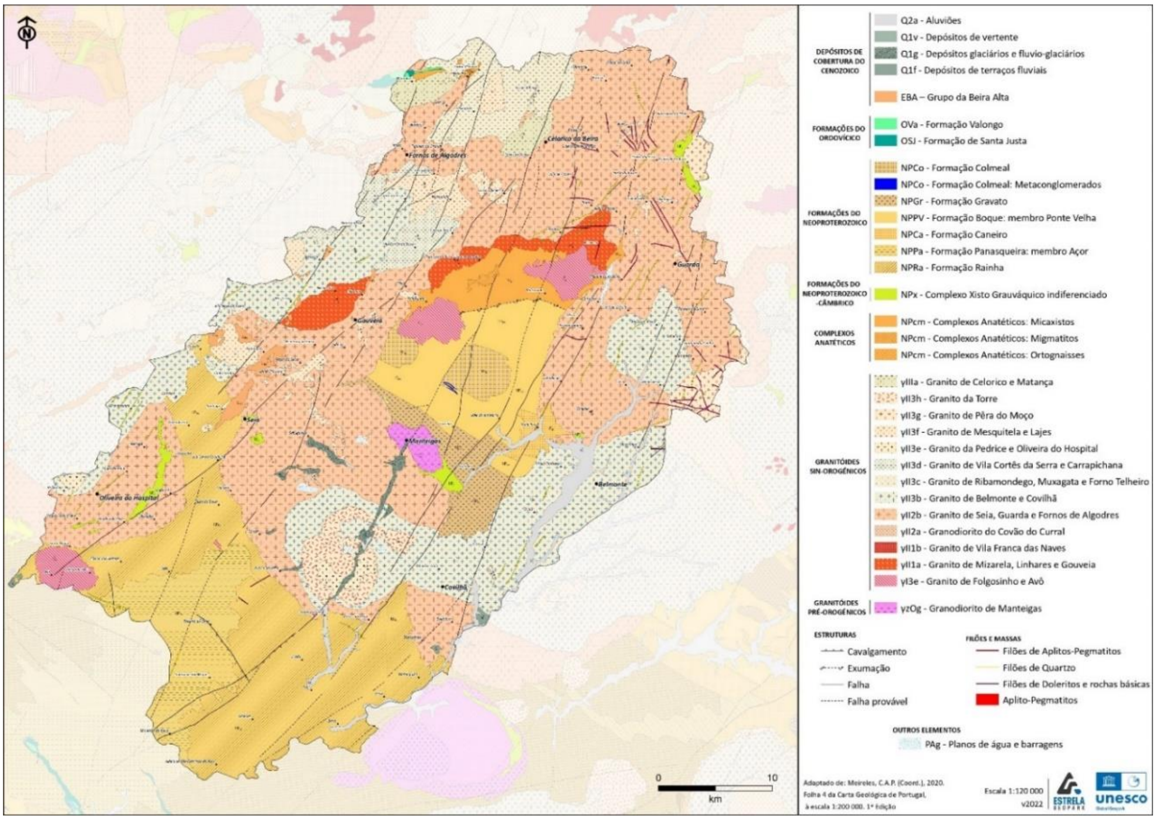


Figure 7: Geological map of Estrela UNESCO Global Geopark (Adapted from Meireles (Coord.), 2020). Source: https://www.geoparkestrela.pt/geopark/geodiversidade.

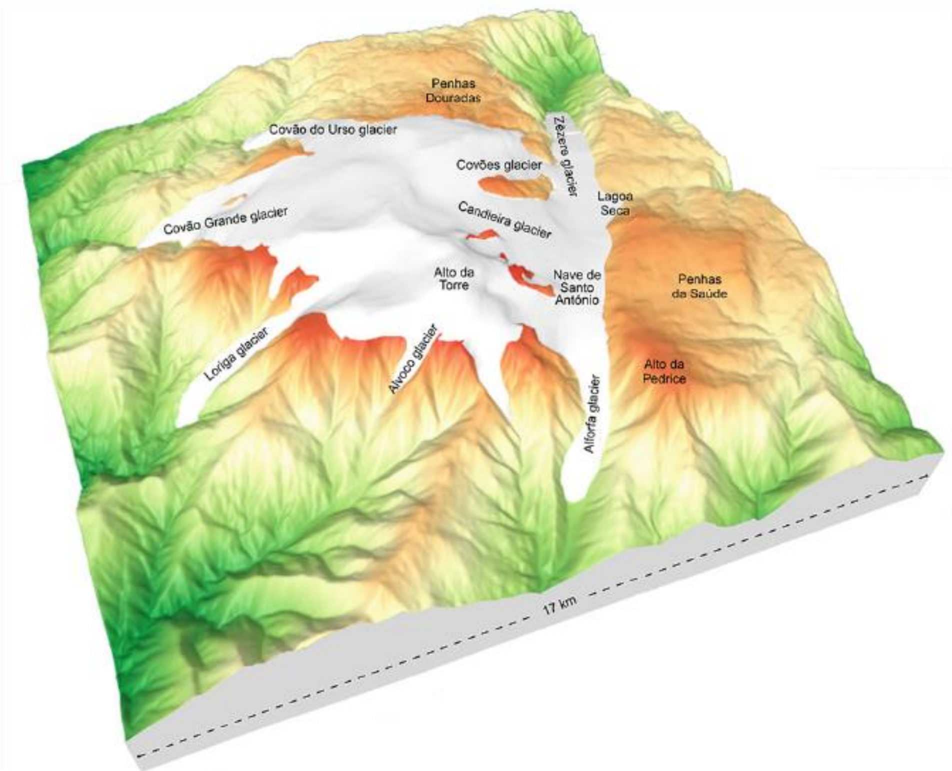


Figure 8: Serra da Estrela plateau ice field and valley glaciers at the Last Glacial Maximum (LGM). Small glaciers, such as the cirque glacier at Covais or the one at Covão do Teixo, are not represented. View from the south-east (Vieira et al., 2020).

The glaciers left remarkable geomorphological vestiges, translated into the form of U-shaped valleys, glacial circuses, lagoons, deposits of moraines and erratic blocks which can be seen today at Estrela UGGp (POPNSE, 2008). For instance, small lakes associated with glacial overdeepenings, as well as numerous areas with roches moutonnées and polished rock surfaces prevails in the upper Loriga valley and close to Lagoa Comprida. Glacial cirques, such as the Covão Cimeiro (Zêzere valley) and the Covão do Ferro (Alforfa valley), are found at the headwalls of the main valleys. Moraines occur along the glacial valleys and in several sectors of the western plateau and most of them are composed by large bolders (1 to over 5 m). Besides, the territory also shows several well-developed glacial troughs with a perfect U-shape, with the Zêzere Valley being the best example. Moraines and paraglacial deposits are found below 1650 m, such as the moraines at Nave de Santo António, Lagoa Seca and Covão do Urso, among others. Periglacial deposits are also found at Estrela UGGp, with key sites at the Pedrice blockslope, the talus slopes of Souto do Concelho and São Sebastião, close to Manteigas, as well as at several localities of stratified slope deposits. Granite weathering landscapes are present at Penhas Douradas, Covão do Teixo, and in lowlands, with various landforms (e.g., tors, nubbins, bornhardts and castle koppies) (Vieira et al., 2020).

There are two main rivers in the Estrela UGGp: the Zêzere and the Mondego. The Zêzere River in an important tributary of the Tagus River and a source of drinking water to Lisbon. It rises in the highest point of continental Portugal, near the Torre. The Mondego River is the longest river flowing exclusively in the Portuguese mainland. It rises at Serra da Estrela, at an altitude of 1,525 m, covering 258 km before flowing into the Atlantic Ocean and feeding the alluvial plains between Coimbra and Figueira-da-Foz (its estuary). The existence of a dense network of fractures gives rise to the hydrographic network in the territory. In the central area of the massif there are several lakes of glacial origin, some of which have been used for the construction of dams (POPNSE, 2008; Vieira et al., 2020).

3.3 Geoheritage

The Estrela UGGp became a UNESCO Global Geopark in 2020 (the newest UGGp in Portugal). It is a territory with a remarkable geoheritage with emphasis on evidence resulting from the last glaciation showing an outstanding scientific value, besides high scenic and educational values. The Estrela UGGp builds a solid strategy for regional development together with the municipalities, promoting geotourism, local economy, science, and education. The territory shows remarkable geomorphological features, mainly glacial landforms and deposits, which are the core of its scientific value and were essential for its recognition by UNESCO (Vieira et al., 2020). The 146 geological sites of special interest at Estrela UGGp are grouped according to their genesis in different categories. Most of them are in the glacial and fluvioglacial category (Figure 9).

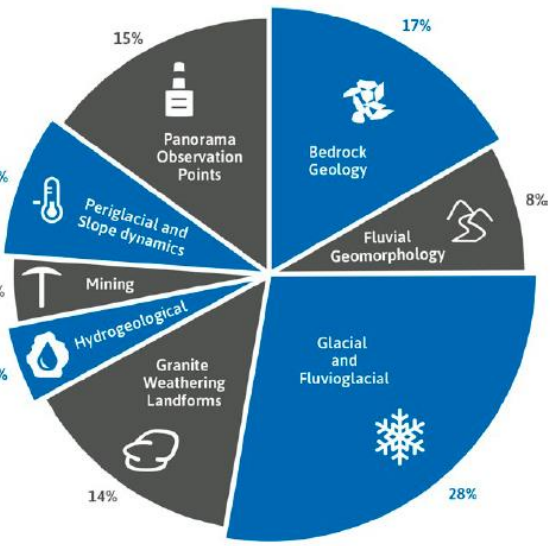


Figure 9: Estrela UNESCO Global Geopark geosites distribution by themes (Castro et al., 2021).

The characteristics of each category are described according to Vieira et al. (2020) as follows:

a) Glacial and Fluvioglacial

The Glacial and Fluvioglacial category is the most representative at the Estrela UGGp and the most important for its recognition as a UNESCO Global Geopark. The geosites of this category show the effects of glacial erosion and accumulation at different scales, with at least three of them standing out with very high scientific value and international relevance: the granite columns of the Covão do Boi, the Lagoa Seca col moraine field, and the Zêzere Glacial Valley. The relevance of these geosites is mainly associated to the tor-like granite columns of Covão do Boi, the moraine ridges with large metric granite boulders and till exposure of Lagoa Seca, and the perfect U-shaped cross-section of the Zêzere valley.

b) Periglacial and Slope Dynamics

Periglacial and Slope Dynamics category is represented by Pleistocene periglacial deposits and deposits associated with paraglacial dynamics. Some geosites in this category show the effects of slope processes, mainly debris flow activity, with the remobilization of either deeply weathered bedrock from the upper parts of the slopes or moraine deposits from the last glaciation. This situation occurs mainly along the Zêzere and Alforfa valleys usually following wildfire and heavy rainfall events and have been used pedagogically in relation to geohazards.

c) Fluvial Geomorphology

The geosites from the Fluvial Geomorphology category are mainly associated to scenic, cultural (mainly local tradition) and educational values. Some examples are waterfalls (Candieira, Caniça and Caldeirão), potholes and kettle holes (Vila Soeiro, Caniça and Mondego), meanders, both incised (Alto Mondego) and abandoned (Vale de Amoreira), and alluvial plains (Zêzere). Fluvial incision has deeply sculpted most of the Estrela UGGp valleys.

d) Granite Weathering Landforms

This category comprises geosites with various granite weathering landforms across different scales, many of them with a high scenic value. Some also have high scientific value for the understanding of long-term landscape evolution and denudation. Most of granite weathering geosites are tor-like landforms, but cases of inselbergs (Belmonte), mushroom boulders, pedestal rocks (Penedo do Sino) and balancing rocks are also present. Archaeological and cultural values of some geosites are associated to traces of occupation from the Roman and High Medieval periods (archaeological heritage), e.g., Penedo do Sino; and zoomorphic or anthropomorphic features of some tors and boulders (cultural relevance), such as the Cabeça da Velha (old-lady head) and Cabeça do Velho (old-man head).

e) Hydrogeological

Hydrological geosites are represented by springs, both related to drinking mineral waters and to thermal waters, with associated spas. The interplay between meteoric waters, weathering and deep tectonics generates these geosites, many of which have high economical value. Examples of hydrological geosites are the Paulo Luís Martins spring in the upper Zêzere valley with its waters that flow at a constant 6 °C, and the Manteigas and the Unhais da Serra thermal springs, with warm waters associated with the deep Bragança–Vilariça–Manteigas fault.

f) Bedrock geology

Bedrock category includes geosites of stratigraphic, petrographic, and tectonic relevance, and some of them are also geomorphologically relevant showing rock control on landform development. A good example is the Poço do Inferno geosite which is a very touristic site showing a small gorge and pothole, carved in the contact metamorphism zone between the metasediments (hornfels) and granites at the Leandres valley, close to Manteigas.

g) Mining and Panorama Observation Points

Mining sites, both active and inactive, are identified at Estrela UGGp and are part of the culture, tradition, and socioeconomics of this region. They have been valued to emphasize the significance of georesources and problems associated with their exploitation. Panaroma Observation Points (POP) are selected viewpoints with scenic and educational values providing an analysis of the landscape, linking natural landscape evolution and human occupation. Excellent examples are those located at Varanda dos Carqueijais, Varanda dos Pastores, Varandas de Avô, Linhares da Beira Castle, Cabeço de Santo Estevão, Mocho Real, Fraga Negra and Piornos.

Besides its relevant geoheritage, the territory also comprises an important cultural heritage related to a time when inhabitants erected megaliths facing the “star-mountain” which became traditional knowledge and a very strong identity of its peoples. Historical sites such as megaliths, Roman structures, medieval castles and settlements, and traditional villages are examples of tourist attractions at Estrela UGGp, together with museums and interpretation centres, rich regional gastronomy and valuable endogenous products (GEOfood), as well as numerous high-quality fluvial beaches and thermal spas (Vieira et al., 2020).

4. Materials and Methods

Forest fires may have natural or anthropic cause and can put the integrity of geosites at risk. The intensity and spread of forest fires can also be affected by anthropic factors such as public use (e.g., density of population, legal protection, land use and cover, and others), or natural factors such as climate (e.g., heatwaves, temperature, wind speed, and others) and topography. Geosite values and uses were selected to perform a quantitative methodology to assess the vulnerability of geosites considering the impacts of forest fires in geoheritage. A numerical assessment was performed considering different criteria, parameters, and indicators. The vulnerability results were considered together with the fire hazard classification from ICNF (2020) in order to obtain the risk of degradation by forest fire (Figure 10).

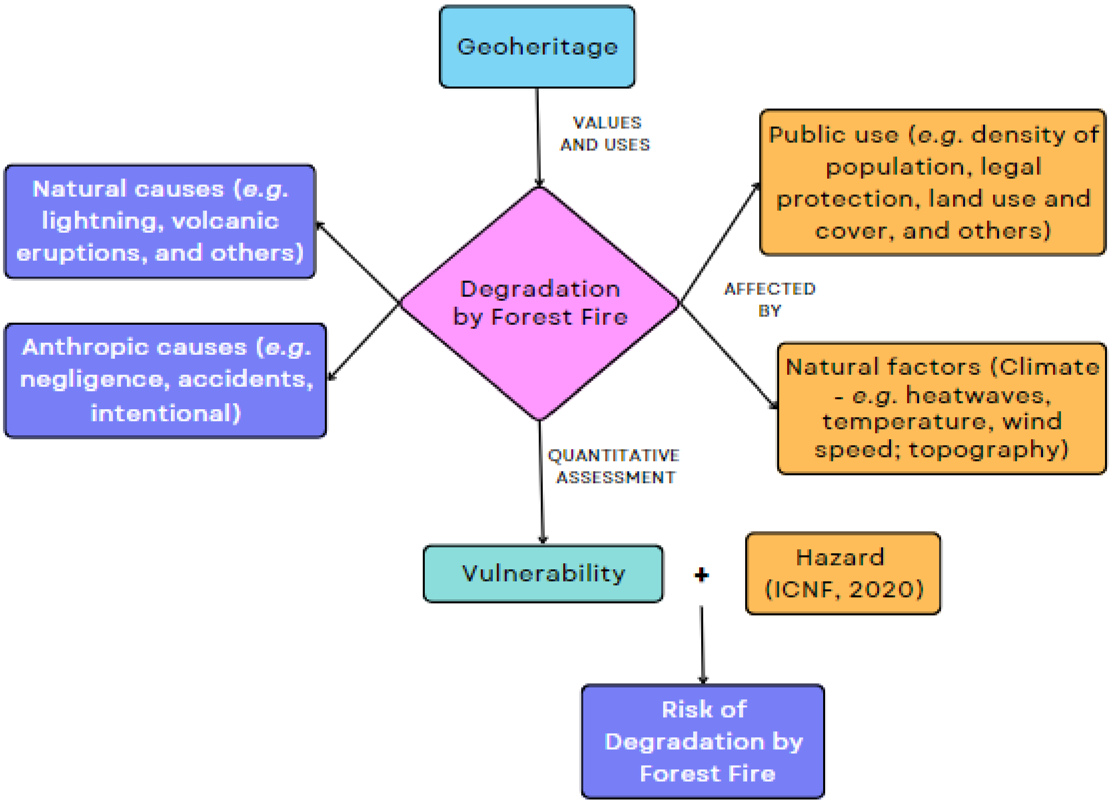


Figure 10: Methodological framework to assess the risk of degradation of geosites by forest fires.

The methodology was applied to Estrela UGGp's geoheritage, Portugal, where a forest fire burned 24,334 hectares in August 2022, affecting some important geosites. The area of Estrela UGGp was used as a case study to test the validity of the proposed methodology which was applied in some geosites directly affected by fire but also in others, aiming to collect data regarding degradation (post-occurrence) and vulnerability. Thus, this study intends to provide a useful tool for the management of geosites regarding the impact of forest fires and that can be applied to other types of geosites and locations.

4.1 Geosites selection

The geosites were selected based on previous field work in the area and considering the different themes described in section 3.3. The purpose was to use examples of geosites affected and not affected by the 2022 forest fire from each theme (Table 3). A total of 20 geosites were selected (8 geosites affected and 12 geosites not affected).

Table 3: Estrela UNESCO Global Geopark selected geosites for the assessment of vulnerability to forest fires.

	Geosite	Code	Theme
Geosites affected by fire	Zêzere Glacial Valley	GF32	Glacial and Fluvioglacial
	Lagoa Seca col Moraine Fields	GF28	
	Metasediments of Quinta da Taberna	BG2	Bedrock Geology
	Poios Brancos Granite Landforms	GW7	Granite Weathering Landforms
	Souto do Conselho Screes	PS5	Periglacial and Slope Dynamics
	Alluvial Plain of Zêzere River	F6	Fluvial Geomorphology
	Azibrais Cassiterite and Wolframite Mine	M1	Mining
	Rapa Panorama	POP24	Panorama Observation Points
Geosites not affected by fire	Poço do Inferno	BG19	Bedrock Geology
	Seixo Branco Pink Quartz	BG16	
	Rua dos Mercadores Dolerite Dyke	BG1	
	Penhas Douradas and Vale do Rossim Granite Landforms	GW1	Granite Weathering Landforms
	Varanda dos Carquejais Panorama	POP16	Panorama Observation Points
	Fragão do Corvo Panorama	POP5	
	Paulo Luís Martins Spring	H1	Hydrogeological
	Nave de Santo António Col and Poio do Judeu	GF25	Glacial and Fluvioglacial
	Lagoa Comprida	GF4	
	Cântaro Gordo Horn	GF5	
	Cântaro Magro Peak	GF6	
	Glacial Cirque of Covão Cimeiro	GF11	

4.2 Vulnerability assessment

The quantitative methodology for the assessment of geosites vulnerability to forest fires was based on two main criteria, i.e., (1) geosite value and (2) educational and touristic uses. Specific parameters and indicators were used to numerically assess each criterion (Table 4).

The guidelines to support how to address each indicator were based on the categories of geoheritage resource site types described by Prosser et al. (2018): (1) Exposure or extensive sites contain geological features that are relatively extensive beneath the surface, i.e., the removal of material does not significantly deplete the resource, as new material of the same type is freshly exposed as material is removed; (2) Integrity sites are geomorphological sites which are often more sensitive to threat than exposure sites and require holistic management to conserve the feature, including both active process and relict (inactive) geomorphological features; (3) Finite geosites are sites containing geological features of limited extent, such as restricted mineralization or a fossil bed of limited extent, so that removal of material may damage or destroy the resource. In some cases, the features may be unique and irreplaceable.

Scores between 0 and 3 were assigned to each parameter, representing low vulnerability (or degradation) and high vulnerability (or degradation), respectively, with the total vulnerability score estimated by summing the scores of each criterion. The lower the score obtained, the lower the level of degradation or vulnerability of the geosite.

The assessment of the geosite values was based on four parameters:

a) Scientific value

This parameter considers the geodiversity elements with scientific relevance. Forest fires can cause degradation of the main geodiversity elements with scientific relevance in different ways, such as loss of sensitive features (e.g., fossil specimens), erosional processes (post-fire occurrence), and micro-scale mineralogical and textural changes that can contribute to subsequent decay processes (e.g., limestone decomposes to calcium oxide (quicklime) at high temperatures (800–1000°C), when dispersed in water, it can easily react with it and thus create exothermic reactions (Martinho and Dionisio, 2018). Erosional processes from the loss of vegetation cover can result in loss of exposure and lead to some surfaces becoming much more susceptible to scouring and gullying when subjected to intense rainfall (e.g., geomorphological sites). Besides, the loss of vegetation, and thus its role in stabilizing soils, during periods of drought could lead to increased sediment discharge into cave systems during subsequent periods of heavy rainfall. Exposure or extensive sites and sites where the main geodiversity elements are characterized by very hard rocks are usually more resistant to fire. In contrast, small geosites, with a restricted, finite, and sensitive geological resource may be more vulnerable.

b) Scenic value

The scenic value is associated to the aesthetics of a geosite. The possible loss of scenic value will be related to the damage of elements associated with the scenic beauty of the site (e.g., finite, small geosites with sensitive geological elements, color loss, changes in color diversity). Erosional processes caused by the loss of vegetation cover can also affect the scenic value, besides some post-event forestry activities (e.g., cutting and hauling burnt wood, afforestation, slope stability measures). However, these impacts are likely to be reversible by appropriate management.

c) Ecological value

The ecological value considers the importance of a geosite for maintaining and supporting ecological systems. It is associated to the presence of important species and habitats, which can be endemic to the area or not. The loss of ecological value will be related to the loss of important species and habitats. Geosites with rare species and habitats or small geosites with high ecological value may be more vulnerable to fire. The appropriate management through post-fire ecological restoration (e.g., enrichment planting with indigenous species) can restore the ecological value of some less vulnerable geosites.

d) Cultural value

The cultural value is associated in this case to tangible cultural heritage (e.g., historical settlement and castles, monasteries, etc.) which can be affected by fire. There can be loss of cultural elements, or they can be slightly damaged. Erosional processes and micro-scale mineralogical and textural changes that can contribute to subsequent decay processes can also affect the cultural value of the site in a long-term, besides human responses to the fire (e.g., damage caused by fire suppression and mitigation activities). The loss of cultural value will be related to the loss of cultural elements by the direct action of fire or secondary processes acting on those elements in a long-term depending on its composed material (cultural elements composed of resistant material, e.g., very hard stones, will be less sensitive to fire).

Table 4: Criteria, parameters, indicators, scores and guidelines used in the quantitative assessment of vulnerability to forest fires degradation of UNESCO Global Geopark selected geosites.

ASSESSMENT OF VULNERABILITY TO FOREST FIRE DEGRADATION				
Criteria	**Parameters**	**Indicators**	**Points**	**Guidelines**
Geosite's value	Scientific Value	The main geological elements with scientific relevance can not be damaged or destroyed by fire (no loss of scientific value)	0	Exposure or extensive sites and sites where the main geological elements are characterized by very hard rocks are usually more resistent to the action of fire. In this case, there is no possibility of loss of scientific value by fire or secondary processes.
		The main geological elements with scientific relevance can not be destroyed by fire but secondary processes are likely to impact the geosite's integrity in a long-term	1	Geomorphological sites, for example, are less likely to be destroyed by a fire but secondary processes can impact the geosite's integrity in a long-term, e.g., erosional processes associated to the loss of vegetation cover, or micro-scale mineralogical and textural changes that can contribute to subsequent decay processes (e.g. limestone decomposing to calcium oxide at high temperatures).
		Deterioration of one or more geological elements with scientific relevance (partial loss of scientific value)	2	Finite geosites where one or more of the main geological elements with scientific relevance can be lost by fire (e.g., loss of sensitive features, such as fossil specimens, stromatolites, etc.) or be damaged by secondary processes acting in the geosite in a long-term causing partial loss of the scientific value. Enhanced weathering caused by the loss of vegetation cover may have adverse effects where it results in increased degradation of minerals and fossils.
		Deterioration of all the main geological elements with scientific relevance (total loss of scientific value)	3	The geosite's main geological features are completey deteriorated by fire causing the loss of its scientific value. The size of the geosite and its main geological elements will determine the geosite's suscetibility to degradation by fire. Small geosites, with a restricted, finite and sensitive geological resource may be more vulnerable to the action of wildfires.
	Scenic	The scenic value of the geosite can not be affected by fire	0	There is no loss of scenic value in cases when the scenic beauty of the geosite is associated to elements that can not be damaged by fire, such as water bodies or very hard rocks, or when the geosite is not exposed to the flames in case of fire.
		The scenic value of the geosite can be affected in a long-term by secondary processes	1	The scenic value of the geosite can be affected in cases when its scenic beauty is associated to elements that can be deteriorated by fire in a long-term. For example, small geosites where the geological elements can be deteriorated by decay processes (e.g., limestones), color loss or changes in color diversity.
		Partial loss of scenic value from the direct action of fire	2	Partial loss of scenic value in cases when the scenic beauty of a geosite is related to elements that can be deteriorated by the direct action of fire. For example, the loss of a significant area of vegetation cover in a geomorphological site with a view point can significantly impact its scenic value. Erosional processes from the removal of vegetation cover can also impact the scenic beauty of the site in a long-term. Besides, the need of afforestation can change color diversity/contrast.
		Total loss of scenic value	3	The total loss of scenic value is related to the loss of elements that are associated to the scenic beauty of a site (e.g., deterioration of all vegetation cover, color loss). Small, finite geosites with sensitive geological elements are more likely to be damaged by fire causing the loss of its associated scenic value.
	Ecological	The ecological value of the geosite can not be affected by fire	0	There is no loss of ecological value when the geosite does not have an ecological value or, in case of fire, the geosite was not exposed to the flames and all the main species and habitats are still preserved.
		The ecological value can be affected by fire but is likely to be reversible through appropriate management (e.g. post-fire ecological restoration)	1	The ecological value can be affected by fire in geosites where there are important species and habitats but the loss of ecological value is likely to be reversible through appropriate management, such as post-fire ecological restoration (e.g., enrichment planting with indigenous species). Also, when the pressure of threats like fire is removed from any degraded area, natural vegetation will normally colonize the site. The initial colonists will be early seral species.
		The ecological value can be affected by fire and exotic or commercial species may recolonize the geosite	2	It might be the case of using exotic or commercial species for post-fire ecological restoration in cases where there are social or political issues (e.g., land ownership, economic reasons) which negatively affects the initial ecological value of the geosite.
		Total loss of ecological value (loss of all the main species and habitas)	3	There is the possibility of total loss of ecological value when, for example, the geosite has rare species and habitas. Small geosites with high ecological value may be more vulnerable to fire. In this case, post-fire ecological restoration would not be effective to restore the geosite's ecological value.
	Cultural	The cultural elements, if applicable, can not be damaged or destroyed by fire (no loss of cultural value)	0	Cultural elements associated to the cultural value of the site (e.g., historical settlement and castles, monasteries, etc.), if applicable, will not be damaged by fire if they are composed of resistent material (e.g., very hard stones) or, in case of fire, the cultural elements were not exposed to the flames.
		Cultural elements can be slight damaged by fire and/or secondary processes can affect the cultural value in a long-term	1	Cultural elements associated to the cultural value of the site (e.g., historical settlement and castles, monasteries, etc.) will be slight damaged by fire, e.g., colouring, depending on its composed material. Secondary processes such as micro-scale minerological and textural changes that can contribute to subsequent decay processes can also affect the cultural value of the site in a long-term, besides erosional processes. However, these impacts are likely to be reversible by appropriate management.
		Deterioration of one or more cultural elements (partial loss of cultural value)	2	One or more cultural elements can be destroyed by fire if they are sensitive to the direct action of fire.
		Deterioration of all cultural elements (total loss of cultural value)	3	All the cultural elements can be destroyed by fire if they are composed of sensitive material to the action of fire.

(Continued)

ASSESSMENT OF VULNERABILITY TO FOREST FIRE DEGRADATION				
Criteria	**Parameters**	**Indicators**	**Points**	**Guidelines**
Educational and Touristic Uses	Accessibility and Observation conditions	The acces to the geosite and its observation conditions can not be affected by fire or its visibility may be improved	0	The access and visibility of the geosite are not associated to elements sensitive to the action of fire. It may be the case that, in case of fire, the visibility of the geosite is improved (e.g., removal of vegetation cover).
		The access to the geosite and/or its observation conditions may be affected by fire with no possible impact on educational and/or touristic activities	1	The access and/or visibility of the geosite are associated to elements that can be affected by fire, such as vegetation cover. The removal of vegetation cover or vegetation growth after a fire can cause loss of landform and outcrop visibility (e.g., outcrops on open land or in quarries can quickly become degraded and overgrown by scrub vegetation), besides slope instability. However, these impacts are likely to be reversible by appropriate management with no possible impacts on educational and/or touristic activities.
		The access to the geosite and/or its observation conditions may be affected by fire with possible impact on educational and/or touristic activities	2	Remote geosites, for example, usually have limited access conditions and may be even more difficult to access in case of fires. Small, finite geosites may be more vulnerable to fire affecting its obervation conditions.
		The access to the geosite and/or its observation conditions can be permanently lost	3	In this case, post-fire management procedures may not be effective to restore the geosite's access and observation conditions, such as geosites with limited access and small/finite geosites with sensitive geological elements.
	Signage	The sign(s) indicating the location of the geosite can not be affected by fire	0	The signs indicating the location of the geosite can not be damaged by fire when (1) there are no signs indicating the location of a specific geosite, (2) the composed material is resistent to the action of fire, or (3) in case of fire, the signs were not exposed to the flames.
		The sign(s) indicating the location of the geosite can be slight damaged by fire and may need minor improvements	1	The signs indicating the location of the geosite can be slight damaged by fire in cases when they are composed of a few materials not resistent to the action of fire causing, for example, color changes. However, the signs can be quickly fixed by appropriate management.
		Deterioration of one or more signs indicating the location of the geosite and may need major improvements	2	One or more signs indicating the location of the geosite may need major improvements in case of fire depending on its composed material.
		The sign(s) indicating the location of the geosite can be completely destroyed by fire and may need to be replaced	3	The sing(s) indicating the location of the geosite may need to be replaced in case of fire considering its composed material (e.g., signs made entirely by wood).
	Safety	The geosite is safe to visit and safety facilities, if applicable, can not be damaged by fire	0	Safety facilities, if applicable, can not be damaged by fire in cases when their composed material is not sensitive to the action of fire or they were not exposed to the flames.
		The safety of the geosite can be affected by fire and may need minor improvements	1	Safety facilities can be damaged by fire in cases when they are composed of a few materials sensitive to the action of fire and may need minor improvements. Secondary processes acting in the geosite (e.g., erosional processes) can also affect the safety of the geosite.
		The safety of the geosite can be affected by fire and may need major improvements	2	Safety facilities can be damaged by fire in cases when they are mainly composed of materials sensitive to fire and may need major improvements.
		The geosite may need interventions to garantee minimum safety conditions (total degradation of safety facilities)	3	Total degradation of safety facilities may occur in cases when they are composed entirely of materials sensitive to fire and may need interventions to garantee minimum safety condition.
	Information/Interpretation Structures and Other Infrastructures	The geosite's structures can not be deteriorated by fire	0	The geosite's structures (e.g., interpretative panels, and support, visitation and protection infrastructures) can not be damaged by fire in cases when their composed material is not sensitive to fire or they were not exposed to the flames.
		One or more geosite structures can be deteriorated by fire and may need minor improvements	1	The geosite's structures can be damaged by fire in cases when they are composed of a few materials sensitive to the action of fire and may need minor improvements to garantee its educational and touristic uses.
		One or more geosite structures can be deteriorated by fire and may need major improvements	2	The geosite's structures can be damaged by fire in cases when they are mainly composed of materials sensitive to fire and may need major improvements to garantee its educational and touristic uses.
		The geosite's structures can be completely destroyed by fire and may need to be replaced	3	The geosite's structures can be completely destroyed in cases when they are composed entirely of materials sensitive to fire and may need to be replaced to garantee its educational and touristic uses.

The educational and tourist uses are related to the physical conditions associated to the geosite that can be affected by fire and were assessed based on four parameters:

a) Accessibility and Observation conditions

The accessibility of the site is related to the infrastructures or other ways to access the site (roads, trails, etc.) that can be damaged or destroyed by fire. Post-event forestry activities (reforestation or improving forest infrastructure - e.g., dirt roads, firebreaks) can also affect the access to the site. Fires can create obstacles to the visibility of the geosite or improve its visibility (e.g., removal of vegetation cover). Post-event forestry activities (cutting and hauling burnt wood, reforestation or improving forest infrastructure - e.g., dirt roads, firebreaks) can also affect the visibility of the site. The loss of accessibility or observation conditions is related to elements that can be affected by fire (e.g., loss of vegetation cover, damage of roads). Remote geosites and small, finite geosites with sensitive geological elements may be more vulnerable to fire with possible impact on educational and/or touristic activities.

b) Signage

The signs indicating the location of the geosite can be damaged or destroyed by fire depending on its composed material and may need post-fire appropriate management. Fires can cause slight damage to the signs, e.g., color changes, or may need major improvements or need to be replaced. Signs composed of material resistant to fire will be less vulnerable than the ones composed entirely by wood, for example.

c) Safety

The safety of the geosite is related to safety facilities, such as fences, stairs, handrails, etc. that can be damaged or destroyed by fire. Slope stability affected by erosional processes caused by vegetation loss also threaten the safety of the geosite. Geosites where the safety facilities are composed of material sensitive to fire may be more vulnerable and may need improvements or interventions to guarantee minimum safety conditions.

d) Information/Interpretation Structures and Other Infrastructures

Information/interpretation structures (e.g., interpretative panels) or other infrastructures for support, visitation, and protection of the geosite can be damaged or destroyed by fire depending on their composed material. Geosites where those structures are composed of material sensitive to fire may be more vulnerable and may need improvements or replacements to guarantee its educational and touristic uses.

The total score of the vulnerability of geosites to forest fire degradation can range from 0 to 24, constituting five levels of vulnerability (Table 5). The geosites with 0 to 5 points are considered the less vulnerable to fire. In contrast, geosites that reach more than 20 points are the most vulnerable to fire. This assessment was based on qualitative data obtained from field work at Estrela UGGp, and observation of the impacts of the forest fire that occurred in August 2022. The risk of degradation by forest fire will be estimated by considering these results and the forest fires hazard data from ICNF (2020).

Table 5: Classification of the vulnerability of geosites to forest fire degradation.

Criteria	Partial Score	Total Score		Total Score on Vulnerability	Vulnerability Level
Geosite Value	0-12	0-24		0 - 5	Very Low
Educational and Touristic Uses	0-12			6 - 10	Low
				11 - 15	Medium
				16 - 20	High
				>20	Very High

4.3 Forest Fires Hazard

The forest fires hazard assessment conducted by ICNF was performed using statistical methods to obtain a hazard map with 5 classes (very low, low, medium, high, very high) showing the Portuguese mainland regions that were predicted as most exposed to forest fires (Figure 11). These classes were determined based on different variables, such as data from burned areas during the period between 1975-2018 (excluding occurrences smaller than 5 hectares), topography (slope, altitude), and land use and occupation.

According to ICNF (2022), the propensity for burned areas to occur can be quantitatively assessed through statistical relationships between past burned areas and a set of spatial databases. Slope and altitude were derived from the Digital Elevation Model (DEM) provided by the European Environment Agency. Land Use and Occupation data was provided by the General Directorate of Territory (DGT), for the years 1995, 2007, 2010, 2015 and 2018.

The very high hazard class covers 15.5% of forestry and agricultural territory corresponding to 50% of the burned area in the national territory in the reference period (1975-2018). The high hazard class covers 17.9% of the forestry and agricultural territory and 40.6% of the total burned area. The medium hazard class covers 18% of the forestry and agricultural territory and 6.6% of the total burned area. The low hazard class covers 21.2% of the forestry and agricultural territory and 2.8% of the total burned area. The very low class covers 27.4% of the forestry and agricultural territory, representing the lowest hazard scores and not including any area burned in the last 44 years.

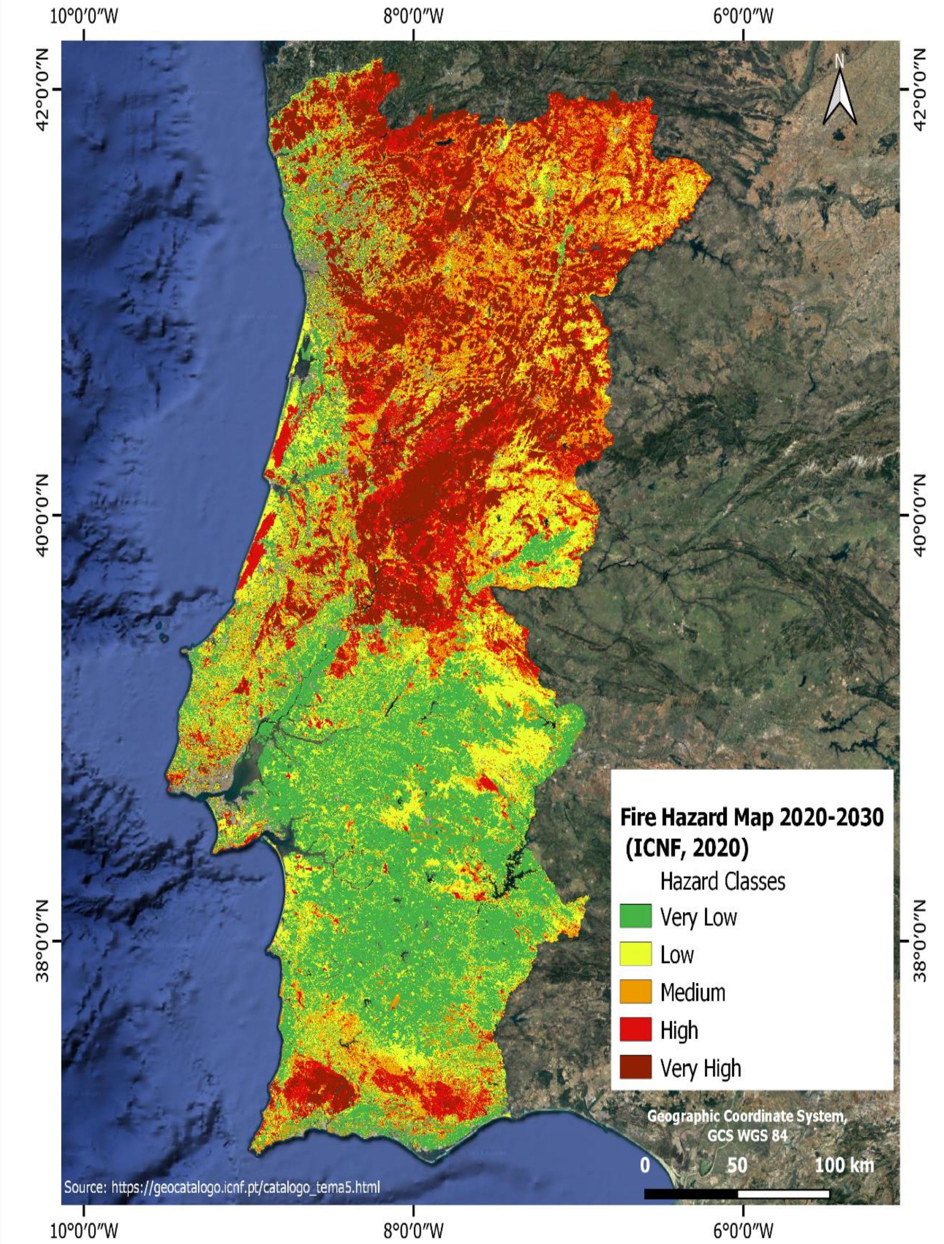


Figure 11: Forest fires hazard (2020-2030) in Portugal mainland (ICNF, 2020).

4.4 Risk Assessment

The geosites degradation risk due to forest fires was assessed considering the results of the vulnerability assessment and hazard classification from ICNF. The risk was also classified in five classes: Very Low, Low, Medium, High, Very High (Table 6).

Initially, the forest fires hazard map was overlap by a vector layer in the software QGIS 3.22 containing the delimitation of the selected geosites. All the geosites are polygon features with area characteristics, except Fonte Paulo Luís Martins geosite, considered as a point feature inside a larger geosite (Zêzere Glacial Valley). The delimitation of the geosites boundaries was performed based on previous studies (Fuertes-Gutiérrez and Fernández-Martínez, 2012; Santos-González and Marcos-Reguero, 2019; Coratza et al., 2021) and using the “Add Feature” tool in QGIS software to create a polygon feature. The geological map of the Estrela UNESCO Global Geopark (at 1:200,000 scale; Figure 7), satellite images from Google Earth, administrative limits, and georeferenced maps from Migon and Vieira (2014) and Vieira et al. (2021) were used as base maps, depending on the characteristics of each geosite. Geosites with glacial geomorphology interest were delimited considering mainly the extension of the most relevant landforms (e.g., moraines or valleys) and the area covered by the glaciers. It was the cases of the Moreias da Lagoa Seca, Circo Glaciário do Covão Cimeiro, Nave de Santo Antônio e Poio do Judeu, Cântaro Gordo, Cântaro Magro and Zêzere Glacial Valley geosites.

Table 6: Risk chart of geoheritage degradation by forest fires, combining data from vulnerability and hazard.

		Vulnerability				
		Very Low	Low	Medium	High	Very High
Fire Hazard (ICNF, 2020)	Very Low	Very Low	Very Low	Low	Low	Medium
	Low	Very Low	Low	Low	Medium	Medium
	Medium	Low	Low	Medium	High	High
	High	Low	Medium	High	High	Very High
	Very High	Medium	Medium	High	Very High	Very High

Risk Level
Very Low
Low
Medium
High
Very High

The geosites from the Panorama Observation Points category were delimitated considering the observation point and the area observed from this point. The “viewshed” tool from the software ArcGIS 10.2.2 was used to help drawing the limits of the observed area, besides satellite images from Google Earth. The tool uses a raster layer (SRTM data from the area downloaded from <https://earthexplorer.usgs.gov/>) and a feature layer (observation point sites) to produce an output raster layer with visible and not visible areas from the observation points (Figure 12).

After the delimitation procedure, vulnerability and hazard of each geosite were combined to identify the risk (Table 6).

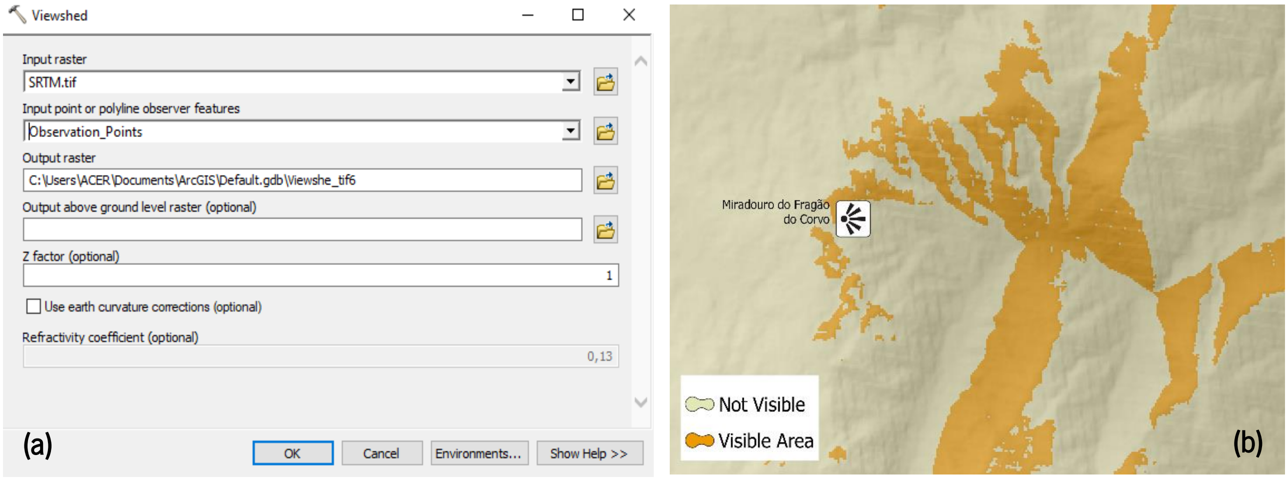


Figure 12: Delimitation procedure of Panorama Observation Points category geosites, with the (a) "viewshed" tool in the software ArcGIS 10.2.2 which uses a raster layer (SRTM data) and a feature layer (observation point sites) to produce an (b) output raster layer with visible and not visible areas from the observation points. Satellite images from Google Earth were also used to help the drawing of the geosites boundaries.

5. Results and Discussion

The 20 geosites selected from Estrela UNESCO Global Geopark (8 geosites affected by the fire event of August 2022 and other 12 geosites) have been assessed according to the methodology described in section 4 to determine the risk of degradation by forest fires. According to Fuertes-Gutiérrez et al. (2016), the assessment of geoheritage risk of degradation is necessary for the identification of potential threats and also for the development of efficient geoconservation strategies.

The methodology performed takes into account previous studies (García-Ortiz et al., 2014; Fuertes-Gutiérrez et al., 2016; Wignall et al., 2018; Selmi et al., 2022) that share a common principle of separating threats to geoheritage by their source according to the concepts of fragility, natural vulnerability, anthropogenic vulnerability, and public use. In this work, a single potential source of degradation (forest fires) is considered, which was not included within these concepts. The reason for this is that forest fires are complex events, as they can have natural or anthropogenic causes and be affected by several factors. Besides, the degradation risk obtained in this work was the result of two different approaches: the vulnerability of geosites to forest fires degradation and the likelihood for burned areas to occur in the territory (hazard).

The vulnerability assessment was performed through a numerical procedure similar to the degradation risk methodology performed by Selmi et al. (2022), but considering different criteria, parameters, and indicators based on the vulnerability of geosites to forest fire degradation (Table 7 and Figure 13). The categories of geoheritage resource site types described by Prosser et al. (2018) (exposure or extensive sites, integrity and finite geosites) were helpful in defining guidelines on how to approach each of these indicators.

The geosites affected by fire were assessed using the same methodology used to assess the vulnerability of geosites not affected by fire. The idea was to test the validity of the proposed methodology and criteria with degradation examples and potential degradation based on the geosites characteristics. Besides, the geosites affected by the fire event in August 2022 could be vulnerable to possible fire events in the future. The results show that the criteria, parameters, and indicators used for the quantitative assessment of the vulnerability of geosites to forest fire degradation were suitable for both degradation (post-occurrence) and vulnerability analysis.

Table 7: Results of the quantitative assessment of vulnerability to degradation by forest fires of the 20 UNESCO Global Geopark selected geosites.

	Theme	Geosite	Geosite Value				Geosite value	Educational and Touristic Uses				Educational and Touristic uses	TOTAL SCORE 0-24
			Scientific Value	Scenic Value	Ecological Value	Cultural Value		Accessibility and Observation Conditions	Signage	Safety	Information/Interpretation Structures and Other Infrastructures		
Geosites affected by fire	Glacial and Fluvioglacial	GF32	0	2	1	0	3	2	0	1	0	3	6
		GF28	0	2	2	0	4	2	0	1	3	6	10
	Bedrock Geology	BG2	0	2	2	2	6	0	0	0	0	0	6
	Granite Weathering Landforms	GW7	0	2	1	0	3	0	0	0	0	0	3
	Periglacial and Slope Dynamics	PS5	0	2	2	1	5	0	0	0	0	0	5
	Fluvial Geomorphology	F6	1	2	1	0	4	0		0	0	0	4
	Mining	M1	1	2	2	1	6	1	0	0	0	1	7
	Panorama Observation Points	POP24	0	1	2	0	3	0	0	0	0	0	3
Geosites not affected by fire	Bedrock Geology	BG19	0	2	3	0	5	2	0	1	2	5	10
		BG1	2	2	3	0	7	1	0	0	2	3	10
		BG16	0	2	1	0	3	2	0	1	0	3	6
	Granite Weathering Landforms	GW1	0	2	2	0	4	0	0	1	0	1	5
	Panorama Observation Points	POP16	0	2	0	0	2	1	0	1	1	3	5
		POP5	0	2	2	0	4	1	0	0	2	3	7
	Hydrogeological	H1	2	2	1	0	5	1	0	0	0	1	6
	Glacial and Fluvioglacial	GF25	0	2	1	0	3	1	0	0	2	3	6
		GF4	0	0	3	1	4	1	0	0	2	3	7
		GF5	0	0	3	0	3	1	0	0	2	3	6
		GF6	0	0	3	0	3	1	0	0	2	3	6
		GF11	0	0	3	0	3	1	0	0	2	3	6

Most (65%) of the assessed geosites present low vulnerability and 35% of them have very low vulnerability, based on the methodology described in section 4.2. Estrela UGGp geosites are mostly landforms which are less sensitive to forest fire degradation due to their large size and to the lithological components that make up the landscape (mostly granites). The maximum score of vulnerability to degradation by forest fires obtained was 10 (low vulnerability) in the Poço do Inferno (BG19) and Rua dos

Mercadores Dolerite Dyke (BG1) geosites, both from the Bedrock Geology category, and in the Lagoa Seca col Moraine Fields (GF28) from the Glacial and Fluvioglacial category (Table 7 and Figure 13).

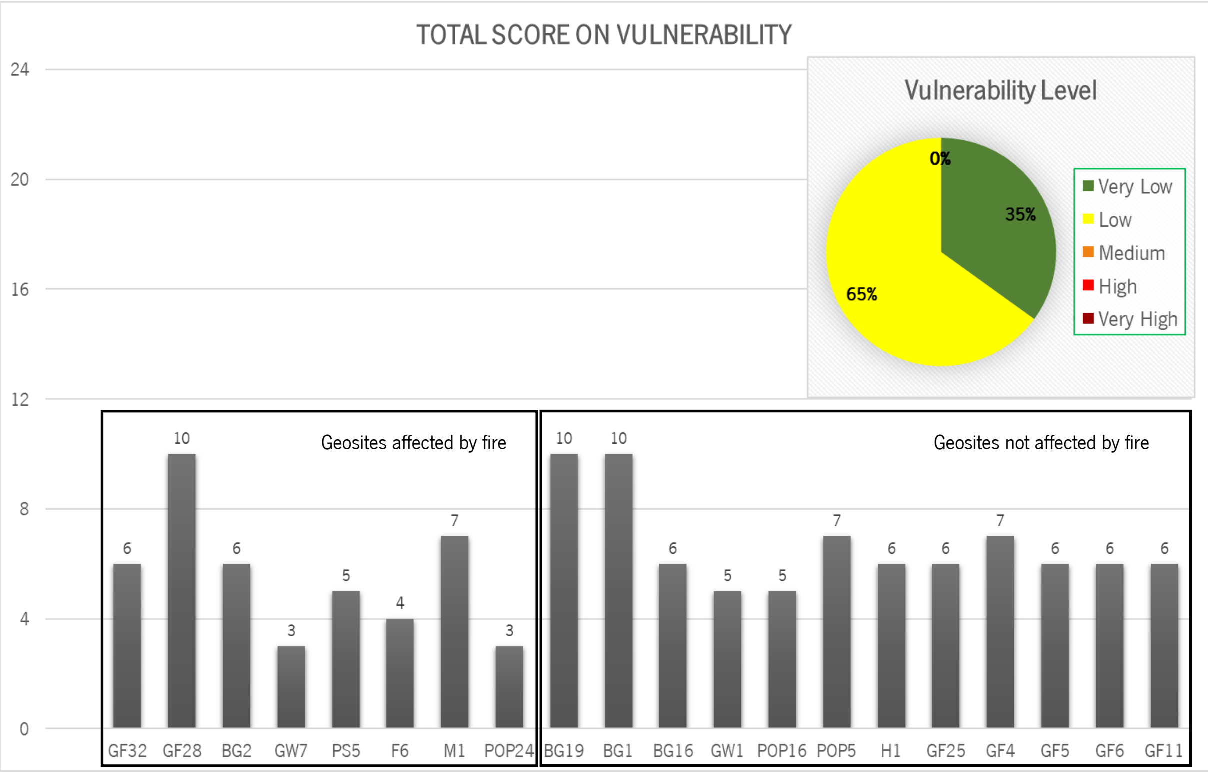


Figure 13: Results of the quantitative assessment of vulnerability to degradation by forest fires of the 20 UNESCO Global Geopark selected geosites. The small chart shows the vulnerability classes, based on the methodology described in section 4.2.

The impacts of forest fires on the geosite value and educational and touristic uses are shown in Figures 14 and 15, respectively. Most of the geosites showed no loss of scientific value (zero points), except in the Alluvial Plain of Zêzere River (F6), Azibrais Cassiterite and Wolframite Mine (M1), Paulo Luís Martins Spring (H1), and Rua dos Mercadores Dolerite Dyke (BG1) geosites (Figure 16). The loss of scientific value is mainly related to geosites of limited extent and erosional processes associated to the loss of vegetation cover that can impact the geosite in a long term.

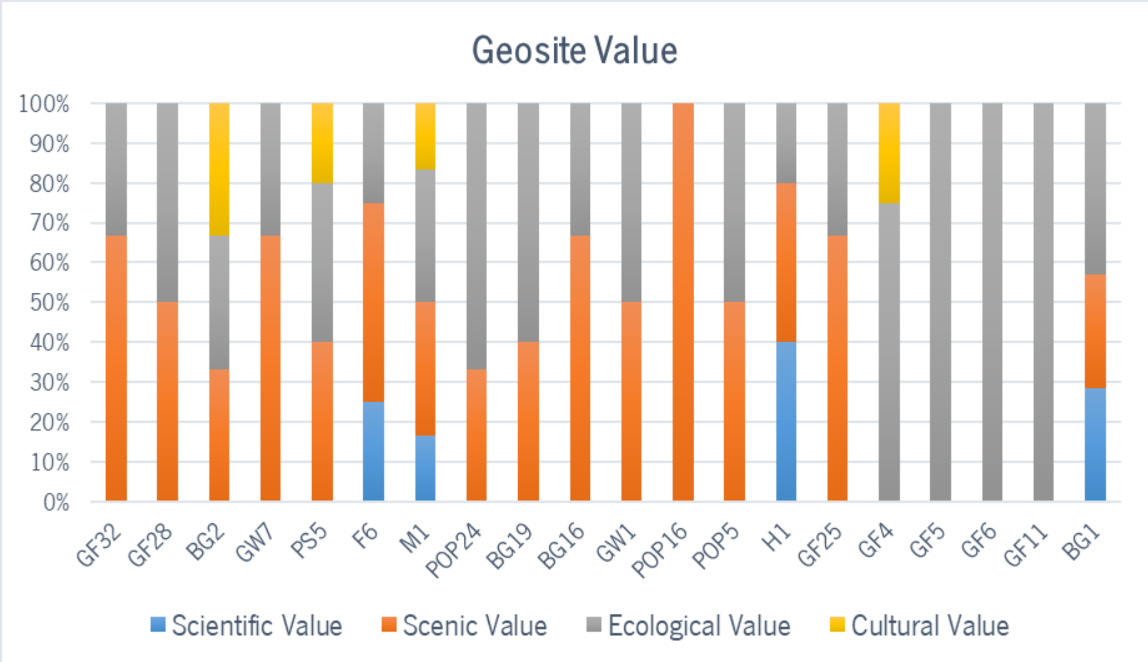


Figure 14: Relative contribution of each parameter of the geosite value criterion in the quantitative assessment of vulnerability to degradation by forest fires of the 20 UNESCO Global Geopark selected geosites.

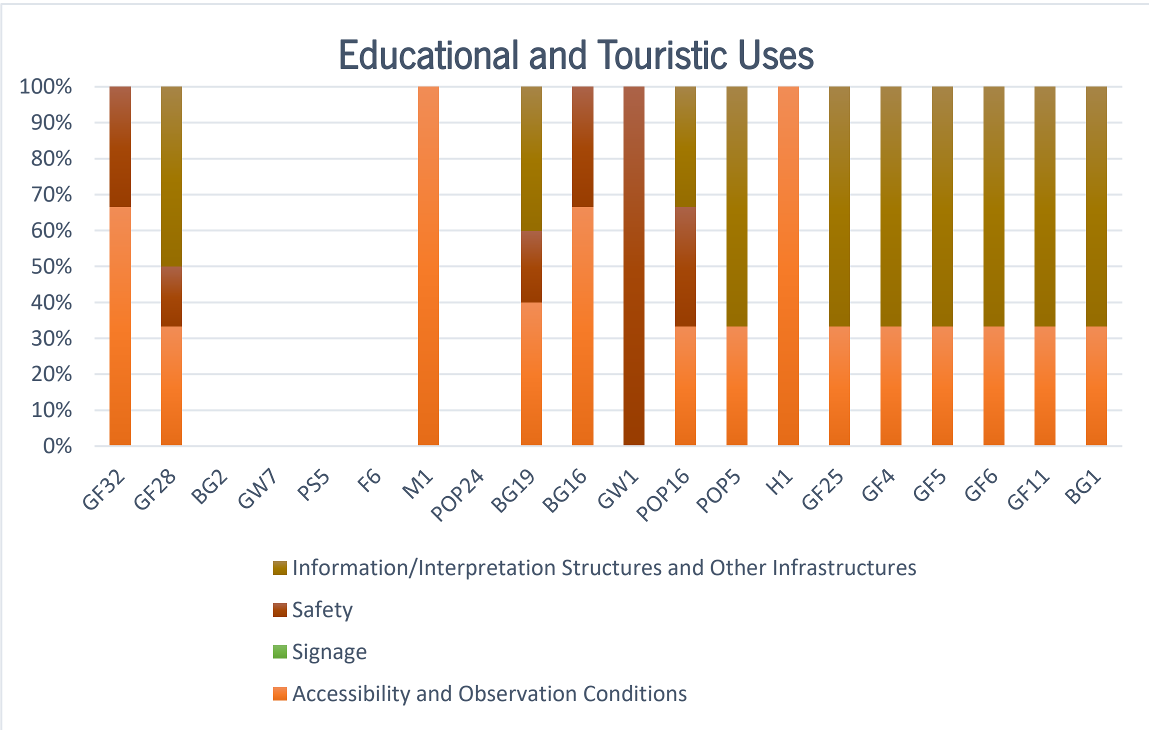


Figure 15: Relative contribution of each parameter of the educational and touristic uses criterion in the quantitative assessment of vulnerability to degradation by forest fires of the 20 UNESCO Global Geopark selected geosites.

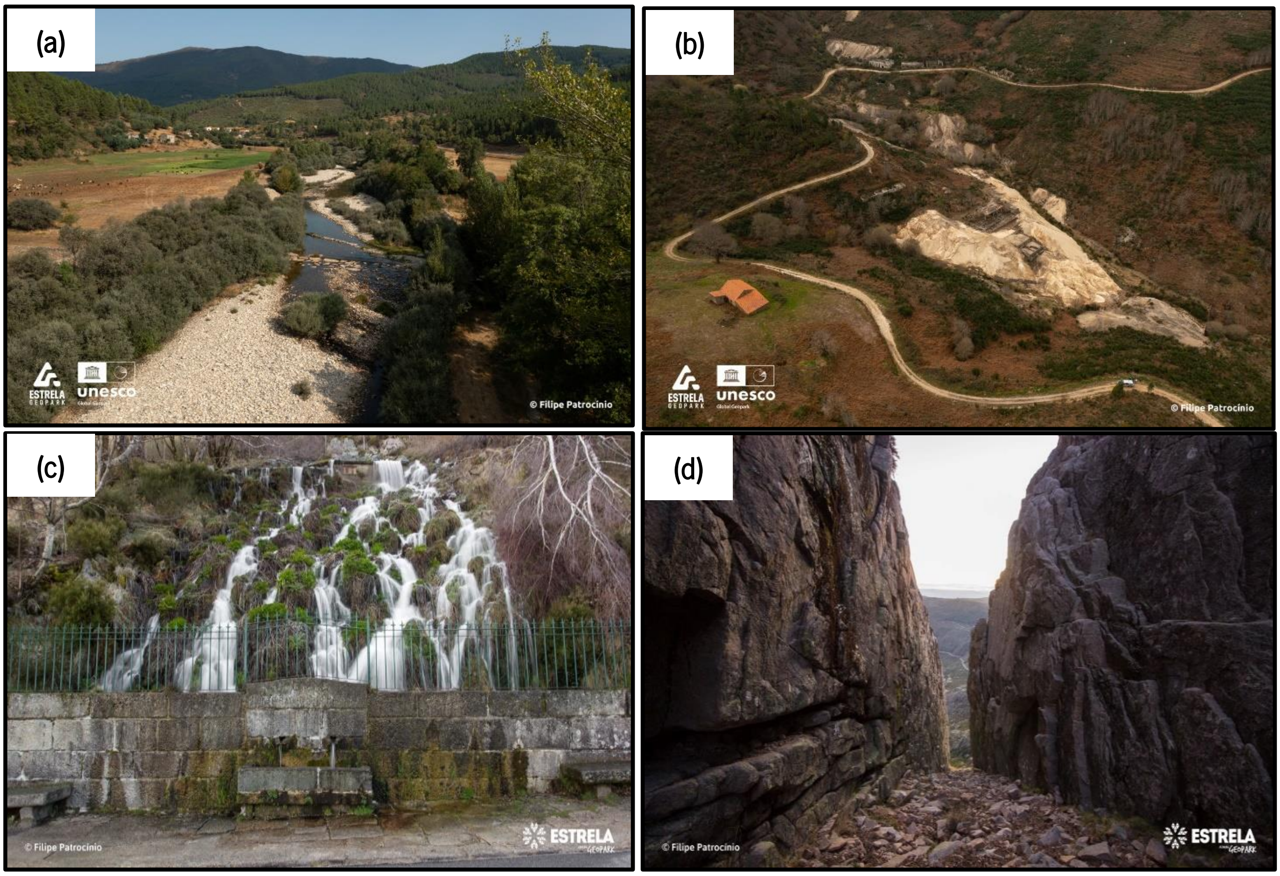


Figure 16: Examples of UNESCO Global Geopark selected geosites with vulnerable scientific value to degradation by forest fires. (a) Alluvial Plain of Zêzere River (F6); (b) Azibrais Cassiterite and Wolframite Mine (M1); (c) Paulo Luís Martins Spring (H1); (d) Rua dos Mercadores Dolerite Dyke (BG1). Photos by Estrela UNESCO Global Geopark.

In opposition, all the geosites assessed are vulnerable in their associated values (scenic, ecological, or cultural), with the scenic and ecological values being the most affected. The loss of cultural value caused by the fire event in August 2022 was observed in 3 geosites (Metassediments of Quinta da Taberna – BG2, Souto do Conselho Screes – PS5, and Azibrais Cassiterite and Wolframite Mine– M1), and possible degradation must be considered in case of fire in the Lagoa Comprida (GF4) geosite. The Metassediments of Quinta da Taberna geosite (Figure 17) was the most impacted in relation to its cultural value, characterized by inscriptions on the walls of the houses made of schists. These inscriptions record all the important events and dates during the life of a shepherd that used to live there and reflects a cultural and historical heritage linked to the mountain (Serra da Estrela).

The educational and touristic uses include geosite accessibility and observation conditions, signage, safety, and other structures and infrastructures (e.g., interpretative panels, and support, visitation, and protection infrastructures). They are affected by forest fire events in most of the assessed geosites, except for Metasediments of Quinta da Taberna (BG2), Poios Brancos Granite Landforms (GW7), Souto do Conselho Screes (PS5), and Alluvial Plain of Zêzere River (F6), which were hit by the flames in August 2022 with impacts only on the geosite values. The "Signage" parameter did not show vulnerability to forest fire degradation in none of the geosites. The parameters "Accessibility and Observation Conditions" and "Information/Interpretation Structures and Other Infrastructures" are the most affected, especially interpretative panels (made of recycled plastic) and geosite access blockages.

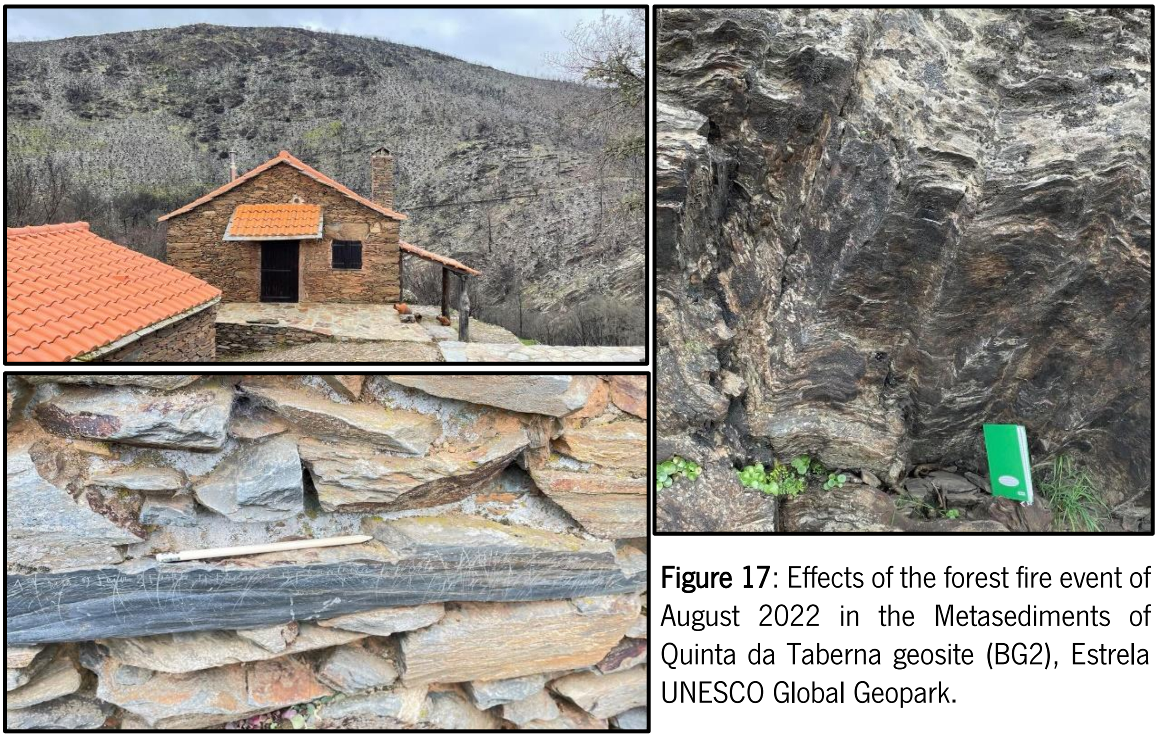


Figure 17: Effects of the forest fire event of August 2022 in the Metasediments of Quinta da Taberna geosite (BG2), Estrela UNESCO Global Geopark.

In relation to the geosites not affected by the August 2022 forest fire, Poço do Inferno (BG19) and Rua dos Mercadores Dolerite Dyke (BG1) geosites present the highest score on vulnerability (Table 7 and Figure 13). Poço do Inferno geosite (Figure 18) is a very touristic place characterized by a small gorge with a deep pot-hole and the presence of hornfels and granites formed more than 300 million years ago. The hornfels are more resistant to erosion than the granites which resulted in the formation of vertical bumps and the waterfalls that can be seen today in this site. The stream incision took place in the lithological contact between the granite and the hornfels (Vieira et al., 2020). Because of its fire-resistant rocks, the scientific value is not affected by fire, but its scenic and ecological values may be affected which are mostly related to its fauna and flora. This is one of the rare places in Portugal where the Teixo tree (Taxus *baccata*) can be found and are currently in a situation of great vulnerability. The Rua dos Mercadores Dolerite Dyke geosite (Figure 16b) is one of the geosites with possible impacts on its scientific value, and is characterized by a small gorge resulted from the erosion of a dolerite dyke between two vertical walls of granite rock (more resistant to erosion). The possible loss of the geosite value is associated to its small size and the limited extent of its geological features (Prosser et al., 2018). The lowest score (five) was obtained in the Varanda dos Carquejais Panorama (POP16) and Penhas Douradas and Vale do Rossim Granite Landforms (GW1) geosites, mostly related to potential impacts on their scenic and ecological values (Figure 19).

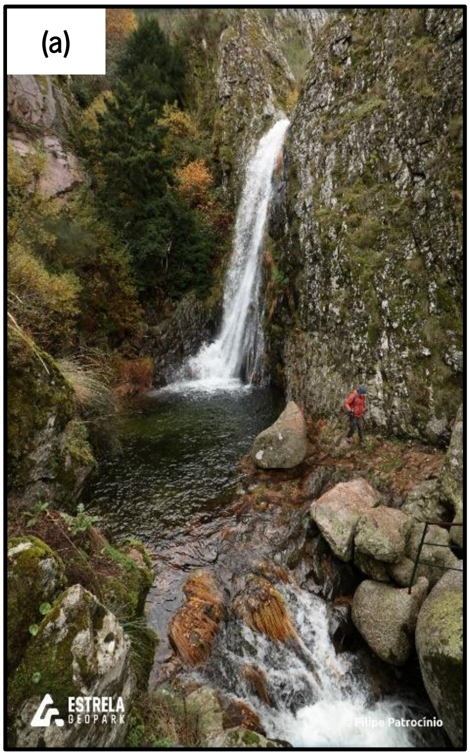


Figure 18: Poço do Inferno geosite (BG19). Photo on the left by Estrela UNESCO Global Geopark.

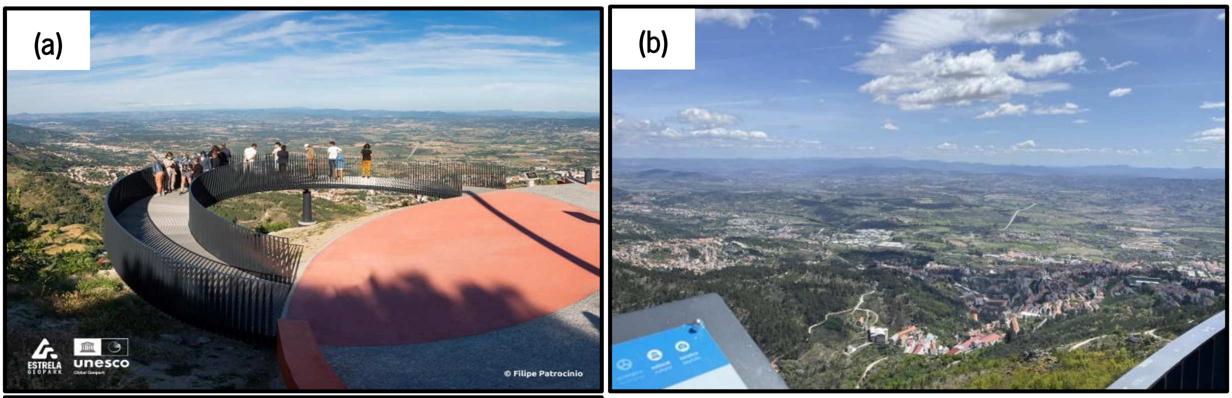


Figure 19: Varanda dos Carquejais Panorama geosite (POP16): (a) Observation point (photo by Estrela UNESCO Global Geopark); (b) Observed area; (c) Penhas Douradas and Vale do Rossim Granite Landforms geosite (GW1). Photo by Estrela UNESCO Global Geopark.

The Lagoa Seca Col Moraine Fields (GF28) is one of the eight geosites hit by the flames in August 2022, presenting the highest score on vulnerability (ten points). This geosite includes four frontal moraine ridges evidencing the difluence of the Zêzere glacier at the maximum ice thickness stage (Vieira et al. 2020). A large area of this geosite was burned causing degradation of its values (scenic and ecological values) which also affected its observation conditions making it more difficult to identify the moraine fields (Figure 20). Besides, the interpretative panel was totally destroyed by the flames and needs to be replaced to garantee its educational and touristic uses. The geosite needs minor improvements regarding its safety conditions, such as slope stability, which is currently being applied in this area. The lowest score (three) was obtained for the Poios Brancos Granite Landforms (GW7) and Rapa Panorama (POP24) geosites (Figures 21 and 22), with impacts on their scenic and ecological values, which are mostly related to the loss of vegetation cover with the fire.

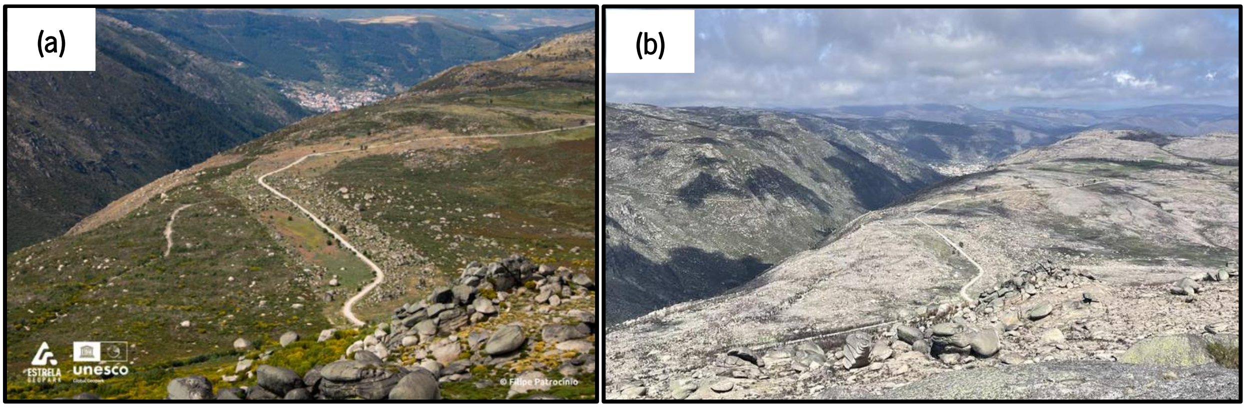


Figure 20: Lagoa Seca col Moraine Fields geosite (GF28): (a) before (photo by Estrela UNESCO Global Geopark) and (b) after the forest fire event of August 2022; (c) view of the geosite main geomorphological features (orthomosaic over high resolution digital surface model). View towards the north-east (Vieira et al., 2020).

Figure 21: Poios Brancos Granite Landforms geosite (GW7), seven months after the forest fire event of August 2022.

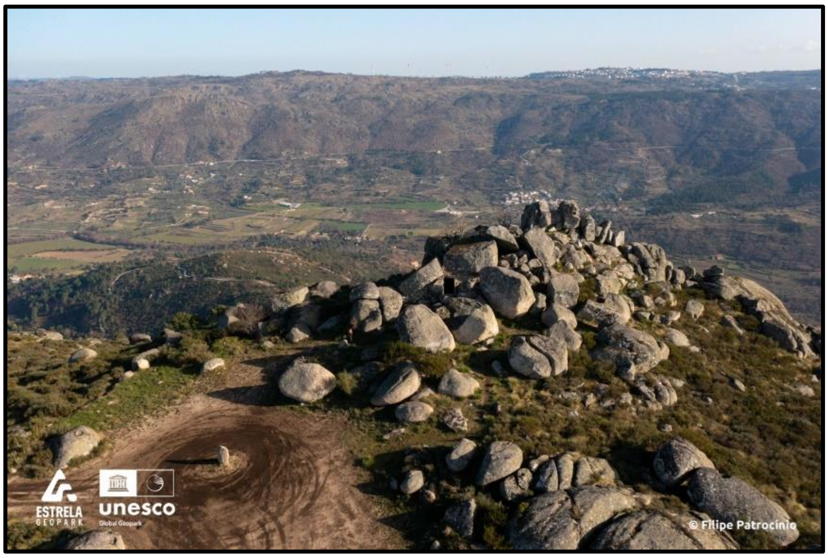
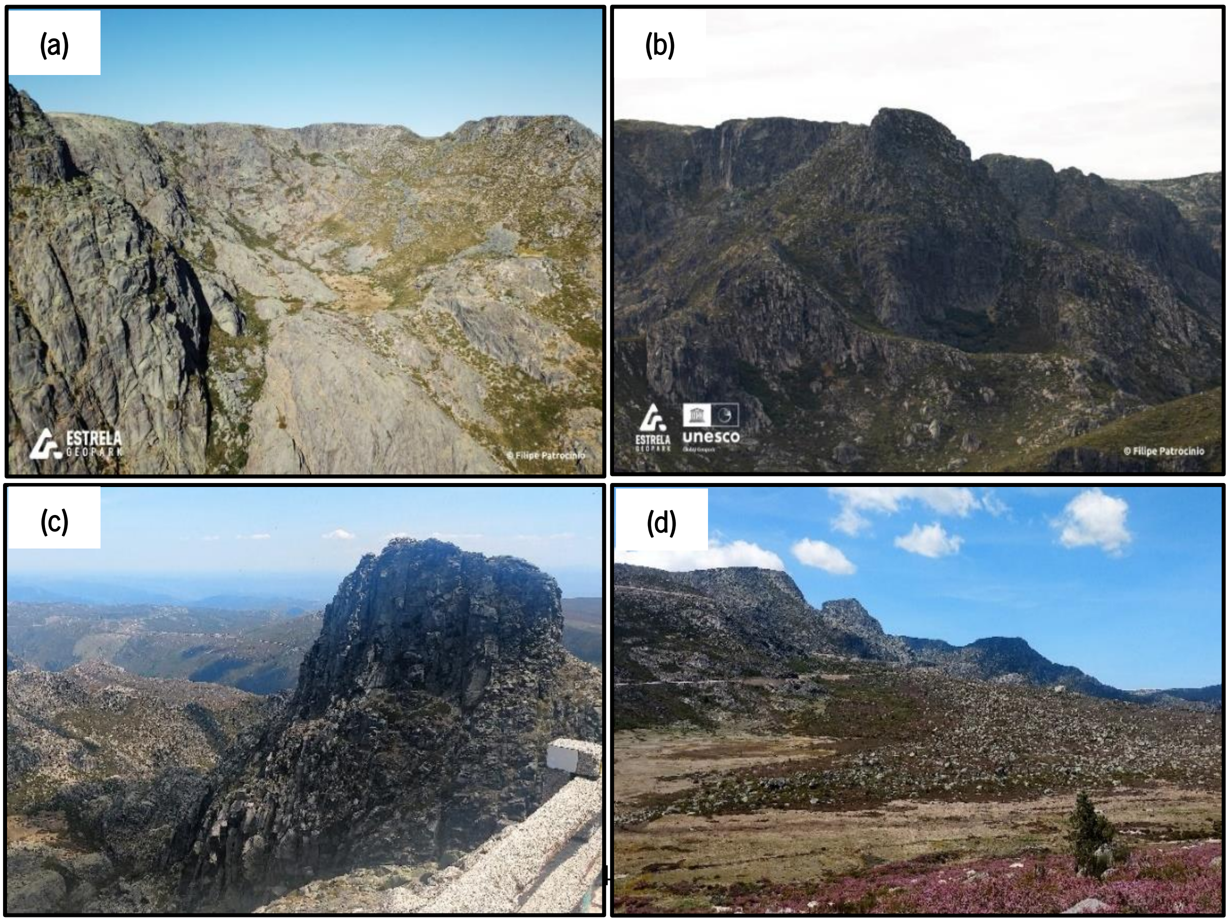


Figure 22: Rapa Panorama (POP24) geosite. Photo by Estrela UNESCO Global Geopark.

The geosites delimitation procedure was performed considering previous methodologies on geoheritage mapping (Fuertes-Gutiérrez and Fernández-Martínez, 2012; Santos-González and Marcos-Reguero, 2019; Coratza et al., 2021; Nascimento et al., 2021). The concept of geosite typology and its classification in points, lines, and polygons was taken into account in this work but not applied in the same way as previous studies. Instead, the idea that all the geosites have area dimensions was considered in the delimitation procedure which was based on the geological map of the area, satellite images from Google Earth, administrative limits, and georeferenced maps from Migon and Vieira (2014) and Vieira et al. (2021), as described in section 4.4.

The Geosites with glacial morphology interest were delimited considering their main geomorphological features. It was the case of the Lagoa Seca Col Moraine Fields (Figure 20), Glacial Cirque of Covão Cimeiro (GF11), Nave de Santo António Col and Poio do Judeu (GF25), Cântaro Gordo Horn (GF5), Cântaro Magro Peak (GF6), Lagoa Comprida (GF4), and the Zêzere Glacial Valley (GF32) (Figure 23) geosites. A similar approach was performed by Fuertes-Gutiérrez and Fernández-Martínez (2012) for a geomorphological area with glacial morphology interest where the limits were marked taking into account the geomorphological landforms (e.g., moraines, terraces, lakes, etc.) and previous studies in the area which establish the relationships between the glacial elements and determine the limits of the area affected by the same glacier or group of glaciers.



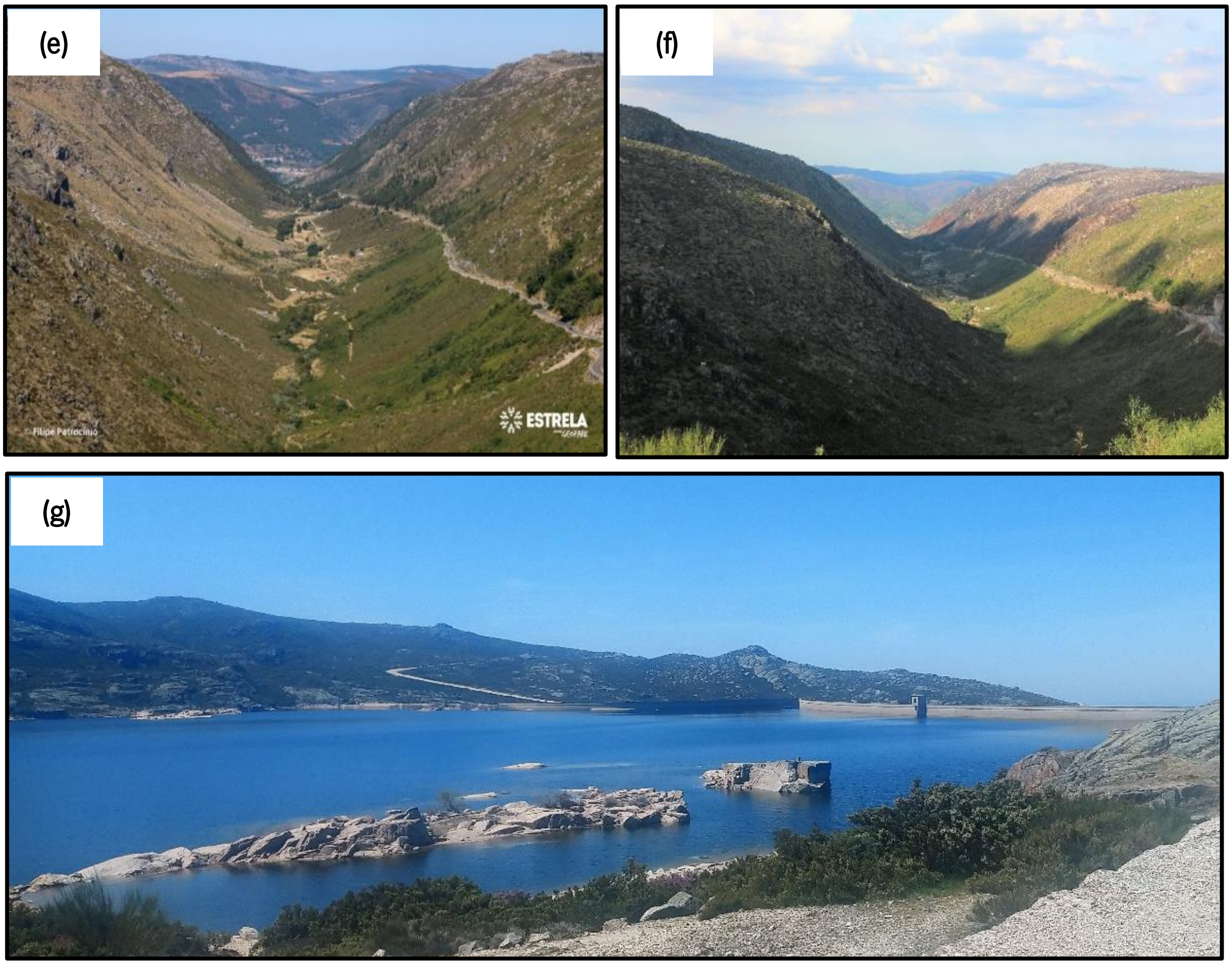


Figure 23: Examples of UNESCO Global Geopark selected geosites with glacial morphology interest, whose boundaries were delimited in this work: (a) Glacial Cirque of Covão Cimeiro (GF11, photo by Estrela UNESCO Global Geopark); (b) Cântaro Gordo Horn (GF5; photo by Estrela UNESCO Global Geopark); (c) Cântaro Magro Peak (GF6); (d) Nave de Santo António Col and Poio do Judeu (GF25); Zêzere Glacial Valley (GF32) (e) before (photo by Estrela UNESCO Global Geopark) and f) after the fire event of August 2022; (g) Lagoa Comprida (GF4).

According to Fuertes-Gutiérrez and Fernández-Martínez (2012), a viewpoint includes two different elements, a large area of geological interest and an observatory point from where this area may be viewed. Using a procedure also performed by these authors, the geosites from the Panorama Observation Points category (Rapa Panorama - Figure 22, Varanda dos Carquejais Panorama – Figure 19, and Fragão do Corvo Panorama - Figure 24), were delimited using a Digital Elevation Model (DEM) of the territory and the Viewshed tool from ArcGIS ESRI (version 10.2.2). This tool, along with satellite images from Google Earth, were useful to define the limits of these geosites from the observer's point of view.

The results from the delimitation procedure are presented in Figure 25. Although all geosites have area dimensions, the Paulo Luís Martins Spring geosite is represented as a point feature on the map, and not as a polygon feature, since it is located within a much larger geosite (Zêzere Glacial Valley) and has very small dimensions. The Rua dos Mercadores Dolerite Dyke geosite was mapped as a polygon feature using mainly the satellite images from Google Earth, but is observed as a polilyne on the map because of its smaller dimensions compared to most of the geosites in the area which are mostly characterized by geomorphological features (Figure 26). Other geosites were delimited considering mainly the geological map of the area, satellite images from Google Earth and administrative limits (Figure 27).

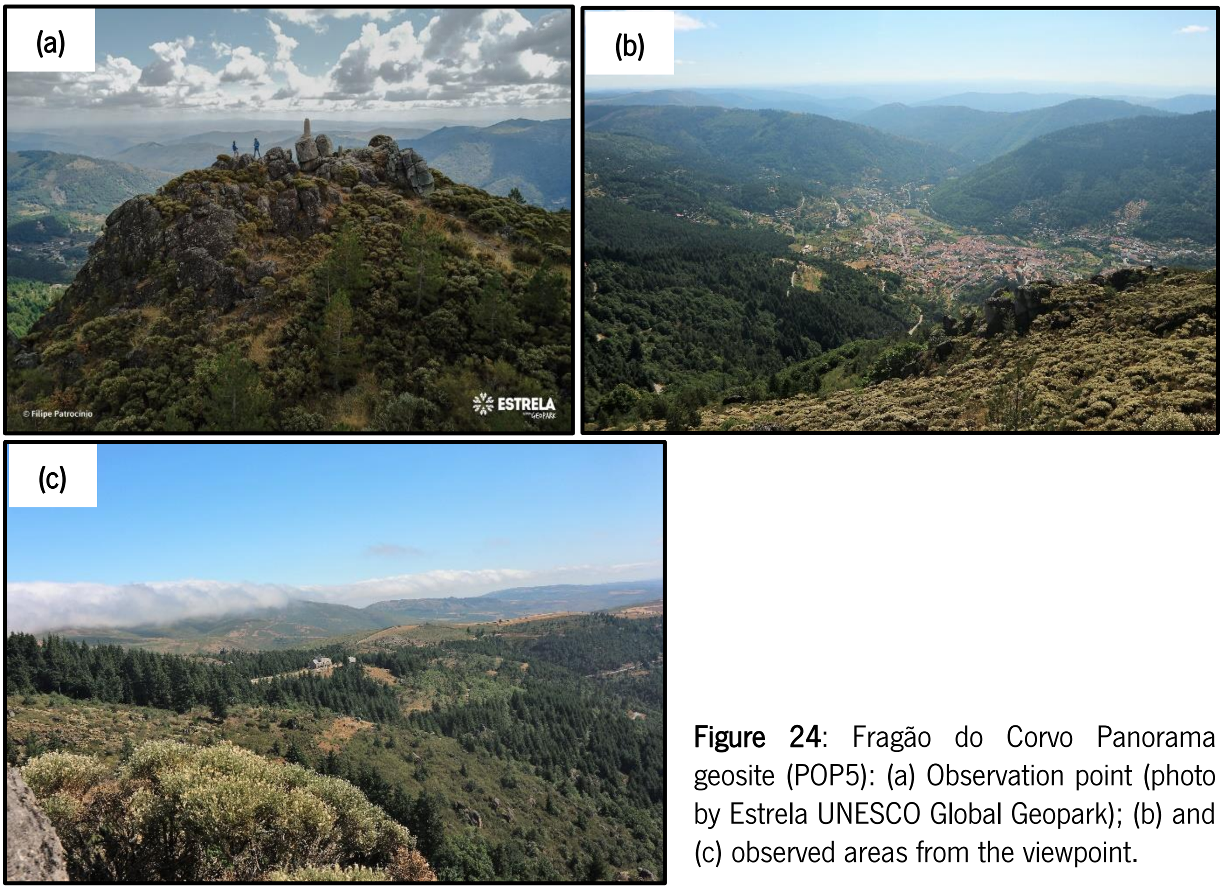


Figure 24: Fragão do Corvo Panorama geosite (POP5): (a) Observation point (photo by Estrela UNESCO Global Geopark); (b) and (c) observed areas from the viewpoint.

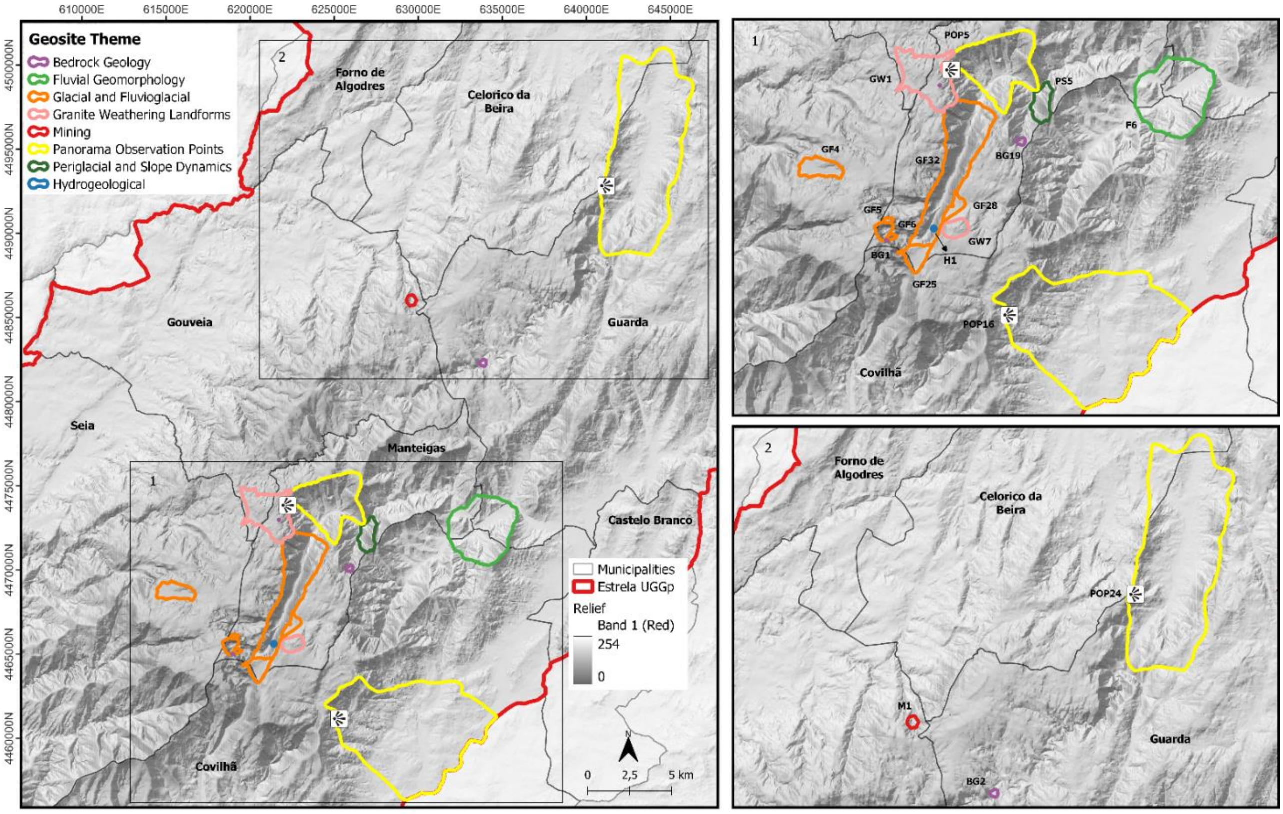


Figure 25: Location and delimitation of the 20 UNESCO Global Geopark selected geosites assessed for their risk of degradation by forest fires. The nomenclature of the geosites is presented in Table 3. (Projected coordinate system: UTM zone 29N, WGS 84).

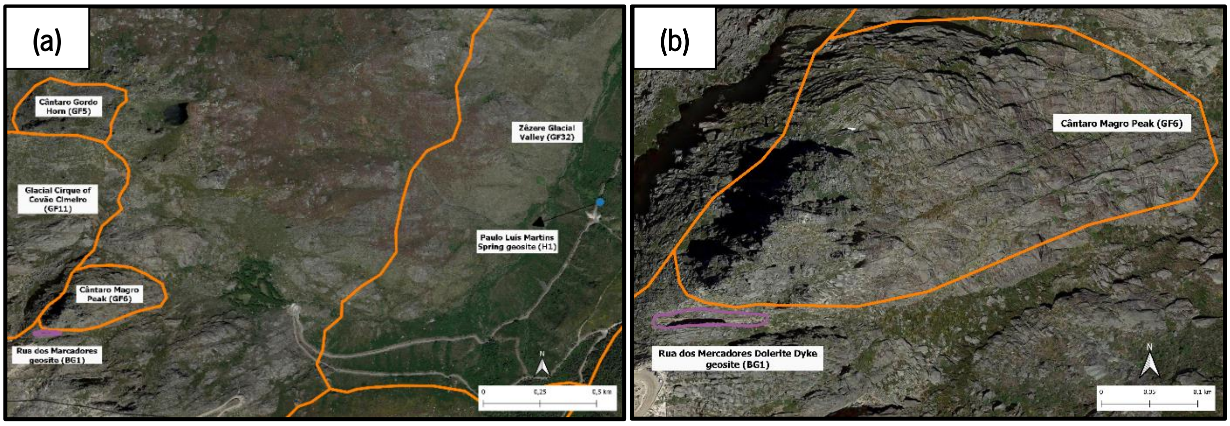


Figure 26: (a) Paulo Luís Martins Spring geosite (point feature in blue), located within the Zêzere Glacial Valley geosite; (b) Rua dos Mercadores Dolerite Dyke geosite (polygon feature in purple).

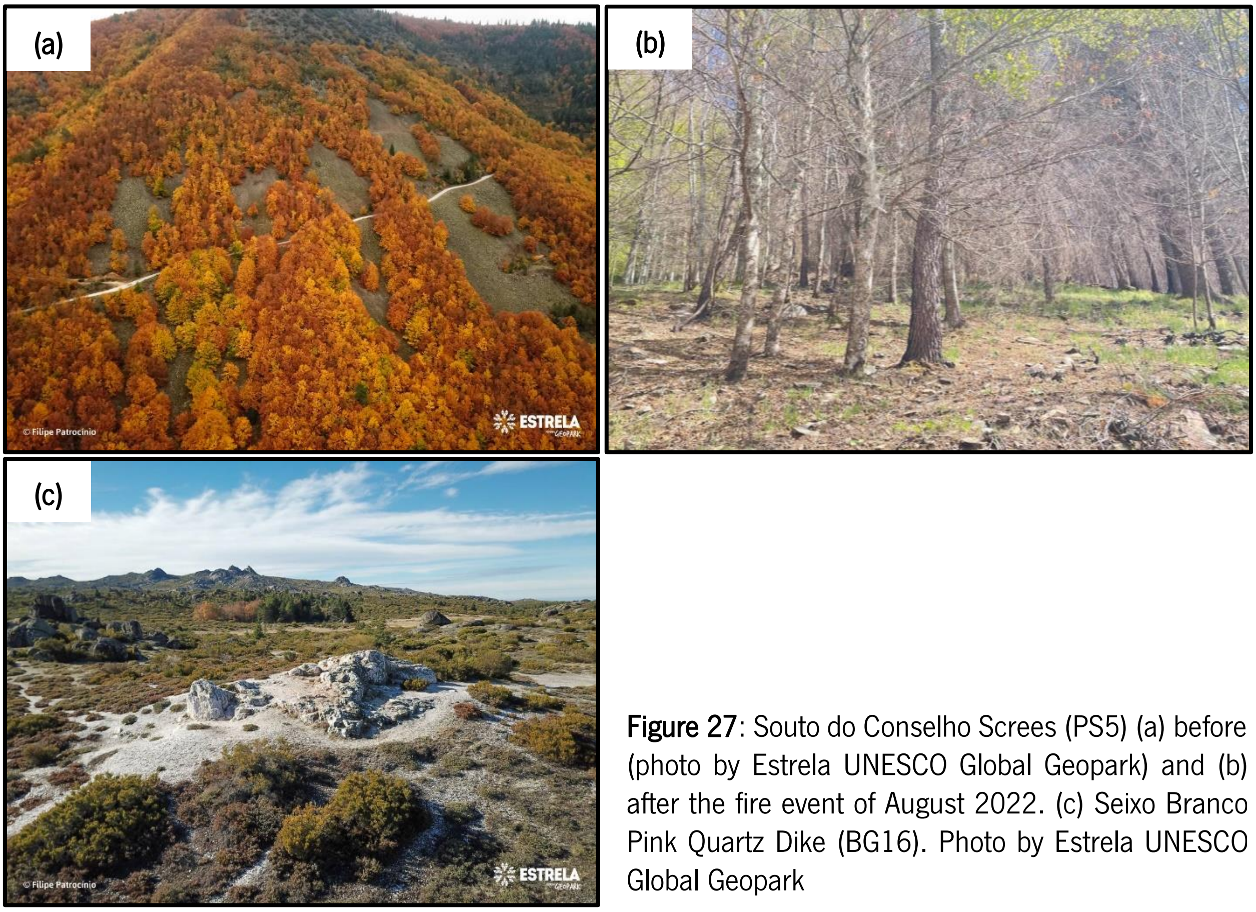


Figure 27: Souto do Conselho Screes (PS5) (a) before (photo by Estrela UNESCO Global Geopark) and (b) after the fire event of August 2022. (c) Seixo Branco Pink Quartz Dike (BG16). Photo by Estrela UNESCO Global Geopark

Once the geosites have well defined limits, the risk of degradation by forest fires was obtained (Figure 28) using the risk chart that combines vulnerability and hazard (section 4.4, Table 6). Although this region is very prone to forest fire events due to various factors (topography, land use and occupation, previous fire events), the geosites assessed in this work present "medium" degradation risk as maximum level, which is the result of their low or very low vulnerability to degradation by forest fires combined with the forest fire hazard classification by ICNF (2020). A lower level of degradation risk was already expected as most of the geoheritage of Estrela UGGp is characterized by geomorphological features and mostly granite rocks, which are less likely to be destroyed by fire.

Most of the geosites present different levels of risk within their limits, mainly the largest geosites such as the ones from the Panorama Observation Points category. Geosite degradation may occur differently at various locations within the geosite area, depending on its characteristics, location, and threat. The assessment of the risk of degradation of geosites considering different levels of risk within their area is not yet found in the literature and can be useful for management and conservation procedures that would focus on the highest risk locations within the geosite.

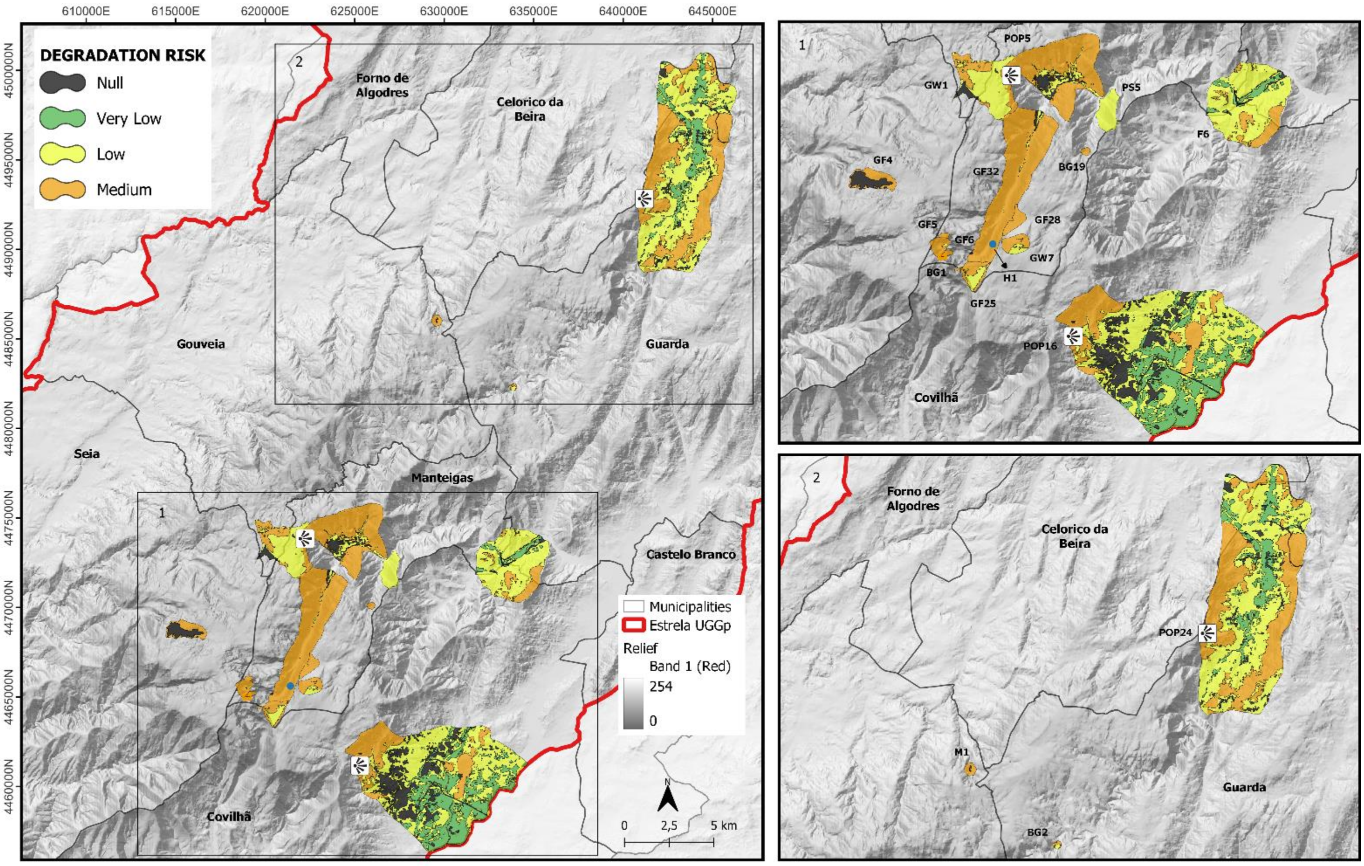


Figure 28: Degradation risk by forest fires of 20 geosites selected in Estrela UNESCO Global Geopark (UGGp). Different levels of risk were assessed within the geosites' limits, with the highest level being "Medium" (Projected coordinate system: UTM zone 29N, WGS 84).

6. Final Remarks

Forest fires are a threat to both biodiversity and geodiversity, but their impacts on the latter still lack practical approach. The present study is a first attempt to identify and assess possible impacts on geoheritage by forest fires, which are complex events in their origin and spread and have been increasing in severity and duration worldwide, especially in Europe.

A forest fire event during August 2022 affected a large part of Estrela UGGp, including some important geosites. The development of methodologies that consider the impact of forest fires on the geological heritage is, therefore, essential to assist in policies for the conservation and management of the territory. A methodology to assess the risk of degradation of geosites by forest fires was developed as the combination of two different approaches: (1) assessment of vulnerability to forest fire degradation; and (2) fire hazard assessment. This contrasts with previous studies that considered the risk of degradation of geosites as their vulnerability to extrinsic factors (natural and anthropic vulnerabilities). Therefore, this work applied the vulnerability concept from previous recent studies on this topic but included a hazard assessment to obtain the risk of degradation of geosites. In this case, the hazard assessment is the propensity for burned areas to occur according to different factors such as topography, land use and occupation, and previous fire events.

As already mentioned in previous studies, the establishment of a generally accepted methodology to assess the risk of degradation of geosites, besides the adoption of similar concepts and meanings, is important to properly address management and geoconservation strategies. The present work is a contribution on the topic of assessment of geosites degradation risk, with the development of a methodology that evaluated the impacts of forest fires on geoheritage with the intend to be tested and applied to other areas and contexts, especially protected and conserved areas. The numerical assessment of vulnerability revealed to be useful on providing information of the sensitivity of geosites to forest fire degradation and its application in future studies may further improve the method.

Another contribution of this work regards geoheritage mapping, which has been discussed in the literature as a support for territorial planning, nature conservation and geotourism. The precise delimitation of the selected geosites based on previous methodologies on this topic was an important step for the assessment of geosites degradation risk due to forest fires. The boundaries were drawn with the intention of not overlapping other geosites. However, some limits ended up encompassing other geosites already existing at Estrela UGGp, such as the Paulo Luís Martins Spring geosite which was considered as a point feature inside a much larger geosite (Zêzere Glacial Valley). The idea of considering such geosites as a single site may be something to be evaluated in the future to facilitate management procedures by the geopark's technical staff. Thus, the procedure carried out in this work was also intended to be a contribution to the geosite delimitation efforts currently being developed at Estrela UGGp in order to increase the promotion and protection of its geoheritage. The resulting thematic map showing different levels of risk within the geosite boundaries can help focus geoconservation actions on areas of greatest risk.

The geodiversity of Estrela UGGp has high scientific, scenic, educational, ecological, touristic, and cultural values associated to its geoheritage which is mainly supported by geosites with glacial and fluvioglacial interest. Although forest fires are generally difficult to predict, the degradation risk assessment performed in this work can be a useful tool for geoheritage management in the territory, revealing that 'Medium' risk is the maximum risk of geosites degradation by forest fires. Generally, the geosites scientific value is not affected by fire due to the geological characteristics and size of most geosites, although impacts on their associated values (ecological, scenic, cultural) and educational and touristic uses were observed.

In order to prevent or mitigate these impacts some management strategies can be proposed to strengthen the geoconservation actions already carried out in the territory. A good management planning in relation to fire events is important to protect the provision of forest goods and services and the integrity of geosites and their values. Land use plans from the municipalities (Municipal Master Plans - PDM) and from the Serra da Estrela Natural Park (PNSE) provide legal protection for several geosites at Estrela UGGp and support actions for firefighting and monitoring in the territory. The addition of a geosite degradation risk assessment to these plans can be a valuable tool to help monitor these sites. However, it is necessary to constantly monitor their conservation status and update their vulnerability to forest fires.

Geospatial analysis has been used as a tool for fire risk monitoring and mapping and provide effective information for management and the public. The use of geotechnologies is a growing field in geoheritage research which can be applied to monitor geosite degradation to facilitate decision making and support geoconservation actions (e.g., 3D models, web applications). This can be especially useful for monitoring and conservation of the most vulnerable geosites with educational and touristic potential. The cartographic representation of risk levels presented in this work for geosites with well-defined boundaries is also a contribution in this sense.

Other management procedures should focus on slope stability, which is currently being carried out at Estrela UGGp in areas of the Zêzere Glacial Valley and Lagoa Seca col Moraine Fields geosites to avoid impacts on the educational and touristic activities, and the replacement or reinforcement of structures with more fire-resistant materials. This could prevent the loss of interpretative panels, for example, as happened in the Lagoa Seca col Moraine Fields geosite. Besides, the development of educational programs focusing on the impacts of forest fires on both biodiversity and geodiversity may be useful in preventing these events, which are mostly of anthropic origin.

In conclusion, forest fires are a current threat at Serra da Estrela and in other regions of Portugal and are expected to increase in future climate change scenarios. The degradation risk methodology performed in this work is meant to be a tool to be included in the current management strategies in the territory to help monitoring current and future degradation of geoheritage by forest fires. Moreover, it is expected that the results presented in this work contribute to the discussion regarding geoheritage mapping and management.

References

Bilbao, B., L. Steil, I.R. Urbieta, L. Anderson, C. Pinto, M.E. González, A. Millán, R.M. Falleiro, E. Morici, V. Ibarnegaray, D.R. Pérez-Salicrup, J.M. Pereira, J.M. Moreno. (2020). Wildfires. In: Adaptation to Climate Change Risks in Ibero-American Countries — RIOCCADAPT Report [Moreno, J.M., C. Laguna-Defi or, V. Barros, E. Calvo Buendía, J.A. Marengo, and U. Oswald Spring (eds.)], McGraw Hill, Madrid, Spain (pp. 435-496, ISBN: 9788448621667).

Brilha, J. (2016). Inventory and quantitative assessment of geosites and geodiversity sites: a review. Geoheritage, 8(2), 119-134.

Brilha, J. (2018). Geoheritage: inventories and evaluation. In Geoheritage (pp. 69-85). Elsevier.

Calviño-Cancela, M., Chas-Amil, M. L., García-Martínez, E. D., Touza, J. (2016). Wildfire risk associated with different vegetation types within and outside wildland-urban interfaces. Forest Ecology and Management, 372, 1-9.

Castro, E., Loureiro, F., Gomes, H., Vieira, G. (2021). O Património Geológico do Geopark Estrela e a sua valorização. Geopatrimónio–geoconhecimento, geoconservação e geoturismo: experiências em Portugal e na América Latina. (in Portuguese)

Costa, H., de Rigo, D., Libertà, G., Houston Durrant, T., San-Miguel-Ayanz, J. (2020). European wildfire danger and vulnerability in a changing climate: towards integrating risk dimensions, EUR 30116 EN, Publications Office of the European Union, Luxembourg. ISBN: 978-92-76-16898-0, doi:10.2760/46951, JRC119980

Coratza, P. et al. (2021). Advances in geoheritage mapping: Application to iconic geomorphological examples from the italian landscape. Sustainability, 13(20), 11538.

do Nascimento, M. A. L., da Silva, M. L. N., de Almeida, M. C., & dos Santos Costa, S. S. (2021). Evaluation of typologies, use values, degradation risk, and relevance of the Seridó aspiring UNESCO Geopark geosites, Northeast Brazil. Geoheritage, 13(2), 25.

EEA. (2021). Forest fires in Europe. EEA (European Emvironment Agency). Available in: https://www.eea.europa.eu/ims/forest-fires-in-europe. Accessed on 22 jun. 2023.

Evelpidou, N., Tzouxanioti, M., Gavalas, T., Spyrou, E., Saitis, G., Petropoulos, A., Karkani, A. (2021). Assessment of fire effects on surface runoff erosion susceptibility: the case of the summer 2021 forest fires in Greece. Land, 11(1), 21.

Ferreira, A. C., Rocha, L. C., do Amaral Figueiredo, M., da Silva Cardozo, F., Gomes, I. (2019). O impacto dos incêndios florestais na geodiversidade da serra do lenheiro–São João del-Rei/MG-Brasil. Territorium, (26 (I)), 87-96.

Ferreira-Leite, F., Ganho, N., Bento-Gonçalves, A., Botelho, F. (2017). Iberian atmospheric dynamics and large forest fires in mainland Portugal. Agricultural and forest meteorology, 247, 551-559.

Figueiredo, R., Paupério, E., Romão, X. (2021). Understanding the impacts of the October 2017 Portugal wildfires on cultural heritage. Heritage, 4(4), 2580-2598.

Forestry Commission. (2014). Building wildfire resilience into forest management planning. Building wildfire resilience into forest management planning.

Fuertes-Gutiérrez, I., and Fernández-Martínez, E. (2012). Mapping geosites for geoheritage management: A methodological proposal for the Regional Park of Picos de Europa (León, Spain). Environmental management, 50, 789-806.

Fuertes-Gutiérrez, I., García-Ortiz, E., Fernández-Martínez, E. (2016). Anthropic threats to geological heritage: characterization and management: a case study in the dinosaur tracksites of La Rioja (Spain). Geoheritage, 8, 135-153.

García-Ortiz, E., Fuertes-Gutiérrez, I., Fernández-Martínez, E. (2014). Concepts and terminology for the risk of degradation of geological heritage sites: fragility and natural vulnerability, a case study. Proceedings of the Geologists' Association, 125(4), 463-479.

Gordon, J. E., Tormey, D., Wignall, R., Brazier, V., Crofts, R. (2022, January). Climate change will challenge the management of geoheritage in protected and conserved areas. In Parks Stewardship Forum.

Gray M (2013) Geodiversity: valuing and conserving abiotic nature, 2nd edn. Wiley, Chichester

ICNF. (2020). Metodologia para a produção da Carta de Perigosidade de Incêndio Rural de cariz estrutural. Instituto da Conservação da Natureza e das Florestas. (in Portuguese)

ICNF. (2022). 5.º Relatório Provisório de Incêndios Rurais. Instituto da Conservação da Natureza e das Florestas. Divisão de Gestão do Programa de Fogos Rurais. 5.º RPIR/DGPFR/2022. (in Portuguese)

IPCC. (2022). Climate Change 2022: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [H.-O. Pörtner, D.C. Roberts, M. Tignor, E.S. Poloczanska, K. Mintenbeck, A. Alegría, M. Craig, S. Langsdorf, S. Löschke, V. Möller, A. Okem, B. Rama (eds.)]. Cambridge University Press. Cambridge University Press, Cambridge, UK and New York, NY, USA, 3056 pp., doi:10.1017/9781009325844.

IUCN. (2021). Forests and Climate Change. IUCN (International Union for Conservation of Nature). IUCN issues briefs: iucn.org/issues-briefs. Available in: https://www.iucn.org/resources/issues-brief/forests-and-climate-change. Accessed on 22 jan. 2023.

IUGS. (2022). The First 100 IUGS Geological Heritage Sites. IUGS (International Union of Geological Sciences). IUGS 60th Anniversary.

Martinho, E., and Dionísio, A. (2020). Assessment techniques for studying the effects of fire on stone materials: a literature review. International Journal of Architectural Heritage, 14(2), 275-299.

Mc Keever, P.J. and Narbonne, G.M. (2021). Geological World Heritage: a revised global framework for the application of criterion (viii) of the World Heritage Convention. Gland, Switzerland: IUCN.

Migoń, P., and Vieira, G. (2014). Granite geomorphology and its geological controls, Serra da Estrela, Portugal. Geomorphology, 226, 1-14.

Parente, J., Pereira, M. G., Amraoui, M., Tedim, F. (2018). Negligent and intentional fires in Portugal: Spatial distribution characterization. Science of the total environment, 624, 424-437.

POPNSE. (2008). Parque Natural da Serra da Estrela - Plano de Ordenamento. Relatório, 45p. (in Portuguese)

Prosser, C. D., Díaz-Martínez, E., Larwood, J. G. (2018). The conservation of geosites: principles and practice. In Geoheritage (pp. 193-212). Elsevier.

Reynard, E., and Brilha, J. (2018). Geoheritage: a multidisciplinary and applied research topic. In Geoheritage (pp. 3-9). Elsevier.

Santos-González, J., and Marcos-Reguero, A. (2019). Applying the geological heritage in land management: Cartography and management proposals of geosites in Burgos Province (Spain). Geoheritage, 11(2), 485-500.

Selmi, L., Canesin, T. S., Gauci, R., Pereira, P., Coratza, P. (2022). Degradation risk assessment: understanding the impacts of climate change on geoheritage. Sustainability, 14(7), 4262.

Turco, M., Jerez, S., Augusto, S., Tarín-Carrasco, P., Ratola, N., Jiménez-Guerrero, P., Trigo, R. M. (2019). Climate drivers of the 2017 devastating fires in Portugal. Scientific reports, 9(1), 13886.

UNESCO. (2023). UNESCO Global Geoparks.
Available in: https://www.unesco.org/en/iggp/geoparks/about. Accessed on 15 jun. 2023.

Vieira, G., de Castro, E., Gomes, H., Loureiro, F., Fernandes, M., Patrocínio, F., Firmino, G., Forte, J. (2020). The Estrela Geopark—From planation surfaces to glacial erosion. In Landscapes and Landforms of Portugal (pp. 341-357). Cham: Springer International Publishing.

Vieira, G., Palacios, D., Andrés, N., Mora, C., Selem, L. V., Woronko, B., Soncco, C., Úbeda, J., Goyanes, G. (2021). Penultimate glacial cycle glacier extent in the Iberian Peninsula: new evidence from the Serra da Estrela (Central System, Portugal). Geomorphology, 388, 107781.

Williams, M. A., McHenry, M. T., Boothroyd, A. (2020). Geoconservation and geotourism: Challenges and unifying themes. Geoheritage, 12(3), 63.

Wignall, R.M.L., Gordon, J.E., Brazier, V., MacFadyen, C.C.J. Everett, N.S. (2018). A climate change risk-based assessment for nationally and internationally important geoheritage sites in Scotland including all Earth science features in Sites of Special Scientific Interest (SSSI). Scottish Natural Heritage Research Report No. 1014.