Green Energy and Technology

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Climatic and Structural Safety in Multi-Hazard Regime of Cultural and Natural Heritage

Methodological Advances and Case Study Applications

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Preface

The protection of a Country's cultural heritage, both architectural and environmental, is a highly relevant political and scientific concern, given its profound implications for the social and cultural fabric of societies.

Safety assessment requires a comprehensive understanding of the various sources of risk (climatic, geomorphological, structural, etc.), demanding interdisciplinary approach to the problem. The topics involved are of considerable interest for the scientific community and constitute a knowledge base for any planning strategy, both for preventive actions (maintenance, building and site safety) and reactive interventions (emergency management, evacuation plans).

This book addresses the issue of climatic and structural safety in multi-hazard regime of cultural and natural heritage, drawing on the outcomes of a three-year technology transfer project, funded by the Italian National Recovery and Resilience Plan -PNRR T4Y PP 4.7.1. In particular, the project is entitled Open Platform *phigital space* (physical and digital) of the type *user-profiling* for the advanced and dynamic codesign of interventions on the built and ex novo.

The book is organized into two main parts collecting peer-reviewed papers from approximately twenty involved researchers and begins with a chapter detailing the methodologies adopted and the final goals of the project.

The first part of the book aims to deepen theoretical knowledge related to cultural heritage analysis, proposing advanced models for damage assessment on structures and their surrounding environments. These models also incorporate uncertainties related to material properties and consider different environmental stressors under three projected climate scenarios for the years 2030, 2050, and 2085.

The second part of the book features some chapters with a more applied focus. Thanks to some large-scale case studies, it proposes a digital platform to support all the meta-files relating to the security data collected. This platform, along with the creation of a Living Lab (physical platform), will provide a methodology for the transfer of digitalized data to different stakeholders: including institutions, professionals, and local communities.

The Editors sincerely thank all the senior and the young researches who have contributed by their outstanding contributions to the quality of this book.

October 2025

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Theoretical and Methodological Approaches

Advanced Methodological Framework for Assessing Climate Change Impacts on Cultural Heritage Toward a Multi-scale Vulnerability Index

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Abstract. Cultural heritage assets monuments, historical buildings, landscapes are increasingly vulnerable to climate change-induced impacts. Southern European regions, including the Mediterranean basin, are particularly exposed to risks such as heatwaves, hygrothermal oscillations, flooding, wind, and seismicity. In Calabria, local geomorphological and socio-environmental fragilities further exacerbate the condition of minor historic centers. This chapter presents an advanced methodological framework for assessing climate change impacts on cultural heritage, with the goal of constructing a theoretical basis for a replicable and scalable climate vulnerability assessment tool. The framework connects environmental stressors with physical and biological deterioration pathways, extending its focus to the societal implications of heritage degradation. Based on established references, it identifies a coherent set of midpoint and endpoint indices to translate complex climate-heritage interactions into operational knowledge. The approach aims to guide strategic adaptation and co-design through digital and physical Living Labs, involving communities and institutions. While rooted in experimental evidence, the chapter focuses on methodological and modeling aspects, aiming to support innovative and adaptive strategies for the structural and environmental safety of heritage assets.

Keywords: cultural heritage · climate-related hazard · heritage impact · adaptation · risk assessment

1 Introduction

Extreme weather events on cultural heritage in Europe have become increasingly evident in recent years. They are progressing at unprecedented speed and scale. Deep scientific knowledge about future climate projections is required to develop appropriate preservation strategies. Changes in weather and climate conditions aggravate the physical, chemical, and biological mechanisms of degradation, affecting the structure and/or composition of archeological sites, historic buildings or museum collections (Sabbioni

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et al., 2012; Sesana et al., 2021; Bertolin 2019, Loli et al., 2020, O'Neill et al., 2022, Grossi et al., 2007).

Changes in preservation conditions due to climate-related decay processes are unavoidable phenomena for both movable and immovable cultural heritage.

Understanding the mechanisms behind these processes, and their real effect on heritage significance, enables a rational use of materials and anticipation of the behaviour. This knowledge supports preventive conservation, heritage management and restoration.

The degradation progress, which depends on external agents of decay, exposure, the intrinsic properties of the material to be studied, and object construction vulnerability, is nowadays exacerbated by both anthropic factors and the impact of climate change. Due to more frequent and severe weather events, greater exposure, material ageing, and past conservation interventions, the need for adapting cultural heritage to both anthropic and climate change-related effects is increasingly urgent (Bertolin, 2019).

On these topics, Cacciotti et al. (2021) showed that the following damages are often reported at different levels:

- At site level: erosion, soil displacement, earth deposition, damage to forest, parks, or individual trees;
- At building level: material degradation, roof and façade damage, and primary and secondary structural damage.
- At object level (i.e. movable heritage): widespread damage to furniture, musical instruments, artworks, books, paper, glass and ceramic objects.

In this context, the paper describes a preliminary study of the mechanisms of climate change impacts and the strategic role of climate scenarios in identifying the most appropriate interventions for different heritage typologies.

The study consists of three parts: 1) a survey at the European and National levels of key climatic factors and impact mechanisms on cultural heritage materials, based on scientific reports (ICOMOS, 2019; Rebollo et al., 2020); 2) a review of modelling approaches for mitigation and adaptation to climate change scenarios, from which methodologies for developing tools and indices for climate vulnerability and risk assessment are systematized; 3).The elaboration of a framework correlating physical and biological impact mechanisms, climate drivers, expected effects on cultural heritage, and community impacts, including a set of midpoint indices as benchmarks to measure vulnerability of buildings, structures, and urban heritage.

2 Climate Drivers and Degradation Mechanisms

In recent years, the increasing frequency and severity of extreme climate events, together with the gradual transformation of global atmospheric conditions, have prompted a deep re-evaluation of the exposure and vulnerability of cultural heritage, particularly its tangible forms. Climate-induced alterations not only accelerate the physical, chemical, and biological deterioration of materials, but also significantly reshape the environmental and territorial contexts in which heritage assets are embedded. These changes create increasingly critical conditions for the preservation, management, and transmission of cultural heritage to future generations.

According to leading international bodies (ICOMOS, 2019; IPCC, 2021), interactions between climate change and cultural materials result in measurable impacts on historic buildings, cultural landscapes, traditional infrastructures, and artistic objects, threatening their integrity, meaning, and utility value. The urgency of integrating climate risk into preventive conservation protocols is now widely recognized across scientific literature and in adaptation strategies at both European and national levels.

To ensure sustainable management of cultural heritage, it is essential to understand how climate will evolve at specific sites and to what extent future changes will influence heritage typologies and materials (Morel et al., 2022; Richards et al., 2022).

UNESCO's 2007 report Climate Change and World Heritage (Augustin, 2007) was the first attempt to provide an overview of threats posed by climate change to cultural heritage. It emphasized that Climate change – alone or in combination with air pollution - can affect materials, artefacts, collections and cultural landscapes.

A subsequent assessment published in 2016 by UNESCO, UNEP and UCS (Markham et al., 2016), further developed monitoring recommendations, actions and policy responses.

More recent frameworks, such as the Climate Vulnerability Index (CVI), highlight the importance of integrating exposure, sensitivity, and adaptive capacity into risk assessments. This section therefore outlines current foundations and methodologies adopted at the European and international level, emphasizing the need for locally adaptable and diagnostically informed indices.

Following IPCC and ARCH models, the main climatic drivers acting on heritage include:

- Temperature rise and variation: thermal stress, freeze–thaw cycles.
- Humidity fluctuations: salt crystallization, surface scaling, bio-colonization.
- Precipitation and runoff: erosion, infiltration, mold.
- Wind and storms: loss of protective layers, structural instability.
- Solar radiation: photochemical decay, surface drying.

As ICOMOS (2019) stresses, responding to climate change requires adjusting to risks, either in reaction to or in anticipation of a changing climate. Understanding its impact on natural and physical systems, human communities and cultural heritage is therefore essential - not only to evaluate risks and adaptive capacity - but also to recognize the positive role heritage can play as a source of resilience for ecosystems, cities, neighborhoods and landscapes.

Predictions of future climate impacts and cultural heritage responses must be developed using recent and current observations as proxies for future change, integrated with the emission scenarios presented in the latest IPCC Assessment Reports (2023). The ability to downscale 20- and 30-year climate scenarios will become an essential competence for heritage managers. In describing climate impacts and their effects on cultural heritage, it is useful to distinguish between rapid-onset and slow-onset events:

- Rapid onset events, which are short-lived, acute and highly damaging (e.g. extreme winds, hurricanes, storm surge, flash floods, landslides, heat waves, wildfires). Their frequency and intensity are expected to increase globally;

- Slow-onset events, which are progressive and potentially permanent (e.g. glacier melt, sea level rise, aridification, desertification, shifts in seasonality and species distribution). For building heritage, longer-term interactions with air pollution are particularly concerning, leading to degradation of limestone and marble façades, soiling of stone surfaces, leaching of stained glass, metal corrosion and salt crystallization in porous materials such as stone, brick, plaster, mosaics, wall paintings.

3 Typological Risk Classification

This section proposes a typological classification of the main hazards threatening cultural heritage, based on their origin and impact mechanisms.

Cultural heritage is increasingly exposed to a wide range of hazards -environmental, anthropogenic, and biological- that often act simultaneously or in sequence. Rarely isolated, these hazards tend to interact, amplifying their impact through both climatic and non-climatic drivers. According to the IPCC (2014), hazards are processes, phenomena, or human activities that may cause loss of life, injury, or damage to property, infrastructure, and ecosystems. The UN General Assembly (2016) further specifies that hazards should be analyzed in terms of their location, intensity, frequency, and probability. The magnitude depends on both exposure and vulnerability and can be intensified by cascading or compound effects.

In the context of cultural heritage, such risks often result in material decay, structural damage, or the loss of historical and aesthetic value. Following the typologies proposed in the H2020 ARCH project (Rebollo et al. 2020), hazards can be grouped into four main categories: climate-related, human-induced, geological, and biological. These categories are not mutually exclusive, as hazards often overlap or trigger one another. Figure 1 illustrates the interdependencies and cascading effect that characterize these hazards, which also vary across geographical and socio-environmental contexts.

Below is a critical analysis of the main hazards affecting European cultural heritage.

3.1 Climate-Related Hazards

This includes hazards driven by short-term meteorological events or long-term climatic variations.

- Extreme temperatures and thermal stress: rising global temperatures affect traditional materials. In Mediterranean areas, heatwaves cause thermal cracking in stone and ceramics, while moisture loss promotes salt efflorescence. Freeze-thaw cycles, c in alpine and continental zones, induce flaking and loss of cohesion. Higher temperatures also enhance biological activity, increasing risk of fungi and insect infestations in wood and plaster.
- Humidity, precipitation, and hydrogeological hazards: irregular rainfall and flooding erode remains, detach mural paintings, and damage mosaics or flooring. Capillary rise transports salts into masonry, causing plaster detachment. Wet-dry cycles degrade lime mortars and adobe, while landslides and subsidence threaten structures on unstable ground.

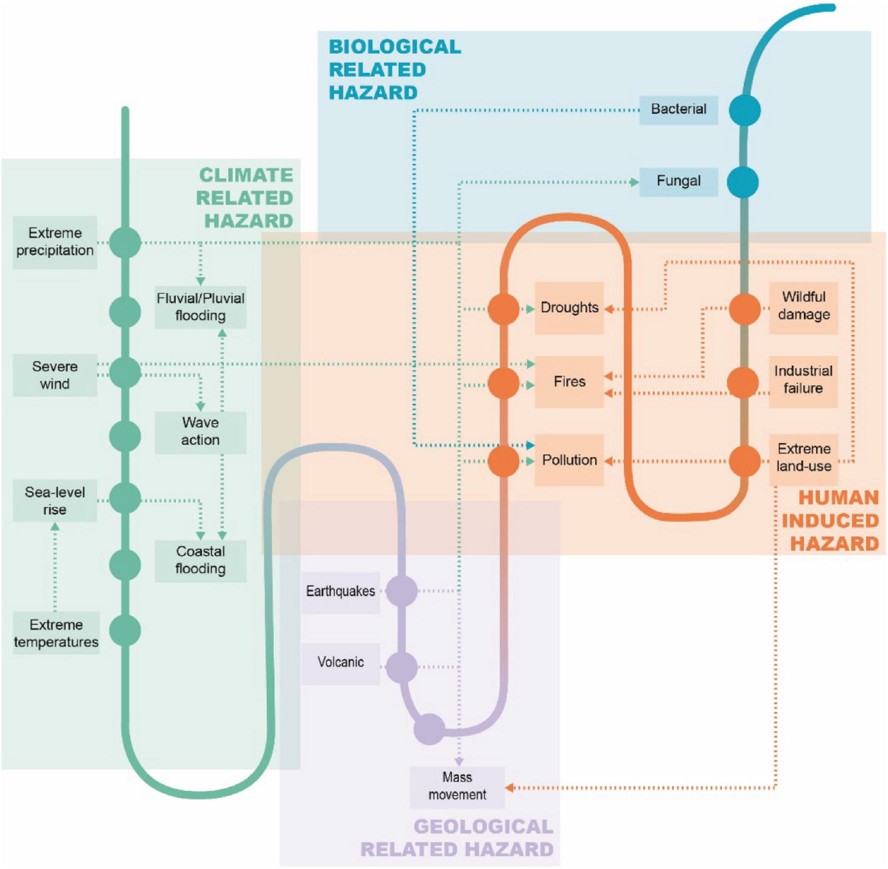

Fig. 1. Schematic categorisation of main hazards affecting European cultural heritage and the inter-connections in between them. The prevalence of the above hazards varies of course depending on geographical variables. 2020 Source: Ri-elaboration of the author from (Giglio et al.2023; Rebollo et al.)

- Wind, salt, sand, and atmospheric pollutants: Wind accelerates abrasion and pollutant transport. Marine salts and airborne particles erode surfaces, while reactive gases (NO_2, SO_2, O_3) form acid rain and corrosive residues, damaging stone, stained glass, and metals.
- Sea level rise and saline intrusion: in coastal areas, sea level rise and storm surges cause erosion and salt infiltration, leading to corrosion, efflorescence, and osmotic damage. This is particularly critical in stilt houses, lagoons, and intertidal zones.

3.2 Geological-Related Hazards

- Earthquakes major structural damage, often followed by cascading effects such as fire, flooding, landslides. Mediterranean countries including Italy, Greece, Turkey, and Spain are particularly vulnerable (Russo et al., 2014; Adnan et al., 2015).

- Mass movements: landslides, rockfalls, avalanches, debris flows, and mudflows triggered by earthquakes, rainfall or snowmelt, threaten heritage structures (Russo et al., 2014).
- Volcanic eruptions: although rare in Europe, they pose significant risks in Italy, Greece, the Canary Islands, and French Antilles. Despite the high density of heritage sites, volcanic risks remain underexplored (Russo et al., 2014).

3.3 Human-Induced Hazards

- Extreme land use: industrial development, mining, agriculture, and fossil fuel extraction damage ecosystems directly (vegetation loss) and indirectly (pollution). These activities increase the risk of landslides and droughts (Turner, 2012).
- Air pollution: pollutant such as NO_2, SO_2, O_3 and formaldehyde accelerate stone decay, chemical alteration, crusting, and discoloration. Acid rain and particulate matter further degrade marbles and stone façades (Rosu et al., 2020; Comite et al., 2020).

3.4 Biological-Related Hazards

Biological agents -from bacteria to plants- alter heritage materials through metabolic activity. These processes intensify in warm, humid climates. Fungi and lichens dissolve minerals and stain surfaces, while plant roots penetrate structures, causing cracks or collapses. The extent of damage depends on organism type, material properties, exposure, and pollutants (Laoupi et al., 2007; Coumou et al., 2012; Nicu, 2017). These biological processes often act synergistically with climatic stressors, exacerbating deterioration.

4 Modelling for Climate Change Mitigation and Adaptation: An Overview on Methodologies and Indices for Assessing Vulnerability and Risk to Cultural Heritage

The increasing exposure of cultural heritage to climate change requires the use of predictive tools and integrated risk assessment methodologies that can inform adaptive decisions at both management and design levels. Although the literature increasingly acknowledges the role of cultural heritage in territorial resilience, there remains a persistent gap in systematically integrating both material and immaterial dimensions of heritage into analytical frameworks for climate vulnerability assessment. Current approaches often emphasize exposure, while overlooking crucial variables such as the adaptive capacity of local systems, the cultural and identity values attributed to heritage, and the historical dimension of conservation knowledge.

Several methodological proposals have sought to address this fragmentation. Carroll and Aarrevaara (2018) introduced a priority intervention index, based on a 1–10 scale, linking local climate factors (e.g. temperature increases, growing seasons length, precipitation, wind speed) to direct visual observations of material damage. Although heuristic, this approach suggests an operational path for allocating resources on a comparative basis.

Similarly, Loli and Bertolin (2018) proposed a multi-risk modelling framework using data from the Climate for Culture project. Their approach integrates physical degradation trajectories (mechanical, chemical, biological) of historic materials with the regulatory protection levels of assets, thereby defining critical thresholds for adaptive interventions. Projections to 2100 indicate increased biological and chemical risks, particularly for exposed structures in southern and central Europe.

Ciantelli et al. (2018) applied high-resolution modelling with the EC-Earth climate system to future scenarios (2039–2068), producing damage functions that reveal accelerating surface recession, biological accumulation, and salt crystallization/solubilization cycles, especially in archaeological sites and porous stone materials subject to capillary moisture.

These approaches informed the experimental strategy adopted in the T4Y case studies, where climate projections, material behaviour, and degradation processes were combined to support the development of a comprehensive assessment tool.

Taken together, these studies converge on several fundamental principles:

- Climate risk assessment should not be limited to exposure alone but must include a dynamic estimate of vulnerability, based on the physical-mechanical properties of materials, the microclimatic context and maintenance conditions.
- Integration of climate data, decay parameters and land use models is essential for defining contextualized and scalable adaptation strategies.
- Continuous monitoring is indispensable, not only to validate predictive models but also to build awareness and legitimacy for adaptation policies.

From an operational perspective, risk matrices derived from the interaction of climate variables (ΔT, ΔP, ΔRH, ΔW) and material types (wood, stone, plaster, metals) provide a forecasting frameworks. Within this framework, accelerated degradation processes are linked to phenomena such as:

- Freeze/thaw cycles
- Salt crystallization
- Corrosion by atmospheric pollutants combined with acid rain
- Biodeterioration in high humidity environments
- Erosion from wind or wind-driven rain (WDR)

Finally, Sesana et al. (2018) emphasizes that adaptation governance must also overcome barriers in perception and institutional capacity. The absence of shared guidelines, limited technical training among managers and the scarcity of georeferenced data on conservation status and climate vulnerability significantly constraint the effectiveness of adaptation strategies. It is therefore necessary to develop decision-support tools that combine quantitative approaches (modelling, monitoring, simulations) with qualitative dimensions (cultural values, local practices, tacit knowledge).

5 Toward a Set of Climate Vulnerability Indices for Cultural Heritage: A Framework Linking Climate Drivers, Impact Mechanisms, and Societal Effects

The data presented in the preceding sections -concerning physical and biological impact mechanisms, climate drivers, projected effects on cultural heritage, and broader societal consequences- have been systematically selected and correlated through a structured methodology aimed at developing a coherent analytical framework (Table 1). This framework identifies the main pathways through which climate-related hazards compromise the material integrity and structural stability heritage assets, as well as their societal and cultural functions.

Building upon foundational contributions (UNESCO, 2007; ICOMOS, 2019) and subsequent analyses (Rebollo et al., 2020; IPCC, 2021), the framework integrates case studies and projections, providing an updated overview of climate- heritage interaction.

Table 1. Analytical framework: Climate Change Impacts on Cultural Heritage (Re-elaboration of F. Giglio and F. Armocida, fonts: ICOMOS, 2019; ICLEI, 2020)

Climate Driver	Impact Mechanism	Hazard / Effect	Heritage Impacts	Urban Heritage & Community Impacts
Temperature Rise	Heatwaves, altered freeze-thaw cycles	Urban Heat Island, material decay	Chemical/mechanical degradation, cracking, salt crystallization	Abandonment of assets, migration, loss of traditional knowledge
Fire	Direct fire damage, post-fire erosion	Wildfire, fire suppression, runoff	Burning, discoloration, collapse, erosion	Loss of sites, increased flooding, shift in materials or layouts
Drought	Soil drying, water scarcity	Desertification, reduced humidity	Cracking, salt spalls, impact on water-based heritage systems	Migration, loss of livelihoods, neglected heritage
Sea Level Rise	Coastal erosion, salinization	Chronic/acute flooding, salt infiltration	Foundation subsidence, salt damage, corrosion, total or partial loss	Inaccessibility, urban transformation, displacement of communities

(*continued*)

Table 1. (*continued*)

Climate Driver	Impact Mechanism	Hazard / Effect	Heritage Impacts	Urban Heritage & Community Impacts
Coastal Flooding	Wave impact, storm surge	Structural failure, salinization	Collapse, salt crystallization, relocation pressures	Historic site loss, damage to roads/ports, erosion of cultural landscapes
Coastal Erosion	Land loss, exposure of structures	Accelerated by sea level rise and storms	Collapse, rust, relocation	Graveyard and landmark loss, landscape degradation
Air Pollution Climate induced hazard	Acidification, deposition, chemical reactions	Combined with temperature/humidity changes	Material erosion, corrosion, façade darkening, glass degradation	Loss of visual integrity, plantings, significant viewsheds
Storms	High winds, surge, debris	Increased frequency/intensity of events	Collapse, water infiltration, physical erosion, damage to utilities	Destruction of historic urban landscapes, access loss
Wind	Direct loading, wind-borne debris	Scouring, horizontal pressure	Surface abrasion, water penetration, cracking	Collapse of weak structures, wind damage to archaeological sites
Extreme Rainfall	Flooding, saturation, landslides	Soil erosion, fungus, instability	Swelling, rot, collapse (especially adobe), spalling	Loss of earthen towns, soil movement, waterlogging of gardens
Pollution	Acid deposition, soot, contaminants	Rain acid interactions, biological growth	Erosion of stone, color change, stained glass degradation	Damage to landscapes, reduced visibility of landmarks
Precipitation & Humidity	Flash floods, capillary rise, saline water	Intense rain, efflorescence	Sediment damage, pollutant accumulation, salt crystallization	Flash flooding of sites, efflorescence, drainage issues

Drawing on this foundation and the extensive literature review, the study advances a proposal for a set functional indices, defined as quantitative indicators linking specific climatic stressor to measurable degradation patterns of materials and structures. These indices are intended to provide reference benchmarks for assessing vulnerability across different scales, from single elements to entire heritage complexes.

A comprehensive assessment must incorporate both structural and non-structural dimensions, acknowledging the cumulative effects of climate change in interaction with non-climatic stressors. Crucially, both rapid onset events (e.g. flood, landslides, storm urges) and slow-onset phenomena (e.g. sea-level rise, desertification) must be considered within governance frameworks that reflect local adaptive capacity.

Equally important is the inclusion of community values, traditional practices, and socio cultural resilience, which can mitigate vulnerabilities often overlooked by purely technical assessments. Long-term monitoring of climate-induced degradation - particularly in historic buildings, interiors and archaeological contexts is essential to track susceptibility and support responsive conservation strategies.

In this perspective, the framework identifies a set of midpoint indices, reflecting average impacts of climate stressors over time and space, and endpoint indices, representing their cumulative effects on heritage assets (Giglio et al. 2024). The following midpoint indices are proposed:

- Deterioration Index (general material degradation rate)
- Carbonation Index (relative to substrate alteration).
- Efflorescence Identification Index (salt crystallization and surface deposits)
- Corrosion Index (specific to metallic elements)

Each index is associated with defined climatic stressors, as summarized in Table 2, and is designed for application across multiple scales – from laboratory experimental analyses (e.g., XRD, SEM) to in situ monitoring and geospatial modelling (Lucanto et al. 2024). This multiscalar flexibility ensures that the indices can function both as a diagnostic tool and as policy-relevant benchmarks for adaptation planning. Offering a structured basis for evaluating climate vulnerability in cultural heritage contexts (Table 2).

Table 2. Identification of a set of midpoint indices as benchmark to measure climate vulnerability on cultural heritage buildings and structures selected from Hazard Climate Impact (ICOMOS, 2019)

Hazard Climate Impact (ICOMOS, 2019)	Functional impact indices to measure climate vulnerability on cultural heritage buildings and structures
Alteration of frost/thaw cycles (temperature level rise)	Deterioration index
	Carbonation index (relative to the reference substrate)
	Efflorescence identification
Heatwaves (temperature level rise)	Deterioration index

(*continued*)

Table 2. (*continued*)

	Carbonation index (relative to the reference substrate)
	Efflorescence identification
Drought and Desertification (temperature level rise)	Deterioration index
	Carbonation index (relative to the reference substrate)
	Efflorescence identification
Chronic or acute flooding (sea level rise)	Deterioration index
	Carbonation index (relative to the reference substrate)
	Efflorescence identification
	Corrosion index of metal elements
Increased intensity and frequency of storms (Combination of climate change effects)	Deterioration index
Increased intensity and frequency of winds (Combination of climate change effects)	Deterioration index
Extreme rainfall (Combination of climate change effects)	Deterioration index
	Carbonation index (relative to the reference substrate)
	Efflorescence identification
	Corrosion index of metal elements
Pollution (Combination of climate change effects)	Deterioration index
	Corrosion index of metal elements
Increase in humidity (Precipitation and humidity)	Carbonation index (relative to the reference substrate)
	Efflorescence identification.

6 Conclusions

Cultural heritage is increasingly exposed to climate-induced risks, requiring a shift in conservation and adaptation strategies. This chapter proposes a methodological framework for assessing such risks, highlighting the relationship between climatic drivers, degradation mechanisms, and material vulnerability. By integrating multi-scale data, ranging from European policy frameworks to site-specific characteristics, the work establishes a theoretical basis for constructing flexible and scalable assessment tools.

The framework links environmental stressors to physical and biological deterioration pathways, while also considering the societal implications of heritage degradation. Based on established references, it identifies a coherent set of midpoint and endpoint indices to translate complex climate-heritage interactions into operational knowledge.

These indices serve as key instruments for monitoring, prioritizing, and guiding adaptive conservation strategies. Midpoint indices (e.g., deterioration, carbonation, efflorescence, corrosion) allow the disaggregation of vulnerability into measurable phenomena, while endpoint indices reflect the cumulative effects of climate stressors over time.

Importantly, the analysis recognizes that climate change impacts are not solely material but also affect identity, memory, and social cohesion. Therefore, vulnerability assessments must integrate technical, cultural, and community-based dimensions.

Future research will focus on operationalizing these indices through field applications in the T4Y pilot area of Bova, aiming is to refine their structure and interdependencies. This approach will support a dynamic decision-support process to enhance long-term resilience in cultural heritage management.

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References

Sabbioni, C., Brimblecombe, P., Cassar, M.: The Atlas of Climate Change Impact on European Cultural Heritage: Scientific Analysis and Management Strategies. Anthem Press, London (2012)

Sesana, E., Gagnon, A.S., Ciantelli, C., Cassar, J.A., Hughes, J.J.: Climate change impacts on cultural heritage: a literature review. WIREs Clim. Change **12**(4), e710 (2021). https://doi.org/10.1002/wcc.710

Bertolin, C.: Preservation of cultural heritage and resources threatened by climate change. Geosciences **9**(6), 250 (2019). https://doi.org/10.3390/geosciences9060250

Loli, A., Bertolin, C., Kotova, L.: Service life prediction of building components in the times of climate change. In: IOP Conference Series: Materials Science and Engineering, vol. 949, p. 012048 (2020). https://doi.org/10.1088/1757-899X/949/1/012048

O'Neill, S., Simon, F., Tett, B., Donovan, K.: Extreme rainfall risk and climate change impact assessment for Edinburgh World Heritage sites. Weather Clim. Extremes **38**, 100514 (2022). https://doi.org/10.1016/j.wace.2022.100514

Grossi, C.M., Brimblecombe, P., Harris, I.: Predicting long-term freeze–thaw risks on Europe's built heritage and archaeological sites in a changing climate. Sci. Total. Environ. **377**(2–3), 273–281 (2007). https://doi.org/10.1016/j.scitotenv.2007.02.014

Cacciotti, R., et al.: Climate change-induced disasters and cultural heritage: optimizing management strategies in Central Europe. Clim. Risk Manag. **33**, 100301 (2021). https://doi.org/10.1016/j.crm.2021.100301

ICOMOS Climate Change and Cultural Heritage Working Group. The Future of Our Pasts: Engaging Cultural Heritage in Climate Action. Paris: ICOMOS (2019)

Rebollo, V., Latinos, V.: Arch D 7.2 Good practices in building cultural heritage resilience. ICLEI (2020)

Intergovernmental Panel on Climate Change (IPCC). Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. In: Masson-Delmotte, V., et al. (eds.). Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA (2021)

Morel, H., et al.: Global Research and Action Agenda on Culture, Heritage and Climate Change. Charenton-le-Pont & Paris, France: ICOMOS & ICCROM Climate Heritage Working Group (2022)

Richards, J., Brimblecombe, P.: Moisture as a driver of long-term threats to timber heritage—Part I: changing heritage climatology. Heritage **5**(3), 1929–1946 (2022). https://doi.org/10.3390/heritage5030100

Augustin, C.: Climate change and world heritage: Report on predicting and managing the impacts of climate change on world heritage and strategy to assist States Parties to implement appropriate management responses. UNESCO World Heritage Centre (2007)

Markham, A., Osipova, E., Lafrenz Samuels, K., Caldas, A., Ullstein, B.: World Heritage and tourism in a changing climate. United Nations Environment Programme, Nairobi, Kenya, and United Nations Educational, Scientific and Cultural Organization, Paris, France (2016)

IPCC. Climate Change 2023: Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, H. Lee and J. Romero (eds.)]. IPCC, Geneva, Switzerland, pp. 35–115 (2023). https://doi.org/10.59327/IPCC/AR6-9789291691647

IPCC. Annex II: Glossary [Mach, K.J., Planton, S., von Stechow, C. (eds.)]. In: Pachauri, R.K., Meyer, L.A. (eds.) Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. IPCC, Geneva, Switzerland, pp. 117–130 (2014)

United Nations General Assembly. Report of the open-ended intergovernmental expert working group on indicators and terminology relating to disaster risk reduction. United Nations General Assembly, New York, NY, USA (2016)

Giglio, F., Frontera, P., Malara, A., Armocida, F.: Materials and climate change: a set of indices as the benchmark for climate vulnerability and risk assessment for tangible cultural heritage in Europe. Sustainability **16**(5), 2067 (2024). https://doi.org/10.3390/su16052067

Russo, S., Dosio, A., Graversen, R.G., Sillmann, J., Carrao, H., Dunbar, M.B., Vogt, J.V.: Magnitude of extreme heat waves in present climate and their projection in a warming world. J. Geophys. Res. Atmos. **119**(22), 12,500 (2014)

Adnan, A., Ramli, M.Z., Sk Abd Razak, S.M.: Disaster management and mitigation for earthquakes: are we ready. In: Proceedings of the 9th Asia Pacific Structural Engineering and Construction Conference (APSEC 2015), pp. 34–44 (2015)

Turner, S.D.: World Heritage Sites and the extractive industries. Independent study commissioned by IUCN in conjunction with the UNESCO World Heritage Centre, ICMM and Shell (2012). www.icmm.com/document/3787. Accessed 14 June 2025

Rosu, A., Constantin, D.E., Arseni, M., Timofti, M.: Atmospheric measurements in the context of protection and conservation of cultural heritage objects. In: AIP Conference Proceedings, vol. 2218, no. 1, p. 030015. AIP Publishing LLC (2020)

Comite, V., Randazzo, L., La, Russa, M.F., Fermo, P.: A multi-analytical approach for the characterization of black crusts on the facade of an historical cathedral. Microchem. J. 105121 (2020)

Laoupi, A., Tsakiris, G.: Assessing vulnerability in cultural landscapes. In: EWRA Symposium "Water Resources Management: New Approaches and Technologies," Chania, Crete, Greece, 14–16 June 2007 (2007)

Coumou, D., Rahmstorf, S.: A decade of weather extremes. Nat. Clim. Chang. **2**(7), 491–496 (2012). https://doi.org/10.1038/nclimate1452

Nicu, I.C.: Natural hazards—a threat for immovable cultural heritage: a review. Int. J. Conserv. Sci. **8**(3), 391–402 (2017)

Carroll, P., Aarrevaara, E.: Review of potential risk factors of cultural heritage sites and initial modelling for adaptation to climate change. Geosciences **8**(9), 322 (2018). https://doi.org/10.3390/geosciences8090322

Loli, A., Bertolin, C.: Indoor multi-risk scenarios of climate change effects on building materials in Scandinavian countries. Geosciences **8**(10), 347 (2018). https://doi.org/10.3390/geosciences8100347

Ciantelli, C., Palazzi, E., Von Hardenberg, J., Vaccaro, C., Tittarelli, F., Bonazza, A.: How can climate change affect the UNESCO cultural heritage sites in Panama? Geosciences **8**(9), 296 (2018). https://doi.org/10.3390/geosciences8090296

Sesana, E., Gagnon, A., Bertolin, C., Hughes, J.: Adapting cultural heritage to climate change risks: perspectives of cultural heritage experts in Europe. Geosciences **8**(9), 305 (2018). https://doi.org/10.3390/geosciences8090305

Lucanto, D., Nava, C., Mangano, G.: Digital prototyping and regenerative design toward carbon-neutrality and a climate resilient built environment: a multi-scale assessment of environmental multi-risks. Buildings **14**(12), 3934 (2024). https://doi.org/10.3390/buildings14123934

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