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Materials and Climate Change: A Set of Indices as the Benchmark for Climate Vulnerability and Risk Assessment for Tangible Cultural Heritage in Europe

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Abstract: Among the issues most related to climate change, the built environment is also subjected to short- and long-term risks. Referring to tangible cultural heritage, materials and buildings are subjected to different types of damage that require adaptive risk prevention and containment strategies, currently missing from conventional risk assessments. Thus, there is an increasingly urgent need for scientific and technical knowledge, tools, and solutions aimed at solving critical issues in cultural heritage due to climate change. In this context, the aim of this study is to study the mechanisms of impacts brought about by climate change and the formulation of a possible set of indices as benchmarks to measure climate change's effect on cultural heritage buildings. The study is structured on a methodology that identifies three sections: the first and second parts systematize and critically interpret data on impact mechanisms and indices for climate vulnerability and risk assessment; the third part, data processing, reports the perspective findings. The main intermediate indices, contributing to a comprehensive damage index, were identified, and a procedural protocol was developed. Finally, through the correlation of indices, a potential case study could be analyzed, and benchmarks made effective. The study reports partial results of one of the "Ecosystems of Innovation" pilot projects funded by the National Recovery and Resilience Plan. The study is still a work in progress and needs advancement and deepening to verify case study indices.

Keywords: cultural heritage; climate vulnerability; indices; benchmark; risk assessment

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Citation: 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* **2024**, *16*, 2067. https://doi.org/10.3390/su16052067

Academic Editor: Antonio Caggiano

Received: 8 January 2024
Revised: 13 February 2024
Accepted: 27 February 2024
Published: 1 March 2024

1. Introduction

Hazards to the built environment (short- or long-term) are among the most pressing concerns associated with climate change (CC). When dealing with a tangible cultural heritage (CH), different forms of impact may require the use of techniques to prevent and contain potential risks.

Despite its importance, CH has long been absent from the debate on sustainable and social development, and the process of recognizing this relevance at a national and international level should also be used to fully reach the target amounts from the Sustainable Development Goals (SDGs) of the UN Agenda 2030 [1].

In recent years, due to the increased intensity of extreme weather events on CH in Europe and a consequent speed of propagation at an unprecedented scale of the latter, in-depth knowledge of future climate projections is needed to define adaptive conservation strategies and appropriate measures for heritage sites. These changes inevitably aggravate the physical, chemical, and biological mechanisms, causing mechanical degradation, structural damage, and other pathologies in the heritage system [2–6].

Such changes in conservative conditions are due to degrading processes linked to climate-altering events whose knowledge is, for this reason, fundamental. Their regulation mechanisms and their real impacts on the heritage system will allow us to define a more rational use of the material in anticipation of the behavior in a perturbative regime to ensure heritage management, prior conservation, and possible restoration processes. It becomes essential to consider in this context the local CC, as weathering actions and the exposure to the intensity and frequency of extreme events that can lead to the alteration in the degradation processes of building materials, such as physical and chemical damages [5–7], excluding static and dynamic alterations of load-bearing structures [7].

In addition, the latest IPCC report (AR6 SYR 2023) [8] highlights how adaptive intervention processes help to strengthen cities' response to CC and related hazards, especially with regard to climate vulnerability.

Although CH traces those identity values of a community potentially exposed and vulnerable to climate risks, the latter has, at the same time, a particular precariousness that, in most cases, is far from the canonical risk assessments. Indeed, these risk assessments represent a fundamental first step in identifying effective mechanisms for climate change adaptation (CCA). Otherwise, by ignoring the influence of CH, decision-makers would proceed by limiting their effective understanding of risk, thereby avoiding deepening possible viable opportunities for building and maintaining local resilience. In all the literature analyzed, risk assessments focus mostly on an isolated exposure of the concept of vulnerability or adaptive capacity, whereas, where the vulnerability is included, there is no coherent definition or criterion [9].

Based on the studies presented in this field, it is evident that a long-term CCA strategy should include careful risk assessment, appropriate adaptation measures, and specific monitoring processes [4]. Thus, there is an increasing gap of knowledge on scientific–technical knowledge tools of CH, the harmonization of available data sets, and the need for solutions aimed at solving critical issues due to CC.

In this context, the study's overall objective is to help provide adaptive tools, solutions, and methodologies for climate mitigation of tangible CH. The originality and relevance of the study are the analyses of the mechanisms of impacts brought about by CC and the elaboration of the outcome as a possible set of indices as benchmarks to measure the climate vulnerability of buildings, structures, and urban heritage.

The study is structured on a methodology that identifies three parts: (i) systematizing climate effects, impact mechanisms, and hazards; (ii) systematizing methodologies for developing tools and indices for climate vulnerability and risk assessment; and (iii) data processing reporting prospective findings, which are the expected results applied to a potential case study. The individuation of the experimental phase will provide specific data on a variety of case studies, which can then be analyzed and used to make benchmarks more effective.

The study presents partial results of the Pilot Project 4.7.1—open platform "phigital space" (physical and digital) of the type "user profiling" for the advanced and dynamic co-design of interventions on the built and ex novo, in spoke 4 "Safeguarding and Enhancing the Natural and Cultural Heritage and Identity of the Territories—Technologies for Resilient and Accessible Cultural and Natural Heritage" of Innovation Ecosystem Tech4You "Technologies for Climate Change Adaptation and Quality of life Improvement" funded by the National Recovery and Resilience Plan (PNRR), Mission 4, Component 2 Investment 1.4, funded from the European Union—NextGenerationEU. The study is still in progress and needs advancement and deepening to verify the indices on the case studies.

2. Background

With reference to the analysis of the scientific literature and the main reports of recent years, "*The increase in temperatures over time and changes in weather patterns that disrupt the normal balance of nature. This entails many risks for humans and all other life on Earth. (e.g., high temperatures, heavy rains, extreme winds, etc.)*" [10] are defined as "effects" of CC. Similarly, the IPCC defines the "impacts" of CC as: "*The effects of CC and extreme weather and climate events on natural and human systems, divided into: potential impacts (all impacts that may occur* *as a result of expected CC, without adaptation) and residual impacts (impacts that occur after adaptation)*" [11]. These impacts correspond, on the "heritage system", to potential climate risks that are always defined by the IPCC as: "*The potential consequences in which something of value is at stake and where the outcome is uncertain, recognizing the diversity of values. Risk is represented as the probability of the occurrence of dangerous events or trends multiplied by the pacts that would occur if these events or trends occurred. The risk comes from the interaction of vulnerability, exposure, and dangerousness*" (Figure 1) [11].

Figure 1. Schematization of the main factors influencing a risk, as reported in IPCC, 2014 [11].

Regarding the concept of risk, the current response of the research landscape moves towards the definition of forecasting scenarios that define climatic systems that can be modulated and kept under control. Forecasts of possible future impact scenarios related to the effects of the CC and the related responses of the CH need to be developed, taking as a reference and using current data and observations that retrace the range of climate scenarios developed in the latest IPCC assessment reports. This ability is fundamental for heritage managers who, at the same time, are called to distinguish the magnitude of the disruptive event (hazard) on the CH, starting from the mode and mechanism of occurrence. In describing climate hazards and their effects on CH, in fact, it is essential to distinguish between rapid-onset and slow-onset events:

- The first includes events of short duration, sudden, intense, recurring, extremely harmful, and uncontrollable. In the coming years, CC are expected to increase the frequency and intensity of many of these types of events;
- The latter are events of long duration, progressive in time, and potentially permanent that, although in the short term, may be less harmful, risk presenting serious long-term consequences.

Starting from these mechanisms of onset (rapid or slow), it is essential to understand how the degradation process depends on external agents related to the exposure factors of the heritage system, the intrinsic properties of the materials that make up the CH, the vulnerability factor of the object itself, and the potential anthropogenic or natural risks arising from the effects of the CC. The urgency of the processes of microclimatic adaptation of CH is becoming, in recent years, an increasingly emerging process due to the exacerbation of extreme weather events that, increasing in frequency and severity, place in a position of greater exposure to the entire heritage system [4].

On these topics, Cacciotti et al. [12] demonstrate how such impacts inevitably create a relationship to the different scales of the site affected by the climate disturbance. According to the author, in fact, such impacts can be observed as follows:

- At the site level, physical damage to the site concerned (erosion, soil displacement, land deposition, and damage to forest, park, or individual trees);
- At the building level, through physical damage related to the architectural object that indicates material degradation processes (damage to roofs, facades, and structures);
- At the object level, regarding movable heritage.

3. Materials and Methods

The theme related to the processes of climate adaptivity of tangible CH and the construction of strategies for increasing the resilience of these contexts has provided for a working methodology structured by a framework divided into three phases (Figure 2):

- The first phase (analytical background) is related to the systematization of the thematic aspects concerning the effects of CC and the related and most common impact mechanisms (hazards) affecting the "heritage system". This analysis is necessary for constructing the reference apparatus relating to the criteria to be considered in the next phase of methodological systematization,
- The second phase (critical review) of the methodological systematization of studies and research on methodologies for developing tools and indices for climate vulnerability and risk assessment related to contexts of tangible CH;
- The third phase (prospective findings) reports the partial results of one of the pilot projects of the project "Ecosystems of Innovation", funded by the National Recovery and Resilience Plan (PNRR). These elaborations have produced a concise possible set of indices benchmarks to measure the climate vulnerability of cultural heritage buildings and structures.

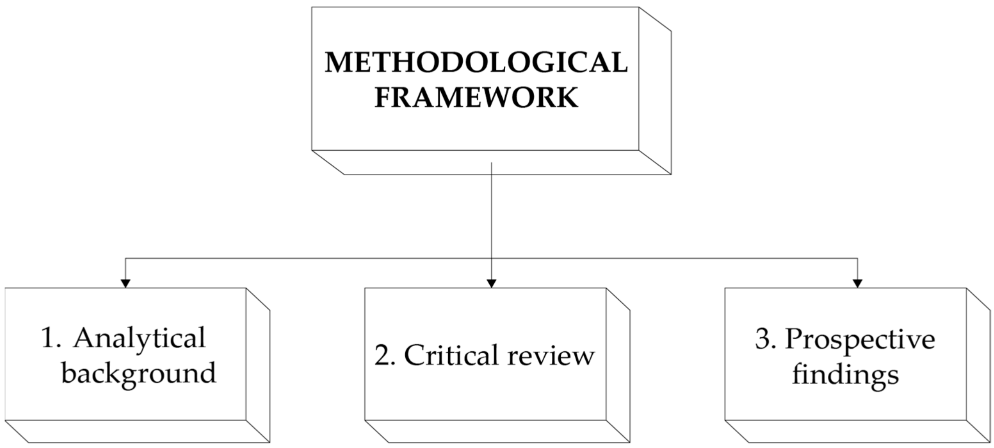

Figure 2. Schematic representation of the methodology according to the three phases of the framework.

4. Analytical Background

4.1. Tangible Heritage: Systematization of Effects, Impact Mechanisms, and Climate Hazards

In order to manage the theme of microclimatic adaptivity of the heritage system through tangible intervention strategies, it becomes essential to know the evolutionary processes of the climate and how it will change in the future affected sites [13,14].

The fundamental reference is the publication of the *UNESCO 2007 Climate Change and World Heritage: Report on Predicting and Managing the Impacts of CC on World Heritage and Strategy* *to Assist States Parties to Implement Appropriate Management Responses* [15], which represents the first attempt to present a comprehensive overview of the threats to CH by the impacts of the CC. In 2016, in cooperation with the UNEP and UCS, UNESCO produced a new assessment of climate impacts on the world's heritage [16], including monitoring actions and possible policy responses. This report, in an attempt to update the material of the previous report of 2007, identifies some of the physical and biological mechanisms through which climate hazards can influence the material entity of artifacts and cultural landscapes.

Following these references, Figure 3 outlines, in relation to the latest IPCC reports, an updated overview of the main types of CC impact that will affect CH, along with some illustrative examples.

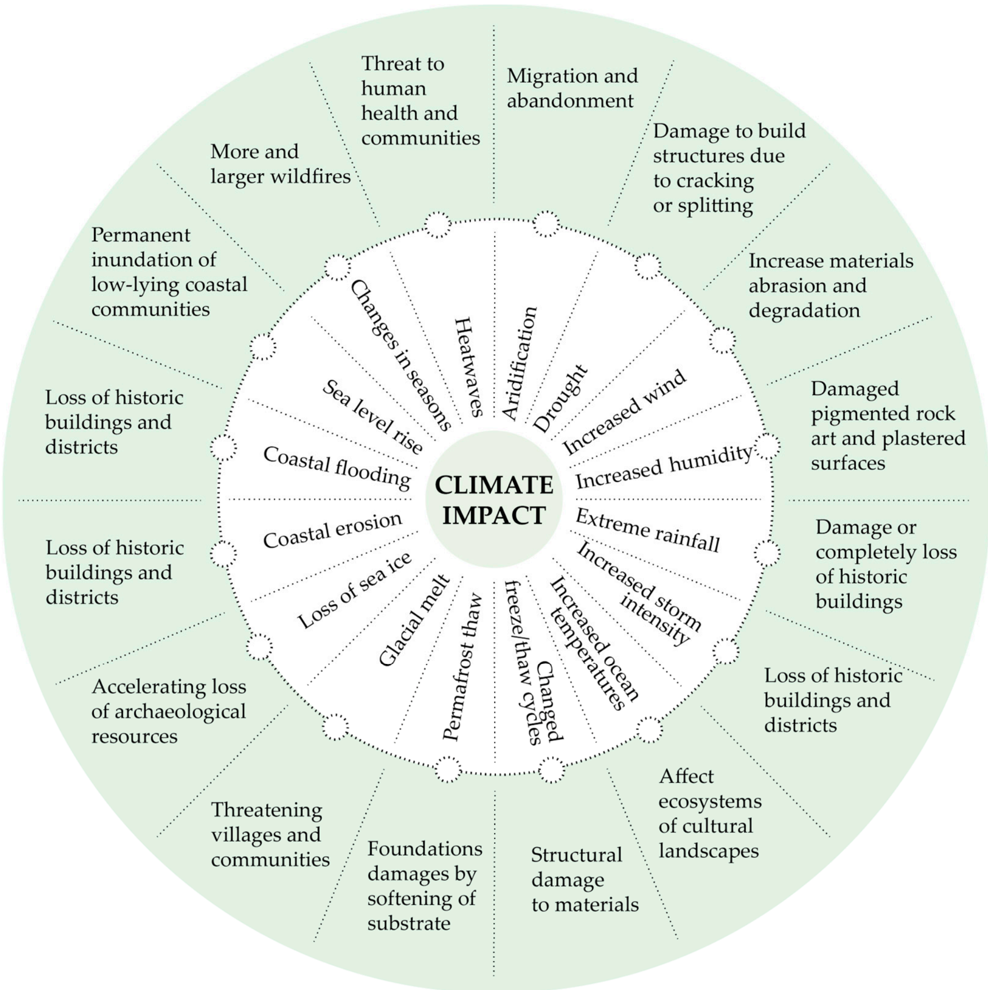

Figure 3. Schematic representation of the climate impacts affecting CH with some examples of those effects [16].

A further implementation of CC impact on tangible CH is provided by Sesana E. et al. [3], who summarize the international literature on the topic by developing impact diagrams that synthesize the relationships between climatic stress (hazard) and related changes in the processes of material and structural degradation for CH. The purpose of these diagrams is to describe the information on the multiple climate impacts synergistically and highlight the interconnections between these factors. For the purpose of this research, two diagrams have been deepened:

- The first shows the impacts related to temperature changes, rainfall, and strong winds on the heritage system directly exposed to the external environment;

- The second highlights the impact of CC in the physical/naturalistic environment of heritage (river floods, rising sea levels, storms, landslides, and heat waves).

  According to the author, such impacts may relate to specific drivers identified as follows:

- Water resulting from an extreme increase in precipitation is the main agent of material degradation. Among the causes found, reference is made to the different mechanisms of structural and non-structural decay (corrosion, biological degradation, efflorescence, and subflorescence due to the crystallization of salt);
- The boost of increasingly strong winds, accompanied by the presence of sand, salt, and air pollutants, will affect the European CH, causing surface abrasion processes, water penetration, structural damage, and a potential collapse of structures;
- Warmer temperatures may increase the number of frost–thaw cycles capable of intensifying the physical aging processes of some families of materials such as stone and ceramic.

However, according to the ICOMOS report [17], responding to such changes means adapting to potential future risks in a preventive manner. It is, therefore, essential to understand how the impacts of CC affect the heritage system and communities in order to evaluate possible risk management through accurate microclimate adaptation strategies. Understanding these adaptive mechanisms inevitably also highlights the positive role that CH can play as a source of resilience for ecosystems, cities, landscapes, and communities that live in it.

4.2. Risks to Cultural Heritage: Hazards Categorization

The muti-risk conditions to which CH assets are subject have different origins, presenting different interrelationships among them. Impacts on CH are often determined by the concatenation of different hazards that can be further aggravated by non-climatic and climatic factors. The IPCC report [11] defines a hazard as "*the potential occurrence of a natural or human induced physical event or trend, or impact that may cause loss of life, injury, or other health impacts, as well as damage and loss to property, infrastructure, livelihoods, service provision, and environmental resources*". According to the UN [18], each hazard is further characterized by its location, intensity or magnitude, frequency, and probability. The events and trends considered in the IPCC definition can have consequences of different magnitudes, depending on the exposure of the system or community to a hazard and the underlying vulnerability of that system or community.

Some of these hazards interact with each other, resulting in complex impact chains in which new hazards emerge based on the vulnerability and exposure of affected CH resources. Based on previous typologies and research conducted as part of the H2020 project ARCH—Advancing Resilience of Historical Areas Against Climate-Related and Other Hazards—the EU-funded project team proposes a schematic categorization of the main hazards affecting CH in Europe and the main interconnections between them.

In the ARCH report, Good Practices in Building Cultural Heritage Resilience [19], hazards have been classified under four main categories: "Climate-related", "Human induced", "Geological-related", and "Biological-related". According to this categorization, Figure 4 represents a graph with a non-exhaustive attempt to describe the complex nature of impact chains, indicating the most evident interactions.

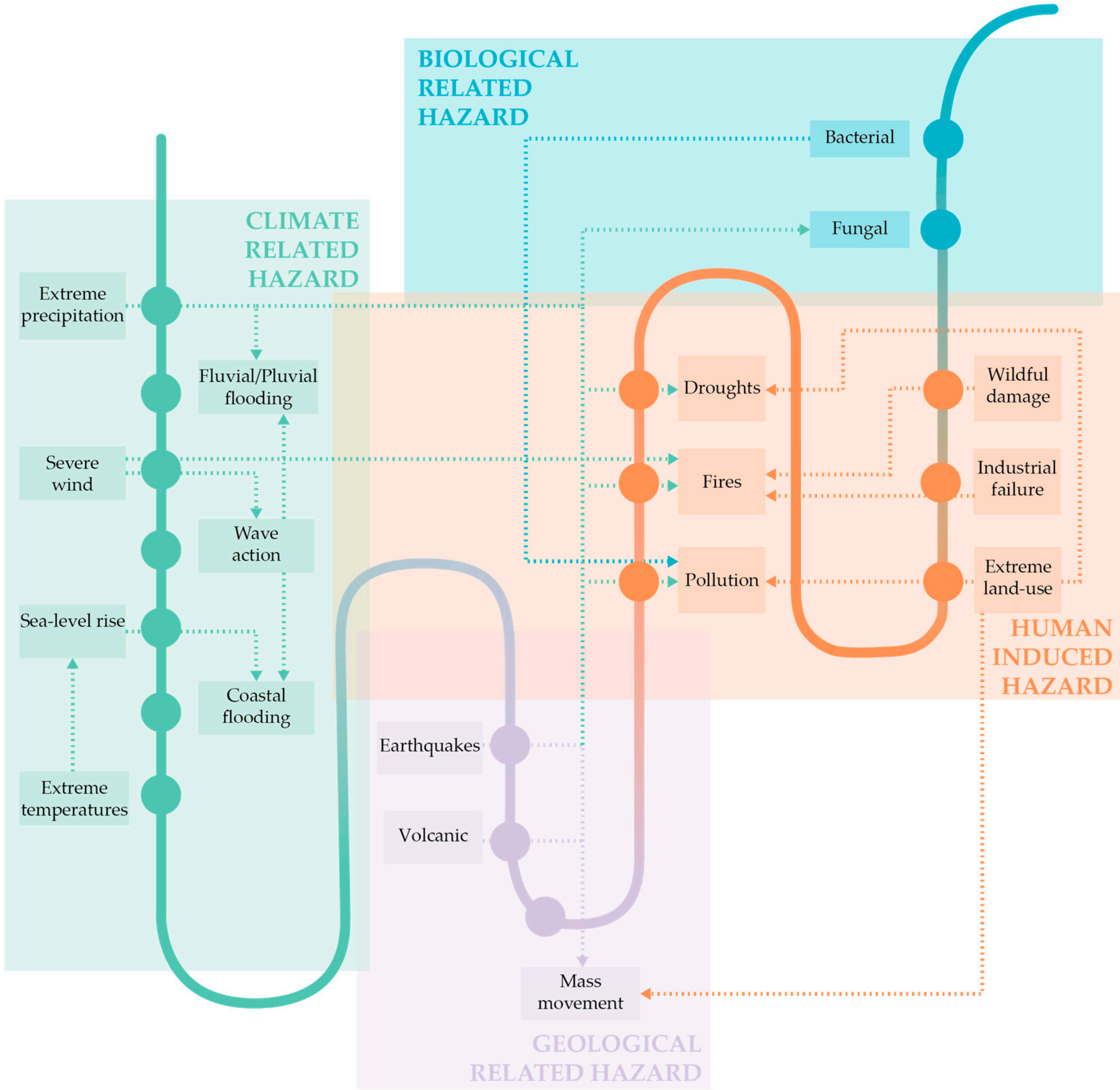

Figure 4. Schematic categorization of main hazards affecting European cultural heritage and the interconnections between them [19].

4.2.1. Climate-Related Hazards

This category encompasses all those hazards deeply influenced by atmospheric variations, whether they are sudden, abrupt, short-term (meteorological), or alternatively prolonged over time (climatic). Some examples:

- Extreme temperatures, heat waves, and droughts: the frequency and intensity of thermal extremes and heat waves (and precipitation) are expected to be affected by the increase in global surface temperature, resulting in an increased likelihood of storms or heavy rains [20];
- Extreme rainfall, storms, and floods represent a serious multi-level threat with direct and indirect impacts, periodic reappearance, and complicated socio-economic impacts [21]. Possible overloads of structures represent the risks of extreme precipitation, the accumulation of pollutants, penetration into the urban fabric, the crystallization

and dissolution of salts resulting from humidification, drying, erosion, and corrosion of metals, as well as biological attacks of organic materials [22];
- Severe wind: the surfaces of the built CH undergo erosive/abrasive effects because the wind is often accompanied by rain, salt, and sand. A further effect is the chemical changes due to moisture penetrating the porous surfaces [23];
- Sea level rise and wave action: landscapes and buildings may be subject to erosion caused by prolonged contact with water, along with salt intrusion and physical and mechanical impacts from waves. Therefore, CH sites located in coastal areas are at risk of this phenomenon and subsequent coastal flooding, with the possibility of interacting with other events, such as storms [24].

4.2.2. Geological-Related Hazards

- Earthquakes: they represent natural disasters with the most devastating effects in relation to loss of life and structural damage to buildings and natural landscapes [25]. They are often followed by other negative impacts, such as fires, floods, landslides, or tsunamis;
- Mass wasting: landslides that often result from the incidence of other hazards such as earthquakes, volcanic eruptions, etc. The latter are associated with extreme precipitation that forms debris or sludge flows at high speeds [20];
- Volcanic eruption: the most vulnerable areas are in southern Europe, but mainly in Italy, Greece, the Canary Islands, and the French Antilles [20].

4.2.3. Human-Induced Hazards

- Excessive land use: This process, resulting from the continuous demand for resources and space, is related to an immense urban growth that endangers CH and cultural landscapes [26]. Moreover, deforestation processes can promote the incidence (even in urban contexts) of events such as landslides or droughts;
- Pollution: The process results from gaseous pollutants that can directly or indirectly affect the quality of heritage sites. Among the effects of these substances, reference is made to chemical change or dry deposition on stone materials and crusts, resulting in loss of integrity and aesthetic value of the heritage element [27,28].

4.2.4. Biological-Related Hazard

In the degradation processes of CH, it is essential to consider that specific metabolic activity related to living organisms is capable of creating potential structural impacts in the composition of places and related processes of material transformation resulting from biological growth [21]. This biotransformation occurs, to a greater extent, in environmental conditions more suitable for biological growth (warm or humid climates). Among the main types of impact are those physical, chemical, and aesthetic that depend on the extent of the organisms involved, the type of material affected by the action of infestation, the environmental conditions at the boundary, and the presence of pollutants [29]. Although in some cases certain organisms contribute, through mineral dissolution processes, to particularly pleasant aesthetic effects, in many cases, weeds and plants can cause physical damage even of great magnitude with fracturing processes that go up to structural collapse [30].

4.2.5. Drivers of Deterioration (Stressors)

In addition to the previously explained hazards affecting CH, there are a number of additional factors that limit the ability of the heritage system to respond effectively and resiliently to external disruptions by accelerating, in some cases, the processes of deterioration. Such factors defined as "drivers" or "stress factors" can be explained as follows [5,6]:

- Lack of awareness of CH values: In environmental disaster situations, CH management is left in the background of the actual response to the emergency situation. These issues could result in a lack of support from the institutions, which is essential to ensure adequate capacity and funding for post-emergency recovery;

- Shortage of economic resources at the administrative level: at a time when CH protection strategies are not a priority in administrations, the availability of conservation resources (economic, technical, or human) may be compromised, entailing the abandonment of the heritage itself;
- Lack of data: A fundamental challenge for the protection of CH relates to the acquisition and cataloging of the basic information and the relative data status of the heritage. There is an insufficient number of updated inventories, georeferenced data on heritage sites and their boundaries, hazard maps, and other relevant resources [31].

5. Critical Review

Systematization of Methodologies for Developing Tools and Indices for Climate Vulnerability and Risk Assessment

This section identifies, through a review of the current panorama of the scientific literature, the main methodologies, and strategies for defining indices and measurement criteria for vulnerability and climate risk for tangible CH.

In order to identify effective mechanisms for CCA and disaster management, the first aspect to consider is the concept of risk assessments. The opportunities to build and maintain local resilience, however, are being reduced due to the limitation, by decision-makers, of actions oriented to the knowledge and understanding of the risk to which the historical heritage is subject. Risk assessments in the literature are focused on exposure isolated from vulnerability or adaptive capacity. Where vulnerability is included, there is no coherent definition [9], highlighting that the most frequently used methods do not consider interactions, albeit minimal, with local community values, experience, and knowledge. It is, therefore, relevant that future climate risk frameworks will need to consider community values to understand the role of CH in relation to adaptive capacity, vulnerability, and resilience.

For the relevant role of monitoring local data to preserve CH from climate aspects, Carroll and Aarrevaara [32] propose an Urgency Rate Index based on an analysis of local climate factors contributing to the degradation of CH buildings and facilities. Specifically, this work proposed a method to gather data on how to focus the conservation resources of any CH site based on an urgency rate index with a rating scale (1 to 10) that can be applied to different categories of CC.

The scientific literature on this topic highlights the importance of basing long-term strategies to adapt to CC on risk assessment, monitoring processes, and adaptation measures. Because concrete constructions are characterized by a higher degree of uncertainty, it is necessary to conduct long-term monitoring of the real impact of CC to better understand its effects on historic buildings [4].

As already stated, monitoring is a key action to observe and analyze decay processes, providing reference data for simulation models, guiding decisions on adaptive or remedial activities, raising consciousness among property owners, managers, and residents, as well as obtaining political and economic support at all scales [32,33].

From research data on prior conservation monitoring, moving on to climate and mathematical modeling of the material components for the assessment of CC, Loli, and Bertolin effects [5], through the experience of the project funded by the European Union (EU) Climate for Culture (CfC) [34], propose multiple risk scenarios of CC on building materials, through an adapted version of the risk assessment method developed in the project. The method aims to select the appropriate adaptation intervention for historic buildings. The authors establish a connection between the factors of climate-induced decay, which include the description of mechanical, chemical, and biological decay on various building materials and structures, and the capacity of buildings to change due to their level of protection. As a result of the relationship between decay factors and the level of protection of the building, the result represents an indicator of the appropriate level and timing for the intervention for CCA. Compared to the study of these variables, Ciantelli et al. [35] have integrated forecasting models to investigate the different types of material decay that could occur in the future. In particular, the following critical points in a future scenario (2039–2068) were indicated by all the considered functions: increase in surface recession, accumulation of biomass and dissolution cycles, and crystallization of halides, compared to the past (1979–2008).

As far as control is concerned, the level of active involvement of institutions in the protection of CH is an important issue to examine and consider. Using semi-structured interviews, Sesana et al. [36] examined the perceptions of experts involved in CH management concerning CC risk adaptation. The work systematizes and provides information related to adaptation (opportunities and barriers), together with requirements for preparation and future strategies for CH protection contextually to CC.

With regard to the objectives of this research, in addition to the analysis of the revised literature, it was fundamental to deepen the international project experiences related to these issues necessary for the construction of a basic framework for the definition of the partial results of this study.

These include the FP6 project Noah's Ark, which produced a Vulnerability Atlas and operational references for CH protection against risks due to extreme weather events typical of CC. Further research was carried out under the Climate for Culture Project of FP7 in the period 2009–2014 to evaluate the slow ongoing impacts of CC rather than extreme events.

Other experiences are related to the project HERACLES-H2020 Heritage Resilience against Climate Events on Site (2016–2019), which, through a multidisciplinary approach, promoted solutions or systems for effective resilience, and the project H2020 STORM (2016–2019). The preservation of CH through technical and organizational management has collected a number of non-destructive methods of detection and analysis to improve projections for future implications of CC on CH.

The first results of the KERES project [37] focus instead on the impact of future extreme climatic events on the built heritage (as well as on historic gardens but not relevant to the current study), highlighting the importance of the use of climate information for the sustainable conservation of CH. The prerequisites of the research are based on the desire to use climate simulations from which the climate parameters required for the needs of CH will be generated. High-resolution climate data and additional monitoring data, captured with sensors, are systematized on a knowledge platform developed to support CH institutions in emergency prevention and management. The climate dataset, as well as input for modeling and building simulation tools for a better understanding and assessment of the risk potential of damage to historic buildings, is the basis for establishing sustainable preventive and emergency measures.

The proposed methodology guides climate scientists on how to better adapt climate information to the needs of CH stakeholders and could help stakeholders integrate climate projection results into emergency prevention and management, in particular for the risk assessment of extreme events.

With respect to the theme of CH adaptability, Philips [38] proposed the concept of the adaptive capacity of CH sites under CC impacts. In light of this definition, it is possible to describe the key factors that determine adaptive capacity as follows:

- Learning ability;
- Space for autonomous change;
- Access to resources;
- Leadership in an institution.

On the basis of these findings, the concept of adaptive ability has been divided into six different factors: resources, access to information, authority, cognitive factors, learning skills, and leadership.

This working methodology identifies a broader scope where the need to combine risk assessment with other skills to successfully manage CH under CC is highlighted.

In the implementation of planned maintenance and preventive conservation programs, risk assessment has, therefore, become the most widely applied methodology, as it simplifies the integration of all available knowledge and its operational rationalization. In order to adequately prioritize future risk treatment strategies, the risk assessment must be able to integrate information on both sudden and slow events [7,9].

The vulnerability assessment of a site is definitely linked to its structural and material characteristics, which outline scenarios on how the site will respond to the different threats that face it. In order to take these variable responses into account, a vulnerability analysis must consider the complexity of aspects, including not only the materials used and their respective resistance to different stress factors but also how these materials will work as a whole and how this structure will withstand the impacts to which it is exposed.

In relation to this, the very concept of vulnerability attempts to overcome the mere ability of the heritage system to cope with the potential consequences of natural hazards while referring to strategies related to the adaptation and mitigation of the effects of CC. For this reason, the literature shows that, for CH, the methods of assessing climate vulnerability focus mainly on considering structural factors and modeling potential impacts [39], whereas only a small part also addresses the non-structural aspects of institutional factors [36,39]. Recognizing this challenge, integrated approaches that incorporate both factors (structural and non-structural) are needed to define a more detailed vulnerability assessment for CH.

On the concept of vulnerability, Ravan et al. [40] conducted a study to contribute to an integrated assessment framework for heritage sites exposed to multiple hazards, providing a specific vulnerability index. By determining the Cultural Heritage Vulnerability Index (CHVI), the author incorporates structural and non-structural factors in the vulnerability assessment procedure, demonstrating how the results are channeled directly into the decision-making process to determine the priorities and climate risk mitigation measures to be prepared. This methodology provides for an assessment of the vulnerability factor in relation to multiple hazards and risk management at the site level.

Vulnerability is a key component in determining risk reduction and CC adaptation strategies, as demonstrated and discussed by many scientific studies [41] and highlighted by the important connections between the two important factors: disaster risk associated with natural hazards and CC effects.

Three main standardization schemes for vulnerability assessment can be distinguished: vulnerability matrix, vulnerability index, and vulnerability curves [42,43]. According to Zschau 2017, a vulnerability matrix is a table that links the expected levels of damage to certain danger intensities, where the results can be represented in qualitative or quantitative terms. In parallel, a quantitative method for vulnerability assessment is provided by vulnerability curves.

Tarbotton et al. [44] defined empirical vulnerability functions as "*a continuous curve associating the intensity of the hazard (X-axis) to the damage response of a building (Y-axis)*", which only takes into account the structural damage component. This methodology adopted the vulnerability index to assess the vulnerability factor of the tangible entity of CH. The strength of this study lies in the ability to integrate multiple factors that can influence the vulnerability level of a numerical system that defines the Cultural Heritage Vulnerability Index (CHVI). This index comprises the following two main components:

- Susceptibility or sensitivity: this depends on the physical characteristics of the reference site and also on the structural performance with which the reference site can withstand the external effects of natural hazards;
- Adaptability: this refers to the institutional capacity of systems to cope with risk conservation and management at local and national levels.

This framework defines a multi-scale vulnerability assessment, from the scale of the site to that of the single artifact. It also sets out an aspect related to the different levels of competence at the level of adaptation strategies at the regional and national levels. The results highlight the determinants to be implemented in the field of CH to cope with the effects of CC, paying particular attention to incorporating vulnerability and risk reduction strategies into local policies. In doing so, the adoption of this scoreboard, together with relevant indicators, will facilitate the integration of CH into risk management and CCA plans at local and national levels.

Another fundamental study was carried out by Forino et al. [45], who reported the Cultural Heritage Risk Index (CHRI), which establishes a scoring scale (1 to 10, where 1 represents the absence of risk and 10 represents the maximum loss of assets and the highest level of risk for CH) suitable for the risk assessment for the capital system. This index was defined in order to be applied to sites with specific characteristics, initially requiring three categories of preliminary analysis: hazard, exposure, and vulnerability. From the analyses mentioned above, the results, suitably combined, are then subjected to a risk investigation in order to obtain the real result.

Another crucial aspect is modeling different types of environmental hazards linked to disaster risk reduction (DRR) and disaster risk management (DRM) to diminish disasters, such as impacts resulting from the most devastating effects of CC. In relation to this aspect, the Hyogo Framework for Action (HFA), introduced in 2005 as an international model capable of strengthening the resilience of nations and communities to disasters and natural disasters (Hyogo Framework), became a fundamental mention [17]. To this end, the strategy sets out five different priorities for action linked to the strengthening of national and local priorities linked to institutions, a more aware use of knowledge on the issue of risk, innovation, and education in support of culture and resilience, minimizing risk factors and increasing the response of nations to disasters at all levels to decrease negative impacts.

In relation to this analysis of the current literary landscape, it has been fundamental to rationalize, according to the partial results of this research, the data from some of the previously found and deepened indexes. The results of this critical process are shown in the table below (Table 1).

Table 1. Systematization and comparison of climate vulnerability indices [32].

Index Denomination	Measurement Criteria	Ranking Criteria/Score	Performance/Indicators
Urgency rate index	Data monitoring (future prediction)	Scale from 1 to 10: • 1: mild or minor perceivable long-term effect (100 years or more); • 3: major perceivable long-term effect (50–100 years); • 5: mild or mi-nor perceivable short- to mid-term effect (1–50 years); • 10: major short- to mid-term effect.	Calculating urgency rating according to specific climatic data. e.g.,: For warmer climate (CC category of application) measured in °C/year, the effects are: • Freeze–thaw damage; • Rust; • New fauna–pests. These effects affected specific materials/structures: • Stone brick; • Metal; • Wood brick.
Cultural Heritage Vulnerability Index (CHVI)	Vulnerability	Scale from 1 to 3: • 1 (low); • 2 (medium); • 3 (high).	Calculating the Vulnerability Index according to the score assigned to a specific component (e.g., walls, foundations, roof, materials, decorative elements, etc.) related to a specific indicator (e.g., quality of construction, type of ground/foundation soil, material detachment, etc.).
Cultural Heritage Risk Index (CHRI)	Risk	Scale from 1 to 10: • 1: No risk to the CH asset requiring no action to be taken; • 5: Moderate risk to the CH asset some monitoring would be required in case the risk was to increase; • 10: The greatest risk of loss of the CH asset requiring urgent action to prevent loss.	Calculating Risk Index according to specific analytical steps: • Hazard analysis (score 50); • Exposure analysis (score 20); • Vulnerability analysis (score 30).

6. Prospective Findings

In order to assess the susceptibility of CH buildings and structures to CC, it is crucial to take into account a wide range of indicators that may effectively reflect the various consequences of CC on tangible cultural assets. Multiple studies have emphasized the necessity of conducting vulnerability assessments and implementing adaptation methods in order to save cultural assets from the effects of CC [3,4,36,46,47]. The evaluations should encompass both the structural and non-structural aspects of the heritage site, together with its local and national contexts [40]. Additionally, it is important to take into account the ability to adjust, susceptibility, and ability to recover CH in response to CC [9,48]. The effects of CC on cultural assets extend beyond gradual temperature shifts and encompass abrupt alterations in the natural physical surroundings, such as storm surges, floods, landslides, and rising sea levels [3]. Furthermore, the recognition of non-climatic elements contributing to the vulnerability of cultural sites highlights the importance of adopting a comprehensive approach to assessing vulnerability [49].

Furthermore, in the face of CC, it is necessary to identify obstacles and devise solutions to overcome them in order to save cultural assets [47,50]. Incorporating community-scale values and traditional knowledge into climate risk frameworks is crucial for strengthening adaptive capacity and resilience [9,51]. Moreover, it is essential to monitor and manage human pressures on coastal CH and CC and natural risks to guarantee the enduring preservation of CH places [52]. The significance of conducting long-term monitoring of CC effects on historic buildings and interiors has also been stressed as a tool to evaluate susceptibility and provide information for adapting solutions [53].

The criteria used to assess the susceptibility of CH buildings and structures to CC should adopt a comprehensive approach that takes into account several dimensions, including both slow and abrupt CC effects, non-climatic elements, the ability to adapt, and the values of the local population. The determination of these indices should be based on thorough vulnerability assessments, the use of long-term monitoring approaches, and the implementation of policies to address obstacles to adaptation.

For these reasons, the proposal of this work is to consider a set of indices as a benchmark to measure climate vulnerability on CH buildings and structures. To this purpose, it is necessary to discriminate between *midpoint indexes*, which typically represent the average effect of a stressor across different spatial scales or temporal periods, and *endpoint indexes*, which consider the comprehensive and combined effect of midpoint indicators. Among the most representative endpoint indicators, the *damage index* has been selected. Its identification, as well as its definition and quantification, is strictly related to three main factors:

1. Environmental conditions;
2. Material properties;
3. External drivers.

In accordance with those impacting factors, the main *midpoint indices* that actively concur to define the damage index have also been identified. Among these, the deterioration index, carbonation index (relative to the reference substrate), efflorescence index, and corrosion index of metal elements have been selected.

For each index, a *procedural protocol* has been implemented for their quantitative definition, as depicted in the following diagram (Figure 5).

PROCEDURAL PROTOCOL		
	STEP	EXPERIMENTAL APPROACH
1	Identify Damage Factors	Identification of the key factors that contribute to the alteration of buildings or structures
2	Assign Weight to Factors	Assignment of weights to each deterioration factor based on its significance and potential impact on the building's condition. The weighting should reflect the relative importance of each factor in determining deterioration. Consult with experts and stakeholders to determine appropriate weights
3	Data Collection and Standardization	Gather data for each degradation factor. Data sources may include building inspections, maintenance records, construction documents, architectural assessments, and historical records. Standardize the data to ensure that all factors are on a common scale, making it possible to compare and combine them
4	Normalize Data	Normalize the data for each deterioration factor to bring it to a common scale (e.g., from 0 to 1). Normalization is essential when factors have different units or scales. Common normalization methods include min-max scaling or z-score normalization
5	Calculate degration Scores	Multiply each factor's normalized value by its assigned weight to calculate a deterioration score for that factor. Repeat this process for all deterioration factors
6	Aggregate Scores	Sum the deterioration scores for all factors to obtain an overall deterioration score for the building or structure. This overall score represents the degree of deterioration
7	Interpretation and Classification	Establish thresholds or categories that help classify the deterioration scores. For example, you could create categories such as "excellent," "good," "fair," "poor," or "critical" based on predefined ranges of scores
8	Monitoring and Periodic Assessments	Implement a system for regular monitoring and periodic assessments of the building's condition. Update the deterioration index as new data becomes available to track changes over time
9	Sensitivity Analysis	Conduct sensitivity analysis to assess how changes in weighting or data inputs affect the deterioration index. This helps evaluate the robustness of the index
10	Validation and Calibration	Validate the deterioration index by comparing it to observed deterioration in the field, if possible. Calibrate the index based on the observed data and feedback from experts and stakeholders
11	Documentation	Document the methodology, data sources, and assumptions used in developing the deterioration index. Transparent documentation is essential for the credibility and replicability of the index

Figure 5. Schematization of the procedural protocol. Elaboration of the authors.

The accomplishment of each specified step is essential to provide precise and reliable identification of the damage index for both qualitative and quantitative assessments. Moreover, alongside some of the reported steps, the individuation of analytical instrumental techniques is crucial to identify and characterize the type and degree of degradation in structures. These techniques provide non-destructive [54,55] or minimally invasive methods for examining materials and structures, allowing for a detailed assessment of their condition and any extent of damage or degradation. Among the non-destructive techniques, the portable X-ray fluorescence (pXRF) device is a non-destructive analytical instrument that uses X-rays to identify and quantify the elemental composition of materials in situ. In addition, with a microscopic sample of the substrate, different information can be detected by various analytical techniques, such as:

- Scanning electron microscopy (SEM), which utilizes a focused beam of electrons to image the surface and interior of materials at high magnification, providing detailed information about the morphology, composition, and microstructure of degradation;
- Energy-dispersive X-ray spectroscopy (EDS), which is an analytical technique coupled with SEM that identifies the chemical composition of materials by analyzing the characteristic X-rays emitted from the sample;

- X-ray diffraction (XRD), which provides information about the crystal structure and phase composition of materials, aiding in the identification of degradation mechanisms and the assessment of the extent of degradation;
- Infrared spectroscopy (IR), which measures the absorption of infrared radiation by materials, providing information about their molecular structure and the presence of specific chemical groups associated with deterioration processes;
- Thermogravimetric analysis (TGA), which measures the weight loss of a material as it is heated, provides information about its thermal stability and the release of volatiles or decomposition products that may be indicative of degradation;
- Differential thermal analysis (DTA), which measures the difference in temperature between a sample and a reference material as they are heated, provides information about the thermal transitions and phase changes that occur during decomposition or degradation processes.

In this contest, for the different selected midpoint indexes, the proposal of benchmark categorization is reported in Table 2.

Table 2. Set of indices as a benchmark to measure climate vulnerability on cultural heritage buildings and structures.

Index	Benchmark
Deterioration of surface	Monitoring the relative intensity of the diffraction of the principal phase
Efflorescence index	Intensity of crystalized salt
Carbonation index	Identification of carbonation product
Corrosion index	Determination of corrosion product

7. Discussion

The impact of CC on the built CH should be considered in the long-term management of historic buildings.

CC will require reevaluating most CH management methodologies, including inventory preparation, heritage value assessment, documentation and monitoring, impact assessments, vulnerability matrices, preservation management planning, risk assessment, vulnerability assessment, and adaptation planning. The key to all of this is the ability to assess climate risk, which must become a core competency for all those involved in heritage.

Despite risk analysis giving valuable information about the possible occurrence of damage to CH, vulnerability must be considered as one aspect in a wider context of managing cultural sites and buildings. The general Pilot Project, in which this study is located, aims to realize an open platform "phigital space" (physical and digital) of the type "user profiling" for the advanced and dynamic co-design of interventions on the built and ex novo. The Pilot Project has identified two historical centers of the Grecanica area, Bova and Palizzi (province of Reggio Calabria), as intervention scenarios for Southern Italy. So, the instrumental analyses described, which will be conducted in the coming months (second year of the research) on two historical centers selected, will contribute to the development of the set of indices specific to the analyzed context of the indicated historical centers, useful for implementing the platform. The conservative conditions and vulnerability processes will be developed, acquiring instrumental data from the historical public buildings of these two historical centers.

8. Conclusions

The proposed study identifies the main intermediate indices that actively contribute to defining the damage index. Among them, the deterioration index, carbonation index (relative to the reference substrate), efflorescence index, and corrosion index of metal elements were selected. The aim is to be able to establish indexes with a simple applicability, allowing them to be used through the protocol that has been developed for a variety of contextual conditions.

The next step that will characterize these partial results of the research will address the application of the identified steps of the procedural protocol using instrumental analytical techniques capable of identifying and characterizing the type and degree of degradation of the structures. In turn, this experimental phase will allow us to provide specific data on possible different case studies, validate the applicability of established indexes, and finally make the defined benchmarks effective.

With regard to the field of applicability of this experimental investigation, the research will move toward the analysis of historical architectural heritage and public properties protected and regulated by the Code of Cultural Heritage, Legislative Decree 42/2004.

The multidisciplinary nature of the study highlights an added value with respect to the implementation of technical/scientific knowledge levels that may relate to the connections between CC effects, CH, materials, and instrumental validations.

Author Contributions: Conceptualization, F.G. and P.F.; methodology, F.G.; validation, P.F. and A.M.; investigation, F.G. and P.F.; resources, F.A.; data curation, A.M.; writing—original draft preparation, F.G. and P.F.; writing—review and editing, F.A.; visualization, A.M.; supervision, F.G. and P.F. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the National Recovery and Resilience Plan (PNRR), Mission 4, Component 2 Investment 1.4, funded from the European Union—NextGenerationEU for the realization of Innovation Ecosystem Tech 4 you "Technologies for climate change adaptation and quality of life improvement", Pilot Project 4.7.1—Open platform "phigital space" (physical and digital) of the type "user profiling" for the advanced and dynamic co-design of interventions on the built and ex novo (Project code: ECS_00000009, CUP: C33C22000290006).

Informed Consent Statement: Not applicable.

Data Availability Statement: Dataset available on request from the authors.

Acknowledgments: We acknowledge, for the support and the use of material, Consuelo Nava, Mediterranea University of Reggio Calabria, Italy, scientific responsible for the Pilot Project 4.7.1—Open platform "phigital space" (physical and digital) of the type "user profiling" for the advanced and dynamic co-design of interventions on the built and ex novo; in spoke 4 "Safeguarding and enhancing the natural and cultural heritage and identity of the territories—Technologies for resilient and accessible cultural and natural heritage" of the consortium Innovation Ecosystem Tech 4 you "Technologies for climate change adaptation and quality of life improvement" supported by the National Recovery and Resilience Plan (PNRR), Mission 4, Component 2 Investment 1.4.

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

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