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Climate Change Threats to Stone Cultural Heritage: State of the Art of Quantitative Damage Functions and New Challenges for a Sustainable Future

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Abstract: Climate change effects are a warning of the planetary crises threatening our collective future. This is a topic largely considered in the context of the environmental crisis, but we are now aware that climate change represents an increasingly alarming threat also in terms of the conservation of cultural heritage sites. Cultural heritage preservation should aim to an active environmental and societal strategy built on a renewed ethics of responsibility on long-term effects. This work provides a review of the current state of the art on the damage functions used for assessing the impacts of climate change on stone heritage surfaces. Within this framework, it introduces new concepts such as (i) the Loss of Details (LoD), in terms of the readability reduction of decorative elements and, subsequently, (ii) the Future Cultural Value (FCV), as the capacity of a cultural heritage to transmit its cultural message in its future appearance. The valorization of the historical legacy is a win–win solution to fix new planning tools and to achieve multiple goals oriented to a sustainable development for future generations. From this point of view, plaster cast galleries and museums play a crucial role in preserving cultural identity since they report a careful documentation of the original artifacts and monuments over the time.

Keywords: cultural heritage; climate change; sustainability; carbonate rocks; stone decay; 3D reconstructions

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1. Introduction

The maintenance of cultural heritage preserves genuine culture and guarantees well-developed nation psychology [1]. Climate change and its consequences are becoming mandatory issues to be tackled by international and local authorities in charge of risk assessment and responsible for taking actions to mitigate their effects: this is true not only with regard to the environment, but also with respect to cultural heritage. Indeed, the combined action of natural weathering agents (e.g., rainfall, fog, snow, or salts) and atmospheric pollutants derived from anthropogenic activity drastically changes the material–atmosphere interface, causing the loss of the surface material and, consequently, the loss of its aesthetic quality [2–6].

The presence of atmospheric CO_2 plays an important role in the weathering process and it is the cause of carbonate stone dissolution [7–9], while SO_2 can react with $CaCO_3$ to form gypsum ($CaSO_4 \cdot 2H_2O$), causing the common decay pattern characterized by a succession of "black crusts" in sheltered areas and white colored areas on surfaces exposed to rainfall (washed areas) [3,10,11] (Figure 1a,b). The dissolved HNO_3 significantly raises carbonate solubility, increasing specific surface and stone porosity, thus widening the interface where surface interactions (and consequently deterioration) operate between the material and the surrounding environment [9,12–15]. In environmental conditions where temperature can drop below freezing and where airborne salts (e.g., from sea spray) are present, strong decay occurs due to the overpressure generated in pores by the crystallization of ice and salts, respectively [9,16,17] (Figure 1c–e). Wind erosion also is one of the most relevant causes of degradation which affects building surfaces in cultural heritage (Figure 1d). Moreover, when decay processes are taking place, stone materials become a favorable environment to the biological growth of various living organisms (fungi, algae, and cyanobacteria in the most sheltered areas, and superior plants in the most exposed areas) [18,19] which colonize the surface and subsurface of the buildings' façades, monuments, and statues (Figure 1f,g), causing biodeterioration. In general, the deterioration rate is closely linked to the environmental conditions as well as the atmospheric composition, and is obviously dependent on the specific physical and chemical features of the exposed material. On areas exposed to rain wash out, loss of material, in terms of the recession of the surface, can occur. This process mainly affects carbonate stones, marbles, and limestones, which historically are the most used as ornamental stones. The recession rate is related to the local microclimate conditions (e.g., the abundance of rain, rain drop size, rain pH, and temperature), but also to the local exposition (cardinal orientation and the presence of other buildings or elements which protect parts of monuments from rainfall or intense solar radiation) and the surface geometry of the manufact. Indeed, since the wash out is dependent on the water that can flow over the surface and the time of wetness, local exposition and surface geometry are two crucial factors in controlling recession rate.

Figure 1. Black crusts developed on areas protected against direct rainfall or water runoff: details of (**a**) the Benedictine Monastery of San Nicolò l'Arena in Catania (Italy) and (**b**) the Carmo Church in Lisbon (Portugal). Differential erosion and alveolization due to wind and salt effects (**c**) in a statue in St Mark Square in Venice (Italy), (**d**) in a portal on the Street of Knights in Rhodes (Greece), and (**e**) in an historical building in Valletta (Malta). Biological growth (**f**) in the church of San Pietro in Tuscania (Italy) and (**g**) in a statue in Turin (Italy).

With the weathering of stones being an inexorable process, developing mathematical models to simulate the rate of deterioration as a function of measurable environmental parameters and stone properties is increasingly needed in order to predict (and so control) future scenarios.

The implementation of dose–response functions, system modelling, and the quantification of the effects of climate events are key tools in order to identify resilient solutions in multi-hazard risk circumstances: consequently, they are essential in developing holistic sustainable mitigation plans providing prevention measures to preserve the historical built heritage [20–22]. In adaptation strategies, vulnerability is often assessed on a large scale (e.g., regional or local), and therefore historical buildings and monuments are often not properly considered. Nevertheless, any heritage building should be viewed in terms of its own history of deterioration and its own history of treatments and restoration. A number of researchers have focused on measuring and modelling the degradation on safety-critical elements, such as the collapse of historic retaining walls, the destruction of masonry by the washing out of joint mortars, or the saturation of materials, with water causing a wide variety of actions and damage (volumetric changes, chemical weathering, and the loss of load capacity) which can severely impair the structural integrity of the building. However, the preservation of monuments as expressions of our identity is also strictly dependent on the preservation of their surface topography, namely, the "skin", hosting details in its morphometry which makes a monument different from others in a specific context. Considering that the air quality has changed and is changing over time, the analysis of the interaction between surface heritage materials and the environment can be considered one of the most relevant current topics for the scientific research aimed to safeguard cultural properties. The surface recession produced by this recession poses threats not only at a cultural level but also in terms of safety and cost to properly maintain cultural legacy for the future. In this regard, the assessment of environmental risk factors of a territory is a key element to assess heritage conservation. Indeed, it is an essential activity in order to identify monuments exposed to the greatest deterioration in order to plan priority maintenance interventions and to reduce the intensity of decay. In this view, the management of historical areas requires new approaches, which consider all the elements, including decorations, as part of the urban environment [23].

With the 2030 Agenda (United Nations, 2015) and, specifically, with the Sustainable Development Goal 11 (SDG 11), countries have pledged to "make cities and human settlements inclusive, safe, resilient and sustainable" [24]. Target 11.4 aims to "strengthen efforts to protect and safeguard the world's cultural and natural heritage", emphasizing the role played by education, science, and the conservation of natural and cultural heritage in a sustainable development. Since the Brundtland report (United Nations, 1987), also known as "Our Common Future", the idea of sustainable development has been based on the principle of conservation. Attempting to understand the interconnections between social equity, economic growth, and environmental degradation, the concept was envisioned to develop integrated solutions [25]. Nowadays, we are called to reform the sustainability concept relying on the three strongholds of the preservation of our culture: mitigation systems, adaptation, and resilience. When we say that the maintenance of cultural heritage preserves genuine culture and guarantees a well-developed nation psychology toward a constructive cooperation, that is because "the human identity presupposes the identity of a place" [1]. In a world that constantly changes, the gradual loss of references is one of the most recurrent themes. The same is true with specific regard to the management of historical legacy, where the pressing issue is cultural heritage deterioration. In this context, a question arises: how to navigate this change? This question can be answered focusing on planning cultural heritage conservation, cultural landscape valorization, and the conceptualization of cultural values. Prevention, as a matter of fact, has a fundamental documentary role in guaranteeing cultural heritage integrity for the future. Although material degradation cannot be avoided, the knowledge of environmental and climatic context can support appropriate choices to better protect heritage in the future and slow down the weathering process. The physical place of heritage (location and microclimate) becomes crucial in relation with the immaterial meaning of heritage (collective memory and cultural identity). Cultural identity is influenced by the environment and is reflected in the functional bonding between places, people, and heritage. The surfaces of historical monuments hold tangible elements, in their geometry and details, which hold intangible phenomena: based on this combination, heritage becomes a meaningful vehicle for cultural and educational purposes. This work provides a state of the art of the current understanding of climate change effects, in the short and long term, through the quantification of the recession rate: an approach contributing to identify resilient solutions in multi-hazard risk circumstances. Furthermore, it also provides recommendations for further studies in order to consider disregarded aspects, such as the assessment of the loss of material in terms of the deprivation of cultural message readability for the future. Fighting the Loss of Details (LoD) leads to an increase in the sense of belonging within the territory and thus is an issue to take into account in order to build a more sustainable society. For these purposes, plaster cast galleries and museums are crucial for cultural value preservation and therefore the well-being of future generations. Historical replicas of monuments (with a known date of production) hold outstanding 3D pinpoints for determining and quantifying the surface recession rate in comparison with the current state of conservation of original monuments outdoors. In this view, digital imaging technology can offer useful tools to study differential decay according to exposition and 3D surface morphometry.

2. The State of the Art: A Literature Review

In the past 40 years, various researchers have tried to assess and quantify the degradation phenomena of stone materials imposed by climate change, considering changes in their surface topography (recession rate) and/or loss of material (e.g., desegregation or detachments). This activity was intended to make sound projections on cultural heritage preservation. A large part of these contributions was aimed to test the decay of carbonate rocks under specific environmental conditions, reproducing, as closely as possible, the chemical characteristics of natural rainfall [26], often using environmental test chambers in order to simulate natural conditions [27].

The main environmental parameters considered in dose–response functions are (i) the concentration of specific pollutants in the atmosphere, (ii) $[H^+]$ concentration in rainwater, (iii) rainfall, and (iv) temperature. Several static and dynamic mathematical models were refined to describe surface changes over time and at any point in time. Many authors tried to assess degradation phenomena by considering changes in surface recession using micrometers [28–30] or calipers [27,31]. Other authors tried to assess the effects of environmental parameters (pollutants, rainfall, humidity, temperature, and petrographical features) using climate chamber simulations and defining damage functions [27,32–41]. There are very few examples of true long-term (up to 30 years) observations of stone surface erosion [30,42]. In terms of air pollution and particulate matter (PM), the damage functions are mainly defined as the effect of the concentration of pollutants combined with other environmental factors ([6], and the literature therein). Qualitative weathering models based on the morphological evolution or damage indexes were introduced to assess the stone deterioration process [43–45]. In recent years, 3D modeling has proved to be an innovative tool for understanding surface morphology [44,46,47], but until now all approaches have been mainly qualitative.

In Table 1, the main equations that have been proposed for describing surface recession or loss of material are reported. Lipfert [33] identified in dissolution, air pollution, and acid rains the three main factors of damage for limestones. He set the Lv (Lipfert value) at 18.8 $\mu m \cdot m^{-1}$ (microns of recessed surface per meter of precipitation), based on the solubility of calcite in equilibrium with 330 ppm of CO_2, and quantified the loss of material as annual surface recession per meter of precipitation. Reddy et al. [32] normalized the annual surface recession as annual rainfall, while Baedecker et al. [36] designed another equation to define the material loss based on the combined effect of temperature and the concentration of hydrogen ions.

Webb et al. [35] estimated the weight loss of material per unit surface considering the influence of various pollutant agents, rainfall, and acid ionic concentration. Other authors considered the time of wetting (TOW), the period of time when the relative humidity is higher than 80% and the temperature is above 0 °C, as an important parameter to study the degradation effect due to the presence of water. Kucera and Fitz [37] derived a new equation of the total loss (expressed in g/m^2) based on run-off tests (which lasted 4 years), while the surface recession of marble (per meter of rainfall) was modeled with field measurements by Yerrapragada et al. [38], and it was found that the loss of surface due to the impact of rain droplets was seven times greater than that caused by black crust formation. Delalieux et al. [39] modified previous equations in order to express the material loss as a linear recession measured in microns, and defined a new equation considering five different locations, collecting more than 30 thousand data over three years of measurements, and interpreting them using regression mathematical models in order to identity the significant variables to implement in the functions. Lan et al. [40] studied the effect of stone exposition to sheltered and unsheltered environments after on-site experiments.

Table 1. Recession rate equations from the previous literature with a brief note on the material considered, the calculated parameters, and the input data. Legend: Materials ("Mat", abbreviation in table): M = Marble; PL = Portland Limestone (limestone <25% pores); SL = Limestone; VS = Volcanic Stone; B = Brick.

Equation	Mat	Input Data	Parameters	Ref.
$\frac{\text{loss }(\mu\text{m})}{\text{rain }(\text{m})} = 4.88 + 0.0015\ H^+ + 0.069\ SO_2$	M	SO_2 and H^+	Annual surface recession normalized to annual rainfall.	[30]
$\frac{\text{loss }(\mu\text{m})}{\text{rain }(\text{m})} = 18.8 + 0.016\left[H^+\right] + 0.18\ (Vd_S \cdot [SO_2] + Vd_N \cdot [HNO_3])/R$	PL	CO_2, SO_2, HNO_3, H+ rainwater, and time	Surface recession rate per meter of precipitation	[33]
$\frac{\text{mmol } Ca^{2+}}{\text{L}} = 0.16[1.0–0.015\ T + 0.0000922\ T^2]/0.683 + 0.49\ [H^+]$	LS	Effects of (T) and concentration of H^+ ions	Material loss (mmol/L of Ca^{2+} ions).	[36]
$\frac{g}{m^2} = -0.162 + 0.0058\ SO_2 + 0.0666\ R + 638\ \text{acid} - 0.026\ NO_2 + 0.0155\ NO + 0.0007\ O_3$	LS	SO_2, NO_2, and rainfall R in m/yr	Weight loss of material per unit surface	[35]
$\frac{g}{m^2} = 34.4 + 5.96\ [TOW] \cdot SO_2 + 388\ R \cdot [H^+]$	LS	Time of wetting (TOW), SO_2, NO_2, and rainfall R in m/yr	Weight loss of material per unit surface	[37]
$\frac{\text{loss}(\mu\text{m})}{\text{rain}(\text{m})} = \frac{0.1}{R} \cdot (34 + 6.0\ [TOW] \cdot SO_2 + 390\ \left[H^+\right] \cdot R)$	LS	Time of wetting (TOW), SO_2, NO_2, and rainfall R in m/yr	Material loss measured in microns	[39]
$\Delta m = 6.56 + 27.38\ H+ + (1.131 \cdot 10^{13} \cdot {C_{SO2}}^{0.7} \cdot {C_{NO2}}^{0.3}/V)\ t$	M	SO_2, NO_2, H^+ rainwater, and time	Surface recession rate per meter of precipitation	[38]
$\text{loss }(\mu\text{m}) = 3.95 + 0.0059\ SO_2 \cdot RH_{60} + 0.054\ R\ \left[H^+\right] + 0.078\ HNO_3 \cdot RH_{60} + 0.0258\ PM_{10}$	LS	Temperature (T), humidity (H_{60}), SO_2, HNO_3, H^+ rainwater, and time	Annual surface recession in microns	[41]
$\frac{\text{loss }(\mu\text{m})}{\text{rain }(\text{m})} 9.4 \cdot \left[1.0 - 0.015\ T + 0.000092\ T^2\right] + 20\ [H^+]$	LS	Effects of (T) and concentration of H^+ ions	Material loss measured in microns, from [36]	[39]
$\frac{\text{loss}(\mu\text{m})}{\text{rain}(\text{m})} = \frac{150}{R} \cdot (-0.16 + 0.0020\ SO_2 + 0.18\ R + 1.7\left[H^+\right] \cdot R - 0.0013\ NO_2 + 0.0086\ NO + 0.0003\ O_3)$	LS	SO_2, NO_2, H^+ rainwater, and time	Material loss measured in microns, from [35]	[39]
$\frac{\text{loss }(\mu\text{m})}{\text{rain }(\text{m})} 9.4 \cdot \left[1.0 - 0.015\ T + 0.000092\ T^2\right] + 20\ [H^+]$	LS	Effects of (T) and concentration of H^+ ions	Material loss measured in microns, from [37]	[39]
$\frac{\text{loss}(\mu\text{m})}{\text{rain}(\text{m})} = \frac{0.015}{R} \cdot (-29 + 590\ R + 800\ \left[H^+\right] \cdot R + 5300\ [SO_4^{2-}] \cdot R + 5.5\ SO_2)$	LS	(R, m/yr), SO_2, H^+, and SO_4^{2-}	Material loss measured in microns	[39]
$\text{loss}(\mu\text{m}) = (0.00233\ RH \cdot SO_2) \cdot t + 0.00309\ R$ (unsheltered environments) $\text{loss}(\mu\text{m}) = (0.00111\ RH \cdot SO_2) \cdot t^{0.784}$ (sheltered environments)	LS	Total rainfall R (mm), exposure t (years), SO_2, and RH	Stone exposure to unsheltered and sheltered environments	[40]
$\Delta Ca^{2+} = \Delta SO_4^{2-} + 0.5\ \Delta N_3^- + 0.5\ \Delta Cl^{-Na^+} + 0.5\ \Delta Alk + \Delta Organics.$	LS	Difference in concentration SO_4^{2-}, N_3^-, Cl^-, Na^+, and organic acids	Effect of acid rain runoff and dry deposition on carbonate dissolution	[34]
$Yeq = ((DWL/\rho_{bulk})/S_{Total}) \cdot (t_{exp}/MRD)$	LM, VS	Loss of weight (DWL), stone density (ρ_{bulk}), total area of sample (S_{Total}), time (t_{exp}), and recession measured on monument (MRD)	Number of years of natural aging to achieve the same state of erosion with artificial tests	[38]
$UCP = \sum^{n}_{i=1} a_i \cdot cp_i$	B	UCP is defined by the combination of climatic parameters (cp_i = HR, T, salts, rains, . . .) and a_i is the weighting coefficient.	Recession is formulated as a linear combination of cp_i. It is defined a DED according to the cardinal exposition.	[47]

Kucera and his research group [41] investigated the effect of different pollutants on materials, including carbonate rocks, in the context of international exposure programs (MULTI-ASSESS Project 2007). They proposed a damage function for carbonate rocks, considering the increasing values of SO_2 and the increasing values of nitrates, HNO_3 and PM, due to the increase in vehicular traffic in recent decades in Europe. The results indicated that SO_2 is the predominant factor of decay in multi-pollutant areas. Livingston [34] calculated the acid neutralization path in the pH range 3.5–6 and the effect of dry deposition, describing material loss in terms of amount of Ca^{2+} ion released by the material, and applying the electroneutrality condition between the solution chemistry of rainfall and runoff. Martinez-Martinez et al. [17] analyzed stones in aggressive environments, counting the number of years of natural aging required to achieve the same state of erosion in the stone after artificial tests. Salvini et al. [27] studied selected Italian carbonate stones by simulating the wetting effect of rainwater in environmental chambers and demonstrated that a careful evaluation of petrographic features, such as grain size, porosity, pore-size distribution, and mineralogy (content of clay minerals, sulfurs, etc.) also has an important role in determining the surface recession rate.

On-site studies are very limited, and mostly qualitative. Some authors [46,48] proposed a different classification of deterioration patterns observed on monuments in order to perform stone damage diagnosis. Other authors proposed qualitative weathering models based on the morphological evolution during the deterioration process [49] or assessed stone damage using damage indexes [43,45,50]. Bonomo et al. [44] reported the on-site 3D decay mapping performed at the UNESCO site of Matera (Italy), proposing an approach based on image analysis and a quantitative classification of the natural mechanical loss of material, applying the Structure from Motion (SfM) technique, and classifying the morphometric features to the qualitative decay processes of alteration (from the ICOMOS-ISCS Atlas, 2008). In 2022, Vidović et al. [6] reported a critical review of the previous literature on the impact of air pollution and particulate matter on outdoor cultural heritage.

Recently, Hernández-Montes et al. [47] defined a parameter called the Unified Climatic Parameter (UCP), formulated as a linear combination of the climatic parameters affecting recession (e.g., rainfall, temperature, salts, freeze–thaw, and relative humidity), which allows researchers to assume quantitative recession for brick masonries over time with reference to a Deterioration Evolution Diagram (DED).

3. The Loss of Details (LoD) and the Future Cultural Value (FCV)

Despite the extensive literature on recession rate functions, currently there is no specific progress towards understanding and measuring short- and long-term climate change effects on cultural heritage preservation.

Recession measurements are considerably affected by the analytical procedure, the extreme variability of rainwater composition, and the time of exposure considered. Realistic exposition tests should be designed for much longer periods, at least 10 years, to assess meaningful recession estimates, since the rate of stone decay is relatively slow if compared to the standard times required by a scientific research project [30]. Moreover, most of the literature considers the recession rate on flat surfaces, neglecting the possibility of a differential decay correlating to different morphometry and geometry. Quantifying the loss of material considering the morphometric features proves, instead, to be fundamental with reference to cultural heritage since decorative elements, architecture, statues, and artefacts consist of many geometric shapes with different curvatures, sheltered/unsheltered areas, or jutting-out objects. Consequently, differential decay in relation to the surface geometry of the materials, also considering climate and environmental conditions (e.g., rainfall or wind direction) and cardinal expositions (south, north, etc.), is of the utmost importance and should be implemented (Table 2).

Table 2. Traditional modes' gap and new challenges to go beyond this gap.

Traditional Modes	New Challenges
Stone recession rate is usually considered on slabs, disregarding the morphological aspects.	Approaches to measuring surface changes should evaluate the differential effect of climate and micro-climate conditions on geometric features in stone recession.
Stone cultural heritage is considered for its intrinsic property while its cultural value is considered separately.	Cultural heritage is filled with details holding cultural messages. The differential loss of material should also be considered in terms of the quantification of Loss of Details (LoD), as an indicator of cultural identity preservation.
Studies are disconnected from the real environmental and urban context.	Monuments and historical buildings should be considered in relation to the real setting (connected with specific micro-climate conditions, urban environment, and orientation), and results should effectively support authorities in the adoption of strategies by formulating guidelines, providing a reliable damage assessment for sustainable management, and playing an active part in the transition towards more sustainable socio-economic models.
Reliable projections into the future are lacking.	New technologies (e.g., 3D reconstruction or digitalization) can make visual projections according to climate projections (IPCC) and estimate the Future Cultural Value (FCV) of the monuments, as their capacity of holding and transmitting their cultural message to future generations, increasing awareness and education for a resilient society.

Moreover, the recession rate is always evaluated as material deterioration in itself, disregarding the depletion and the quantification of loss of its cultural value (Table 2). Cultural heritage is the result of a radical transformation of material through human actions, increasing its intrinsic value as a result. Nowadays, the importance of this endosmosis process, thanks to which we recognize ourselves in the vestiges of the past, is becoming stronger as our cultural identity is affected by the impact of climate change. We recognize the urgency to implement sustainable strategies and to mitigate aggressive environmental conditions, not only for our environment's sake but also in order to avoid losing our cultural references. For this purpose, the protection of cultural heritage against climate change is a major concern for decision-makers, stakeholders, and citizens across Europe. This is the reason why one of the Sustainable Development Goals of the 2030 Agenda (United Nations, 2015) is also dedicated to the protection and safeguarding of natural and cultural heritage (SDG 11), towards Europe's increasing resilience to the impacts of climate change [24].

According to Brandi [51], cultural heritage has a value for the message it holds, and not for its material consistency. He distinguished a marble from a quarry as something that "was subjected to a radical transformation to be a vehicle of an image" [51]. Concerning heritage artifacts, indeed, the value of a material is not only that of its intrinsic properties but also the one that derives from its importance as a society image, or the epiphany of a society at a certain time in the past. Cultural identity, stored in cultural heritage, is formed by embryo-past successions (instants), in which monuments, buildings, and sculptures (expressions of ideas, feelings, and thoughts) found new life from creative actions and subsequences of stratification during time (Figure 2). Our perception of the past is formed by an accumulative memory and our present identity is developed by embryo-past successions conserved in cultural patrimony (duration). Duration is the preservation of instants of the past in the present, and it is coincident with our cultural identity (Figure 2).

In duration (= cultural identity), society recognizes all the attributes forming the present as by-products of past activity.

From this perspective, surface changes and the loss of materials in stone heritage, which are caused by the climate and atmospheric and environmental conditions, are not just aesthetic but become a loss of identity. In this sense, cultural identity increases in relation to our capacity to preserve details (for example, in decorative elements and/or reliefs), which hold the cultural message for future generations (Figure 3).

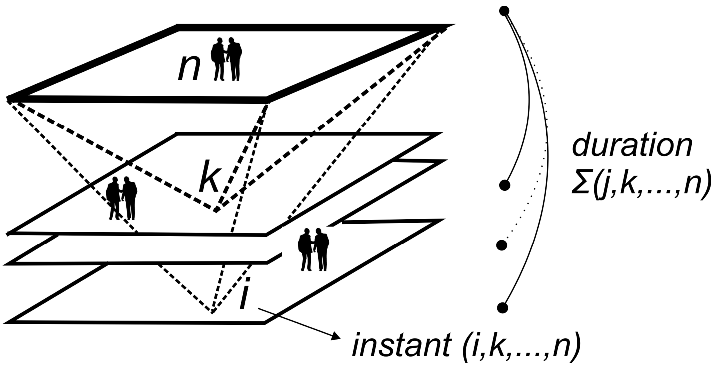

Figure 2. Cultural identity is the synthesis (duration) derived from the succession and sum of instants ($\sum(j, k, \ldots.\, n)$), which are the expression of human creative actions. Image modified by Bergson [52].

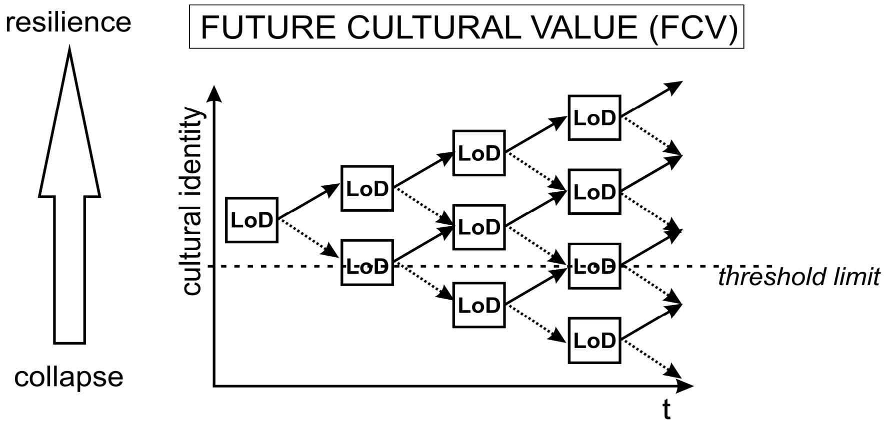

Figure 3. Conceptual scheme for cultural identity preservation based on the Loss of Details (LoD) for the maintenance of the Future Cultural Value (FCV) of heritage.

If we act in order to limit the Loss of Details (LoD) (black arrows in Figure 3), cultural identity can be preserved; on the other hand, if we do not direct our actions to stop the LoD (dotted arrows, Figure 3), cultural identity decreases. As cultural identity increases, resilience also increases. The threshold limit (horizontal dotted line, Figure 3) defines the point beyond which future generations could be deprived of the chance to receive the cultural message.

The future appearance of cultural heritage should be considered for this reason in terms of Future Cultural Value (FCV), that is, the future appearance after a certain period (e.g., 20, 50, 100, . . . years). The use of such a concept has a twofold consequence: the value derived from an external aspect, in terms of the maintenance of aesthetic qualities in the future; and the value derived from the representation of society, in terms of the maintenance of cultural identity for the future.

Today, more than ever, the human imprint needs regimentation and a rediscovered awareness of its influence on Earth. The reappropriation of the dose–effect interactions between humans and the environment is a unique opportunity to safeguard our identity and preserve it for future generations. The preservation of details in historical cultural heritage moves towards the improvement of the quality of life for the community and increases the sense of belonging within the territory. A collaboration between politics and research is fundamental in order to fix new guidelines for good practices for the purpose of increasing identity by means of resilience as well as decreasing habits and situations which impoverish territories and drive them toward collapse (Figure 3).

Viewed in this way, museums and historical documentations are meaningful in preserving cultural identity since they testify the aspect of monuments in past epochs. Many academies, museums, and plaster cast galleries conserve historical plaster casts of the

Mediterranean Area (Figure 4), which represent precious references to assess the process of decay during the time elapsed from the reproduction of the monuments, until their current state or until the moment of their relocation to museums. The practice of reproducing sculptures, architectural elements, and inscriptions from different cultures and periods in plaster originally dates back to the 16th century; however, plaster cast replicas were particularly used during the 18th and 19th centuries when extensive collections were put together for aristocratic home decoration, museums, and teaching art at academies and universities.

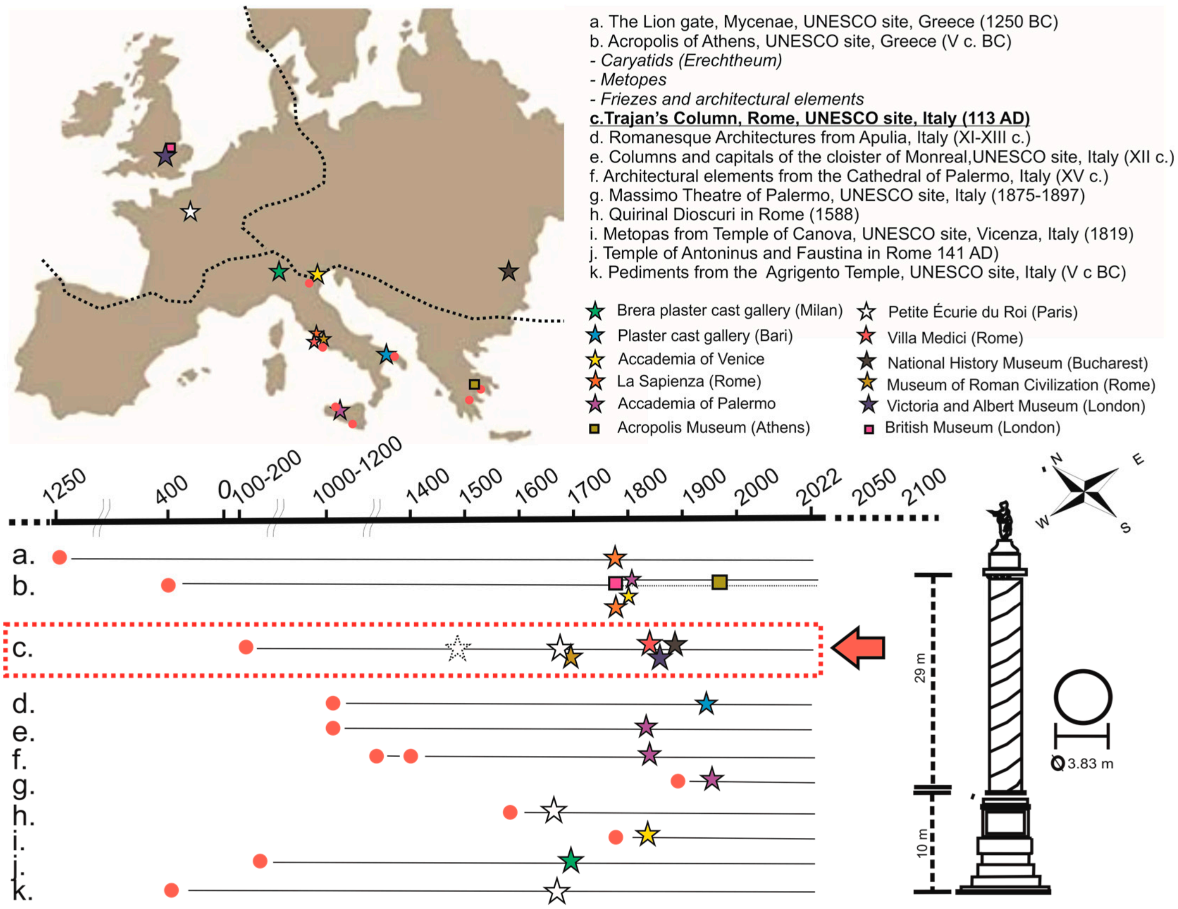

Figure 4. Schematic draft of some original monuments (with known period/date of production, red circles) in the Mediterranean Area which have historical replicas in some plaster cast galleries and academies housing historical plaster casts (stars, colors explained in the image), or some original parts of them that have been moved at museums where some monuments (squares, colors explained in the image). Trajan's Column in Rome (113 AD, Italy), made with Carrara marble, is one of the most promising case studies from this point of view since several plaster casts are available, realized in the 17th century (Louis XIV, 1665–1670) and 19th century (Napoleon III, 1861–1862). The overall friezes were reproduced in 1938–43 and conserved in the National History Museum in Bucharest (Romania). While a historical copy was also attested in the 16th century (dotted white star), fragments are housed in the Pinacoteca Ambrosiana (Milan, Italy).

The plaster cast technique faithfully reproduces a 3D object, obtaining a 1:1 replica from the original monument by molding. Although this practice made monuments accessible and affordable for a larger part of society in the past, during the 20th century, they lost their public interest and they were often rejected. Nowadays, there is growing interest in these objects. This new interest comes from a renewed evaluation of their aesthetic and historical representation, but also because they may represent a precious documentation to understand the process of decay during the time elapsed from the reproduction of the monuments, until their current state or until the moment of their relocation to museums.

Surface differences between monuments and their historical plaster casts are qualitatively observable [53,54]. New technologies based on digital imaging (e.g., 3D reconstruction or digitalization) can prove to be useful new approaches for quantitatively measuring surface changes and assessing the differential effect of climate and micro-climate conditions on geometric features in stone recession. Results can be managed in relation to the monument's exposure to the main stressors (e.g., rainfall or sun irradiation) by using climate data from historical climate series and according to climate projections (IPCC). High-resolution models obtained by 3D meshing point clouds can extrapolate differential data as expressions of the morphometric loss of surface material, such as: (i) different exposition related to cardinal orientations (angular factor, α); (ii) elevation from ground level (vertical factor, h); and (iii) geometric index (GI; stone surfaces are categorized into different tiers of complexity).

Digital data can be useful for modelling new damage functions which also consider geometrical factors, estimating differential recession on 3D surfaces and, thus, assessing the Future Cultural Value (FCV) of the monuments in future scenarios with reliable 3D simulations.

Digitizing cultural artifacts can be pivotal nowadays. By automating digitization processes and extracting knowledge, Artificial Intelligence (AI) and Machine Learning (ML) can speed up cultural heritage preservation, allowing researchers to explore and study a large number of artifacts remotely, to monitor their conservation state, and to manage a large number of variables (climate, material composition, surface features, and porosity) for preventive damage models. This approach has scientific perspectives, but can also be a supporting tool for local authorities as an instrument for addressing reliable mitigation plans, suitable conservation–restoration, and increasing awareness in public and cultural stakeholders to lay the foundation for a sustainable society.

Among a large number of possible case studies, Trajan's Column (Rome, Italy) (Figure 5A) can be considered as the most significant demonstration site in the Mediterranean Area, in order to optimize this novel approach. Indeed, some research studies have already reported that historical replicas of outdoor monuments reveal, even under the naked eyed, their surface transformation (Figure 5B1–C2), also after short times [53,54]. Camuffo [54] observed that comparing the state of deterioration of the original monument of Trajan's Column in Rome and its plaster cast made in 1861–62 and conserved at the Museum of the Roman Civilization in Rome, the latter is pitted with small craters (up to several millimeters) which disappeared from the monument, especially where exposed to S–SW. He interpreted this observation as the effect of lichens which probably flourished on the stone surface before the 19th century, and then disappeared during the 20th century, giving way to dissolution processes. Although the local historical reconstruction of the historical climate conditions in Rome demonstrates that atmosphere and climate have been also affected by natural events (volcanic eruptions and temperature fluctuation in warming and cooling times) [54–56], it is well recognized that during the past century, the anthropogenic imprint has had a great impact on the environment [57–59] and, consequently, on monuments [60,61].

Trajan's Column has great potential for reconstructing the decay evolution on its reliefs since it has been obsessively documented over the centuries by historians and archaeologists with drawings (famous are those of Giovanni Battista Piranesi, 1720–1778), photographs, and replicas [62–64]. Other reasons make it relevant: (i) Trajan's Column is made of Carrara marble (or "lunense marble"), a metamorphic carbonate rock quarried from the Apuan Alps region (Northern Tuscany, Central Italy). It is one of the most famous types of Italian marble used in sculptures and building décors since Roman times [15]. (ii) The bas-reliefs of Trajan's Column are characterized by complex decoration and a large number of details. For this reason, this monument is particularly significant for defining standards for a morphometrical and geometrical analysis in relation to the deterioration process. (iii) The column, cylindrical-shaped and well exposed in all geographical directions and in height, is an extraordinary case study for assessing the different effects of microclimate conditions on surface recession and the consequent Loss of Details. Based on all these reasons and the interest demonstrated by the local authority, Trajan's Column can be the pilot site for developing and optimizing that approach, but the same concept can be applicable according to local climate trends in most historical cities around the world.

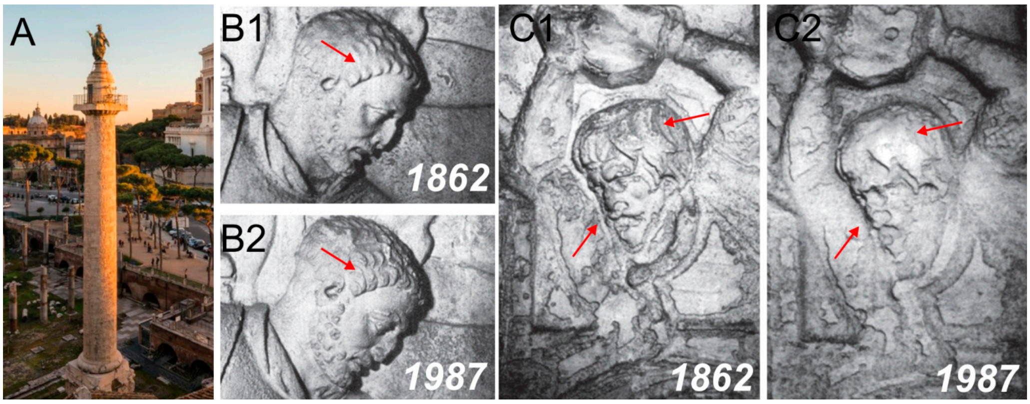

Figure 5. (**A**) Trajan's Column, Roman Forum (Archaeological Park of the Colosseum) in Rome. (**B1**,**B2**,**C1**,**C2**) Details of bas-relief: comparison between the original (1987) and the plaster cast of the Museum of Roman Civilization in Rome (1861–62). Red arrows help the reader to identify Loss of Details (LoD), for example, in the hair or details of the face (photos modified after Zanardi 2014 [53]).

Understanding decay rate in relation to the volumetric plasticity of monuments is a true challenge in order to answer the question of "how to preserve cultural identity referring to future climate conditions" and to envision future scenarios regarding human cultural heritage.

In recent decades, digital technologies have acquired great importance in cultural heritage since they can provide highly valuable elements of solution to the problems of monitoring and public access. From this point of view, the possibilities opened up by the progress in digital innovations, from 3D technology to artificial intelligence and virtual/augmented reality, can be of great help for new decision-making in cultural preservation [65], also considering the geometrical and volumetric issues of monuments and stimulating new approaches for the quantification of the recession rate according to the Intergovernmental Panel on Climate Change (IPCC) impacts and future risks (Table 2).

The ability to provide reliable projections for current and future effects due to climate is fundamental to protect and manage our diminishing cultural references.

Borrowing the words of Karima Bannoune (United Nations Human Rights Council, United Nations General Assembly, on 27 October 2016): "Cultural heritage is significant in the present, both as a message from the past and as a pathway to the future. Viewed from a human rights perspective, it is important not only in itself, but also in relation to its human dimension".

It is high time we evaluated and predicted how much climate change can impact our cultural identity.

4. Conclusions

The preservation of cultural heritage is crucial to successfully accomplish the Sustaining Development Goals (SDGs) of the 2030 Agenda. With weathering being an inexorable process, it is necessary to develop mathematical models to simulate the rate of deterioration as a function of measurable environmental parameters and stone properties in order to predict future scenarios. This is a primary urgency in the Mediterranean Area, where the majority of our monuments, columns, statues, capitals, and friezes are made of carbonate rocks: essentially, a large variety of limestones and marbles.

Despite the rich literature, at present, there is no definitive achievement on the understanding and quantification of climate change effects on surface recession. Moreover, cultural heritage is considered for its intrinsic material property while the aspect of the cultural value enclosed therein has been widely neglected. Previous authors have considered the relation between the material itself and the surrounding environment, without correlation with the morphological aspects and the quantification of the potential cultural loss. But our cultural identity hinges on details (losing details = losing identity). Architectural elements, friezes, and decorations hold the cultural expression of the societies of the past, the survival of which depends on our ability to preserve their complex 3D geometries and their surface integrity. Ensuring the resilience of our society also means preventing such Loss of Details (LoD), in order to preserve the cultural message for future generations (FCV). Surface recession should be considered in terms of the loss of integrity (LoD) of the heritage object, leading to a reduction in the readability of decorative elements and, therefore, to a reduced Future Cultural Value (FCV), intended as the result, over time, of heritage objects' appearance preserving the cultural message for future generations. For this purpose, beyond challenges and difficulties, containing the LoD and retaining the FCV may increase the resilience of a society capable of preserving and developing itself. With the recent developments in 3D digital technologies and photogrammetric techniques, it is now possible to acquire and create accurate models of historical artifacts, archaeological sites, and built heritage. The use of these advanced technologies, also combined with AI and ML, may be very impactful both from a cultural and educational viewpoint and from a research perspective, in terms of an unrestricted access to historical sites and monuments, and the improvement of new tools for their conservation. Virtual collections, indeed, can be archived, indexed, and visualized over a very long period, and they can be monitored, restored, and interpreted as required.

Science-based decision-making is a win–win perspective for defining tools for risk assessment and adaptation planning: combined with existing methods, it will form a strategic guidance to support local stakeholders in developing knowledge that will enable them to make up-to-date and sustainable decisions.

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