

Article

Review of Potential Risk Factors of Cultural Heritage Sites and Initial Modelling for Adaptation to Climate Change

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Abstract: There are a range of local weather- and climate-related factors that contribute to the degradation of cultural heritage buildings, structures, and sites over time. Some of these factors are influenced by changes in climate and some of these changes manifest themselves through a speeding up of the rate of degradation. It is the intention of this paper to review this situation with special reference to the Nordic Countries, where typical trends resulting from climate change are shorter winters and increased precipitation all year round. An attempt is made to initially draw up a classification of materials and structures relevant to cultural heritage that are affected, with a proposed numeric scale for the urgency to act. The intention is to provide information on where best to concentrate cultural heritage site preservation resources in the future.

Keywords: cultural heritage; preventative conservation; climate change; mitigation; adaptation; climate modelling

1. Introduction

There are a range of local weather- and climate-related factors that contribute to the degradation of cultural heritage buildings, structures, and sites over time. Some of these factors are influenced by changes in climate and some of these changes manifest themselves through a speeding up of the rate of degradation. The authors will be looking at existing literature from relevant geographic areas, especially concentrating on the models proposed, which contain a promising methodology aimed at contributing to the body of knowledge to apply to preventative conservation in Finland. The emphasis will be on built heritage and structures constructed from all materials most commonly used in the Nordic Countries.

Researchers in this multi-disciplinary area usually tend to concentrate on particular aspects of either the mechanisms of climate change, or its effects on particular material groups. While it is the intention here to refer to a range of these, the emphasis will be on approaches relevant to Southern Finland, which have either a sub-arctic or warm summer continental climate (according to the Köppen system). In this area, typical trends resulting from climate change are shorter winters, warmer summers, and increased precipitation all year round. While several of the studies referenced occurred under different climate zones, the adaptability of the methodology, and thereby the relevance of the results of these to the region of special reference in the present study, will be reflected on in each case. Our interest in cultural heritage sites is also connected with the UNESCO (The United Nations Educational, Scientific and Cultural Organization) global geopark concept, in which the valuable geology, cultural heritage, and liveability of the area are reviewed together. This perspective requires not only the preservation and sustainable use of the geologically valuable formations, but

also the need to promote the maintenance and sustainability of the cultural built tradition in the area, together with the development of geotourism and environmental education [1]. Visitors to geoparks in this network expect to experience both natural geological features in their natural form, as well as cultural heritage existing as a result of human activities, reflecting the special features of the region and how people through time have used the local natural features of their region to make a living and express themselves.

UNESCO [2] distinguishes between two types of tangible cultural heritage: there are moveable (paintings, sculptures, coins, and manuscripts) and immovable (monuments and archaeological sites) types, and then also those of the underwater variety. Ethnography divides cultural tradition into material (buildings, artefacts, etc.) and immaterial (culture, customs, ceremonies, storytelling, music, etc.). This study will deal with the immovable type of cultural heritage above the surface.

Research dealing with climate change impacts on cultural heritage has gathered more attention over the past decades. The FP6 project Noah's Ark was carried out from 2004 to 2007 and the project produced a Vulnerability Atlas and Guidelines for cultural heritage protection against climate change. The scientific report introduced the vulnerability risks due to extreme weather events typical of climate change. Further research was prepared under the FP7 Climate for Culture Project during 2009–2014. The focus of this project was to evaluate the slow ongoing impacts of climate change, instead of extreme events. The report also included the prediction of sea-level rise impacts on coastal cultural heritage. The ongoing project HERACLES—H2020 Heritage Resilience against Climate Events on Site (2016–2019)—will promote solutions or systems for effective resilience with a multidisciplinary approach. Another H2020 project STORM (2016–2019)—Safeguarding Cultural Heritage through Technical and Organisational Management—is collecting a set of non-destructive methods of surveying and analysis to enhance better predictions for the future climate change impacts on cultural heritage. The project is carried out in collaboration with ICCROM (International Centre for the Study of the Preservation and Restoration of Cultural Property). Several other research projects are working with similar research goals and targeting certain parts of Europe and the most typical threats in their regions [3].

2. Potential Risk Factors to Cultural Heritage

The range of elements in local weather that are being and will be potentially altered as a result of global level climate change is not always agreed on, but there is general consensus on those which could be damaging to aspects of cultural heritage. Brimblecombe [4], referring to the increasingly damp English climate, lists the following five: 1. Rainfall; 2. flooding and soil moisture content; 3. extreme weather (winds and rainfall); 4. temperature and relative humidity; and 5. pests and diseases (humidity and temperature affect pests). Humidity prevents wooden and brick buildings from drying during certain periods of the year, leading to structural stress.

Lemieux et al. [5] refer to Last Chance Tourism (LCT), but interpret the increased interest in it as being based on perceptions of climate change and specific aspects, such as glaciers melting and icecap ice retreating; the central idea of the concept being that people are motivated to visit places while they still exist in the present form. Forino et al. [6] give a longer list of nine categories of climate change-related impacts on cultural heritage, referring specifically to Australia. This paper first generally summarises them as fitting into the three categories based on how their effects come about, which are: meteorology, hydrology, and climatology. Here, meteorology refers to different types of storms, and climatology to extremes of temperature. The longer list itemises: 1. various types of physical damage; 2. soil instability; 3. susceptibility to changing soil moisture; 4. changes in hydrology; 5. changes in humidity cycles; 6. changes in vegetation; 7. migration of damaging pests; 8. climatic zone movements impacting cultural landscapes; and 9. changing economic and social patterns of settlements.

Philips [7] interviewed a range of professionals involved with UK World Heritage sites in order to assess, firstly, how climate change was taken into account in preservation plans and, secondly,

how those working with these sites are informed or react to the information provided to them on climate change considerations. Since 2006, it has been a requirement for the management of sites in this network in the UK to have not only an appropriate management plan for their protection for future generations, but specifically one for dealing with the possible impact of climate change. The range of reactions obtained from the interviewees fitted into five categories: not knowing what information they receive is relevant or reliable; uncertainty about the whole science of climate changes; a lack of availability of the skills or knowledge needed to act; difficulties with risk perception and getting others motivated about climate change issues; and lastly, the challenge of devoting additional time or financial resources to cope with climate change challenges. Accordingly, she observed that the obstacles identified in her study as a whole have slowed down climate adaptation in the management of UK World Heritage sites, and that the mainstreaming of such considerations is required and will be able to happen if climate change impact is not dealt with as a separate issue of its own, but rather within the context of other risk preparedness.

In another publication, Philips [8] introduces the concept of the adaptive capacity of cultural heritage under the impacts of climate change. Adaptive capacity is an approach to investigating the state of the management of cultural heritage sites in consideration of climatic change. The key determinants of adaptive capacity are defined: as 1. learning capacity, 2. room for autonomous change, 3. access to resources and, 4. leadership in an institution. The qualitative research material was gathered from persons engaged with the management of different heritage sites in the UK that had suffered from severe weather event impacts in the previous five years. Based on the results obtained, the concept of adaptive capacity was divided into six different factors: resources, access to information, authority, cognitive factors, learning capacity, and leadership. This concept creates a wider framework in which risk assessment is an important factor and must be combined with other competences to successfully manage cultural heritage under climate change.

According to Kaslegard [9], increasing strain will affect buildings with cultural value. A warmer and damper climate will cause the deterioration of building materials. Coastal buildings face the impacts of sea level rise, flooding, and erosion. In general, more extreme weather events will cause more acute damage to traditional buildings. Due to climate change impacts, the management of cultural heritage will face new challenges. It is suggested that more attention will need to be paid to the identification, documentation, and mapping of those heritage sites that are most vulnerable from the point of climate change. More intensive maintenance and coastal defence methods will be needed as future actions.

Arctic regions are predicted to face the greatest increase of warming in the winter time. The temperature is expected to rise by 3–4 °C by 2050. The rainfall in Nordic countries will increase by about 10% on an annual level. Exceptionally, the west coasts of Norway and Finland might face as much as a 20–30% increase in rainfall in winter periods. At least extreme rainfall events are expected to appear more frequently in the whole Nordic area in the future. For example, in Norway, two out of three cases of building damage are classified as having been caused by humidity affecting the outer surfaces of buildings, such as roofs, facades, and floors in contact with the ground. All kinds of building materials suffer from high humidity, while in Nordic countries, the building tradition is mostly based on timber constructions. Impacts of rainwater and meltwater are also identified in wooden buildings, causing favourable conditions, for example, for fungal growth, different pest damage, and biological growth, such as mosses and algae, while water penetrates into the building through different surfaces.

Physical disintegration means the decomposition of materials into smaller fragments; that is typical, for example, with traditional brick buildings. In practise, this can be caused by frost damage or salt crystallisation, which both cause damage to the appearance of the building. The character of frost damage can be described through the freeze/thaw cycle, meaning the phenomenon when the temperature falls below zero and then climbs to over 0 °C again. Considering both freeze-thaw cycles and wet frost, most parts of Finland, the inner and northern part of the Scandinavian Peninsula, and

the Arctic regions are likely to face greater risks of frost damage, although the risk will remain at a moderate level. The salt crystallisation is likely to grow in all Nordic countries because the increase of humidity brings the salt out from the built structures more easily.

Cultural heritage buildings, especially old industrial buildings, but also other types of buildings, contain metal building elements like iron beams, iron bolts, and wall anchorages in stone or brick walls, as well as roofing and guttering of copper or zinc. Chemical decomposition causes corrosion in these kinds of structures and might also affect the stone and brick structures of the building. Corrosion, together with humidity and temperature, is a threatening combination. Although, it has been noted that the occurrence of acid rain due to SO₂ pollution is not currently as serious a problem as it used to be in earlier decades [9]. The blackening of building facades was earlier caused by industrial processes. However, due to environmental legislation, this kind of poor air quality is no longer a problem, but instead of that, the building facades are suffering from emissions consisting of organic-rich pollutants (like fine carbonaceous particles) from vehicle exhausts which can also cause a change in the colour of the façade, especially in buildings constructed of calcareous stone or other porous material [3].

La Russa et al. [10] have described how the environmental impact on cultural heritage can be observed through the formation of black crusts on stone, which appears to be principally due to airborne heavy metals formed through combustion. Although more relevant to urban environments and not resulting from climate change, the X-ray spectrometry analytical methods described in this study provide information that can help in better protecting the structures in question.

Cultural heritage will face several threat factors caused by climate change, but one can also conclude that the traditional building materials and structures have capabilities to recover more easily from heavy rain events and flooding. Usually, the structures are more permeable, which ensures natural ventilation and helps with drying out [9].

3. Modelling for Mitigation and Adaptation to Climate Change

Forino et al. [6] presented the *Cultural Heritage Risk Index* (CHRI), which gives a score from 1 = next to no risk to 10 = the greatest risk of loss of cultural heritage assets. It is designed to be applied to particular sites and first takes three categories of analysis: hazard analysis, exposure analysis, and vulnerability analysis. The findings from these are then combined and subjected to a risk analysis to give the result. Hazard analysis is stressed more in scoring, with the ratio between the three initial analysis types being 5:3:2.

As part of the EU research project Climate for Culture [11], an innovative method for assessing climate change impact was proposed and described, but applied it to a specific aspect of cultural heritage, namely to wooden buildings. Nevertheless, the methodology applied contains a number of aspects that are relevant and transferable to other materials. Here, the Regional climate Model REMO, which was developed at the Max Planck Institute for Meteorology [12] was used, to give a more accurate set of predications for future climate conditions.

Modelling of different kinds of environmental hazards is also connected with disaster risk reduction (DRR) and disaster risk management (DRM) in order to reduce the impacts of different disasters, like severe climate change impacts. In 2005, the Hyogo Framework for Action (HFA) 2005–2015 was introduced as the first international model for Building the Resilience of Nations and Communities to Disasters (Hyogo Framework) [13]. The strategy launches five different priorities of action, like national and local priorities connected with institutions, the use of knowledge, innovation, and education to support culture and resilience, reducing the underlying risk factors and strengthening of disaster preparedness at all levels to minimise the impacts. Priority action 2 concentrates on identifying, assessing, and monitoring disaster risks and enhancing the early warning of them. These viewpoints can be successfully adapted for the modelling of and adaptation to climate change.

Romão et al. [14] concluded that a framework adaptable to risk assessment in the built environment needs to involve the following viewpoints: (1) reliable and sufficient data to establish suitable hazard models; (2) sufficient and reliable data on the assets under risk; (3) suitable procedures

to model the vulnerability; (4) adequate models to predict the multidimensional consequences of the hazardous event; and (5) sufficient human, time, and economic resources. It is recognised that there is often a lack of adequate models to predict impacts, as well as a lack of sufficient resources. They also conclude that it is important to have a simple methodology adaptable to preliminary risk analysis, especially in the case of cultural heritage. A qualitative approach is suggested as a usable method to evaluate multidimensional risks in the cultural environment, due to its complexity. Understanding the behaviour of cultural heritage sites and structures is more important than detailed measurements of the objectives when developing a simplified model for practical use.

One of the principal materials of interest in this study is stone. Hambrecht & Rockman [15] point out that although stone is considered a very strong material and one that is resilient in the face of climate change, that this is not always the case; they refer to several study projects, such as that of Goudie [16], that reveal the worrying vulnerability of stone under the influence of variables such as moisture and vegetation. The type of rock is another relevant factor and softer stones such as limestone and soapstone are eroded much more quickly [17]. While the predominant stone type in Fenno-Scandinavia is hard granite, there are also natural occurrences of softer stone types.

Gomez-Heras and McCabe [18] go so far as to propose that by studying past environmental changes on stone structures, it can be possible to predict potential future impacts. They add that although the weathering of such structures is similar to that of natural stone as such, we can still get more information about anthropogenic impacts from the stone that has been used by humans at some stage in history. Stone weathering as an indicator of climate change offers interesting potential for future study and its incorporation as a tool in further models for working with cultural heritage protection.

The model being proposed by the authors of the present paper (the main elements of which are combined in Table 1 below) is intended to serve the purpose of prioritising cultural heritage elements and sites for protection against the ravages of climate change and therefore to help in the planning of adaptation and/or mitigation steps.

Table 1. Causes, results, and proposed level of urgency for acting, with comments on relevance to the case study.

Climate Change Category	Measure or Scale	Result/Effect	Materials/ Structures Affected	Proposed Urgency Rating *	Case Study: Application of the Criteria
Warmer Climate	Rise in °C/year	Freeze–thaw damage	Stone Brick	3	Partly visible in stone constructions (cow house), although the structure is also affected by the current use and site conditions.
		Rust	Metal	5	Limited use in case study buildings. Non-painted roofs are suffering from rust.
		New fauna–pests	Wood Brick	5	Clearly visible increased effect, especially in wooden facades, but also brick facades.
Longer Growing Season	Days/year	New/increased flora, algae, moss, root damage	Wood Brick Stone	5	Clearly visible increased effect, especially in wooden facades, but also cement surfaces like staircases and foundations (moss).
Increased Precipitation: rain or snow	mm/year	Humidity	Wood Brick Structures	10	Clearly visible effect in all facades, especially in northern and shaded facades and wooden building parts.
		Increased loads (snow)	Wood Brick Roof/Roof Structures (Typically Wood)	5–10	Depending on the roof material and declination; the lower the declination, the higher the risk of damage due to the increased load.
		Soil and material degradation	FoundationsBase Floor	5	The highest risk with the buildings situated on slopes of the site (combination of different soil types).
		Flooding (from any increased precipitation effect)	Wood Brick Structures	10	The highest risk with the buildings situated on slopes of the site (surface runoff gathering).

Table 1. Cont.

Climate Change Category	Measure or Scale	Result/Effect	Materials/ Structures Affected	Proposed Urgency Rating *	Case Study: Application of the Criteria
Severe Rain Incidents	mm/hour	Erosion	Wood Brick Stone	5	The highest risk is with the buildings situated on slopes of the site (possible soil erosion).
Extreme Winds	m/s	Damage to structures through falling trees or wind causing damage to the roof	Metal Roofs Wood & Brick Structures	5–10	High steel roofs facing the dominating wind direction are subject to the largest threat of damage from extreme winds (residential building, cow house’s high roof).

* A key to the numeric scale is given in Table 2 below.

Table 2. Proposed scale for urgency to act with particular materials/cultural heritage sites.

1	A mild or minor perceivable long-term effect (100 years or more)
3	A major perceivable long-term effect (50–100 years)
5	A mild or minor perceivable short- to mid-term effect (1–50 years)
10	A major short- to mid-term effect

Then, by combining elements of the modelling methods outlined above, and illustrated in summary in Figure 1, the following scoring system from 1–10 (described in Table 2 above) is suggested as a means of evaluating the relative risks to different materials. The score in question can apply to either individual materials or to an entire structure or site, and takes into account both the vulnerability of the item in question and over how long a timescale potential damage to it may have an effect, as well as how severe this effect is likely to be.

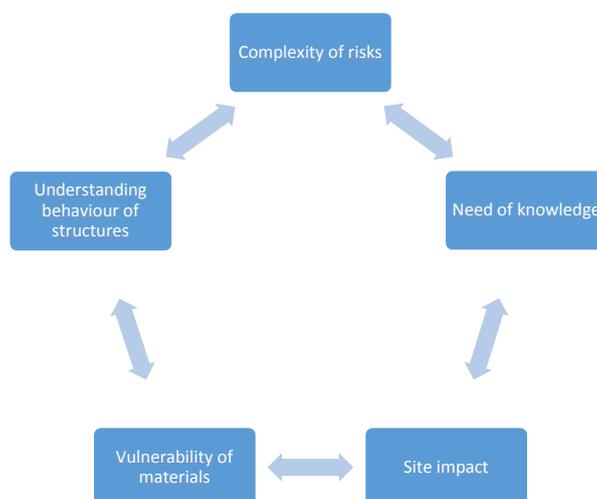


Figure 1. Elements having an impact on a practical-based model.

4. Case Study—Model Application

As a case study, we present a Finnish farmhouse complex consisting of several buildings, the map location and aerial views of which can be seen in Figure 2a,b below respectively. The built environment is classified as part of a regionally valuable village and cultural landscape [19]. The residential building is built in several parts: the oldest part is a log construction from the 19th century and a two-storey addition was constructed in the 1930’s with wooden frames. The façade consists of horizontal wooden panelling with double glazed windows. The residential building is situated on a hill and other buildings are on lower positions of the site or on slopes. Most of the storage buildings are also

horizontal log structures, except for a cow house built of cement brick in 1930. The roof materials are mostly steel and the largest storage hall has cement brick tiles. Similar traditional farmhouse complexes are quite usual in Finnish rural areas, and sometimes animal buildings are constructed of ordinary brick or granite stones. Natural granite stones have been used in the foundations of the residential building, but the stone surface has been covered with cement at a later phase. In the above table, the case study buildings and site are evaluated according to the proposed model and conclusions made dealing with the adaptability qualifications.

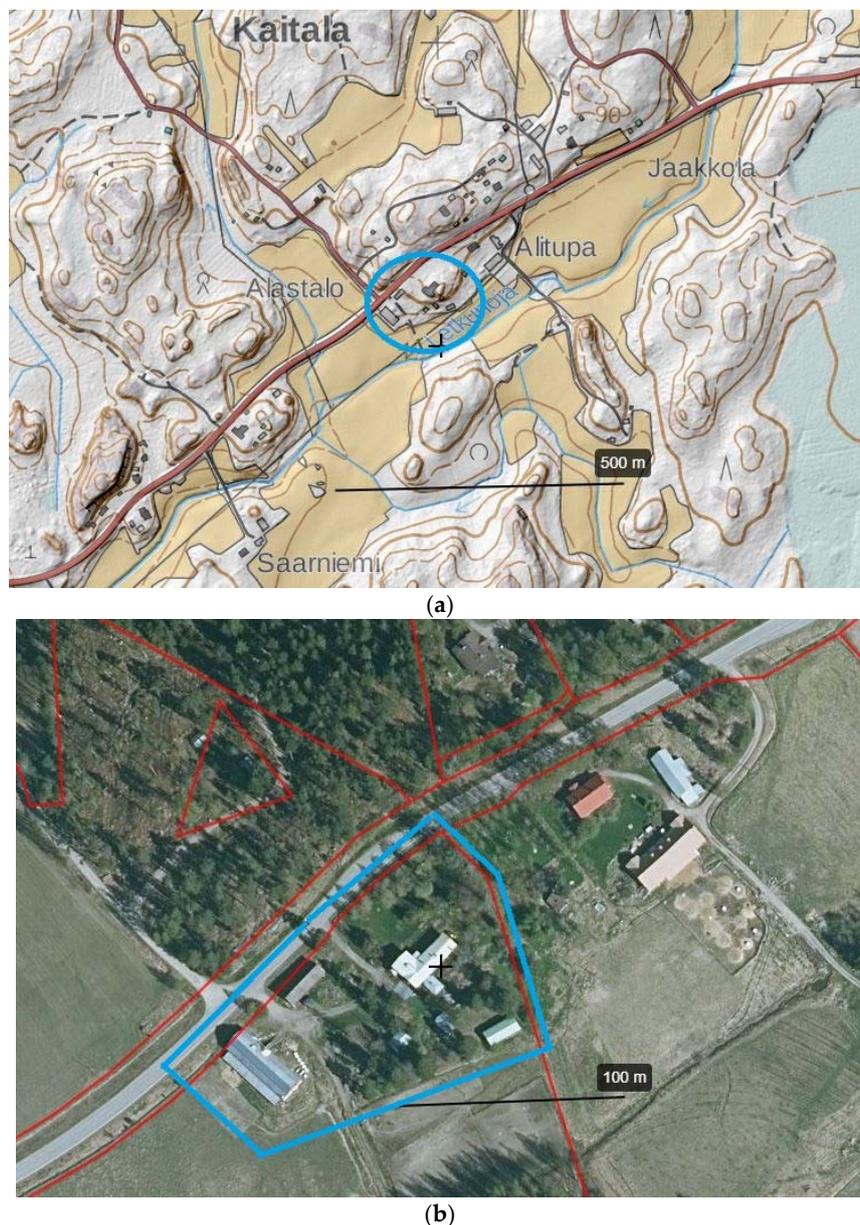


Figure 2. (a) The case study farm location in the village [20]. (b) Location of the case study buildings at the site [20].

5. Comments and Conclusions Based on the Case Study

The observations of the climate change impacts are based on the professional experience of an architect (one of the co-authors) living in the building complex, designing renovations and maintaining separate buildings, and following the changes caused by climatic conditions.

In this case, study wood is the dominating material of separate buildings. Natural stone has been used together with a cement surface, mostly in the foundations of the buildings. An exception is the big cow house built of cement tiles, which are not as durable as burnt tiles but have mostly survived in a moderate condition for almost ninety years. Cement tiles were fabricated in situ and the quality of the sand used in them had a significant impact of the total quality of the material, which is also visible in different parts of the building. In wooden buildings, the facades need repair and repainting regularly. The maintenance has not been very intensive, but the facades are mostly in a moderate condition. It has been clearly noticed that wooden facades are suffering more and more from the increased humidity, because they get dirty due to different kinds of flora and moss starting to grow on them. They need primarily cleaning with a limited use of water and suitable chemicals, instead of repainting.

In the case study, the conditions of the site also have a significant impact on the buildings. While the residential building is situated on a hill, this position protects it from severe impacts of flooding. The other buildings situated on slopes of the site are more sensitive to suffering in some ways from severe rain events and run off, as well as erosion. The site is sometimes subject to strong winds, especially those coming from the southwest, which is the dominating wind direction in Southern Finland. There has been damage caused by the strong wind tearing away parts of the roof in the highest buildings with steel roofs.

It has to be mentioned that it is essential to separate different types of damage in traditional buildings. Some of them can be caused by the wrong repair and renovation methods, like the use of unsuitable materials and paintings in old structures and surfaces. The use of different kinds of plastics and unsuitable insulation materials has caused damage to old structures when humidity is blocked inside them, causing, for example mould. In this case study site, there have not been unsuitable materials used, and the problems discussed are connected to climate change impacts.

6. Final Discussion and Conclusions

In predicting and planning to combat the detrimental effects of climate change on cultural heritage sites, we are faced with many unknowns: it is not clear by what scenario climate change will proceed, meaning somewhere from the optimistic slower rate to a pessimistic more rapid and intense one. Projections are currently being generated by different Global Climate Models (GCMs) hosted by different research institutions, each with its own formulation of the atmospheric flow dynamics and physics.

Four Representative Concentration Pathways (RCPs) have been considered in the fifth Assessment Report (AR5) of the Inter-Governmental Panel on Climate Change (IPCC) [21]. These Greenhouse Gas (GHG) concentration (not emission) trajectories, all considered as realistic, are used by modellers as atmospheric system forcing for generating climate response and change projections. The RCPs, namely RCP2.6, RCP4.5, RCP6.0, and RCP8.5, have been defined according to their contribution to atmospheric radiative forcing in the year 2100, relative to pre-industrial values. RCP4.5 is based on active GHG emission reduction interventions that could lead to a ceiling of approximately 560 ppm CO₂ (a doubling of atmospheric concentrations since the start of the industrial revolution) by the year 2100, while concentrations could stabilise or even decrease after the year 2100 [21]. The RCP4.5 and RCP8.5 trajectories are associated with CO₂ concentrations of approximately 560 ppm and 950 ppm, respectively, by the year 2100 [22].

The local weather changes will also vary in terms of amounts of precipitation and extremes of temperature, storms, and so on; then, the predictions for how various materials (here, in particular, all traditional materials that are typical elements of Nordic cultural heritage: wood, brick, and stone) will react, contain uncertainties. Nevertheless, it is still possible to at least initially classify these risks using indexing methods, and then based on what the risks are perceived to potentially be, models can be drawn up for how to deal with them and as a whole serve to reduce the levels of uncertainty involved. It is important to collect more case examples to evaluate in practise the climate impacts on cultural

heritage in different regions and places, test the models, and draw conclusions on the basis of the case studies. More advanced monitoring systems and regular evaluations will help to share the findings with researchers, professionals, and common users.

Combining ideas from the work described above on the potential for using stone as an indicator for the effects of climate change on stone [18] and the field experiments carried out by Daly [23] in Ireland, where small cubic samples of various types of stone were exposed to the influences of the weather for defined periods, there could be very useful results obtained in a future controlled experiment, for example, in the Nordic climate context such as that of Finland. This could potentially involve a set of samples of different kinds of stone materials exposed to the elements throughout all weather extremes of the year. Combined with observations from the past of the weathering of stone, the new data obtained from such a field test could reveal valuable information about the usefulness of stone as an indicator and ultimately about the effects of climate change on cultural heritage involving stone.

It can be concluded that the natural processes which lead to the deterioration of cultural heritage features will, as a whole, increase in their effect as a result of climate change; there will also be new potential threats involved. Many unknowns remain as to the relative influence of certain factors on particular materials, and although predicting these is difficult, there is a benefit of using models and attaching them to different scenarios for how severe climate change could be. Furthermore, an awareness of the relative urgency to react to threats to different building materials and types of structures can help in planning to protect them in time. Although the numeric scale for this purpose provided above, as well as the respective classifications into climate change threats and material features, all contain approximations, it still may, as a whole, contribute to the planning process towards the mitigation of the effects of climate change on cultural heritage, and to the appropriate adaptation to these changes.

Even if risk analysis provides important information about the possible occurrence of damage involving cultural heritage, the vulnerability should also be regarded as one aspect in a larger context of management of cultural sites and buildings. The preconditions of a successful management system are being able to secure the preservation of cultural heritage and to identify other actions needed to prepare and mitigate for the damage likely caused by changing climate conditions.

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