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Multi-determinant climate change risk assessment for heritage: A review of current approaches and future needs

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ABSTRACT

Anthropogenic climate change is radically changing the way we relate to and interact with our shared histories. Culturally important sites have already been damaged and lost due to our changing climate and this will only continue. Considering the extent of climate change impacts, it is vital that assessing the risks of climate change looks beyond the changing prevalence of climatic hazards, such as sea level rise, to consider the predisposition of the historic environment to be impacted by the hazard, the location of heritage sites and their relative exposure, adaptive responses and their associated risks, and the cultural significance of the places themselves. This review provides an overview of current climate change risk assessments for heritage, with specific attention paid to how the Intergovernmental Panel on Climate Change's (IPCC) risk framework, and its risk determinants (exposure, hazard, vulnerability, and response) have been conceptualised. It systematically reviews scholarly literature published between 2017 and 2022 to determine: the uptake of the four risk determinants; how these terms are represented; and the methods for combining these elements into a dynamic risk framework which can be scaled to assess multiple sites. Significant advances have been made in identifying and preparing for the future impacts of climate change, but there is still an imbalance towards single-site risk assessments — particularly for the historic built environment. Furthermore, the review identifies and provides summaries of multi-determinant risk assessments that engage with the complexities of heritage futures beyond just changing climatic hazards to better understand the impacts of climate change on the historic environment in its totality.

1. Introduction

The world is getting warmer, with disastrous consequences for individuals, groups, societies, and the heritage they value. This has been recognised by those studying the historic environment for over twenty years (Cassar, 2005), and climate change has been named the "fastest growing threat" to heritage globally (ICOMOS, 2017). Cultural heritage includes archaeological sites, the tangible fabric of buildings, collections and interiors, cultural landscapes, shipwrecks and underwater archaeology, as well as intangible knowledge and traditional cultural practices. Collectively, they shape our understanding of the past, create and maintain identities, and influence the long-term development of sustainable communities. Research on climate change impacts is often divided

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into mitigation and adaptation, however, these are not separate sequential steps in response to our changing climate but rather, complementary, interdependent processes. Both rely on understanding the risks and impacts of climate change and any analysis of climate-induced damage and loss must be grounded in this understanding, as well as its uncertainties.

Risk assessments are well-established in cultural heritage, for example Stovel (1998), Ramalhinho and Macedo (2019), with projects such as Noah's Ark and Climate for Culture recognising the need for climate change-specific assessments (Cassar et al., 2010; Leissner et al., 2015). The intersection of climate change and cultural heritage as a field has been steadily growing and since 2016 there have been multiple reviews that evidence this (Horowitz et al., 2016; Fatoric and Seekamp, 2017; Sesana et al., 2021; Quesada-Ganuza et al., 2021; Orr et al., 2021; Dembedza et al., 2022; Nicu, 2017). There are two literature reviews specifically assessing climate change risk for cultural heritage: the first looks at 15 years of peer-reviewed literature on Climate Change Adaptation (CCA) and emphasises the lack of community voices, the need for agile approaches, and identifies key barriers for heritage adaptation (Crowley et al., 2022). The second concludes that there is no pre-existing robust risk assessment method for analysing the large scale impacts of climate change on heritage (Vokes et al., 2023). Both of these add significantly to the field and demonstrate the increasing need to develop appropriate tools to meet this challenge. However, neither systematically analyse how current approaches represent risk components nor how these approaches can be scaled to include multiple risk determinants and heritage sites.

This review analyses recent multi-determinant risk assessments for cultural heritage, namely those that look beyond climate hazards or site vulnerability to consider how risk factors exacerbate and mitigate each other across sites and landscapes. The aim is to identify scalable methods that consider multiple determinants of risk. The first section reviews the use of the risk framework from the Intergovernmental Panel on Climate Change (IPCC) in cultural heritage climate change risk assessments and its four determinants: hazard, exposure, vulnerability, and response (IPCC et al., 2022). How the IPCC determinants have been applied in cultural heritage risk assessments and how they should be defined is central to this article. This section then continues to identify risk assessments (or aspects of them) that are statistically robust, data-driven, and are multi-site in scope. Stewarding heritage into and through our changing climate requires evidence-based decision-making tools that provide a strong basis from which to inform future adaptation plans. While past literature has rightly called for more stakeholder engagement and bottom-up approaches (Fatoric and Seekamp, 2017; Crowley et al., 2022), there is also no framework for assessing the risks of climate change on heritage in its totality (especially non-designated heritage). The methodologies reviewed here provide a state of the art for current multi-determinant assessments and analyse their potential scalability for multiple site assessment.

The final section discusses research challenges in climate change and heritage; the focus is not on barriers for risk assessment (see Crowley et al., 2022), but instead on identifying future directions such as standardising terminologies with the IPCC, investigating approaches for integrating heritage significance, highlighting scalable methodologies, and proposing a series of requirements for the evidence base that facilitates the type of risk assessment that can inform large-scale climate adaptation planning.

2. Methodology

This review has two components: the first is a general review of climate change heritage scholarship. There is no one journal tailored to the discussion of these issues and relevant frameworks are published across disciplinary journals from those on climate change to heritage policy. Future needs for the field determined from this first survey are addressed in Section 4. The second component is a bibliometric analysis of peer-reviewed articles published between 2017 and 2022 that matched a specific search criteria, and a survey of non-peer reviewed reports published in the last 10 years. This is outlined below:

2.1. Method for the literature review

A bibliometric review following the PRISMA 2020 method was conducted to establish an overview of current approaches to climate risk and impacts (Fig. 1). Articles that met this search in Elsevier Scopus for terms occurring in the title, abstract, and keywords were included:

> [cultur*] AND [histori* OR heritage* OR site* OR enviro*] AND [climat*] AND [vulnerability OR exposure OR hazard OR resilience OR change] AND [risk* OR impact*]

The inclusion of 'impact' as well as 'risk' was to ensure that literature defining and measuring the impacts of climate change on heritage, but not using risk terminology, were considered. According to the IPCC, risk is the potential for negative consequences, while impacts are the realised effects of these consequences (IPCC et al., 2021). An initial search with the above query returned 5020 articles in total. This review only looked at those published between 2017 and 2022; over 50% of the articles were published in these five years and all after the Paris Agreement came into the effect in November 2016. From these 2712 articles, 88% were excluded after an initial analysis of the titles and abstracts for the following criteria:

1. Articles researching the impacts of climate change on cultural heritage (broadly defined) in the past. An example of this is a study on how the palaeoclimate affected Bronze Age culture (Kulkova et al., 2022) — 5.1% of the exclusions (n=122).
2. Articles without sufficient focus on climate change impacts on, or risks for, cultural heritage. This ranged from articles in separate fields to articles discussing relevant issues such as developing sustainable ecotourism strategies for heritage sites. A particular subset of these exclusions were articles that looked at traditional ecological knowledge from Indigenous perspectives but did not specifically mention Indigenous heritage. This accounted for the majority of the exclusions — 94.7% (n=2259).

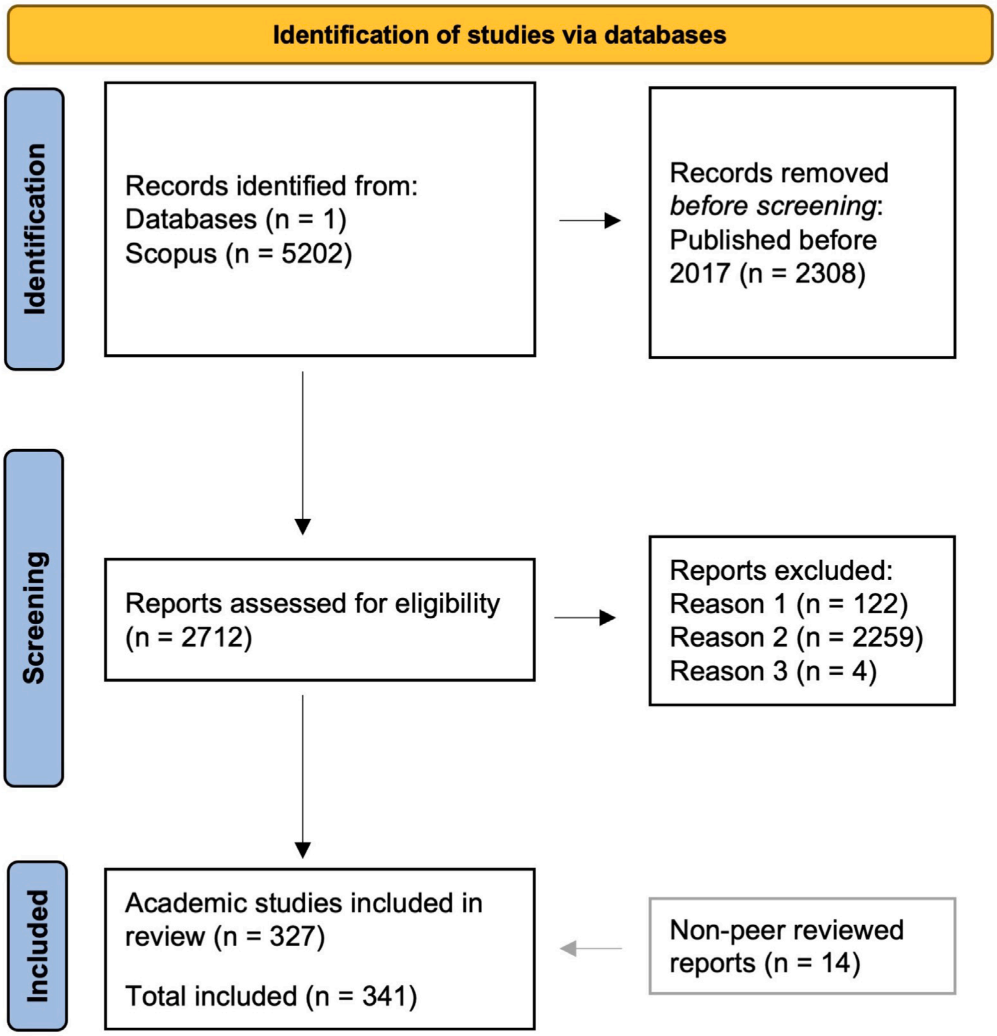

Fig. 1. Diagram of this review's screening process following PRISMA 2020.

3. Main text was not in English although the abstract was - 0.2%. The languages were Chinese (*n*=2), Bosnian (*n*=1), and Spanish (*n*=1).

Climate risk approaches developed between 2012 and 2022 by governmental and non-profit organisations were also considered and 14 risk assessments (or reviews of them) were included — national adaptation plans such as Ireland's were excluded (Daly et al., 2022). These were added to the remaining 327 academic articles and all were analysed individually and coded against these specific criteria:

- **Location:** region(s) and continent(s).
- **The type(s) of heritage studied:** monument/single building; groups of buildings; archaeological sites; collections; cultural landscapes; intangible heritage; Indigenous heritage; and a final category for those that only referred to 'cultural heritage' generally (adapted from ICOMOS, 2019).
- **Scale:** site; region; national; transnational; not applicable.
- **Climate change hazard(s)**: sea level rise (including associated salinisation, coastal flooding, and erosion); increased rainfall (including wind-driven rain, fluvial, and pluvial flooding); tropical storms and hurricanes; increased global average warming; flood outbursts (glacial); landslides; heat stress; drought (agricultural and hydrological); wildfire (from increased aridity and lightning strikes); and none specified. This was adapted from a white paper on climate risks for heritage (Simpson et al., 2022c) — at the time of analysis there was no standardised list of climate change hazards for cultural heritage though one has since been proposed (Thomas et al., 2024).

- **Risk assessment:** presence of a risk assessment method; inclusion of hazard, vulnerability, exposure and response using the IPCC definitions (coded as "IPCC"); or engaging with the concepts but referencing an alternate definition or no definition (coded as "Other").

Once the literature had been coded, trends were determined for each of the above criteria using percentages of the total (n=327). The analysis of this body of literature according to this categorisation is discussed in Section 3.1. Articles that had risk assessments that looked at two or more determinants of risk, particularly those using the IPCC risk framework, were identified and their methods closely reviewed (these are discussed in detail in Section 3.4).

3. Results

3.1. General trends

This section provides a thematic summary of how peer-reviewed literature has approached climate change impacts on cultural heritage between 2017 and 2022. Of the 327 articles reviewed, 40% were concerned with the impacts of climate change on built heritage (both individual and groups of buildings), compared to 23% looking at archaeological sites and 16% at cultural landscapes. Very few looked at collections (5%), Indigenous heritage (4%), and intangible heritage (2%) though these were not specifically elicited in the search criteria. The remaining 9% referred to 'cultural heritage' as an overarching category. The emphasis on studying built heritage is also found in robust multi-element risk frameworks and those using the IPCC terminology; archaeological monuments, sites, landscapes, and deposits are less well-represented in the literature surveyed.

More than half of the articles were concerned with single sites or took a regional approach. Far fewer were at national (14%) or transnational (13%) scales. The hazard of changing precipitation was studied most frequently (22%), but closely followed by global average warming (17%) and sea level rise (16%). A previous survey of the field also concluded that precipitation was most commonly studied (Orr et al., 2021), but identified a high prevalence of research on storms and extreme events (only 6% in this study) suggesting that climate change risk assessments for heritage are particularly concerned with slow-onset impacts rather than extreme weather events. While there is a well-established link between disaster response and disaster risk reduction for heritage (UNESCO, 2015; Pica, 2018; Rosa et al., 2021; Durrant et al., 2023), only recently has more attention been paid to quantifying the risks of extreme climate change events (Bonazza and Sardella, 2023; Sardella et al., 2020).

Of the 208 studies that looked at specific hazards, 41% considered only one hazard; for example, looking solely at the impacts of sea level rise (Sitzia et al., 2022). Of the 59% that considered multiple hazards, no study quantitatively looked at how these hazards interact as compound events (when hazards combine to increase risk levels) or cascading events (when hazards trigger a sequence of events that creates a greater impact than the hazard would have in isolation) (IPCC et al., 2022; Simpson et al., 2023).

3.2. Use and definition of the risk determinants

The analysis of risk assessments and their component parts follows the IPCC risk framework which has four determinants: hazard, vulnerability, exposure and response. Less than half (40%) of these studies conducted a risk assessment. These 131 papers form the 'risk subset' and the subsequent discussion on their use of risk determinants refers only to this group. Hazard was the most studied (81% of the risk subset), followed by vulnerability (47%), exposure (37%), and response (7%) though understandings of these concepts varied widely. The IPCC definitions and a discussion of how each determinant has been approached is detailed below.

3.2.1. Hazard

A hazard is defined by the IPCC as:

> "the potential occurrence of a natural or human-induced physical event or trend that may cause loss of life, injury or other health impacts, as well as damage and loss to property, infrastructure, livelihoods, service provision, ecosystems and environmental resources." (IPCC et al., 2022, p. 2911).

Hazard was the most studied risk determinant in the articles reviewed (81%), yet proportionally it was the least cited IPCC definition — only 13% (n=17). Even when studies considered multiple determinants (usually hazard, vulnerability and exposure), some only defined the latter two — an understanding of hazard was assumed. However, since the concepts of 'threat', 'driver' and 'impact' are often used interchangeably with the risk determinant 'hazard' (Simpson et al., 2022c) and because there is no agreed list of hazards for heritage, in the risk assessment context these terms should be defined. Threat is not officially used by the IPCC, a driver is a factor that causes change in a system, hazards have potential negative consequences (and could be seen as drivers in a risk system), while impacts are the actual negative effects.

Hazard analysis can be qualitative, but for cultural heritage risk assessments it is primarily quantitative with climate change projections being used to analyse the change in hazards in areas where heritage is present. This requires hazard indices to determine levels above the norm (for example Climdex). These can be both extreme events or long-term changes in typical climate profiles. The impacts of exceeding these climate indices for specific heritage sites will depend on various factors such as age of the site and its current condition (vulnerability) and the site placement and significance (exposure).

While it is the risk determinant most studied and understood for heritage, hazard assessments still have limitations: uncertainty in the climate change projections which increases with down-scaled regional projections more relevant to heritage micro-climates (Vandemeulebroucke, 2023); incomplete knowledge of damage mechanisms for climate hazards and heritage materials;

technical requirements for accessing and processing climate projections; varying data quality for these projections, often of lower resolution for low and middle income countries (Simpson et al., 2022b); as well as the unequal impacts of climate change itself (Hadré et al., 2023; Sánchez, 2018). In the context of heritage climate change risk assessment, hazards are the natural or human-induced physical events that have negative consequences for the historic environment.

3.2.2. Vulnerability

Vulnerability is defined by the IPCC as:

> "the propensity or predisposition to be adversely affected. Vulnerability encompasses a variety of concepts and elements including sensitivity or susceptibility to harm and lack of capacity to cope and adapt" (IPCC et al., 2022, p. 2927).

Just under half of the risk subset (47%) considered vulnerability, though only 11% (*n*=14) used the IPCC definition. The concept of vulnerability is widely used in heritage studies beyond climate risk and approaches were the most divergent of any of the four terms. This ranged from holistic concepts of risk, i.e. a vulnerability assessment for a single site that incorporated multiple risk determinants (Nguyen et al. (2022) as an example), to community perceptions of the vulnerability of tangible heritage aspects and its links to intangible value (Henderson and Seekamp, 2018).

There are two determinants of vulnerability as defined by the IPCC: sensitivity and adaptive capacity. Sensitivity is often approached as a biophysical component and adaptive capacity as a social element; for example, the sensitivity of an archaeological deposit to increasing temperatures will be influenced by the amount of organic versus inorganic remains (Hollesen et al., 2017), while its adaptive capacity may be determined by the area's legal protection or status (Carmichael et al., 2018). Adaptive capacity can be part of the site's overall 'resilience', though resilience according to the IPCC is a broader concept emphasising the capacity of interconnected systems to adapt and reorganise to threats, while adaptive capacity is more site focused (IPCC, 2021) — a distinction not always made in heritage studies, for example Aktürk and Dastgerdi (2021). Sensitivity was more often studied than adaptive capacity and Fig. 2 summarises two different approaches: one, specifically dividing criteria into these sub-determinants (Gandini et al., 2020); while the other does not demonstrating that this separation is not always necessary (Carmichael et al., 2018). For a thorough discussion of adaptive capacity see Sesana et al. (2020).

Vulnerability is often determined by a series of criteria against which heritage can be assessed; in fact, the IPCC defines a 'vulnerability index' as "typically derived by combining, with or without weighting, several indicators assumed to represent vulnerability" (IPCC et al., 2022). Fig. 2 includes the criteria for two recent vulnerability indicators to demonstrate the divergent approaches for two heritage types: cultural sites and urban buildings. Climate change risk assessments for the natural environment use the same terms with a similarly diverse set of indicators. For example, in conservation biology drivers of species' adaptive capacity ranges from their genetic variation (Nicotra et al., 2015) to their response mechanisms such as "persist in place" or "shift in space" — a potentially useful dichotomy for heritage (Thurman et al., 2020). Determining sensitivity and adaptive capacity will vary depending on the type of heritage but current condition, protection measures, and level of resourcing are all important considerations. In the context of heritage climate change risk assessment vulnerability is determined by the heritage site's sensitivity to change (for example, damage processes) and the site's ability to cope with this change (such as the presence of staff or volunteers).

3.2.3. Exposure

Exposure is defined by the IPCC as:

> "the **presence** of people; livelihoods; species or ecosystems; environmental functions, services, and resources; infrastructure, or economic, social, or **cultural assets in places and settings that could be adversely affected** (IPCC et al., 2022, p. 2908)." [emphasis added]

Exposure was studied by 37% of the risk subset articles in the last five years, with 9% (*n*=12) using the IPCC definition. If the authors used a previous version of the IPCC risk framework where exposure is considered part of vulnerability, this was included as "IPCC". The scale of exposure assessments varied widely yet there were three ways that it was commonly defined: location, density, and value.

Geographical location is the most frequent mechanism to determine exposure in both the IPCC and Other risk assessment approaches. This includes qualitative statements, for example noting the location of certain building elements (Hay et al., 2019); quantitative site-level assessment — one study records the differing levels of mould growth on the north versus south facades (Choidis et al., 2021); and quantitative regional assessments, often by plotting site location(s) in a Geographic Information System (GIS) to determine the number of sites affected by changing hazards, commonly predicted sea level rise (Westley et al., 2021; Guiney et al., 2021; Garcia Sanchez et al., 2020).

The second approach considers site density: the number and type of heritage sites in certain locations determines overall exposure to the impacts of climate change (formally defined as quantity per area). For example, this could consider the placement of certain monument types, such as historical defences like pill boxes which are often located on cliff edges increasing their overall exposure to the hazard of coastal erosion. Or sites can be grouped by characteristic, such as motte-and-bailey earthworks which are geographically diffuse, to determine climate change impacts on single heritage type. While only one study using the IPCC exposure definition considered site density (Wang et al., 2022), others using alternate definitions took similar approaches (ORourke, 2018; Westley et al., 2021).

Sensitivity indicators for rock-art sites	
Sensitivity	**Example Indicator**
Nature of the remains	Rock art - ochre type
Nature of the substrate	Rock art - rock hardness
Nature of the protection	Rock art - rock overhang
Built protection	Fence - effectiveness
Legal protection	Site is on: (a) Indigenous owned land (b) listed under heritage protection legislation

Sensitivity and adaptive capacity indicators for buildings	
Sensitivity	**Example Indicator**
Current situation	State of conservation
Constructive	Ground floor typology
Envelope	Openings on the ground floor
Criticality	Use
Structure	Structural material
Adaptive Capacity	**Example Indicator**
Interventions	Drainage systems
Socio-economic	Previous interventions
Cultural	Cultural value

Fig. 2. Comparison of two criteria for vulnerability assessments for rock-art sites (Carmichael et al., 2018) and buildings (Gandini et al., 2020).

The third approach assesses heritage value or significance as part of exposure and was the least common way of approaching the concept. Since exposure is defined as the presence of cultural assets, the cultural value of these places or parts of them (for example, exterior decoration) is also a factor. This may be considered by only analysing climate risk to sites designated as significant or specifically creating value assessments for aspects of the site, which is how Safeguarding Cultural Heritage through Technical and Organisational Resources Management (STORM) defines exposure (Ravankhah et al., 2019).

Studies specifically considering exposure (whether using the IPCC definition or not) approach the concept similarly either through location, density, or significance. In the context of heritage climate change risk assessment exposure is determined by the presence of the cultural asset which includes not just the physical location, but the heritage type, the density of sites and site types, and the significance of elements or places.

3.2.4. Response

Response was added to the IPCC framework in the most recent report (AR6) and does not yet have its own official IPCC definition; currently the concept is embedded into the overall risk definition:

> "In the context of climate change responses, risks result from the potential for such responses not achieving the intended objective(s), or from potential trade-offs with, or negative side-effects on, other societal objectives [...]. Risks can arise, for example, from uncertainty in implementation, effectiveness or outcomes of climate policy, climate-related investments, technology development or adoption, and system transitions (IPCC, 2022, p. 2921)."

This includes actions (or lack of actions) that could directly or indirectly change the level of risk, such as maladaptation when deliberate adaptation measures increase risk (Andrews et al., 2023). In the historic environment, this could be the addition of a roof to protect sensitive aspects of a site from intense precipitation that leads to increased humidity and mould growth (Schulze and Moreno-Triana, 2014) or the presence of a storm-water tunnel that diverts flood water decreasing overall risk to traditional buildings in Kuala Lumpur (DAyala et al., 2020). These are not aspects intrinsic to the heritage site, but reactions to anticipated or observed impacts of the environment (potentially caused and exacerbated by climate change) that modulate overall risk.

No study in the risk subset specifically cited the IPCC response risk determinant. However, considering the timeline of this review's search (until December 2022) and the integration of response by the IPCC in late 2022, this is not unexpected. Overall, 7% of the studies engaged with the concept, most often looking at the impacts of energy retrofits on historic buildings, making it the least studied risk determinant. There is overlap between vulnerability's sub-determinant adaptive capacity and response. For example, in the case of retrofits, the results of retrofit might increase the site's adaptive capacity and reduce overall vulnerability, but the action of the retrofit itself is a response to the changing climate. It is one of the more challenging determinants to include, but rightly acknowledges the dynamic process of risk assessment creating space to consider how climate change mitigation and adaptation impacts risk (Andrews et al., 2023; Simpson et al., 2021).

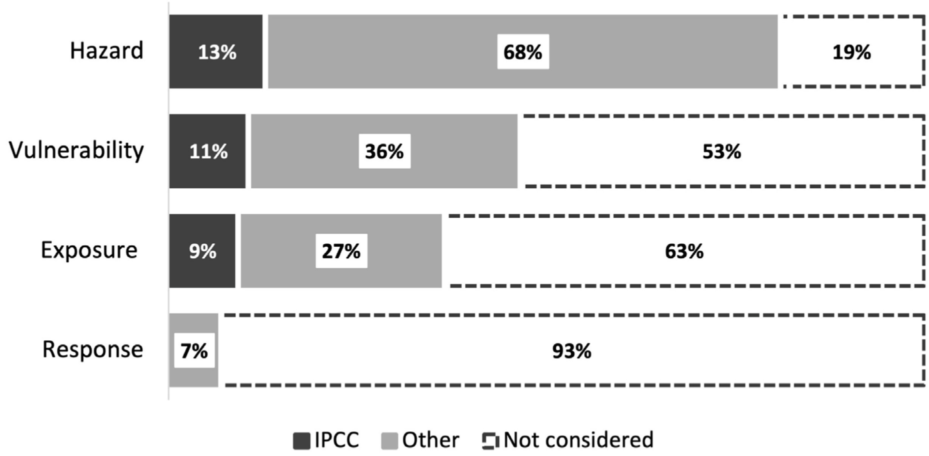

Fig. 3. The number of articles from the risk subset (*n*=131) between 2017 and 2022 using either the IPCC terminology (IPCC), engaging with risk determinant concepts and/or using alternate definitions (Other), or not considering the determinant (Not considered).

3.3. *Use of the IPCC risk framework*

Some previously developed risk frameworks for cultural heritage have used the IPCC terminology: the Cultural Heritage Risk Index developed in Australia sees hazard, vulnerability, and exposure as components of risk (Forino et al., 2016) and the Climate Vulnerability Index (CVI) developed for the rapid assessment of World Heritage Sites adapts the previous AR4 vulnerability framework (Day et al., 2020, 2022). Others have specifically advocated for the use of the IPCC climate change risk terms in heritage (Simpson et al., 2022c) and aligning risk assessment approaches with the IPCC has three key benefits: it creates a pathway for heritage to be integrated into future climate change assessment reports; it facilitates interdisciplinary collaboration — these terms are commonly used in other fields, for example Terzi et al. (2019); and it aids comprehension and comparison within heritage science.

While the use of the IPCC terminology for heritage risk assessments has increased over the period reviewed (2017–2022), comparatively few studies in this review explicitly reference the IPCC determinants: 13% for hazard, 11% for vulnerability, 9% for exposure, and 0% for response (Fig. 3). However, these concepts are being studied whether the term is used or the IPCC definition cited — for example, studies using site placement as a risk factor but not calling it ‘exposure’. Overall, climate hazards are studied the most (81%), followed by vulnerability (47%), exposure (37%), and response (7%). Articles that explicitly cited the IPCC terminology were more likely to consider two or more risk determinants (usually exposure and vulnerability). No other single risk framework was used as often in holistic risk assessments, although the International Organization for Standardization (ISO) risk management standard and the Sendai Disaster Risk Framework were used in natural hazard assessment (for example, United Nations, 2016; Rodriguez-Rosales et al., 2021; Rosso et al., 2022), with Sendai sometimes referenced in the climate change context (Gandini et al., 2018).

3.4. *Multi-determinant risk assessments*

From 2017 to 2022, 16 studies from the reviewed cohort (13 peer reviewed articles, two reports, one web resource) conducted climate change risk assessments for cultural heritage that substantively considered two or more risk determinants, over half of which (*n*=9) used the IPCC framework (though six used the earlier AR3 or AR4 reports which conflate risk and vulnerability). These 16 risk approaches are presented in the supplementary material. The identified frameworks were either specifically looking at climate change projections to determine hazard and incorporating aspects of vulnerability and exposure; or focusing on vulnerability and exposure with climate change hazards as the driving force behind potential impacts.

3.4.1. *Methods for representing determinants*

Four prevalent approaches for calculating representations of the determinants were identified (Fig. 4):

- **Descriptive** — qualitative descriptions used to characterise determinants. For example, when determining adaptive capacity, site leadership can be classified as “a trust is managing the site and it is encouraging social responses” or “the managers are recognised by the community” (Sesana et al., 2020).
- **Ranked** — uses a ranked scale. Either with simple written phrases such as Likert scales – for example the CVI’s exposure assessment which ranges from ‘not likely’ to ‘very likely’ (Historic Environment Scotland, 2019) – or using a numerical range, for example, in ProteCHt2save where site planning is ranked from zero to three with the lowest level corresponding to ‘no resilience and risk management plan’ (Bonazza et al., 2021). Ranked approaches may also employ a traffic-light colour system.

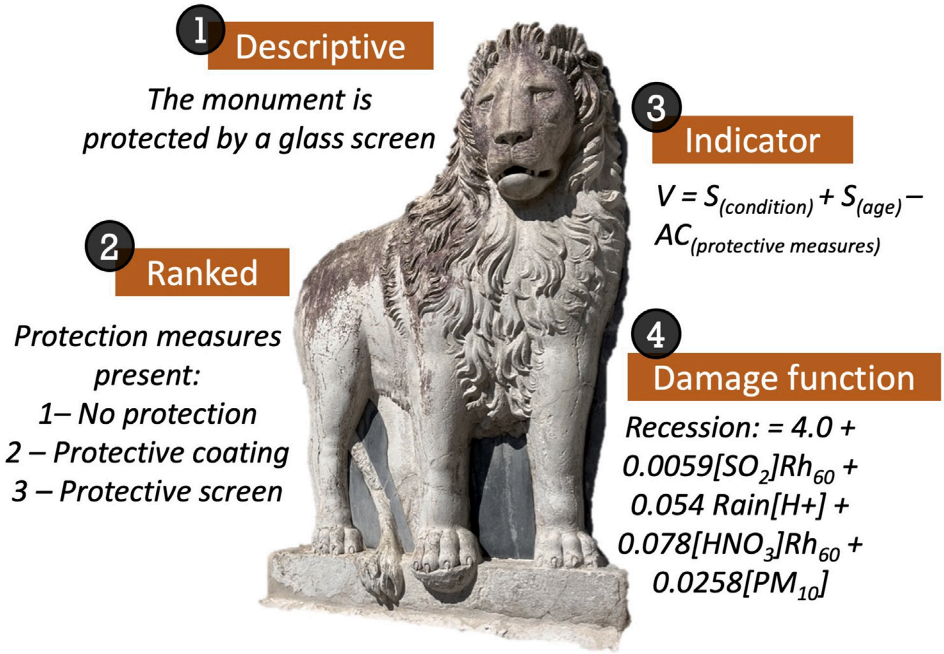

Fig. 4. Examples of each approach: a descriptive sentence describing hypothetical protection measures; a ranked series with escalating levels of protection; an indicator where vulnerability is determined through sensitivity minus adaptive capacity; and a damage function for the recession of Portland limestone from Bartolini et al. (2022).

- **Indicator** — creates a component for each sub-determinant combining them to obtain an overall representation of the variable. The complexity of these indicators vary widely, for example in a study of precipitation risk the age and material of listed heritage in China is divided into categories with the material sensitivity weighted more heavily in the final equation (Wang et al., 2022).
- **Damage function** — using a equation that simulates potential damage, usually determined through experimentation. An example of this is the Revised Universal Soil Loss Equation (RUSLE) which is used to evaluate the amount of soil loss per year and thus calculate the increasing exposure of archaeological sites (Angeli and Battistin, 2021).

The first two methods (descriptive, ranked) are usually qualitative or semi-quantitative. They are straightforward approaches that facilitate easy data collection and comprehension, but ranked or ordinal scales have limitations. Unlike data with intervals or ratios, ordinal datasets do not have fixed distances between the ranks meaning that while some positional measurements like median values can be determined (though interpretation of the median may be difficult), mean or standard deviations cannot be calculated (Agresti, 2010). This hinders the comparability (to other sites) and scalability (to multiple sites) of the analysis.

The second two approaches (indicator, damage function) are always quantitative and are primarily used to determine vulnerability and exposure. In the CLIMA project that uses RUSLE the outcome is simplified into a ranking from zero to three (Angeli and Battistin, 2021), but damage functions can be used to link the potential risk of the determinant to its consequence for cultural heritage (Strlič et al., 2013) — this is explored further in Section 4. While all four approaches have their strengths, differing data sources will determine which approach is appropriate, and if determinants can be combined to calculate risk.

3.4.2. Combining determinants

Combining determinants is usually done quantitatively to create an overall risk score. Many risk assessments decide that hazard, vulnerability and exposure indicators contribute equally to the overall metric. However, some more nuanced approaches weight the various factors; in the approaches reviewed, this is either determined internally by the authors or externally by consulting sector experts. An assessment of future precipitation impact for Edinburgh World Heritage Sites interviews practitioners to inform their five-point damage function (O'Neill et al., 2022), while Gandini and colleagues (Gandini et al., 2020) use the MIVES methodology (the Spanish acronym for The Integrated Value Model for Sustainability Assessment) and expert consultation to determine that building criticality (i.e. the relative impact of the building being unusable for a period of time) will have the highest impact on a site's vulnerability. Both of these examples are for historic buildings, and while there are no standards for weighting indicators for specific types of cultural heritage, there is considerably less scholarship for archaeology (Angeli and Battistin, 2021; Nakhaei Ashtari and Correia, 2022) and cultural landscapes (Ducusin et al., 2019).

3.4.3. Incorporating heritage significance into multi-determinant frameworks

Heritage value is incorporated into holistic climate change risk assessments in multiple ways; firstly, the act of conducting a risk assessment (especially labour-intensive site specific ones) assumes the site has value. Secondly, value can be considered before the risk calculation. The CVI (Day et al., 2020), Adapt Northern Heritage (ANH) (Boro and Hermann, 2020), and an assessment of World Heritage Sites (Sesana et al., 2020) all identify site values as the first step of their assessments which then informs the magnitude of potential impacts; for example, ANH dedicates a first step to defining the significance of historic places on a four-point scale (Boro and Hermann, 2020). Finally, there are risk assessments for cultural heritage that directly include significance as part of the framework and this is considered as drivers of both vulnerability and exposure.

As previously stated, vulnerability can be represented through sensitivity and adaptive capacity. Adaptive capacity is primarily a social concept and for heritage is often equated to the protection level given to certain types of heritage; for example buildings designated as special interest or nationally significant may have a higher adaptive capacity and lower overall risk (Miranda and Ferreira, 2019). However, sites may be perceived as significant by their community and not be designated or sites (or site aspects) may not be vulnerable to the impacts of climate change. For example, there may be physical protections, such as display cases, or the value may be intangible and less integrally connected to material form. This is one of the reasons it is more appropriate to consider heritage significance as part of exposure, since exposure is determined by presence which does not necessarily need to have a physical manifestation.

The valued aspects of sites (or the sites themselves) are "the presence of cultural assets" to which the IPCC exposure definition refers. One example of how relative significance becomes a determinant of exposure is a study in which exposure is a function of provincial versus national site density (Wang et al., 2022). Sites that are designated on the national heritage list are considered as having four times the value than those that are provincially listed; while a simple value judgement (and easily contestable by those who may not see local heritage as 75% less significant) it provides a mechanism to quantitatively represent significance in a broad risk assessment method. STORM also considers value as part of exposure and assesses sites and their intangible elements on a five point scale for nine categories: aesthetic, architectural / technological; historical; archaeological; economic; educational; scientific; social; and environmental (Ravankhah et al., 2020).

3.4.4. Scalability of assessments

Three of the strongest frameworks for site-level assessment are STORM, ANH, and the CVI. STORM is one of the few with a clear hazard definition and methodology for prioritising hazards (Ravankhah et al., 2019). ANH has three levels of assessment requiring increasing levels of resources creating flexibility for site management (Boro and Hermann, 2020). The CVI is very effective for what it was created to do: swiftly assess the vulnerability of World Heritage sites and associated communities, though its focus on only three hazards limits its scope. All three integrate heritage significance, though the time-intensive nature of the data collection and the commendable emphasis on community vulnerability makes their approaches difficult to scale to multiple sites.

In recent years, assessment methods have been developed for multi-site scales: ProteCHt2Save advances hazard map creation for central Europe, creating accessible hazard maps on a 12 km x 12 km scale (Bonazza et al., 2021). This is combined with site-level vulnerability assessment (called 'criticalities') and represents a common approach which combines landscape-level hazard mapping with individual site assessment (Canesi et al., 2024). A precipitation risk assessment used in the Chinese context is the closest to providing a framework that can be applied to thousands of places simultaneously, in this case over 28,000 sites (Wang et al., 2022). Their approach follows the AR6 IPCC risk framework with determinants clearly defined and combined. Elements are missing: response, adaptive capacity, exposure as site location, and heritage significance beyond provincial versus national sites, but it represents a promising step forward for the field.

4. Discussion

To supplement the bibliometric review, which has been the focus of the above sections, a broader consideration of the opportunities, challenges, and needs for cultural heritage climate change risk assessment follows. Some of the main challenges are illustrated in Fig. 6.

4.1. Risk frameworks and scale

One of the strengths of the IPCC risk framework is its scalability; the same determinants (hazard, vulnerability, exposure, and response) could be applied to assess climate risk for a single stone tool in a collection to its site of manufacture to the wider prehistoric landscape. Currently, assessments are primarily developed for single sites, with some looking at multiple sites, with fewer frameworks applicable to thousands of sites or a nation's heritage.

The advantages of site-level assessments is the ability to gather new data, such as the current condition of the site, and to engage with the associated communities. Previously identified barriers to risk assessment for cultural heritage – for example, lack of data, data quality, resources, access to technology and skills – are likely contributing to this site-level imbalance where thorough data gathering is more feasible (Crowley et al., 2022). While a unified approach to site-level assessment would allow comparison across sites, localised assessments cannot determine the risk climate change poses to regional or national heritage nor provide a method for identifying areas or heritage types that are particularly at-risk. Furthermore, heritage that is not single site-specific (cultural landscapes) or is harder to access or accessed by remote sensing technologies such as marine or polar heritage requires a landscape-level approach. Some of the strength and weakness of the two scales are summarised in Table 1.

Table 1
Strengths and challenges of two different scales of climate change risk assessment for heritage.

Scale	Strengths	Challenges
Site-level	Can be easily tailored to the characteristics of the site	Can be resource intensive
	Easier to incorporate different types of data (i.e. for significance)	Inconsistency in approach across sites makes it hard to make comparisons
	Communities and stakeholders can be involved	Cannot inform regional planning
Multi site-level	Can be integrated with other datasets, particularly geospatial data	Data quality and availability
	Can support large-scale planning and policy decisions	Often requires technical knowledge
	Able to consider the whole of the historic environment	Cannot be used for site-level decisions

Table 2
The evolution of the IPCC risk determinants and frameworks.

Report	Year	Overall concept	Determinants
AR4	2007	Vulnerability	Exposure, Sensitivity, Adaptive capacity
SREX	2012	Risk	Hazard, Vulnerability, Exposure
AR5	2014	Risk	Hazard, Vulnerability, Exposure
AR6	2021–22	Risk	Hazard, Vulnerability, Exposure, Response

At the landscape level, governmental departments or management bodies that steward both natural and cultural environments could be ideal places for the creation of an integrated climate change risk assessment that places heritage in its wider context — especially considering the artificiality of the nature culture divide in the age of the Anthropocene (Lowenthal, 2005; Harrison, 2015). One example of this combined approached is the Cultural Resource Environmental Vulnerability Assessment Toolbox (CREVAT) developed for the central US National Parks Service. Regional level assessments are not reflective of the risk to individual sites – site-level assessment will always be more accurate for a single place – but the resource-intensive nature of site-level assessment and the need to inform regional disaster resilience planning means there has to be a method to look at risk at a coarser, more representative, scale. Using consistent terminology is one step towards effectively scaling risk approaches.

4.2. The evolution of the IPCC risk framework and clarification of terms

The IPCC climate change risk framework evolved from a standalone vulnerability assessment and the changing terminology over the past 20 years is summarised in Table 2. Within IPCC publications, vulnerability was considered as a 'social construct' of risk with sensitivity and adaptive capacity sufficiently representing these complex social processes (Field et al., 2012; Oppenheimer et al., 2015; Ishtiaque et al., 2022). In the 2012 SREX (Field et al., 2012), the IPCC adopted a risk approach rather than vulnerability, integrating climate change adaptation and disaster risk reduction, emphasising the importance of determining likelihood, and placing hazards – as the cause of most climate change impacts – firmly within the framework (Zebisch et al., 2017). There have been critiques of this shift (Ishtiaque et al., 2022); the foremost one for heritage is that useful vulnerability indices for cultural heritage were built on this earlier framework such as the CVI (Day et al., 2020), and others, such as UNESCO's Flood Vulnerability Index, which have been productively applied to heritage sites (Nguyen et al., 2022).

While the criticisms of this shift from vulnerability to risk has its merits, there must be a certain flexibility to change with international climate science directions rather than using outdated terminology, perpetuating miscommunication, and hampering interdisciplinary collaboration. Although not specific to heritage, several examples demonstrate how vulnerability assessments can be adapted to align with the IPCC risk framework through clearer conceptual definitions (Zebisch et al., 2017; Das et al., 2020; Zebisch et al., 2021; ISO, 2021). Adapting the CVI in a similar way could be highly beneficial for the field.

There is a continued conflation of risk and vulnerability in the articles reviewed, with many conducting a vulnerability assessment with multiple determinants making it comparable to a risk assessment, despite it being over 10 years since the IPCC adopted a risk approach. The significant difference between these two methods is the promotion of exposure from a factor of vulnerability to its own determinant. The IPCC states that exposure is a "necessary [..] determinant of risk" since it is possible to be exposed but not vulnerable to climate change (i.e. have sufficient means to respond to potential impacts) (Cardona et al., 2012). It matters whether exposure is considered as part of vulnerability or if exposure is a separate risk modulator that can act upon vulnerability and response.

How to approach the IPCC exposure definition is worth exploring since in heritage risk assessments there is often a conflation of exposure and hazard, with the colloquial use of 'exposed' or 'very exposed' to mean unsheltered, causing confusion. Exposure has been defined similarly to vulnerability – "the degree to which a given resource is expected to be affected by a stressor, threat, or

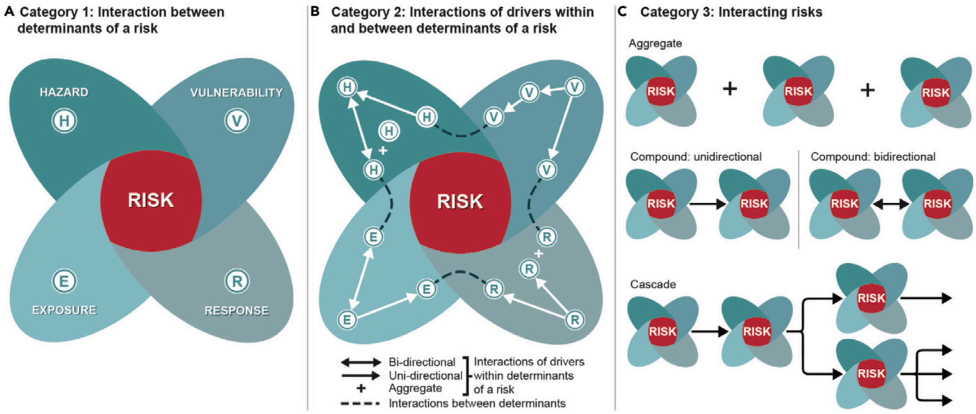

Fig. 5. Increasing complexity of climate change risk assessments (Simpson et al., 2021, p. 493) CC BY 4.0.

hazard" from the US National Parks Service (Peek et al., 2022, p. 127) – and hazard: "Exposure refers to the climatic conditions that can negatively impact on the cultural assets and it is thus considered to encompass all potential climate change related risks" (Sesana et al., 2020, p. 213). The actual IPCC exposure definition, "the presence of [...] cultural assets in places and settings that could be adversely affected" (IPCC et al., 2022) means the elements that are at risk. To give an example from O'Neill and colleagues' work on rainfall risk, Edinburgh's location (exposure) means that it experiences a certain number of heavy precipitation days, however, the definition of a heavy precipitation day and the frequency of these days for Edinburgh is part of the hazard assessment (O'Neill et al., 2022). What the future increase of heavy precipitation days (hazard) means for the potential material damage is determined by location (exposure) and sensitivity and ability to respond (vulnerability).

The promotion of exposure is one of the main shifts from the vulnerability to the risk approach and provides an opportunity to incorporate significance into climate risk assessments, a necessary step in a value-driven field. Any assessment of heritage significance must be conscious of the wider heritage ecosystem: for example, an exposure assessment of the Romanesque Pòrtico de la Gloria at Santiago de Compostela, Spain (Becherini et al., 2013) could consider the significance and placement of the medieval stone carvings, the location of other Romanesque porticos on the pilgrimage route to Compostela and their risk levels, and even whether the plaster copy in the Victoria and Albert Museum, London lowers the original's exposure and adaptive capacity since it serves as a record of the portico. The consideration here is what other factors might change the value ascribed so questions of uniqueness, scarcity, and the mitigation of potential impacts are all drivers. While some of these are impossible to quantify, in a holistic exposure assessment these are all contributors to overall risk. This concern with valued aspects is one way that heritage climate change risk assessments may differ from other forms of assessment, such as building performance, and why heritage-specific frameworks are necessary.

4.3. Uncertainty in climate change risk assessments

Risk assessments can work by representing the heritage site, or material, as a system where the impacts of external factors, such as the climate, are known and measurable. However, the conclusions will always have an element of uncertainty and there are various ways of communicating this, from error bars to the confidence statements used by the IPCC. Confidence statements signify the level of uncertainty in the evidence or in the understanding of how the system functions (Mastrandrea et al., 2010). IPCC authors are advised how, and if, they can attribute these confidence statements based partially on descriptions of the variables. These range from "variables are ambiguous, or the processes determining it are poorly known or not amendable to measurement" where confidence should not be assigned, to "a probability distribution or a set of distributions can be determined for the variable either through statistical analysis or through use of a formal quantitative survey of expert views" where 'very high' levels of confidence could be assigned (Mastrandrea et al., 2010). The IPCC, however, does not integrate the methods of other disciplines for determining uncertainty, an issue raised by social science contributors (Kause et al., 2022). The recent inclusion of Indigenous and traditional ecological knowledge in AR6 shows it is possible to consider the risks to heritage without confidence statements (IPCC et al., 2022, p. 1330–2). However, for incorporating heritage into climate change risk models it is important to explore how confidence is attributed and the key questions this type of attribution raises for cultural heritage: first is it possible to develop risk assessments for heritage where high levels of confidence can be assigned to the outcome; and second, is it even desirable to do so in a value-laden field like heritage?

Current climate change risk assessment tools for cultural heritage are relatively simplistic when compared to the three levels of complex climate change risk assessment proposed in Simpson et al. (2021). They increase from: "(1) only a single driver for each determinant of risk, (2) multiple interacting drivers within determinants of risk, and (3) interacting risks" (Simpson et al., 2021) (Fig. 5). For heritage, this relative simplicity is understandable considering that deep uncertainty, described as "processes for which robust probability distributions do not exist" (Rising et al., 2022), is widespread in historic environment risk assessments.

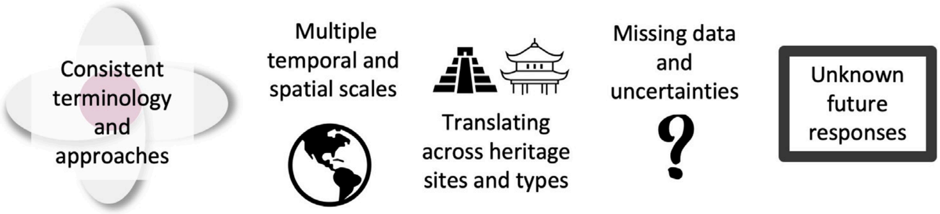

Fig. 6. Some of the main challenges identified for multi-determinant holistic climate change risk assessments for heritage.

Kohler and Rockman explore how the attribution of causal archaeological conclusions might be validated statistically to meet IPCC requirements and conclude that it is possible, but places heavy demands on the field (Kohler and Rockman, 2020).

It is useful to think what this might look for one specific part of climate risk assessments, the interaction between hazard and vulnerability. Damage functions for heritage, which are ways of defining unacceptable levels of change exist for some materials, for example paper (Strlič et al., 2015a,b,c). The point at which damage becomes unacceptable is dependent on both the heritage object or site and its audience — see Bartolini's work on acceptable rates of deterioration (2022) and research on the public perception of unacceptable levels of stone discolouration (Brimblecombe and Grossi, 2005; Grossi and Brimblecombe, 2004). These functions provide a tool for predicting the interaction of environments and materials, but this could be just one material (of many) on a heritage building or in a collection, climate hazards are going to have an impact which may compound this damage (hazard), different settings – especially exterior versus interior – are going to experience differing intensities of the event (exposure), and pre-existing damage (vulnerability) may exacerbate degradation. Not all climate change risk assessments need to be this detailed, this depends on the decisions it informs and the resources of those responsible, but expanding existing damage functions and degradation pathways is one way to meet the validation requirements for attributing confidence.

Aiming for this level of statistical certainty, however, will never account for the fact that heritage and heritage values are dynamic processes, shaped by context and community (Fouseki, 2022). The uncertainty discussed above acts internally within the modelled system, but there are external contingencies which are harder or impossible to model (Shepherd et al., 2018). This is partly addressed by the addition of 'response' to the AR6 risk framework which creates the space to consider direct and indirect actions that increase (or decrease) climate change risk, such as flood defences or government inaction. However, this will still not fully account for the human element in risk. There is a reason that those in material culture studies might despair at the idea of engaging with "deterministic" attribution considering the post-processual turn since the 1980s away from derivative behavioural models, neglectful of social contexts, to placing emphasis on the agency of cultural heritage to transform, rather then merely reflect, social interactions (Hodder, 2009; Hicks, 2010; Kohler and Rockman, 2020). Anthropogenic climate change will cause heritage loss and damage. Complex risk assessment models must be developed to prepare for, respond to, and prevent, this loss. But these will never be able to account for the experience of loss, for how this will change and challenge a community, and for the unpredictable responses to the loss itself.

4.4. Time and risk assessments

One of the motivators for developing specific climate change risk assessments, rather than using pre-existing natural hazard ones, is the timescale of future projections. To prepare for the impacts of increasing global temperatures, future climate hazards are calculated in different emission and warming scenarios often ending arbitrarily in 2100 (see Orr et al., 2021 for the most studied time periods). However, this means that at the core of climate change risk assessments is a compression of time where current condition must stand in for future condition. This gap assumes that heritage sites are stable, that constituent parts can be classified and analysed, despite risk frameworks inherently modelling change (though no change can still mean damage). Present condition may be indicative of future condition, but it is also representative of past exposure, vulnerability, hazard, and response. A site's current good condition may lead it to having a low risk score, yet a withdrawal of resources (such as climate-change induced migration of local communities) may drastically change the vulnerability of the site. In fact, there is a case to be made that the most at-risk sites to the impacts of climate change are non-designated heritage sites, since at least for designated heritage there is a record of its existence and some evaluation of its significance.

The historic environment has always been in flux and approaching heritage as a process has been suggested as a way of meeting the challenges of climate change (Khalaf, 2021). Proactive loss management strategies such as "adaptive release", where cultural values are maintained as natural processes take place, recognise the shifting nature of heritage (De Silvey et al., 2022). The conflation of future, present and past is necessary for climate change risk assessment to function, though despite thorough engagement with heritage loss there is no sustained attention to climate change in recent heritage futures scholarship (Harrison et al., 2020; Holtorf and Högberg, 2020). Considering their fruitful exploration in other fields, core questions concerning adaptation, time perception, and behaviour change deserve more attention in heritage studies (Pahl et al., 2014; Weber, 2006). One potential solution to communicating this flux is the narrative approach where storylines of possible climate futures can be created (Shepherd et al., 2018). These stories are not predictions, they are possibilities, and this complements the often intuitive nature of risk assessment.

Table 3
Requirements for comprehensive risk assessment (Romao et al., 2016) against the IPCC risk determinants.

Ramão et al's framework	IPCC terms
Reliable and sufficient data to establish suitable hazard models	Hazard
Sufficient and reliable data on the assets under risk	Exposure, Response
Suitable procedures to model the vulnerability	Vulnerability
Adequate models to predict the multidimensional consequences of the hazardous event	*Compounding, cascading risks*
Sufficient human, time and economic resources	Vulnerability, Response

4.5. Data requirements for holistic risk assessments

In a 2016 article Romão and colleagues (Romao et al., 2016) identified five key elements for creating comprehensive risk frameworks (not specific to climate change) for cultural heritage. These are useful prompts from which to explore the data required for holistic risk assessments and they have been mapped onto the IPCC risk determinants in Table 3.

The availability and quality of the data (points one to four) are essential for effective risk assessment with data types, accessibility, quality, and consistency as important considerations. However, even with complete datasets, the sufficient resources required for data analysis will always be a limiting factor (point five). To combat this, it is perhaps more feasible to invest in refining large-scale hazard mapping, leaving exposure and vulnerability assessments to be done on-site. However, this has been the approach of the field thus far and it rarely addresses non-designated, lower profile sites nor is it feasible for multi-site assessment. All assessments are limited by data quality, and it is a challenge for the field to explore how scalable risk assessments for climate impacts can meet these five requirements.

4.5.1. Using climate change projections

Hazard analysis is usually done with climate projections, often referencing a future timeline and emissions scenario against a baseline historical period (Cassar, 2005; Kotova et al., 2019; Sardella et al., 2020). Uncertainty is inherent in climate modelling (Lu et al., 2021; Vandemeulebroucke, 2023), with a recent review of 132 studies that look at uncertainty and future weather generation concluding that uncertainties are chronically under-represented (Gaarder et al., 2023). Compounding this is the need to downscale projections to represent the micro-climate of a single site; for example, in the UK the UKCP18 projections have been down-scaled to 1 km grids at their finest resolution introducing further uncertainties (Robinson et al., 2023). These uncertainties make it particularly difficult to predict the change in extreme events (Trenberth et al., 2015), and as a comparison of actual versus predicted damage post-Hurricane Maria on coastal archaeology in Puerto Rico has shown, damage may be much greater than expected (Rivera-Collazo, 2020). Any analysis based on climate projections must be aware of: the scale of the projections, how uncertainty is represented, the missing risks of compounding and cascading hazards, and the methods for combining hazard with exposure, vulnerability, and response. Despite the need for continued assessment and communication of climate data uncertainty, the relative sophistication and statistical grounding of large scale hazard mapping must be matched by vulnerability and exposure assessments to facilitate integration of multiple risk elements. Until this is done, the divide between the two main approaches to climate change risk assessments – large scale hazard maps and site-specific holistic assessment – will continue.

4.5.2. Data about heritage

One of the limitations of assessment effectiveness is the availability of information on heritage sites, especially its coverage and quality. It is one step to develop rigorous climate change risk assessments, but their successful implementation depends on existent datasets. For example, can STORM's nine criteria for exposure (heritage value as aesthetic; archaeological; economic; educational to list a few) be assessed without a visit to the site and its surrounding historic environment? And if not, can these complex elements be represented, even partially, from existing datasets or producible datasets in the era of climate-change induced loss? Furthermore, how can the types of heritage that have not been traditionally recorded in heritage datasets be included? Some solutions come from looking beyond heritage-specific data such as building stock models through which all pre-World War I buildings could be assessed whether designated or not (Steadman et al., 2020); citizen-science research methods to update and add to current understandings of heritage sites (Dawson et al., 2020); engaging with passionate local community groups, such as the Milestone Society who record milestones across the British Isles; and using crowd sourced data to monitor change (Liu et al., 2022).

Non-designated cultural heritage is rarely considered as part of climate change risk assessments. It is easier to work with designated heritage records which lend themselves to the type of analysis required, and arguably contain an inherent judgement of significance with the status of designation. However, the historic environment is more complex than what is officially protected. There are communities whose heritage is under-represented or resists traditional recording practices — intangible aspects of cultural heritage being the obvious example. And while there has been recent attention paid to the fact that climate change will affect Indigenous heritage in more profound ways because of the integral relationship to the land (Higgins, 2022; Orlove et al., 2022), the threat to these vital landscapes are also not considered thoroughly in current climate change risk assessments. The concept of Authorised Heritage Discourse is useful here for thinking of what has historically been valued, and by whom, and thus included on official lists (Smith, 2006). In fact, the concept of 'heritage at risk' has been challenged for its focus on certain values, such as preservation over change and decay, and the types of heritage which are more easily labelled as at-risk (tangible over intangible) (Rico, 2014, 2015). The context behind the creation of any heritage dataset will determine the applicability and relevance of the analysis it informs, and questions of representation are just as important as the more-often-noted practical and technical ones.

5. Conclusion

This review has been concerned with how multi-determinant risk assessments for heritage define and combine drivers of risk, with a particular focus on the use of the IPCC risk terminology. Climate change risk assessments for heritage must not just solely map the absolute or relative changes in projected hazards. To be useful they must also consider the associated communities, the wider social and political context that informs both the extent of these impacts and the response, and the capacity of heritage sites to cope and adapt. There is no single scalable risk framework for cultural heritage that considers all of these determinants, however, some methods come close and represent important steps forward for the field. Furthermore, the thorough risk assessments that exist for individual sites and evolving methods for large-scale hazard mapping show the way towards a scalable assessment for cultural heritage that could provide the confidence for evidence-based decisions that is so sorely missing.

Generally, current climate change risk assessments for cultural heritage:

- look at single hazards and their impacts, however climate change hazards and impacts are compounding and cascading.
- consider multiple aspects of risk but only at the site-level, and yet climate change transcends boundaries and heritage is part of a wider ecosystems of sites and communities.
- or are multi-site in scale but focus on hazard assessment, despite the fact that current condition, community involvement, heritage values, protection status, and the wider climate response – or lack of it – are all powerful risk modulators.

Mitigating and adapting to climate change should not be seen as an existential challenge for the protection of the historic environment. There will be significant loss, but there are also heritage-based solutions to the climate crisis — embodied carbon stored in existing structures, treasured sites as drivers of climate action, carbon sinks in protected landscapes, and evidence of millennia of past climate adaptation. Exploring how climate risk can be determined for value-driven fields such as cultural heritage pushes forward holistic (and necessary) understandings of climate breakdown, not just for historic landscapes but for all environments. Climate change has already contributed to the destruction of natural and cultural heritage and thorough multi-determinant risk assessment methods for the entire historic environment (from materials to sites to landscapes) must be developed in response. This will further understandings of the cumulative impacts of climate change, identifying the resources required to sustainably manage heritage for the future and informing the difficult decisions climate change poses for the continued stewardship of the past.

CRediT authorship contribution statement

Helen Thomas: Writing – original draft, Investigation, Conceptualization, Writing – review & editing, Methodology, Formal analysis. **Valentina Marincioni:** Writing – review & editing, Methodology, Supervision. **Scott Allan Orr:** Supervision, Funding acquisition, Writing – review & editing, Methodology, Conceptualization.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary data

Supplementary material related to this article can be found online at https://doi.org/10.1016/j.crm.2025.100727.

Data availability

Data will be made available on request.

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