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Working with Nature in the Conservation of Stone Heritage: Towards Resilience and Sustainability

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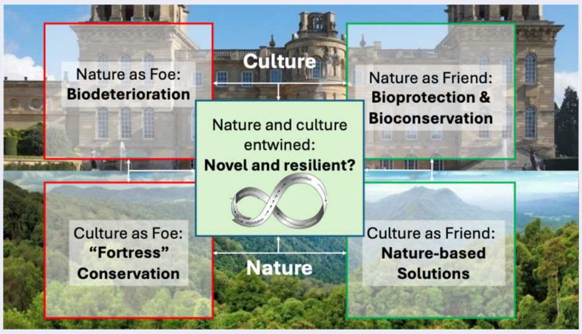
ABSTRACT
There have been many recent discussions about how to link nature conservation more effectively with heritage conservation (including the conservation of stone heritage). These discussions have many historical antecedents and are also a product of today's cultural, economic, social and environmental climate. Building on ecological approaches, this paper develops an adaptive systems framework with which to conceptualise the multiple links between natural and cultural heritage conservation with a focus on stone heritage sites. In particular, this paper addresses the question of how stone conservation can take on board ideas of ecology, adaptive systems, sustainability and resilience to improve the conservation not only of the stone objects themselves but of the people and environments that surround them. Four categories of interactions are identified to account for the ways in which nature growing on and around stone heritage sites interacts (both positively and negatively) with the stone, as well as the ways in which the stone heritage site influences nature on and around the site (positively and negatively). A number of empirical, theoretical, policy and practical challenges to adopting such an approach are explored, and some priorities for the future identified. Working with nature in the conservation of stone heritage necessitates an interdisciplinary and holistic approach and requires the acceptance of a more dynamic future for stone heritage and the nature which surrounds it.



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Introduction

In recent years there has been an explosion of interest in rethinking and rebuilding the interrelationships between nature and culture. How humans interact with their environment is a core concern for environmental science, geography, architecture and many other disciplines. Improving these interactions is vital to ensuring a better global future. Within the sphere of heritage research there have been many attempts to reconsider and critique how and why nature conservation (including measures to support biodiversity) might be more effectively linked to heritage conservation (e.g. Taylor and Lennon 2011; Harrison 2015; Bridgewater and Rotherham 2019). Concepts such as cultural landscapes, biocultural diversity and biocultural heritage have been formalised and debated to focus attention on linkages between nature and culture. Policies at national and international level (such as the UNESCO-SCBD Programme on Linking Biological and Cultural Diversity) have been developed to support integrated management of sites with both natural and cultural elements. Despite these advances, there are many challenges involved in implementing such policies at the scale of individual buildings and sites. In particular it is difficult to relate the sometimes complex theoretical issues to the specific challenges facing the conservation of built heritage in today's changing world. After reviewing some of the historical and theoretical background, this paper explores the complex

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interrelationships between nature and culture at the level of stone heritage, introduces a simple conceptual framework based on adaptive systems, and engages with some key challenges and future priorities which will allow stone conservation to work more effectively with nature.

Historical and theoretical backgrounds

A huge array of heritage buildings and sites around the world are built from natural stone or carved into natural rock. Clearly, these materials are both products of, and parts of, nature. However, the act of human creativity which converts them from inert parts of the physical landscape into integral components of cultural heritage makes them into something more, and imbues them with a cultural dimension. Both as rocks within the natural environment and once they have been carved and crafted into stone buildings and monuments these materials are exposed to environmental forces and become colonised by biota. Such environmental forces and the presence of biota bring dynamism – meaning that stones are constantly changing (sometimes very slowly), as well as possessing a living dimension. As DeSilvey notes in a paper on ruination, such natural materials become exposed to ecology and entropy and: 'Wildlife, weeds and water initiate the transformative 'micro-processes of wear and tear' that ultimately produce an entropic effect: oxidation, biodeterioration, percolation, cryoperturbation, erosion … ' (DeSilvey 2021, 286). Even the simplest of stone built cultural heritage thus has natural and cultural dimensions and can be seen as the combined and evolving product of geological, biological and cultural processes (Figure 1(a)). In some cases, the biota growing on the stone heritage also has value and may need to be conserved.

Stone built heritage sites are also surrounded by wider built and natural environments which also contain a diversity of natural elements, some of which have their own high conservation value (Figure 1(b)). For example, Celka (2011) reports on important floral relics of cultivation at many former settlement and castle sites in Poland, Germany and the Czech Republic. These relics form key habitat islands within largely agricultural environments with high biocultural heritage value. Such biocultural heritage can be very long-lasting, as illustrated from two areas of stone-built enclosures dating back to prehistoric times in granite environments in Galicia, Spain and Cornwall, UK in which important grassland communities have survived despite changing landscapes around them (Grove et al. 2020).

Many different strands of thought are now coming together which encourage the stone conservation field to work more closely with and for nature. Stone conservation, as a subfield of heritage conservation, is highly interdisciplinary and has a long and complex history. A procession of theoretical frameworks since the early nineteenth century have provided guidance and underpinned various practices which have also been informed and enabled by improvements in technology and the development of new products (Jokilehto 2017). As a result, the acceptability of 'working with nature' in stone conservation has also changed over time and ideas continue to evolve (Orbaşli 2017). For example, the 'scrape' and 'anti-scrape' movements of nineteenth century architectural conservation personified by the work of Viollet-le-Duc and Ruskin, came to very different conclusions on the acceptability of ageing and the presence of nature on historic buildings and structures (Leifeste and Stiefel 2018). Orbaşli (2017), in a perceptive review of changing approaches to heritage conservation, notes the parallels between debates around conservation today (with values-based, participatory approaches focused on conservation of meanings in potential conflict with scientific evidence) and those of the nineteenth century. Some authors even consider that heritage conservation as we now know it may be a thing of the past, with Muñoz-Viñas (2025) proposing six symptoms which suggest its imminent demise or transformation into something radically different.

Stone conservation is often carried out under the auspices of conservation and architecture, and there are close parallels between current thinking within these fields. New developments in architecture can feed through into, and influence, conservation practice. Zhong, Schröder, and Bekkering (2022), for example, review recent approaches to biophilic design in architecture and how they can support sustainability. They outline three approaches: nature incorporation (which brings in or creates natural elements, phenomena and processes to buildings), nature inspiration (which involves imitating nature – biomimicry – and other actions which evoke the sense of nature), and nature interaction (which focuses on arrange spaces to facilitate connections between nature, buildings and their occupants). Such a typology could also be used in thinking through how to better link culture and nature in today's heritage conservation.

As Leifeste and Stiefel (2018) discuss in detail, contemporary heritage conservation is heavily influenced by, and embedded within, wider concerns about environmental management within the context of today's global environmental crisis. This provides us with a renewed impetus to examine and trial new ways to work with nature more effectively. Within this context, ideas of sustainability and resilience developed in the field of environmental science have come to the fore. Both terms are quite slippery to define and it can be hard to distinguish between the two concepts. According to Harrison (2015, 33)

Figure 1. (a) One of the 'Emperors' Heads' from outside the Sheldonian Theatre, Oxford, UK. Carved from limestone by Michael Black in the 1970s to replace former, deteriorated sculptures, and subject to deterioration from climatic drivers and air pollution, with extensive cover of mosses and other organisms. (b) Formal gardens and parkland surrounding Blenheim Palace, Woodstock, UK which are part of the World Heritage Listing. (Images: author's own).

'Sustainability can be defined as the capacity to endure'. Fuller definitions of sustainability in the context of human relations with the environment include that of the United Nations Bruntland Commission which defined sustainability in 1987 as 'meeting the needs of the present without compromising the ability of future generations to meet their own needs'. In contrast resilience has been defined simply as '… the ability to adapt to change positively, recover from difficulties and persist in facing challenges' (resiliencetraining.co.uk). More specifically, Walker et al. (2004, 3) define resilience as: '… the capacity of a system to absorb disturbance and reorganise while undergoing change so as to still retain essentially the same function, structure, identity, and feedbacks'. Both sustainability and resilience are often mentioned in stone conservation literature, and similar ideas have been developed within the heritage conservation field, although there has been no overview or synthesis. Viles (2013), for example, argued that stone durability should be thought of more in terms of resilience than some static measure of resistance to deterioration. In a rather different vein, Dal Pozzo et al. (2024) carry out life cycle assessments of stone consolidants to quantify their sustainability. Heritage conservation provides a good opportunity to develop and apply concepts of sustainability of resilience.

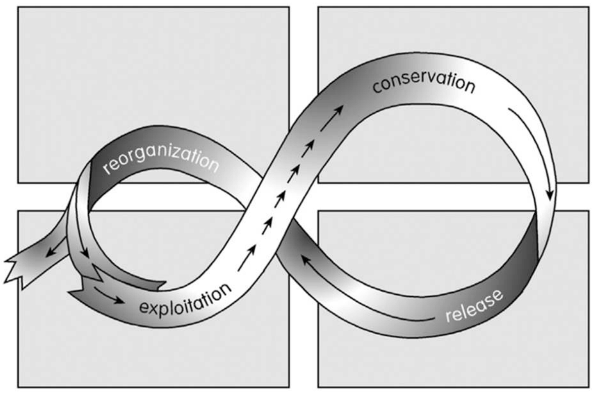

Figure 2. The four stages of an adaptive cycle. Shorter, closely spaced arrows indicate slowly changing conditions. Longer arrows represent more rapidly changing conditions. In reorganisation, the cycle may repeat itself, or it can reconfigure into another cyclical dynamic. The exit arrow on the left represents this potential for reconfiguration. Adapted from Gunderson and Holling (2002) (Source: Stallins and Corenblit 2018).

One approach to narrowing the gap between nature and culture in the field of heritage is provided by taking an ecological approach, as demonstrated for example by the 'heritage ecologies' approach of Bangstad and Pétursdóttir (2021). At the basic level, ecology has been defined as the part of biology which focuses on the relations of organisms to one another and their physical surroundings or environment. Ecologists often use the concept of an ecosystem to frame their studies, in which the relations between organisms and their environment are quantified in the form of flows of energy and matter. Ecologists understand that ecosystem function works towards an equilibrium, which can be disturbed and change over time, often in complex ways. Within the context of today's world, most ecosystems are heavily influenced by human activities which cannot be ignored by ecologists, however there are many challenges in bringing in the multiple roles and aspirations of humans into an ecosystem framework. This has implications for heritage ecologies, for which Bangstad and Pétursdóttir (2021, 5), propose that ' … an ecology of heritage should attempt to exfoliate the binaries of culture and nature, human and non-human and make room for the appreciation that heritage phenomena are entangled in more-than-human material and environmental processes'.

Ideas of ecosystems, resilience and adaptation to changed circumstances have been embraced by environmental scientists and ecologists within the framework of adaptive systems research. For example, Holling's work on adaptive socioecological systems as reviewed by Walker et al. (2004) illustrates the use of resilience ideas within the context of sustainability science for sustainable development. Figure 2 summarises the key features of adaptive cycles as depicted by Stallins and Corenblit (2018) who applied the ideas to biogeomorphological systems – with four phases and varied speeds of transformation from one phase to another. Importantly, Holling's adaptive cycling ideas acknowledge that these transformations are not fixed or regular, and that adaptive cycles interact across multiple scales forming what Holling calls 'panarchies'. These ideas, and many more, have been deployed to understand the dynamics of natural biogeomorphological systems (such as coastal salt marshes and vegetated sand dunes, e.g. Stallins and Corenblit 2018 who provide more information about the meaning of the different phases in Figure 2). More recently, they have started to be explored within the context of heritage as part of a focus on heritage dynamics (Fouseki 2022) and adaptive release (DeSilvey et al. 2021). The complexity of the terminology and the lack of concrete examples at present makes it difficult to apply the framework more widely to heritage conservation. However, such ecological approaches imply that dynamism and change are inherent to the socioecological systems that include heritage, and much more could be done to explore how they could aid the conservation of stone heritage.

Towards a conceptual framework for working with nature in the conservation of stone heritage

How can stone conservation take on board ideas of ecology, adaptive systems, sustainability and resilience to improve the conservation not only of the stone objects themselves but of the people and environments that surround them? In order to answer this question it is useful to begin with some basic concepts relevant to the ecology of stone heritage. The term 'bioreceptivity', for example, was introduced into the literature in 1995 by Guillitte and has since been extended and refined (Guillitte 1995; Miller et al. 2012; Sanmartín et al. 2021). In essence, bioreceptivity describes the ease with which a building material surface is colonised by biota – and is controlled by a range of factors (e.g. porosity, roughness, mineralogy) which themselves can change over time as a result of weathering and biodeterioration.

Once biota is established on the stone surface, it can be involved in biodeterioration (which can be defined simply as any undesirable chemical or physical changes to materials caused by microorganisms or macroorganisms) and/or bioprotection (which can be defined as any desirable chemical or physical changes to materials caused by microorganisms or macroorganisms) or may have no impact. Impacts can involve the organisms themselves or things produced by them, such as extracellular polymeric substances (EPS). Often the boundary between the organism and their exudates is hard to define. Biodeterioration of stone has been the subject of vast amounts of research over many years (see for example the reviews by Warscheid and Braams 2000; Cutler and Viles 2010; Liu et al. 2020; Elgohary, Mansour, and Salem 2024; and Yadav and Purchase 2025). In contrast, bioprotection has received less focused attention although there has been an upswing in interest in recent years (Carter and Viles 2005; Concha-Lozano et al. 2012; Gadd and Dyer 2017). Both biodeterioration and bioprotection can be broken down into a wide range of individual impacts and processes, and new discoveries of biological roles are being made all the time. In recent years, several papers have explored the relative importance of both sets of processes, in relation to particular organism types, environmental contexts and types of substrate (Pinna 2014; Gulotta et al. 2018; Favero-Longo and Viles 2020; Bone et al. 2022; Liu et al. 2022; Zhu et al. 2025). A particularly useful approach was taken by Liu et al. (2022) who develop a Relative Bioprotection Ratio which is the sum of natural weathering divided by the sum of biodeterioration. They note that biofilm communities can shift from being bioprotective to being biodeteriorative and *vice versa*. Rabbachin et al. (2023) come to similar conclusions from a study of biopatina on rock carvings in the Austrian Alps. They point out that removing the current, stable biological community might encourage a rapid phase of biocolonisation and biodeterioration.

Table 1 summarises and categorises different forms of bioprotection and biodeterioration by organisms growing directly on and in stone. A further important concept introduced in Table 1 is that of bioconservation which Ortega-Morales and Gaylarde (2021) see as covering the use of innovative conservation treatments which are biologically-based and more environmentally acceptable than consolidants and other traditional conservation methods based on synthetic materials. These are applied directly to the stone.

Table 1. Typology of direct influences of ecology growing on and in stone on biological impacts on stone heritage.

	Category	Process	Result	Example/comments
Biodeterioration	Biochemical weathering	Biogenic acid corrosion Complexation/ cation release	Loss of material in solution, small scale pitting and enhanced surface roughness	McIlroy de la Rosa, Warke, and Smith (2012) find lichen biopitting on limestone contributes to larger weathering features.
	Biophysical weathering	Swelling/ contracting	Loss of material, cracking, peeling and flaking	Moses and Smith (1993) find wetting and drying of lichens damages stone.
		Growth pressure		Ivy roots have been seen to break apart masonry as they grow into pre-existing holes.
	Biomineralisation	Biogenic production or trapping of minerals/salts	Salt weathering	Zammit, Sánchez-Moral, and Albertano (2011) find damaging salts accumulate in biofilms on wall paintings in limestone catacombs, Malta.
	Discoloration	Biocolonisation	Biofilms and other biota produce undesirable colour changes	Duan et al. (2017) find pigmented bacterial communities disfiguring wall paintings on sandstone grottoes, Maijishan, NW China.
	Biopatina	Many of the above	Combined impacts of bioweathering, biomineralisation and discoloration produce disruptive or unwanted patina	Ding et al. (2021) ascribe unsightly and deteriorating orange patina on limestone walls of a Portuguese monastery to bacteria and air pollution.
	Aesthetic decline	Biocolonisation	Biofilms and other biota produce undesirable aesthetic changes	Extensive climbing plants and mosses can obscure important architectural details (bio-obscuration).
Bioprotection	Biomineralisation	Biogenic production of minerals	Protective mineral patina/ bioconsolidant	Either by natural or imported bacterial communities.
	Biological colonisation	Biological growths form networks over material surfaces	Physical protection from erosion and buffering from environmental forces	Cao et al. (2023) find cyanobacteria and moss-dominated biocrusts protect Great Wall of China from erosion.
	Biopatina	Both of the above	Combined impacts of biomineralisation and biological coverage produce protective and desirable patina	Including those left after death of organisms. McIlroy de la Rosa, Warke, and Smith (2013) give several examples.
Bioconservation	Biocleaning	Using microorganisms or their products to remove black crusts, graffiti etc	Cleaning/ restoration of surfaces	Valentini, Diamanti, and Palleschi (2010) use enzymes to remove unwanted biofilm from travertine.
	Biopolymer use	Use of biopolymers as consolidants, salt crystallisation inhibitors etc	Surface consolidation and protection	Marrone and Franzoni (2025) use of chitosan to encourage salt crystallisation inhibition
	Aesthetic enhancement	Biocolonisation	Biofilms etc produce desirable aesthetic changes	Mixed lichen communities add colour and variety to ashlar surfaces.

They note, for example, the use of plant biopolymers such as those sourced from *Aloe vera* and *Opuntia engelmannii* as consolidants. They further discuss the use of biological cleaning techniques which can involve living bacterial cells or enzymes they produce, to remove unwanted black crusts, graffiti and biofilms. Within this vein, other researchers have reported on the use of biologically-obtained compounds such as chitosan (which is a biopolymer extracted from crustaceans) to inhibit damaging salt crystallisation (Marrone and Franzoni 2025). While there may be some overlap between bioprotection and bioconservation, the concept of bioconservation brings in the additional dimension of biotechnology using bio-obtained or bio-inspired materials rather than making use of living organisms (whether already present or inoculated into the stone). Table 2 does a similar exercise for actions of the wider ecosystem – making a distinction between direct impacts (i.e. where the plant, animal or community is in direct contact with the stone) and indirect impacts (i.e. where the plant, animal or community changes the environmental characteristics as they affect the stone). Both Tables 1 and 2 do not consider the 'no impact' category, but this should also be thought through in future.

No typology of the interactions between nature and culture is simple or without problems, and there are always grey areas. For example, Table 1 shows that biopatinas can be seen as both deteriorative and protective and biocolonisation can be seen to cause aesthetic enhancement or decline – both depending on context. It is also clear that the specific links between biological processes and any observable results are not always clear (correlation does not prove causation) and can vary from place to place. For example, in some cases biodeteriorative bacterial communities may be encouraged by pollutants which have accumulated in surface crusts, whilst in other cases bacterial and other communities may protect the underlying surface from the impacts of airborne pollutants and microplastics (Wilhelm et al. 2024). Table 2 also fails to grapple in equal detail with the impacts of ecosystems surrounding stone-built heritage in comparison with those organisms which grow on and in the stone, as there is far less

Table 2. Typology of direct and indirect effects of the wider ecosystem on stone heritage.

	Category	Process	Result	Example/comments
Direct	Burrowing	Animal burrowing in soils	Undermining surface stability through collapse of soil tunnels	Ferraby (2007) notes the destructive impact of badger burrows on ruins.
	Root growth	Plant root networks in soils	Tree roots undermining surface stability and can damage walls	Trotta et al. (2020) note extensive damage to the Aurelian Walls, Rome, from the invasive tree *Ailanthus altissima.*
Indirect	Microclimate impacts	Surrounding ecosystem ameliorates temperature regime	Reduces solar energy receipt and diurnal temperature cycles on building surfaces	André et al. (2014) suggest that former surrounding forest acted as a 'bioprotective umbrella' at Angkor, Cambodia. Vegetation removal reversed the effect.
		Surrounding ecosystem reduces rainfall receipt	Reduces rainfall hitting building surfaces	
		Surrounding ecosystem reduces local air pollution	Reduces air pollution loadings on building surfaces	
	Aesthetic enhancement	Surrounding ecosystem enhances the appearance of a site	Improves the ambience of a heritage site	Could also have negative impacts on the presentation of the site.
	Impacts on hydrology	Surrounding ecosystem modifies soil water and groundwater regimes	Reduces soil and groundwater ingress to buildings	Could also be negative: changing vegetation in the surrounding ecosystem can enhance soil and groundwater ingress.

written and known about such, often quite indirect, effects. It is clear, however, that human influences on ecosystems surrounding stone heritage sites are often having negative impacts on the stone itself. To improve the typology, it needs to be tested on a wide range of sites and categories added or altered as new information becomes published.

The archaeological site of Angkor in Cambodia provides a good example of the complexities involved in the relationships between nature and stone cultural heritage (both growing on and growing around the ruins). Years of research on the deterioration of sandstones at Angkor have shown the importance of biological communities (dominantly bacterial and fungal biofilms) in the recent deterioration of the stonework (e.g. Warscheid and Leisen 2011). However, other biological agents may also be of importance – as Uchida et al. (2000) note the potential role played by bat guano in biodeterioration here, and the roles of large tree root systems in prising apart sections of the ruined monuments are plain to see. Furthermore, human impacts have upset things in many different ways. Warscheid and Leisen (2011), for example, note that the incautious use of biocides in the 1990s may have initiated a shift from bioprotective lichen cover to biodeteriorative cover of black-coloured cyanobacteria. Liu et al. (2018) explain the importance of water in focusing biological growth and deterioration in certain places, and show how the loss of historical drainage systems has had profound impacts. Similarly, André et al. (2014) explore the role of forest clearance at Angkor and use old and new photos to show an acceleration in sandstone deterioration since forests around the site were cleared in the early twentieth century. They suggest that this is because of the loss of the 'bioprotective umbrella' afforded by the trees against intense solar heating and rainfall.

A simple conceptual framework for analysing the relationships between nature and cultural heritage and their conservation in the context of stone buildings and monuments is presented in Figure 3. The multifarious potential biological processes, roles and their impacts on cultural heritage reviewed in Table 1 form the 'Nature as foe' and 'Nature as friend' boxes in the top part of the framework. The arrows illustrate the many relationships between the different components, and the central box 'Nature and culture entwined: novel and resilient' illustrates that these relationships form an adaptive system. Successful management should lead to this adaptive system functioning effectively and being able to cope with the challenges of climate and societal change. Understanding, on a case by case basis, what the balance of direct and indirect actions by ecological communities growing on and in the stone as well as the wider ecosystem within which the site is located is crucial. But so too is providing clearer understanding of the processes and agents involved in the 'Culture as friend' and 'Culture as foe' boxes in the bottom part of the framework.

While this paper cannot expand and explore the 'culture as friend' and 'culture as foe' boxes in Figure 3 as fully as the 'nature as foe' and 'nature as friend' boxes, it is possible to highlight some of the key dimensions. 'Culture as foe' is a way of portraying the potential conflicts between the conservation of historic stone buildings and monuments and the ecosystems that grow on or around them. In conservation biology literature, this idea is encapsulated within the term 'Fortress conservation' whereby human activity is seen as a threat to nature and should be excluded in order to protect 'pristine' nature. Clearly, if there are unique and valuable lichens or mosses growing on a stone surface which need to be cleaned off because they are causing significant biodeterioration, then that can cause a conflict. Similarly, if stone conservation requires the felling of forests around a site because the trees have been proven to cause biodeterioration, and those forests are of particular botanical or biodiversity importance, then further conflicts can

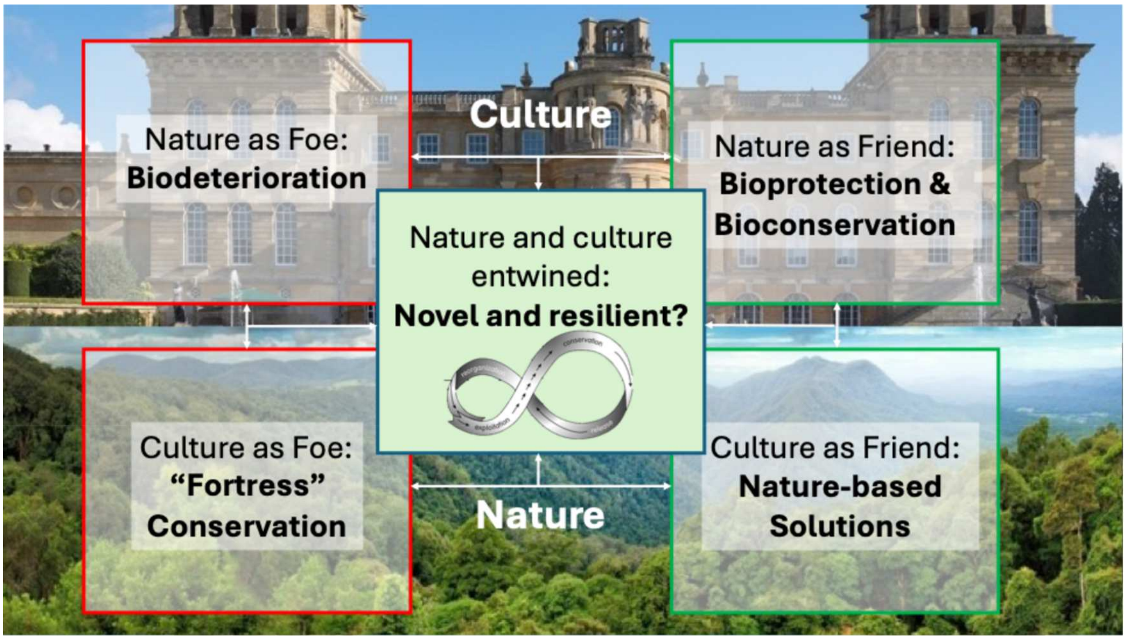

Figure 3. A simple conceptual framework for understanding the multiple dimensions of the relationships between culture and nature at stone heritage sites and how we can best utilise these to produce novel and resilient heritage.

arise. In many cases, the ecological communities (which were often cleared, harnessed and altered to create the stone buildings and monuments) are much older than the cultural heritage site itself. So, which has precedence in terms of conservation today?

Looking at the problem from the other direction, 'Culture as friend' implies that conservation of stone-built heritage can, in some cases, support and enhance attempts to conserve the surrounding ecosystem. For example, where Medieval castles and abbeys created their own 'physic gardens' they produced novel ecosystems which themselves have conservation value today, and other cultural heritage sites have been islands of tranquillity within a sea of urbanisation and development, providing a safe haven for threatened biological communities. Within maritime settings around the UK, Baxter, Coombes, and Viles 2023, found that historic masonry structures support a higher level of diversity in marine wildlife than modern concrete structures (or indeed natural cliffs). The notion of 'culture as friend' well be summarised by the term 'Nature-based Solutions'. According to the Nature-based Solutions Initiative (no date) 'Nature-based Solutions involve working with nature, as part of nature, to address societal challenges, supporting human well-being and biodiversity locally. They include the protection, restoration or management of natural and semi-natural ecosystems; the sustainable management of aquatic systems and working lands; and integration of nature in and around our cities. They are actions that are underpinned by biodiversity and designed and implemented in a way that respects the rights, values and knowledges of local communities and Indigenous Peoples'. In essence, Nature-based Solutions are ways of linking the conservation of biodiversity with other sustainable development goals, and their relevance to urban heritage has been explored by Coombes and Viles (2021).

There is currently a lot of momentum amongst policymakers to enhance the links between conservation of natural and cultural heritage. For example, English Heritage's 'Sustainable Conservation Principles' launched in 2023 include as principle number 4: 'We will integrate nature for the benefit of both the natural and historic environment'. Additionally, in 2024 Historic England, Natural England and the National Lottery Heritage Fund issued a joint statement on their shared goal to integrate the management of the natural and historic environment. However, what is missing is a shared conceptual framework to help those involved with conservation to implement these aspirations. The framework presented in Figure 3 is a first attempt to provide this, with specific reference to stone heritage. The goal is to populate the conceptual framework in Figure 3 with information on nature as friend and foe, and culture as friend and foe in relation to a specific site, with particular known environmental and human threats. This will enable a more balanced assessment of the different interactions, and help conservators and site managers work towards an understanding of how everything fits together and how, if necessary, improvements could be made in order to ensure a resilient system. Until we have more knowledge and data it will prove difficult to produce a fully articulated adaptive systems diagram building on the template shown in Figure 2.

Challenges and priorities for future research and practice

Conservation of natural and cultural heritage over the coming few decades is likely to be increasingly difficult, with the climate crisis, the environmental or biodiversity crisis and global geopolitical and economic changes all providing challenges. On the other hand, conserving nature in response to these challenges is becoming increasingly vital, as it is clear that the loss of biodiversity and the impacts of climate change will impoverish the global environmental system and threaten human habitation. Furthermore, loss of cultural heritage will have deleterious effects on culture and society. Any attempt to join forces and link conservation of culture and nature should be welcomed. In the case of stone heritage conservation, the fact that stone is itself a part of nature and stone buildings and monuments are located within the natural environment makes such a holistic approach particularly pertinent.

The ideas presented in the earlier sections of this paper illustrate a broad framework which can be used to visualise and understand the range of relationships between nature and culture in terms of stone heritage. Several challenges remain which can be divided into four main categories – empirical, theoretical, policy-based and practical. Each one leads to a priority for future research and practice.

Empirical: lack of data and incommensurate data

There is much missing data on how nature and culture mutually impact upon each other in the context of stone-built heritage and so many of the potential linkages and relationships in Figure 3 are unknown or unquantified. Where we have information about the impact caused by a particular species or community in terms of the categories identified in Table 1, it is difficult to extrapolate that to other locations or contexts. We need a consistent way of reporting data so that meaningful comparisons and generalisations can be made. Questions remain about how we can weigh up the direct impacts of lichens growing on stone, for example, against the indirect impacts of surrounding vegetation communities on overall deterioration processes and rates. Some processes are easier to measure than others, but the use of a common metric (such as energy expenditure) might provide a useful way forward.

To address the above issues, the first priority I propose is to establish standard or accepted methods for identifying and quantifying natural impacts on the conservation of stone, both singly and in combination, using comparable metrics.

Theoretical issues including temporal and spatial scaling

The simple conceptual framework presented in Figure 2 hides much complexity which needs further exploration and thought if we are to be able to use the adaptive systems approach in detail as a tool to understand and manage nature and stone heritage more effectively. One question revolves around the difficulty of including humans in an adaptive systems-based approach. Researchers within the field of stone conservation need to find creative ways to work with social scientists to grapple with this. A further issue is the importance of contingency (timing within a series of events) and context (location) in affecting the relationships between nature and stone heritage. In other words, the exact role of a certain species or community will depend on when and where it is operating. How can we move beyond accepting this general principle to making informed judgements on what is happening at any one place or time? Progress has been made on this sort of question within the field of biogeomorphology where, for example, Eichel's concept of the 'biogeomorphic feedback window' has proved to be useful in understanding when in the evolution of an adaptive biogeomorphological system the controlling roles of particular species may be most pronounced (Eichel, Corenblit, and Dikau 2016). Furthermore, the ecological concept of ecosystem engineers (i.e. species or types of organism which are particularly important in shaping the physical and biological conditions within an ecosystem) might usefully be explored by those interested in untangling the links between nature and stone heritage.

Temporal and spatial scale issues surrounding adaptive systems within the context of nature and stone heritage are largely unexplored. For example, how can we effectively manage large forest ecosystems covering several hectares alongside lichen communities on areas of façade a few square metres in dimensions? Can we produce an effective panarchy of adaptive systems as envisaged by Gunderson and Holling (2002)? If so, what might the different scales/types of adaptive system be within the panarchy? Could we think, for example, of different adaptive systems to cover individual stone blocks, facades, buildings and landscapes? What are the rates of change of the biological elements of these different scale of adaptive systems, and how do they compare with the rates of response of the stone, site or physical landscape itself in terms of deterioration and loss? Do the relatively inflexible topographies of building stone surfaces (which might only change at the rate of a few millimetres per year at most) put a brake on the adaptive capacity of the colonising and developing biofilm communities which grow on them? Can we predict when slow rates of deterioration suddenly escalate into larger scale collapse and change in ruined structures and the associated ecological communities on and around them?

The second priority I propose to respond to these challenges is to develop interdisciplinary partnerships which can explore these theoretical questions in more detail, working closely with teams collecting data.

Policy: difficulty of accepting loss and transformation

A more policy-focused challenge is that if we reconceptualise the interactions between nature and stone heritage as adaptive systems it will be vital to think through the implications for conservation policy and for the management of heritage sites. In future these sites could be very different and more dynamic if we work with nature to produce functional adaptive systems which conserve heritage values. For example, where the natural heritage is found to be more valuable than the stone heritage some loss or depreciation in the cultural heritage may need to be accepted. Similarly, if a novel, more resilient adaptive system emerges both cultural and natural heritage values might change and a new set of values might be created. As mentioned above, national and international heritage organisations aspire to linking nature and cultural heritage conservation more closely, but undoubtedly face many challenges in doing so in terms of accepting dynamism, change and uncertainty. As DeSilvey et al. (2022) note, case study examples are needed in order to provide tangible examples of the dynamic outcomes to be expected. A clear framework (such as that presented here) might help discussions and encourage heritage professionals to contribute their knowledge of the relations between plants, animals, humans and stone heritage.

To address policy issues, the third priority I propose is for interdisciplinary researchers to work with national and international heritage organisations and involve policymakers and heritage professionals in developing, critiquing, explaining and publicising a useful adaptive systems framework.

Practice: lack of practical guidelines

The starting point of this paper was the difficulty of linking rather complex theoretical discussions of the relationships between nature and culture to the tangible problems of stone conservation. For any new approach to be successful, such as the adaptive systems approach suggested here, it is necessary to provide clear practical guidelines and explanations. And, of course, the practical stone conservation community brings years of experience and wisdom to the problems faced by stone in today's world and their views and knowledge need to be valued and incorporated. There are many examples in the literature of papers with titles such as 'Should stone surface biofilms be removed or not?', and the answers proposed usually involve stating that fuller knowledge of the history and geography of the case study under consideration is needed before action can be taken, and that leaving nature to take its course is perhaps the safest option. A more formal acceptance of the conceptual framework proposed in this paper should allow conservators to consider a wider range of factors in making any decisions, thus avoiding the sorts of unintended consequences of biocide use and clearing of forest at Angkor, for example.

The fourth priority I propose is to establish a forum for the discussion and development of practical guidelines for stone conservation based on an adaptive systems framework.

To conclude, working with nature in the conservation of stone heritage necessitates an interdisciplinary and holistic approach and requires the acceptance of a more dynamic future for stone heritage and the nature which surrounds it. It will be challenging, but it is necessary in order to maintain and enhance the environment in which we live and of which stone built heritage is a vital part.

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References

André, M. F., F. Vautier, O. Voldoire, and E. Roussel. 2014. "Accelerated Stone Deterioration Induced by Forest Clearance around the Angkor Temples." *Science of the Total Environment* 493:98–108. https://doi.org/10.1016/j.scitotenv.2014.05.141

Bangstad T. R., and P. Pétursdóttir, eds. 2021. *Heritage Ecologies*. Abingdon: Routledge.

Baxter, T., M. Coombes, and H. Viles. 2023. "Intertidal Biodiversity and Physical Habitat Complexity on Historic Masonry Walls: A Comparison with Modern Concrete Infrastructure and Natural Rocky Cliffs." *Marine Pollution Bulletin* 188:114617. https://doi.org/10.1016/j.marpolbul.2023.114617

Bone, J. R., R. Stafford, A. E. Hall, and R. J. Herbert. 2022. "Biodeterioration and Bioprotection of Concrete Assets in the Coastal Environment." *International Biodeterioration & Biodegradation* 175:105507. https://doi.org/10.1016/j.ibiod.2022.105507

Bridgewater, P., and I. D. Rotherham. 2019. "A Critical Perspective on the Concept of Biocultural Diversity and Its Emerging Role in Nature and Heritage Conservation." *People and Nature* 1 (3): 291–304. https://doi.org/10.1002/pan3.10040

Cao, Y., M. A. Bowker, M. Delgado-Baquerizo, and B. Xiao. 2023. "Biocrusts Protect the Great Wall of China from Erosion." *Science Advances* 9 (49): eadk5892. https://doi.org/10.1126/sciadv.adk5892

Carter, N. E. A., and H. A. Viles. 2005. "Bioprotection Explored: The Story of a Little Known Earth Surface Process." *Geomorphology* 67 (3-4): 273–281. https://doi.org/10.1016/j.geomorph.2004.10.004

Celka, Z. 2011. "Relics of Cultivation in the Vascular Flora of Medieval West Slavic Settlements and Castles." *Biodiversity: Research and Conservation* 22:1–110. https://doi.org/10.2478/v10119-011-0011-0

Concha-Lozano, N., J. Pages, G. De Billerbeck, P. Gaudon, and D. Lafon. 2012. "Bioprotective Role of Lichens on Oolitic Limestone Buildings." In *12th International Congress on the Deterioration and Conservation of Stone*. New York: Columbia University.

Coombes, M. A., and H. A. Viles. 2021. "Integrating Nature-Based Solutions and the Conservation of Urban Built Heritage: Challenges, Opportunities, and Prospects." *Urban Forestry & Urban Greening* 63:127192. https://doi.org/10.1016/j.ufug.2021.127192

Cutler, N., and H. Viles. 2010. "Eukaryotic Microorganisms and Stone Biodeterioration." *Geomicrobiology Journal* 27 (6-7): 630–646. https://doi.org/10.1080/01490451003702933

Dal Pozzo, A., G. Masi, E. Sassoni, and A. Tugnoli. 2024. "Life Cycle Assessment of Stone Consolidants for Conservation of Cultural Heritage." *Building and Environment* 249:11153. https://doi.org/10.1016/j.buildenv.2023.111153

DeSilvey, C. 2021. "A Positive Passivity: Entropy and Ecology in the Ruins." In *Heritage Ecologies*, 285–305. Abingdon: Routledge.

DeSilvey, C., A. Blundell, H. Fredheim, and R. Harrison. 2022. *Identifying Opportunities for Integrated Adaptive Management of Heritage Change and Transformation in England: A Review of Relevant Policy and Current Practice*. Historic England Research Report, 18/2022, 34 pp.

DeSilvey, C., H. Fredheim, H. Fluck, R. Hails, R. Harrison, I. Samuel, and A. Blundell. 2021. "When Loss is More: From Managed Decline to Adaptive Release." *The Historic Environment: Policy & Practice* 12 (3-4): 418–433. https://doi.org/10.1080/17567505.2021.1957263

Ding, Y., P. Redol, E. Angelini, J. Mirão, and N. Schiavon. 2021. "Surface Orange Patinas on the Limestone of the Batalha Monastery (Portugal): Characterization and Decay Patterns." *Environmental Science and Pollution Research*: 1–11. https://doi.org/10.1007/s11356-021-15490-1

Duan, Y., F. Wu, W. Wang, D. He, J. D. Gu, H. Feng, T. Chen, G. Liu, and L. An. 2017. "The Microbial Community Characteristics of Ancient Painted Sculptures in Maijishan Grottoes, China." *PLoS One* 12 (7): e0179718. https://doi.org/10.1371/journal.pone.0179718

Eichel, J., D. Corenblit, and R. Dikau. 2016. "Conditions for Feedbacks between Geomorphic and Vegetation Dynamics on Lateral Moraine Slopes: A Biogeomorphic Feedback Window." *Earth Surface Processes and Landforms* 41 (3): 406–419. https://doi.org/10.1002/esp.3859

Elgohary, Y. M., M. M. Mansour, and M. Z. Salem. 2024. "Assessment of the Potential Effects of Plants with Their Secreted Biochemicals on the Biodeterioration of Archaeological Stones." *Biomass Conversion and Biorefinery* 14 (11): 12069–12083. https://doi.org/10.1007/s13399-022-03300-8

Favero-Longo, S. E., and H. A. Viles. 2020. "A Review of the Nature, Role and Control of Lithobionts on Stone Cultural Heritage: Weighing-up and Managing Biodeterioration and Bioprotection." *World Journal of Microbiology and Biotechnology* 36 (7): 100. https://doi.org/10.1007/s11274-020-02878-3

Ferraby, S. 2007. "The Ecology of Ruin Sites." In *Conservation of Ruins*, 195–212. Abingdon: Routledge.

Fouseki, K. 2022. *Heritage Dynamics: Understanding and Adapting to Change in Diverse Heritage Contexts (255)*. London: UCL Press.

Gadd, G. M., and T. D. Dyer. 2017. "Bioprotection of the Built Environment and Cultural Heritage." *Microbial Biotechnology* 10 (5): 1152–1156. https://doi.org/10.1111/1751-7915.12750

Grove, R., J. Evans Pim, M. Serrano, D. Cidrás, H. Viles, and P. Sanmartín. 2020. "Pastoral Stone Enclosures as Biological Cultural Heritage: Galician and Cornish Examples of Community Conservation." *Land* 9 (1): 9. https://doi.org/10.3390/land9010009

Guillitte, O. 1995. "Bioreceptivity: A new Concept for Building Ecology Studies." *Science of the Total Environment* 167 (1-3): 215–220. https://doi.org/10.1016/0048-9697(95)04582-L

Gulotta, D., F. Villa, F. Cappitelli, and L. Toniolo. 2018. "Biofilm Colonization of Metamorphic Lithotypes of a Renaissance Cathedral Exposed to Urban Atmosphere." *Science of the Total Environment* 639:1480–1490. https://doi.org/10.1016/j.scitotenv.2018.05.277

Gunderson L. H., and C. S. Holling, eds. 2002. *Panarchy: Understanding Transformations in Human and Natural Systems*. Washington, DC: Island Press.

Harrison, R. 2015. "Beyond "Natural" and "Cultural" Heritage: Toward an Ontological Politics of Heritage in the age of Anthropocene." *Heritage & Society* 8 (1): 24–42. https://doi.org/10.1179/2159032X15Z.00000000036

Jokilehto, J. 2017. *A History of Architectural Conservation*. Abingdon: Routledge.

Leifeste, A., and B. L. Stiefel. 2018. *Sustainable Heritage: Merging Environmental Conservation and Historic Preservation*. Abingdon: Routledge.

Liu, X., R. J. Koestler, T. Warscheid, Y. Katayama, and J. D. Gu. 2020. "Microbial Deterioration and Sustainable Conservation of Stone Monuments and Buildings." *Nature Sustainability* 3 (12): 991–1004. https://doi.org/10.1038/s41893-020-00602-5

Liu, X., H. Meng, Y. Wang, Y. Katayama, and J. D. Gu. 2018. "Water is a Critical Factor in Evaluating and Assessing Microbial Colonization and Destruction of Angkor Sandstone Monuments." *International Biodeterioration &*

Biodegradation 133:9–16. https://doi.org/10.1016/j.ibiod.2018.05.011

Liu, X., Y. Qian, F. Wu, Y. Wang, W. Wang, and J. D. Gu. 2022. "Biofilms on Stone Monuments: Biodeterioration or Bioprotection?" *Trends in Microbiology* 30 (9): 816–819. https://doi.org/10.1016/j.tim.2022.05.012

Marrone, C., and E. Franzoni. 2025. "Enhancing the Durability of Historic Brick Masonry: The Role of Diammonium Phosphate and Chitosan in Reducing Salt-Induced Damage." *Journal of Cultural Heritage* 73:150–157. https://doi.org/10.1016/j.culher.2025.03.004

McIlroy de la Rosa, J. P., P. A. Warke, and B. J. Smith. 2012. "Microscale Biopitting by the Endolithic Lichen Verrucaria Baldensis and Its Proposed Role in Mesoscale Solution Basin Development on Limestone." *Earth Surface Processes and Landforms* 37 (4): 374–384. https://doi.org/10.1002/esp.2244

McIlroy de la Rosa, J. P. M., P. A. Warke, and B. J. Smith. 2013. "Lichen-induced Biomodification of Calcareous Surfaces: Bioprotection versus Biodeterioration." *Progress in Physical Geography* 37 (3): 325–351. https://doi.org/10.1177/0309133312467660

Miller, A. Z., P. Sanmartín, L. Pereira-Pardo, A. Dionísio, C. Sáiz-Jiménez, M. F. Macedo, and B. Prieto. 2012. "Bioreceptivity of Building Stones: A Review." *Science of the Total Environment* 426:1–12. https://doi.org/10.1016/j.scitotenv.2012.03.026

Moses, C. A., and B. J. Smith. 1993. "A Note on the Role of the Lichen Collema Auriforma in Solution Basin Development on a Carboniferous Limestone Substrate." *Earth Surface Processes and Landforms* 18 (4): 363–368. https://doi.org/10.1002/esp.3290180405

Muñoz-Viñas, S. 2025. "The End of Conservation?" *Studies in Conservation* 70 (4): 267–279. https://doi.org/10.1080/00393630.2024.2370726

Nature-base Solutions Initiative. No Date. *What Are Nature-Based Solutions?* https://www.naturebasedsolutionsinitiative.org/what-are-nature-based-solutions/ Accessed on 30/4/2025.

Orbaşli, A. 2017. "Conservation Theory in the Twenty-First Century: Slow Evolution or a Paradigm Shift?" *Journal of Architectural Conservation* 23 (3): 157–170. https://doi.org/10.1080/13556207.2017.1368187

Ortega-Morales, B. O., and C. C. Gaylarde. 2021. "Bioconservation of Historic Stone Buildings – An Updated Review." *Applied Sciences* 11 (12): 5695. https://doi.org/10.3390/app11125695

Pinna, D. 2014. "Biofilms and Lichens on Stone Monuments: Do They Damage or Protect?" *Frontiers in Microbiology* 5:133. https://doi.org/10.3389/fmicb.2014.00133

Rabbachin, L., G. Piñar, I. Nir, A. Kushmaro, E. Eitenberger, M. Waldherr, A. Graf, and K. Sterflinger. 2023. "Natural Biopatina on Historical Petroglyphs in the Austrian Alps: To Clean or Not to Clean?" *International Biodeterioration & Biodegradation* 183:105632. https://doi.org/10.1016/j.ibiod.2023.105632

Sanmartín, P., A. Z. Miller, B. Prieto, and H. A. Viles. 2021. "Revisiting and Reanalysing the Concept of Bioreceptivity 25 Years on." *Science of the Total Environment* 770:145314. https://doi.org/10.1016/j.scitotenv.2021.145314

Stallins, J. A., and D. Corenblit. 2018. "Interdependence of Geomorphic and Ecologic Resilience Properties in a Geographic Context." *Geomorphology* 305:76–93. https://doi.org/10.1016/j.geomorph.2017.09.012

Taylor, K., and J. Lennon. 2011. "Cultural Landscapes: A Bridge between Culture and Nature?" *International Journal of Heritage Studies* 17 (6): 537–554. https://doi.org/10.1080/13527258.2011.618246

Trotta, G., V. Savo, E. Cicinelli, M. Carboni, and G. Caneva. 2020. "Colonization and Damages of *Ailanthus altissima* (Mill.) Swingle on Archaeological Structures: Evidence from the Aurelian Walls in Rome (Italy)." *International Biodeterioration & Biodegradation* 153:105054. https://doi.org/10.1016/j.ibiod.2020.105054

Uchida, E., Y. Ogawa, N. Maeda, and T. Nakagawa. 2000. "Deterioration of Stone Materials in the Angkor Monuments, Cambodia." *Developments in Geotechnical Engineering* 84:329–340. https://doi.org/10.1016/S0165-1250(00)80027-9

Valentini, F., A. Diamanti, and G. Palleschi. 2010. "New Bio-Cleaning Strategies on Porous Building Materials Affected by Biodeterioration Event." *Applied Surface Science* 256 (22): 6550–6563. https://doi.org/10.1016/j.apsusc.2010.04.046

Viles, H. A. 2013. "Durability and Conservation of Stone: Coping with Complexity." *Quarterly Journal of Engineering Geology and Hydrogeology* 46 (4): 367–375. https://doi.org/10.1144/qjegh2012-053

Walker, B., C. S. Holling, S. R. Carpenter, and A. Kinzig. 2004. "Resilience, Adaptability and Transformability in Social–Ecological Systems." *Ecology and Society* 9 (2). https://doi.org/10.5751/ES-00650-090205

Warscheid, T., and J. Braams. 2000. "Biodeterioration of Stone: A Review." *International Biodeterioration & Biodegradation* 46 (4): 343–368. https://doi.org/10.1016/S0964-8305(00)00109-8

Warscheid, T., and H. Leisen. 2011. "Microbiological Studies on Stone Deterioration and Development of Conservation Measures at Angkor Wat." In *Biocolonization of Stone: Control and Preventive Methods, Proceedings from the MCI Workshop Series (Vol. 2)*, 1–18. Washington, DC: Smithsonian Institution Scholarly Press.

Wilhelm, K., S. Woor, M. Jackson, D. Albini, N. Young, P. Karamched, M. C. P. Wright, et al. 2024. "Microplastic Pollution on Historic Facades: Hidden 'Sink' or Urban Threat?" *Environmental Pollution* 343:p123128. https://doi.org/10.1016/j.envpol.2023.123128

Yadav, S., and D. Purchase. 2025. "Biodeterioration of Cultural Heritage Monuments: A Review of Their Deterioration Mechanisms and Conservation." *International Biodeterioration & Biodegradation* 201:106066. https://doi.org/10.1016/j.ibiod.2025.106066

Zammit, G., S. Sánchez-Moral, and P. Albertano. 2011. "Bacterially Mediated Mineralisation Processes Lead to Biodeterioration of Artworks in Maltese Catacombs." *Science of the Total Environment* 409 (14): 2773–2782. https://doi.org/10.1016/j.scitotenv.2011.03.008

Zhong, W., T. Schröder, and J. Bekkering. 2022. "Biophilic Design in Architecture and Its Contributions to Health, Well-Being, and Sustainability: A Critical Review." *Frontiers of Architectural Research* 11 (1): 114–141. https://doi.org/10.1016/j.foar.2021.07.006

Zhu, C., B. Wang, Z. Liu, Y. Guo, L. Zheng, B. Zhang, and Y. Hu. 2025. "Unveiling the Dual Role of Biocolonization: A Case Study on the Deterioration and Preservation of Sandstone Monuments in Leshan Giant Buddha, China." *World Journal of Microbiology and Biotechnology* 41 (2): 1–17. https://doi.org/10.1007/s11274-024-04237-y