Microbes Can Damage but Also Help Restore Artifacts

Despite damaging wood and stone artifacts in diverse settings, microbes also may be used to restore damaged items

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From the prefabricated wooden huts of Antarctic explorers in the early 20th century to the enduring limestone ruins of the Mayan city Ek' Balam (Black Jaguar) built more than 1,200 years ago (Fig. 1), conservators, archaeologists, and other specialists are striving to understand and combat the physical, chemical, and biological processes responsible for the deterioration of these historic structures and artifacts. Each of these sites represents a cultural trove, one as a testament to a lost civilization and the other as a tribute to a bygone era of exploration. Separated by more than 10,000 km and residing in two very different climates, these sites were constructed of drastically different materials. Yet the artifacts at each location are slowly wasting away, presenting two very different cases of biodeterioration that reflect distinct microbial communities and modes of decomposition.

With their ability to use diverse energy sources and survive under varied environmental conditions, microorganisms are superbly capable of degrading culturally important materials. Given the proper conditions of humidity, temperature, and pH, many components of our precious cultural heritage such as pigments, textiles, metals, polymers, wood, and stone can fall victim to microbial degradation. Biodeterioration of culturally significant artifacts and structures takes on new levels of importance as conservators and archaeologists weigh the benefits of unearthing and displaying artifacts, or even cleaning or repairing such artifacts, against the risks of exposing them to further damage by microbes.

Summary

- The fungal species *Cadophora*, which is causing soft rot in and outside historically important buildings at Antarctic sites, is distinct from microorganisms that typically damage wooden buildings in temperate and tropical zones.
- Microorganisms living along and also below the surfaces of Mayan stone artifacts may threaten archaeological sites throughout the Yucatan region of Mexico.
- Bacteria that can remove sulphate crusts or form layers of calcite to consolidate mineral surfaces could prove helpful to conservators who are working to restore damaged building stones.

Fungi Damage Wood Structures in Antarctica

The early 20th century marked a heroic age of polar exploration. In 1901, Robert Scott and Ernest Shackleton began their quest to reach the South Pole, launching the first of several expeditions to the Ross Sea region of Antarctica. The men brought wooden huts with them to use as their base of operations. Scott himself would perish on an expedition launched from one of these huts in 1911. Shackleton went on to lead the *Endurance* expedition but succumbed to a heart attack 11 years later while attempting to circumnavigate the frozen continent by ship. Despite

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FIGURE 1

Areas of study. Left: Shackleton's hut at Cape Royds, Ross Island, Antarctica. Right: the Mayan city of Ek' Balam, Yucatan, Mexico.

the harsh environment that killed their former occupants, the huts still stand. Yet even in subzero temperatures, fungi are gradually degrading these wood structures.

Investigations of these historic sites reveal decay in the exterior woods, and blooms of fungi on the surfaces of the wood, textiles, paper, and other artifacts inside the huts (Fig. 2). The decay in these huts is not the type usually encountered in temperate and tropical zones, where wood-destroying basidiomycetes are prevalent. Instead, the ascomycete *Cadophora* is the predominant species causing soft rot by producing cavities inside wood cell walls (Fig. 2). This poorly known group of fungi appears to be common in Antarctica, where they live in soils and utilize varied carbon sources. Although it has taken decades of relatively slow growth during the short Austral summers, their cumulative damage to historic wood and other artifacts is substantial, posing serious conservation problems not only in the Antarctic huts but also throughout the world.

Our understanding of such microorganisms and how they damage wood in such varied environments is not well developed. However, from Antarctic huts, we know there are many previously undescribed species of fungi present, leaving us with much to learn about their ability to tolerate high salts and other toxic substances. With so little known about counteracting these damaging fungi, we and other microbiologists now recommend to the Antarctic Heritage Trust, the nonprofit organization that oversees preservation efforts, that microenvironments in and around the huts be changed to make them less conducive for fungal growth. These changes include improving snow melt drainage, reducing moisture levels of wood in contact with the ground, and reducing relative humidity inside the huts. After visitors track snow and ice into the huts, frost typically forms on interior walls, while moisture from storms may filter into the huts, furnishing additional moisture to microbes that augments their growth and leads to further damage. Restricting moisture remains the most practical option for limiting these detrimental microbial effects.

If little is known about the microorganisms that affect the historic huts of Antarctica, less can be said about microbial diversity in polar regions. The fungi causing decay in the historic structures and artifacts appear to be dominant organisms responsible for carbon utilization and nutrient recycling in Antarctic soils. These fungi are distributed not only in Antarctica, but also in the Arctic region. Undoubtedly important in these ecosystems, they were little known and poorly appreciated before investigators recognized that they are responsible for attacking cultural artifacts left behind by early polar explorers.

Archaeologically interesting wooden artifacts typically are found intact at sites where extreme environmental conditions limit microbial growth. Whether in arid terrestrial sites or water-logged at the bottom of the sea, microbes can colonize and degrade wood, raising serious challenges over how to preserve valuable historic structures worldwide. Protecting these important cultural resources is an enormous challenge for conservators, one to which microbiologists can contribute by providing a better understanding of these organisms, which should help toward developing better strategies for controlling them.

FIGURE 2

Biodeterioration of cultural properties from Scott's Cape Evans hut. Left: mold growing on a historic crate (top) and explorer's boot (bottom). Right: Wood decay cross section from Shackleton's Cape Royds hut showing extensive cavities in wood cell walls. (Figure by Benjamin Held, University of Minnesota).

Bacterial Communities Threaten Mayan Stone Works

Mayan archaeological sites in Southern Mexico are among the most important cultural artifacts in the Western Hemisphere. Most of these cities were part of the great Mayan civilization until the 8th and 9th centuries when they were abandoned by their inhabitants and reclaimed by the jungle. Unearthed in recent years, these stone structures are subject to the high temperatures and humidities that prevail throughout the Yucatan Peninsula, fostering substantial microbial growth. In some instances, growth of pigmented microorganisms merely alters the appearance of the historic stone, presenting a purely aesthetic challenge. However, in other cases, microorganisms are a major cause of stone deterioration.

The epilithic microflora on the surfaces of Mayan stone structures make up a diverse community of microorganisms, including heterotrophic bacteria, *Cyanobacteria*, algae, fungi, and lichens. Their growth, particularly the *Cyanobacteria* and algae, can stain stone surfaces green and black. Yet their threat is not purely aesthetic. The autotrophs that colonize these surfaces appear to be a source of organic matter that supports successive growth by large communities of heterotrophic bacteria and fungi. Once established, fungal hyphae can then penetrate deep into stone. Subsequent shrinking and swelling of the hyphae severely degrades the surrounding material, providing entry sites for water and leading to further deterioration.

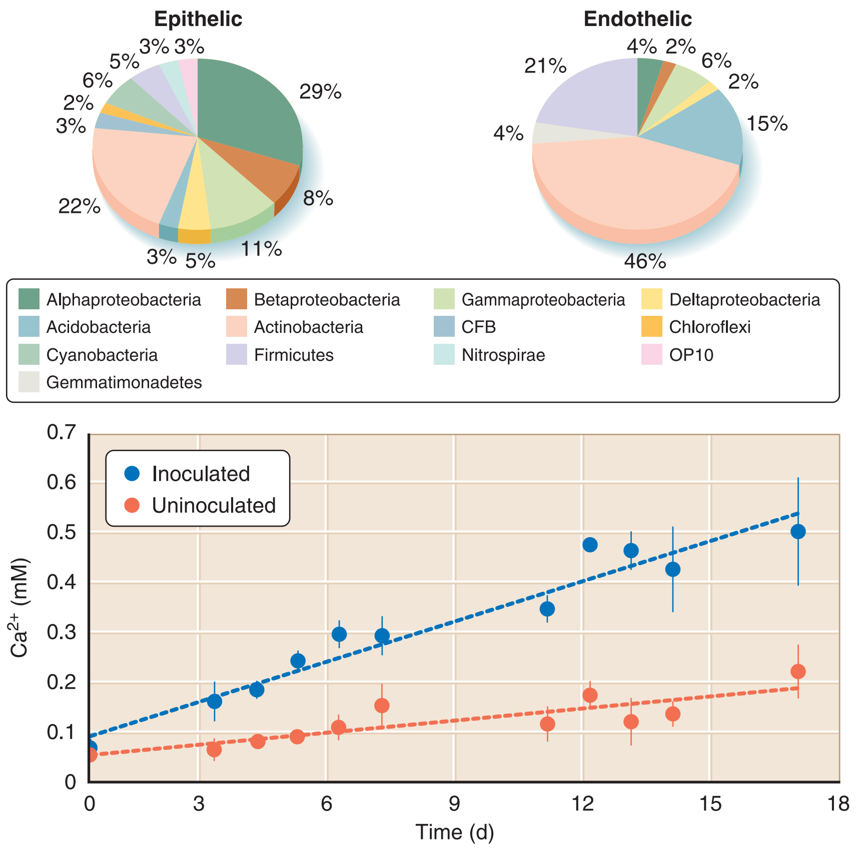
Endolithic microorganisms also colonize the interior of the stone through pores and cracks that form through physical weathering. At the ruins of the city Ek' Balam, 160 km west of Cancun, we discovered that the 16S rDNA diversity of endolithic bacteria residing 1–2 cm below the surface of limestone differs dramatically from the epilithic microflora residing above it. *Actinobacteria* dominate this endolithic community, which also contains large numbers of *Acidobacteria* and *Firmicutes* (Fig. 3).

The bacteria in these endolithic habitats may be damaging culturally important limestone objects. For example, the biofilm matrix in which they reside absorbs water, which shrinks and swells their extracellular polysaccharides. In turn, this mechanical stress opens cracks and fissures in the limestone. Like that of fungal hyphae, this process also exfoliates surface layers and crusts.

Endolithic microorganisms may also accelerate stone-damaging chemical processes. For instance, bacteria can increase the mineral dissolution rate of the limestone in which they reside by producing simple acids. Indeed, in the presence of the endolithic bacteria, limestone releases Ca^{2+} twice as fast as when those bacteria are not added to the mix (Fig. 3).

These microbial communities may be endangering Mayan archeological sites. For example,

FIGURE 3



Top: comparison of epilithic and endolithic bacteria. Percentage of clones in each phylogenetic group from epilithic bacteria (left) and endolithic bacteria (right). Bottom: Ca^{2+} concentration in uninoculated flasks and flasks inoculated with endolithic bacteria.

endolithic growth protects bacterial populations against low temperatures, UV radiation, and desiccation. To what extent does it also insulate these organisms from attempts by conservators to protect and restore these surfaces? Finding bacteria within such artifacts calls into question traditional techniques, such as the application of consolidants, long used for preserving carbonate stone such as limestone and marble. Consolidants, which penetrate the stone surface and bind its components, typically contain biodegradable organic polymers that endolithic bacteria might degrade. We need to better understand the metabolism of endolithic bacteria if we are to preserve Mayan sites, as well as other statues, tombstones, monuments, and historic buildings.

Using Bacteria to Clean Stone Surfaces

Atmospheric pollution and weathering can disfigure or damage stone surfaces by forming salt crusts—typically, gypsum. Such sites present opportunities for bioremediation. While bioremediation is now a routine approach for treating sites contaminated with hazardous chemicals, its application to ameliorate the effects of stone deterioration is rarely practiced.

However, conventional techniques, such as mechanical removal of salt crusts and the use of slaked lime or lime wash, have several disadvantages. They may change the color of the stone, interfere with the ordinary movement of salts within the stone, or remove excess amounts of the original surface. For example, some conservators continue to criticize the mechanical removal of black crusts and patinas from the Parthenon in Athens, while also questioning whether those crusts are linked to past treatment regimes.

Meanwhile, there is growing evidence that bacteria can be used to treat damaged stone surfaces. In particular, some bacteria have the potential to remove sulphate crusts or to form sacrificial layers of calcite that consolidate mineral surfaces. Thus, bioremediation might offer a new means for restoring stone surfaces of heritage buildings.

Conservators involved in the BIOBRUSH project (www.biobrush.org), which is funded by the European community, are evaluating low-hazard bacteria to remove salt crusts from stone surfaces and other bacteria to consolidate stone surfaces. Applying the bacteria directly to stone surfaces minimized the risk to the stone itself, to the immediate environment, and to those who handle these materials.

In one case, multiple short-term applications of aerotolerant sulphate-reducing bacteria within an appropriate delivery system successfully removed black gypsum crusts from marble in the laboratory and in situ on buildings. This approach to removing such crusts occurs in a natural way, as these same microorganisms play an active role in the environment where they contribute to the sulfur cycle. Based on trial results, this form of bioremediation compares favorably to traditional chemical cleaning with ammonium carbonate.

Another BIOBRUSH project explored factors that influence biological precipitation of calcium carbonate. According to studies in Spain, France, the United States, and Italy, biocalcifying bacteria pose little threat to heritage objects. They can deposit a calcite layer without significantly reducing the porosity of the stone. Here again, conservators used bacteria isolated from the environment and controlled the release of nutrients to minimize growth of contaminant microorganisms.

Researchers continue to evaluate the effectiveness and risks of these procedures to provide conservators with greater confidence. Another set of concerns focuses on whether there are any long-term effects from applying the bacteria and nutrient media. Scientists and conservators should collaborate to address these issues.

Despite such questions, the controlled use of microorganisms to help preserve, protect, and restore building stone appears promising as a means for supplementing, not wholly replacing, traditional conservation technologies, some of which are not particularly effective, while others expose users and the environment to toxic materials. During the past 10 years, researchers began to identify suitable microorganisms that either remove salt crusts or consolidate pore structures in damaged stone, and have also addressed some of the environmental risk factors in applying this new technology.

ACKNOWLEDGMENTS

The authors are supported by grants from the National Science Foundation, the Consejo Nacional de Ciencia y Technologica, the Samuel H. Kress Foundation, the European Commission Fifth Framework, Energy, Environment, and Sustainable Development Programme, and institutional funds from their respective Universities.

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