

Breaking Disciplinary Boundaries: Bringing the Biological Role out of the Blind Spot in DRF-Based Assessments of Limestone Weathering under a Changing Climate

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Limestone cultural heritage has increasingly been threatened by the complex interplay of climatic stressors, air pollution, and biological colonization. In this STECCI study, a bio-geochemical dose-response framework was introduced to quantify and interpret the decay of stećci-medieval tombstones constructed from locally sourced limestone, across fifteen culturally significant sites in Southeastern Europe. While existing dose-response functions (DRFs) have traditionally been applied to climatic, chemical and physical weathering, biological link has often been in the Blind Spot, despite mounting evidence that lichens, mosses, and microbial taxa contribute actively to stone decay.

Two widely used DRF models Lipfert (1989) and Kucera et al. (2007) were applied to multi-decadal environmental data (1992-2023), accounting for variations in precipitation, temperature, and pollutant load (SO₂, NO_x, PM₁₀). Bioassessment surveys were conducted to record biological colonization using a modified Braun-Blanquet scale and photographic quadrat sampling. At the same time, spatial overlays of DRF results and biological data were produced to identify zones of specific vulnerability, where climatic exposure and biodeteriogen presence were observed to overlap. As expected, the Lipfert model responded more strongly to high-precipitation karstic settings, while the Kucera model captured the cumulative effect of pollutants and humidity in urban sites. However, both models were shown to underestimate decay in areas with extensive lichen or moss coverage, highlighting the need for biotic factors to be integrated into predictive modeling. To address this, a multi-stressor approach was developed, coupling DRF-predicted surface recession with biological indicators and introducing a coefficient within the both mathematical models, as lithobiontic organisms, such as *Lobothallia cheresina*, *Xanthoria elegans*, and *Grimmia pulvinata*, were found to contribute to micro-fracturing, mineral leaching, and, most importantly, moisture retention, often acting synergistically with atmospheric deposition. Based on these insights, a STECCI Preservation Measures Assessment tool was proposed to

classify heritage sites according to modeled decay, biocolonization intensity, and conservation urgency.

This integrative methodology was conducted to sharpen the diagnostic capacity of DRFs and enabled the generation of science-based insights, integrating risk assessment models for heritage exposed to climatic, natural, and anthropogenic hazards. In light of projected climate shifts and persistent anthropogenic emissions, it is recommended that heritage conservation efforts adopt bio-geo diagnostics to transition from reactive toward preventive conservation strategies. The approach presented here is transferable to other limestone heritage materials and contributes to the growing discourse on climate-resilient cultural heritage preservation.

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