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SPECTROPHOTOMETRIC MONITORING OF SURFACES IN SHOW CAVES AS A PART OF MANAGEMENT PLANS FOR CONTROLLING LAMPENFLORA GROWTH

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Light eutrophication in show caves and other light-deprived humid environments, such as mines, tunnels and catacombs, can support visible growth of microbial mats, with photoautotrophs as the dominant group of organisms. Photosynthetic pigments of aerophytic cyanobacteria and eukaroytic algae impose a greenish patina upon surfaces to which – with other community members – they adhere strongly. For example, sequencing of lampenflora DNA from the Škocjan Caves, Slovenia, UNESCO World Heritage Site, revealed a relative dominance of Cyanobacteria (~70%) among prokaryotes, over Proteobacteria (~10%), Bacterioidetes (~10%) and other groups that represented the remaining ~10% (Planctomycetes, Firmicutes, Acidobacteria, Chlamydiae, Verrumomicrobia, Actinobacteria). Diverse eukaryotic algae, fungi, flagellates and amoebozoans were also identified within the community. These "human induced diversity hotspots" in caves are responsible for the biodeterioration of colonized surfaces that is a common result of the synergistic effects of phototrophs and heterotrophs. When sites become colonized by higher plants, such as mosses, liverworts and ferns in species succession, irreversible biodeterioration impact on rocks and speleothems becomes an even more urgent issue. Historical inscriptions and rock-art paintings are particularly sensitive to biodeterioration. Lampenflora also affects components of the cave fauna, which not only graze upon it, but also facilitate its dispersal to other parts of the caves. It can be considered a direct indicator for light eutrophication and of the available energy within the cave ecosystem.

There is a need for appropriate monitoring to provide alerts that will prompt timely action against lampenflora before it starts to affect the substrate integrity irreversibly, attract excessive and unwanted fauna or become encrusted and armoured against subsequent treatment and removal. Such monitoring could also be expanded to help estimate the efficiency of lampenflora removal in caves where this is carried out routinely. Regular monitoring can facilitate the delimitation of zones within a cave on the basis of the local susceptibility to lampenflora colonization.

Spectrophotometric survey of cave surfaces can cover all of the above-mentioned aspects without adverse effects on the surfaces. Such methods are used widely in the printing, automotive, food, cosmetic, paint, construction, paper and packaging industries, etc. In the field of cultural heritage, the technique is applied to measure the difference in appearance of historical material before and after treatment with different preservative, protective or consolidative materials.

One feasible approach to colorimetric analysis is based on a chromacity system $CIEL^*a^*b^*$ (where L^* stands for luminosity, a^* being the red–green parameter and b^* being the blue–yellow parameter). This system enables easy calculation of colour changes over time or between individual sites. Several sites in the show cave sections

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of the Škocjan Caves were monitored to track surface colour changes after the adoption of LED lighting and treatment of the rock surfaces with hydrogen peroxide to remove lampenflora. Results of the oxidizing effect of hydrogen peroxide treatment on surfaces affected by lampenflora were observed clearly, with the most notable contributions from the red–green parameter followed by luminosity.

Interpretation of the colorimetric results obtained using this system should consider several factors: fresh colonization of lampenflora, increase/decrease of population density due to the application of biocides, encrustation of pre-existing lampenflora (and consequently higher initial values of the green parameter), and fresh deposition of calcite and/or other (coloured) minerals between measurements. It seems that lampenflora grows faster on coloured (e.g., grey-brown) surfaces, that can be attributed to the presence of nutrients or other growth factors. Sites commonly exhibited reduced green colour after being treated with hydrogen peroxide. Although spectrophotometric survey can provide valuable data about the monitored surfaces, sometimes a second step, to identify the key phototrophs by "time consuming" culturing or the quantification of key indicator species, e.g., by quantitative Polymerase Chain Reaction (qPCR), is still needed.

Results of spectrophotometric monitoring of rock surfaces can be related directly to the progress of lampenflora proliferation or removal. Initially, monitoring sites should be selected carefully, particularly if there are already naturally existing green minerals, if the rate of flowstone deposition outstrips the rate of lampenflora growth, or if an encrusted microbial mat is already present. Particular attention should be given to the inhomogeneous nature of surfaces, their unevenness or varying colour, and the presence of water droplets and/or seepages.

In show caves catering for large numbers of visitors, necessitating long periods of illumination, spectrophotometric monitoring of surfaces should become an essential part of the management plan for controlling lampenflora growth. In some caves preventative actions include imposition of a restricted lighting regime with a low light intensity, i.e., with a low photosynthetic photon flux density – PPFD. Sometimes this is cross-coupled with the installation of tuneable, low energy-consuming LED lamps with emission spectra that lie outside the absorption peaks of the main photosynthetic pigment – chlorophyll *a*. Generally, these measures are insufficient to prevent initial colonization and further propagation of lampenflora in the underground. Show cave managers already employ some measures to help the recovery of affected sites in caves, for example by application of biocides based on hydrogen peroxide or sodium hypochlorite.

Early stages of lampenflora colonization with a low population density of microscopic phototrophs cannot be detected by subjective "visual inspection" of critical surfaces; for this reason, application of a spectrophotometry-based monitoring strategy seems a practical and non-invasive initial approach to avoiding the development of green mats on illuminated surfaces. Lampenflora represents a critical issue for cave management worldwide, and the accompanying problems are likewise common. That is why the need for good-practice exchange was one of the key issues pursued at the recent meeting on "Sustainable Management of Show Caves", held at Škocjan Caves, 07–09 October 2019.

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