LAMPENFLORA ALGAE AND METHODS OF GROWTH CONTROL

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Abstract: Karst caves are unique natural features and habitats where specialized organisms live. Some caves are also important as cultural heritage sites. In recent decades, many caves have experienced intensified tourist visits. To attract visitors, artificial illumination was installed that changed conditions in the caves. As a result, communities of organisms called lampenflora develop in close and remote proximity to lights. These phototrophic organisms are inappropriate from an aesthetic point of view and cause the degradation of colonized substrata, which is a particular problem in caves with prehistoric art. Key factors that allow lampenflora to grow are light and moisture. Illuminated spots in caves can be quickly colonized by algae, some of which have broad tolerances for different substrata. Several phototrophs can survive in caves even at photon flux densities lower than the photosynthetic compensation point. In this paper, the pros and cons of physical, chemical, and biological methods to control phototrophic growth are reviewed and discussed. Experiences in show caves can be helpful in controlling undesirable algal growth in other environments.

INTRODUCTION

Caves have a special place in human history. Early in prehistory, humans discovered that caves can provide suitable temporary or permanent shelters. Later, man developed a different relation with caves, not only as shelter but also for their natural beauty and inspiration. In many caves around the globe, remnants of prehistoric man are found. Especially interesting are those caves with paintings. Many caves of natural and cultural importance are listed on the United Nations Educational, Scientific, and Cultural Organization (UNESCO) World Heritage List. Cave tourism is considered to be one of the oldest forms of tourism.

In recent decades, many caves have experienced intensified tourist visits. To attract visitors, artificial illumination was installed. Illuminated areas such as rocky surfaces, sediments, and artificial materials around lamps quickly become colonized by phototrophic organisms. This complex community of autotrophic photosynthetic organisms is called lampenflora and develops in natural and artificial caves around artificial light sources (Dobat, 1998). In this lampenflora community, various aerophytic algae, as well as some mosses and ferns dominate, and are usually strongly adhered to the substratum. Mosses and ferns, also part of lampenflora, are not discussed further because in the early phase of colonization and succession, algae, both prokaryotic cyanobacteria and eukaryotic algae, usually play the most important role, while mosses and ferns appear later in the succession. Vascular plants are sometimes found, but almost always as germinating shoots (Martinčič et al., 1981). Lampenflora is, relative to the aerophytic phototrophs from the cave entrances, completely independent of sunlight and other external climatic factors. In comparison with sunlight, artificial light sources show no oscillations in light intensity. Dobat (1972) named spots with growing lampenflora ecosystems in formation.

One of the characteristics of the natural cave environment is low nutrient input (Simon et al., 2007) that is changed with the introduction of light energy. Such drastic changes to the cave ecosystem directly and indirectly influence cave fauna. Higher nutrient input in cave environments enables newcomers to be more competitive than the originally present troglomorphic organisms. Consequently obligate cave-dwelling organisms are threatened and may become extinct without restoration of previous natural conditions (Pipan, 2005).

In the last few years, many different views about unwanted phototrophs in caves have appeared, but the main question was not what these green cave dwellers are, but how to prevent their growth (Planina 1974; Ash et al., 1975; Caumartin, 1977; Caumartin, 1986; Iliopoulou-Georgoudaki et al., 1993; Gurnee, 1994; Byoung-woo, 2002; Hazslinszky, 2002; Lochner, 2002; Olson, 2002; Merdenisianos, 2005). An important problem occurs when lampenflora becomes covered with $CaCO_3$, irrespective of whether this carbonate is a result of abiotic or biotic precipitation. Such an amorphous mix of dead phototrophs and $CaCO_3$ irreversibly destroys the natural heritage of speleothems or other objects of cultural value (Mulec, 2005). Loss of historic paintings and objects in caves due to biological activities is becoming an important problem. The purpose of this paper is to review various methods to control lampenflora growth and to select the most appropriate one.

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ALGAE OF THE LAMPENFLORA COMMUNITY

Biodiversity of lampenflora is low compared to the flora from cave entrances where cyanobacteria are dominant (Palik, 1964; Golubić, 1967; Buczkó and Rajczy, 1989; Vinogradova et al., 1995; Vinogradova et al., 1998; Asencio and Aboal, 2000a, b; Uher and Kováčik, 2002; Mulec et al., 2008). Mulec et al. (2008) demonstrated that the concentration of chlorophyll *a* per unit surface area of lampenflora algae was slightly higher (max. 2.44 μg cm^{-2}) compared to the epilithic algae from the cave entrance (max. 1.71 μg cm^{-2}). This difference can be explained due to the different light regimes in both microhabitats (i.e., changing light quality and irradiance levels during the day in the cave entrance), different periods of illumination, different *in situ* moisture levels, and different species composition. Generally speaking, areas around lamps have more stable conditions because they are deeper in the constant zone of the cave (Mulec et al., 2008).

As reported by Garbacki et al. (1999) in Belgian caves, Cyanobacteria made up 54% of the phototrophic organisms, Chrysophyta 30%, and Chlorophyta 16%. Dobat (1970) and Chang and Chang-Schneider (1991) recorded the percentages of phototrophs in German caves; Cyanobacteria 55%, Chrysophyta 14%, and Chlorophyta 31%. Cyanobacteria also prevailed in Slovenian caves with 51%, followed by Chrysophyta 27%, and Chlorophyta 22% (Dobat, 1973; Martinčič et al., 1981; Krivograd-Klemenčič and Vrhovšek, 2005; Mulec, 2005; Mulec et al., 2008). It was shown that cyanobacteria, *Aphanothece castagnei* and *Gloeocapsa sanguinea*, and green alga, *Stichococcus bacillaris*, were part of lampenflora in all three countries. Other species that appeared with high frequency included *Aphanocapsa grevillei*, *A. muscicola*, *Chondrocystis dermochroa*, *Chroococcus varius*, *C. westii*, *Gloeocapsa atrata*, *G. compacta*, *G. rupestris*, *Gloeothece rupestris*, *Leptolyngbya lurida*, *L. perelegans*, *Phormidium retzii*, *Schizothrix calcicola*, *Scytonema julianum* (Cyanobacteria), *Achnanthes* sp., *A. lanceolata*, *Elipsoidon oocystoides*, *Navicula contenta*, *Pinnularia borealis* (Chrysophyta), *Chlorella miniata*, *Gloeocystis polydermatica*, *Klebshormidium flaccidum*, *Pleurococus vulgaris*, and *Trentepohlia aurea* (Chlorophyta).

As soon as a lampenflora community is established, these phototrophic organisms start to colonize new, not yet established substrates. Although cyanobacteria are the most adaptable phototrophs to extreme environments, in habitats with less environmental stress, like illuminated spots around lamps, they are easily overgrown by fast-growing eukaryotic algae (Mulec, 2005). In a growth experiment, after 25 days of cultivation under cave conditions, the green alga *Chlorella* sp. had a 10-times greater increase in cell count when compared to the cyanobacterium *Chroococcus minutes* (Mulec et al., 2008). The two organisms are two common phototrophs that are found in subaerophytic habitats in caves. In the mature stage of species succession in the lampenflora community, cyanobacteria become much more abundant, and thus, community composition becomes more similar to the community from a cave entrance where cyanobacteria dominate (Mulec et al., 2008).

In another experiment, limestone disks placed around lamps in show caves were colonized by the following phototrophs: *Apatococcus lobatus*, *Chlorella* sp., *Lyngbya* sp., *Nostoc* sp., *Navicula mutica*, and *Trentepohlia aurea*. Similar composition of the algal community was observed when limestone disks were covered with Jaworski agar (Mulec, 2005), a culture medium commonly used in algology (Warren et al., 1997). Organisms identified on disks covered with agar were: *Apatococcus* cf. *lobatus*, *Chlorella* sp., *Lyngbya* sp., *Stichococcus bacillaris*, and *Trentepohlia aurea*. This later experiment confirmed that eukaryotic microalgae successfully and quickly colonize new stony surfaces around lamps. Fast-growing phototrophs can quickly re-colonize former niches, even with a high frequency of cleaning of rocky surfaces with biocides. Microscopic observations of scrapes from disk surfaces showed that disks covered with agar were colonized to a greater extent by bacteria and fungi when compared to the disks without agar covering (Mulec, 2005). Nevertheless, lampenflora algae are usually ubiquitous, fast reproducing, and adaptable soil algae (Rajczy, 1989). Existence of algae and other higher plants (i.e., ferns and mosses deep in show caves) demonstrates effective transport of viable propagules from outside the caves.

KEY ENVIRONMENTAL FACTORS THAT INFLUENCE LAMPENFLORA GROWTH

Three modes of transport of viable propagules into the karst underground can be distinguished: air currents, water flow, and introduction by animals and humans. (Dobat, 1970; Vegh, 1989). Conditions deep in the cave are usually very stable, but that can be changed when high amounts of energy are introduced. An important factor in the spreading of lampenflora and other organisms is local air currents caused by warm air in the proximity of strong lamps, especially halogen ones (500–1000 W) (Vegh, 1989). Increased temperature notably influences algal growth. Pulido-Bosch et al. (1997) used an incandescent lamp and found that at a distance of 50 cm from the light source the temperature was 8 °C higher than elsewhere. Even low energy lamps can change the cave climate. Mulec (2005) showed that relative humidity 20 cm from a 108 W lamp dropped from normal cave relative humidity of 95% to only 73% relative humidity (Fig. 1). Frequency of switching lights on and off affects relative humidity and temperature. At the point where the highest drop of relative humidity was observed, Mulec (2005) measured a temperature increase of 1.6 °C. Lampenflora do not develop in the immediate vicinity of strong lights due to very high temperature that kills the organisms. Visitors can

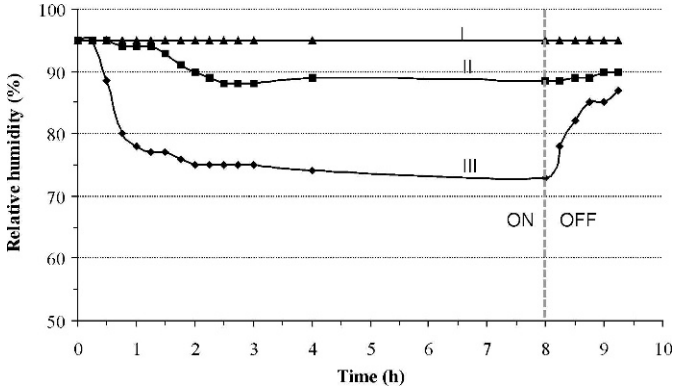

Figure 1. Changes in relative humidity are dependent on distance to the lamp at selected light intensities (I – 0 μmol photons m^{-2} s^{-1} (450 cm); II – 50 μmol photons m^{-2} s^{-1} (48 cm); III – 100 μmol photons m^{-2} s^{-1} (20 cm)) when the lamp was on and after it was switched off.

also increase cave temperatures. Mais (2004) reported that the presence of visitors in ice caves can start to melt the ice. As a consequence of mass tourism in caves, CO_2 concentration can exceed 5000 ppm (Pulido-Bosch et al., 1997). In addition to the natural corrosion processes in caves, the combined effect of an increase in CO_2 concentration and temperature variations induced by visitors can directly affect the intensity, and even the development, of wall corrosion processes. As shown by Sánchez-Moral et al. (1999) in a case study of Altamira Cave (Spain), the corrosion induced by visitors can be up to 78 times greater than the corrosion arising from natural processes.

Aerophytic algae can survive in the environment only when humidity is high enough. Generally, the presence of running and seeping water accelerates growth of plants in caves (Martinčič et al., 1981). Another important ecological parameter that affects algal growth is the type of substratum and the presence of sediment (Martinčič et al., 1981; Chang and Chang-Schneider, 1991). Shade acclimated algae (e.g., from caves) have high photosynthetic efficiencies and low light saturation (Grobbelaar et al., 2000). Some lampenflora algae can survive and reproduce even at light intensities that are lower than the photosynthesis compensation point (i.e., light intensity at which the amount of CO_2 fixed in sugars during photosynthesis is equal to the CO_2 released during respiration). In Slovenian show caves, growth of algae can appear in a light intensity as low as 0.33 μmol photons m^{-2} s^{-1} (Mulec, 2005). Martinčič et al. (1981) showed that algae in caves can survive at photon flux densities in the range of 0.5 to 1 μmol photons m^{-2} s^{-1}. Cyanobacteria and diatoms have an average compensation point between 5 and 6 μmol photons m^{-2} s^{-1}, while for green algae, it is generally around 21 μmol photons m^{-2} s^{-1} (Hill, 1996). In caves, heterotrophy must then play an important role, which is the case for many planktonic and benthic algae (Tuchman, 1996).

Interaction of Phototrophs with Substratum

Complex microbial communities can be found not only as an epilithion, but also inside the rock endolithion. For successful colonization, epilithic organisms must develop in a close interaction with the substratum. A substratum and its characteristics at the micro-level are one of the key factors for aerophytic algae, which were demonstrated with the absence of correlation between photon irradiance and chlorophyll *a* concentrations (Mulec et al., 2008). Epilithic algae also take up essential elements for growth from the base on which they are adhered (Warscheid and Braams, 2000; Hoffmann, 2002). In some cases, a substratum may not support, or can even inhibit, growth of organisms.

Organisms have developed several strategies to take up minerals by utilizing biogenic organic acids and siderophores (Warscheid and Braams, 2000). The often anionic exopolymers strongly absorb cations and dissolves organic molecules from the underlying minerals (Hoffmann, 2002). During the process of mechanical destruction of the rock, the cyanobacterial sheath and various polymers of the outer cell layers play an important role because they can absorb and release huge quantities of water. Such extension and contraction can mechanically destroy the substratum, which is even more evident when water freezes (Asencio and Aboal, 2001). All these biological activities lead to bio-oxidation of minerals and changes in the mineral structure of the rock, which leads to destruction, weathering, and increased porosity and permeability of water deep into the rock (Warscheid and Braams, 2000). Using pH electrodes at the micro-level, Albertano (1993) and Hoffmann (2002) demonstrated photosynthesis linked alkalization of the surrounding milieu, simultaneously with acidification from CO_2 released during fermentation and respiration. Alkalization during illumination induces precipitation of mineral mixtures (Albertano et al., 2000).

In poorly illuminated cave environments, the cyanobacteria *Geitleria calcarea* and *Scytonema julianum* are frequent cave dwellers. For both species, deposition of calcite on cell filaments at a thickness of up to 30 μm was observed. Incrustation of *G. calcarea* is probably controlled by the organism itself (Pentecost and Whitton, 2000). On the outer cell layers of *Leptolyngbya* and *Dischereella*, a huge amount of $CaCO_3$ was also observed (Albertano, 1997). Precipitation of mineral particles on sheaths causes epilithic strains to become endolithic (Asencio and Aboal, 2001). In caves, *G. calcarea*, *S. julianum*, *Loriella osteophila*, and *Herpyzonema pulverulentum* are the best characterized organisms that are able to mobilize calcium ions from the carbonate substrata (Hernandez-Marine and Canals, 1994; Hernandez-Marine et al., 1999).

Biodeterioration processes are undesirable in caves of special cultural or natural heritage. A thick biofilm composed of phototrophs responsible for calcite precipitation and bio-corrosion growing on illuminated prehistoric and more recent cave paintings has been identified by Pietrini and Ricci (1993), Asencio and Aboal (2001), and Cañaveras et al. (2001). It seems that light intensity influences the change of the organisms from epilithic to the endolithic phase (Asencio and Aboal, 2001). When illumination is too high, some epilithic algae simply switch to the endolithic phase. Depending upon the growth as epilithic or endolithic, some species can change their cell size (Asencio and Aboal, 2000b). However, once the substratum is colonized by these organisms and precipitation of $CaCO_3$ starts, the deposited carbonate can act as protection against excessively high photon-flux intensity. Extremely strong illumination causes other changes on the substratum to appear. In Castelana Cave (Italy), it was observed that at a distance of 50 cm from a 1000 W lamp, aragonite crystals started to grow over calcite stalagmites (Hill and Forti, 1997).

CONTROL OF GROWTH OF PHOTOTROPHS IN CAVES

As previously discussed, the lampenflora has various negative effects on the cave environment and in caves with important cultural heritage. Problems connected with illumination and phototrophic biofilms are usually not properly solved. The main obstacle is because the cause (i.e., light) remains on the site and the proper way of preventing lampenflora growth is still missing. The simplest solution to preventing lampenflora growth in a cave would be complete removal of existing phototrophic communities, cessation of the illumination, and abolition of tourist visits, which of course, is not acceptable to the cave management.

Some algae can tolerate the absence of illumination for short or longer periods of time (Dalby, 1966). Once visible lampenflora appears it should be removed. Hazslinszky (2002) reported that in Baradla Cave (Hungary) without any intervention, lampenflora spread quickly, doubling from 1977 to 1984.

Many approaches to lampenflora control in caves have already been tested, including physical, chemical, and biological control.

PHYSICAL METHODS

Cleaning of speleothems overgrown by algae with water and brush is not recommended because the infestation can be more easily dispersed throughout the cave (Rajczy, 1989; Hazslinszky, 2002). The mechanical removal of lampenflora with water and brushes damages the fragile crystals structure of speleothems. Cleaning with high pressure vapour destroys tiny flowstone forms (Ash et al., 1975).

The simplest way to restrict lampenflora growth is time limited illumination of the caves with an automatic switch system to shut down the lighting whenever the user is absent. Planina (1974) estimated that lampenflora cannot develop to a great extent if illumination in the cave does not exceed 100 h yr^{-1}. Growth and spread is further limited if illumination of damp surfaces is avoided (Rajczy, 1989). Byoung-woo (2002) recommended increasing the illumination distance between speleothems and light source by more than two meters.

Growth of phototrophs can be notably diminished by the reduction of light intensity (Gurnee, 1994) and by using special lamps that emit light at wavelengths which do not support maximum absorption of the main photosynthetic pigments (Caumartin, 1986). In Mammoth Cave (USA), Olson (2002) used light-emitting diodes (LEDs) to control lampenflora. Yellow-light (595 nm) LEDs at an intensity of 49.5 lx prevented growth for 1.5 years after complete lampenflora removal. Despite the yellowish light, the LEDs still gave a natural appearance to the cave (Olson, 2002). Quantitative analyses of biofilms formed by the cyanobacterium, *Gloeothece membranacea*, and green alga, *Chlorella sorokiniana*, illuminated exclusively with white or green light suggested that illumination by green light can be a possible treatment for preventing photosynthetic biofilm growth (Roldán et al., 2006). Lochner (2002) determined that using ozone producing lamps did not significantly diminish the lampenflora in Saalfelder Feengrotten Cave (Germany). Suppression of the lampenflora can be achieved using UV irradiation due to its known germicidal effect, but it was shown that it has only a transitory suppressing effect (Dobat, 1998). Lampenflora does not develop, or it develops very slowly, if a dispersed mode of illumination is used, as was done at the speleotherapy station for patients with pulmonary diseases of Sežana Hospital (Slovenia) (Mulec, 2005). Several health centers around the world use speleotherapy to heal bronchial, allergic, and rheumatic diseases. The healing effect is attributed to special properties of air in the subterranean spaces, stability of the temperature, humidity, pressure, and content of gaseous components. The ions in aerosols have not only local disinfectant and anti-inflammatory effect, but they also stimulate the human immune system (Jirka, 1999).

More attention should be applied to planning the illumination system in newly opened show caves and to renovation of systems in existing show caves. An important step in controlling lampenflora growth is appropriate installation of lamps and housings and modes of illumination. In caves with previously installed lamps, lighting of individual sectors with automatic switch systems must be implemented as soon as possible. Reducing the intensity and period of illumination also brings a benefit in reduced energy costs. Light spectra of lamps must be carefully considered. Illuminated places and spots that would be interesting for tourists must be carefully selected, especially places with dripping and seeping water. Lighting sediments and mud should be avoided. Touching of speleothems by

visitors with clothes, fingers, or other materials should be reduced as much as possible, because this results in introduction of nutrients and microbes into caves and cessation of carbonate deposition. Finally, placement of lamps in areas with strong air circulation should be thoroughly considered due to possible increases in lampenflora dispersion.

CHEMICAL METHODS

Chemical substances which would be suitable to control lampenflora growth must fulfill the criteria of minimum side effects on the cave environment and organisms while providing humans with high efficacy in suppressing phototrophs. These biocides should have long lasting effects without any negative influences on cave rocks, speleothems, and electro-installation materials.

Use of DCMU (diuron, N-3, 4-dichlorophenyl-N′-dimetil urea) and bromine compounds as suggested by Caumartin (1977) are absolutely inappropriate due to toxicity. Selective herbicides such as Atrazine (6-Chloro-N-ethyl-N′-(1methylethyl)-1,3,5-triazine-2,4-diamine) and Simazine (6-Chloro-N,N′-diethyl-1,3,5-triazine-2,4-diamine) are not suitable for widespread use in caves since the green coloring on the karst formations persists (Grobbelaar, 2000).

Effective and less toxic biocides are sodium hypochlorite (NaOCl) (Zelinka et al., 2002) or calcium hypochlorite ($Ca(OCl)_2$) (Iliopoulou-Georgoudaki et al., 1993), but some filamentous cyanobacteria, such as *Scytonema julianum* and *Leptolyngbya* spp. trapped in the pores of bedrock, can still survive and later reproduce (Iliopoulou-Georgoudaki et al., 1993). Other authors have suggested formalin (Cubbon, 1976; Caumartin, 1986; Merdenisianos, 2005), cupric ammoniac solution (Merdenisianos, 2005), or butyl alcohol (Hill and Forti, 1997). Sodium hypochlorite successfully restricts growth of lampenflora in caves, but it represents a large burden for the cave environment. From the hypochlorite solution, gaseous chlorine can be released. In the reaction of hypochlorite with ammonia and other nitrogenous compounds, toxic chloramines and even carcinogenic trihalomethanes are released. Low chlorine concentration in the cave environment can kill microbiota, which represents an important source of nutrients for cave-dwelling organisms. Chlorine causes lowering of the pH and thus dissolves calcite (Faimon et al., 2003). Even $Ca(OCl)_2$ is a quite efficient biocide, but it is, like NaOCl, responsible for reddish coloration of carbonate substrata due to the oxidation of Fe^{2+} into Fe^{3+} that precipitates as an amorphous iron hydroxide ($Fe(OH)_3$) (Iliopoulou-Georgoudaki et al., 1993).

For suppressing lampenflora growth, Faimon et al. (2003) suggested use of hydrogen peroxide (H_2O_2) instead of an aggressive 5% aqueous solution of NaOCl. The key question regarding using H_2O_2 is what concentration is high enough to destroy the lampenflora and yet does not have a deteriorating effect on speleothems. A 15% solution of H_2O_2 is sufficient to kill phototrophic organisms if it is applied three times over two to three weeks. However, even a 15% solution of H_2O_2 attacks carbonate bedrock more aggressively than karst water (Faimon et al., 2003). Grobbellar (2000) suggested the following procedure to eradicate lampenflora: application of 200–500 mg L^{-1} H_2O_2 and after 5–30 minutes washing and collecting of the wash water. If lampenflora persists, the application can be repeated or UV-C radiation can be applied, or the area can be sprayed with 20–50 m L^{-1} of Atrazine. Grobbellar (2000) experienced that spraying with H_2O_2 and washing is only required once every six months to a year due to the slow growth rates of the algae. In practice, in order to kill lampenflora in show caves, other commercially available biocides are also applied.

In some caves, lampenflora becomes progressively covered with flowstone and it turns slowly into an amorphous greenish mass of dead biomass. Yellowish-green speleothems remain preserved in caves for years, because the main photosynthetic pigment chlorophyll *a* is not water soluble and carbonate depositing dripping water cannot simply rinse it away (Mulec, 2005). To remove the green color from flowstone, one should use a solution in which chlorophyll *a* is soluble and that has minimal effects on the cave environment. As eligible substances, several non-polar solvents can be used, including alcohols, dietyl-ether, benzene, or acetone (Meeks, 1974). Procedures with minimal negative effects on the environment should be developed. In any case, the porosity and permeability of each flowstone should be taken into consideration, which further complicates the procedure.

BIOLOGICAL METHODS

To date, no studies on the use of biological methods to control lampenflora have been done. One possible way to restrict lampenflora growth is the use of biological antagonists like genetically modified viruses[1]. Another approach would be inactivation of those factors which are crucial for development and establishment of lampenflora community, such as cell signalling molecules, or molecules which are necessary for metabolism of iron (Albertano, 2003).

CONCLUSIONS

Caves are important for humans because they represent geomorphologic, geologic, biologic, historical, archaeological, and paleontological laboratories. Caves are sometimes the only source of information of past geological events. People visit caves due to esthetical, recreational, educational, health, and religious purposes. Anthropogenic influences in fragile cave environments have many consequences; and therefore, everything should be conducted in

[1] Editor's Note: Introducing exotic species to selected areas for the purpose of controlling other unwanted species often results in new, unexpected, and typically much worse environmental problems.

ways that minimize these effects (Boston et al., 2004). In artificially illuminated caves, lighting results in temperature and relative humidity changes in the cave environment. Lampenflora growth as a result of this interference must be restricted. To control its growth, several physical, chemical, and biological methods can be adopted. However, at the moment, there is no ideal solution. The most suitable method, or combinations of methods, are still under investigation.

Cave management should not open new parts of a cave or new caves to the public without careful study, and cave management should not show everything in the brightest way to the tourists. Rather, it should be done in such a way so that some natural or cultural heritage remains in dim aspect of admiring beauty, as it was at the beginning of cave tourism.

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