DIVERSITY OF BRYOPHYTES IN SHOW CAVES IN SLOVENIA AND RELATION TO LIGHT INTENSITIES

DIVERZITETA MAHOV V TURISTIČNIH JAMAH V SLOVENIJI IN POVEZAVA Z INTENZITETO OSVETLJEVANJA

Janez MULEC¹ & Svatava KUBEŠOVÁ²

Abstract

Janez Mulec & Svatava Kubešová: Diversity of bryophytes in show caves in Slovenia and relation to light intensities

In subterranean environments phototropic organisms can grow only in the proximity of light sources. In a study from eight Slovenian show caves: Črna jama, Kostanjeviška jama, Križa jama, Pekel pri Zalogu, Pivka jama, Postojnska jama, Škocjanske jame and Županove jama and two mines, Idrija mercury mine and Mežica zinc mine, equipped for tourist visits, 37 taxa of Bryophyta and Pteridophyta were identified. The most frequent organisms were mosses Amblystegium serpens, Brachythecium sp., Eucladium verticillatum and Fissidens taxifolius. The highest diversity of bryophytes was recorded in Mežica mine with 16 identified taxa where lamps are on continuously. Bryophytes were collected at a wide range of photosynthetic photon flux densities (PPFD) from 0.2 to 530.0 μmol photons/m²/s. Eucladium verticillatum had the highest span of PPFDs, ranging from 1.4 to 530.0 μmol photons/m²/s. Bryophytes compensate for low PPFD with longer exposure to light irradiance. Cratoneuron filicinum identified in Mežica mine developed sporophytes at 2.1 and 2.4 μmol photons/m²/s, in Postojnska jama Brachythecium salebrosum developed sporophytes at 4.7 μmol photons/m²/s. Recolonization of lampenflora in show caves where bleach is applied to prevent its growth is still successful at sites that are exposed to long periods of irradiance and high PPFDs.

Keywords: caves, bryophytes, lampenflora, PPFD, Slovenia.

Izvleček

Janez Mulec & Svatava Kubešová: Diverziteta mahov v turističnih jamah v Sloveniji in povezava z intenziteto osvetljanja

V podzemelju fototrofni organizmi lahko uspevajo zgolj v bližini vira svetlobe. V raziskavi, ki je vključevala vzorce iz osem turističnih jam v Sloveniji, iz Črne jame, Kostanjeviške jame, Krške jame, Županove jama in dveh rudnikov, Rudnika živega srebra Idrija in Rudnika svinca in cinka Mežica, ki sta opremljena za turistični obisk, smo identificirali celokupno 37 taksonov mašov in praproti. Najpogosteji zastopani so bili mašovi Amblystegium serpens, brachythecium sp., Eucladium verticillatum in Fissidens taxifolius. V Rudniku Mežica, kjer so luči stalno prižgane, je bila s 16 taksoni ugotovljena največja pestrost mašov. Mašovi kompenzirajo nizke vrednosti PPFD z daljšo izpostavljenostjo svetlobnemu osvetljevanju. Cratoneuron filicinum identificiran v Mežica jami je razvit sporofit pri vrednosti 2,1 in 2,4 μmol fotonov/m²/s, v Postojnski jami pa pri 4,7 μmol fotonov/m²/s Brachythecium salebrosum s prav tako razvitim sporofitom. Recolonization of lampenflora in show caves where bleach is applied to prevent its growth is still successful at sites that are exposed to long periods of irradiance and high PPFDs.

Ključne besede: jame, mašovi, lampenflora, PPFD, Slovenija.

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To present underground features and to attract visitors, more and more show caves in many areas around the globe are being equipped with electric lighting. In show caves with artificial illumination phototrophs do not grow only at cave entrances where they are exposed to natural sunlight, but also deep in the underground in the vicinity of lamps. Different rocky surfaces, sediments and artificial materials around lamps become colonized by phototrophs. This community of phototrophs named lampenflora is composed of cyanobacteria, algae, bryophytes and ferns – usually prothallii. A prothallus is a short-lived fern haploid structure which forms from a spore with numerous rhizoids growing underneath. Only exceptionally shoots of flowering plants can be recorded deep in the underground (Martinčič et al. 1981; Kubešová 2001). Lampenflora organisms are usually typical surface species (Dobat 1998; Mulec 2008). Some cyanobacteria and microalgae from this community can survive even at photon flux densities lower than their photosynthetic compensation point. At the cave temperature the light saturation point of these organisms is quickly reached (Mulec et al. 2008). Existence of lampenflora deep in show caves indicates constant and efficient transport of viable plant propagules from outside caves by air currents, water flow, or by animals and humans (Dobat 1970; Rajczy 1989).

Soon after installation of lighting system in a cave the question arises how to prevent growth of this alien vegetation. The best way in controlling lampenflora growth is still the physical approach, e.g., proper selection of time-limited irradiation, reduction of light intensity, separation of lighting of tourist trails from other underground inventory, using light spectrum which does not support photosynthesis, and well-considered illuminated surfaces (Rajczy 1989; Olson 2002; Zelinka et al. 2002; Mulec & Kosi 2009). To avoid further infestation of lampenflora its successful removal is a crucial step. However, in some caves lampenflora is preserved as a tourist attraction. Nevertheless, lampenflora in caves shows that natural cave conditions are disturbed which enables invaders from the surface to be more competitive than the originally present trogloomorphic organisms (Mulec & Kosi 2009).

In Slovenia cave tourism has a long tradition, with one of the oldest documented show caves in the world – Vilenica from 1633 and world-famous Postojnska jama which is equipped with electric lightening since 1889 (Shaw 2003). The occurrence of plants growing around

Tab. 1: Caves and mines with lampenflora in Slovenia with data on tourist management and light irradiation of sampled sites

<table>
<thead>
<tr>
<th>Cave/Mine</th>
<th>Lithology</th>
<th>Altitude (m)</th>
<th>Annual number of visitors</th>
<th>Electric equipment</th>
<th>Use of herbicides</th>
<th>Annual illumination (hrs/sector)</th>
<th>PPDF (μmol photons/m²/s) AVG±SD</th>
<th>Min</th>
<th>Max</th>
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<tbody>
<tr>
<td>Črna jama</td>
<td>Cretaceous limestones</td>
<td>540</td>
<td>3,000</td>
<td>1929</td>
<td>+</td>
<td>&gt;70</td>
<td>130±130</td>
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<td>130</td>
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<td>Kostanjeviška jama</td>
<td>Cretaceous limestones, dolomites</td>
<td>170</td>
<td>10,000</td>
<td>1970</td>
<td>-</td>
<td>&gt;60</td>
<td>71±53</td>
<td>9</td>
<td>213</td>
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<td>Krška jama</td>
<td>Jurassic and Triassic limestones, dolomites</td>
<td>540</td>
<td>10,000</td>
<td>1995</td>
<td>-</td>
<td>&gt;100</td>
<td>56±40</td>
<td>7</td>
<td>138</td>
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<tr>
<td>Pekel pri Zalogu</td>
<td>Triassic limestones, dolomites</td>
<td>314</td>
<td>20,000</td>
<td>1972,1976, 1997</td>
<td>+</td>
<td>&gt;100</td>
<td>9±16</td>
<td>1</td>
<td>59</td>
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<tr>
<td>Pivka jama</td>
<td>Cretaceous limestones</td>
<td>540</td>
<td>3,000</td>
<td>1929</td>
<td>+</td>
<td>&gt;70</td>
<td>29±23</td>
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<td>51</td>
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<td>Postojnska jama</td>
<td>Cretaceous limestones</td>
<td>529</td>
<td>500,000</td>
<td>1884</td>
<td>++</td>
<td>1,000</td>
<td>110±124</td>
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<td>530</td>
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<td>Škocjanske jame</td>
<td>Cretaceous and Paleogene limestones</td>
<td>425</td>
<td>90,000</td>
<td>1959</td>
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<td>477</td>
<td>51±64</td>
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<td>200</td>
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<td>Županova jama</td>
<td>Jurassic limestones</td>
<td>468</td>
<td>10,000</td>
<td>1937</td>
<td>-</td>
<td>&gt;80</td>
<td>74±54</td>
<td>17</td>
<td>173</td>
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<tr>
<td>Idrija, mercury mine</td>
<td>Permocarbonian shales, dolomites</td>
<td>330</td>
<td>25,000</td>
<td>1994</td>
<td>+</td>
<td>&gt;214</td>
<td>5±6</td>
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<td>18</td>
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<tr>
<td>Mežica, lead and zinc mine</td>
<td>Carnian limestones, Triassic dolomites, shales</td>
<td>500</td>
<td>17,000</td>
<td>2000</td>
<td>-</td>
<td>8.760</td>
<td>0.9±0.8</td>
<td>0.2</td>
<td>2.7</td>
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</table>

* no tourist visit in the area with lampenflora

Successive electrification
++ regular, + occasional, - never
Eight show caves, Črna jama, Postojnska jama, Kostanjeviška jama, Krška jama, Pekel pri Zalogu, Pivka jama, Škocjanske jame, Županova jama and two mines equipped for tourist visit (Idrija mercury mine, Mežica lead and zinc mine) were screened for the presence of bryophyte lampenflora (Fig. 1). In comparison to the previous studies (Morton 1941; Latzel 1942; Grom 1961, 1962; Dobat 1973; Martinčič et al. 1981) few new caves were added to the list of show caves with lampenflora (Tab. 1).

In show caves tourists observe various natural karstological features, e.g., flowstone formations and underground river flows, while in mines they learn about history of mining and exploitation of natural resources that is why the illuminated objects in caves and mines usually differ. In show caves and mines where lampenflora was sampled, lamps are periodically turned on due to tourist visits or maintenance of the tourist infrastructure. Time when caves are exposed to lighting varies; the longest period of illumination in caves is in Postojnska jama and Škocjanske jame. In Mežica lead and zinc mine at the sampling location, which is not visited by tourists, lamps are on 24 hours due to constant monitoring of the underground water flow. Bryophytes generally grow on restricted illuminated surfaces around lamps in the underground, except in Mežica mine where around two lamps they covered approximately 15 m² of rocky surface (Fig. 4D). Other surfaces in Mežica mine were not colonized with lampenflora. Caves experience different intensities of tourist visits of which Postojnska jama has the longest tradition and highest number of tourists (Tab. 1). The history of lampenflora study and control is different for each cave, for example problem with plants inside Postojnska jama has been reported already by Morton (1941). In Postojnska jama bleach was is used to kill lampenflora every second year.

Sampling was performed between 23rd and 28th of March 2008. When possible the same sites were selected as for the study of cyanobacteria and algae of lampenflora communities in 2003 (Mulec et al. 2008). Prior to taking specimens photosynthetically active radiation at sites was quantified as μmol photons/m²/s using a LI-COR LI-1000 DataLogger (USA), which is a measure of photosynthetic photon flux density (PPFD). If various plants were observed around a selected lamp several specimens were sampled at different distances. After collection field material was sorted and determined under a binocular microscope and a light
microscope (Olympus SZ40 and Olympus CX31, respectively). Identification followed determination keys after Hradilek 1994, Hedenäs 2003 and Frey et al. 2006. The nomenclature is according to Frey et al. 2006.

RESULTS AND DISCUSSION

From eight caves and two mines equipped with electric illumination in this study 37 taxa of Bryophyta and Pteridophyta were identified. The most frequent organisms identified in studied Slovenian caves and mines were *Amblystegium serpens* (frequency in all studied caves and mines was 0.60), *Eucladium verticillatum* (0.50) and *Fissidens taxifolius* (0.50) (Tab. 2).

The highest number of different phototropic taxa were identified in Mežica lead and zinc mine (16) with the highest frequency of *Cratoneuron filicinum* (0.57), *Eucladium verticillatum* (0.19) and Platyhypnidium riparioides (0.14) followed by jama Pekel with 14 organisms (*Eucladium verticillatum*, 0.43, *Fissidens cf. bryoïdes*, 0.36, *Taxiphyllum cf. wissgrillii*, 0.21), Kostanjeviška jama with 13 taxa (*Cratoneuron filicinum*, 0.35, *Fissidens cf. bryoïdes*, 0.35, and *Rhynchostegium murale*, 0.18). Lower taxa numbers were recorded in Postojnska jama with 9 taxa (*Eucladium verticillatum*, 0.94, *Rhynchostegium murale*, 0.17, *Bryum* sp., 0.17), Škocjanske jame with 8 taxa (*Eucladium verticillatum*, 0.91, *Weissia* sp., 0.27), Idrija mercury mine with 7 bryophytes (*Amblystegium serpens*, 0.38, *Brachythecium* sp., 0.38), Županova jama with 8 bryophytes (*Brachythecium* sp., 0.33, *Amblystegium serpens*, 0.22), Krška jama with 6 taxa (*Amblystegium serpens*, 0.40, *Fissidens sp.*, 0.30), Pivka jama with 3 bryophytes *Rhynchostegium murale* (1.0), and Črna jama with one bryophyte *Orthothecium intricatum* (1.0).

Based on previous studies floristically the most diverse was lampenflora from Postojnska jama with 30 identified taxa (Tab. 2). In this study we identified only 9 taxa what can be attributed to regular removal of lampen flora using bleach. A similar decrease in taxa linked to chemical removal of lampenflora and reduction of light intensity was experienced also in show caves in the Czech Republic (Kubešová 2001, 2004). Regular removal of lampenflora patches in Postojnska jama is likely the reason for lower diversity of cyanobacteria and algae compared to other caves (Mulec et al. 2008). For example previous screening of lampenflora organisms in Postojnska jama revealed out of 13 sampled sites (9 cyanobacterial and 8 algal taxa) only three colonized by mosses and ferns (one moss and one fern species) (Mulec 2005).

The highest diversity was found in Mežica mine with 16 identified taxa indicating that lighting scheme was the most favourable for mosses (Tab. 1). Martinčič and co-workers described jama Pekel as “the greenest cave” in Slovenia where they identified 21 taxa of Bryophyta and Pteridophyta (Martinčič et al. 1981). In this study we found only 14 taxa in the cave. Lower number of mosses and ferns from jama Pekel compared to older study can be explained with changed lamps in the cave in the last years which emit lower PPFDs.

In our study lampenflora communities comprised mosses and ferns, but no liverworts were identified. In previous studies they were recorded in jama Pekel and

![Fig. 2: Bray-Curtis dissimilarity index of lampenflora in Slovenian show caves; A-analysis based on bryophytes, B-analysis based on identified bryophytes and pteridophytes (ČR-Črna jama, ID-Mercury mine in Idrija, KO-Kostanjeviška jama, KR-Krška jama, ME-Lead and zinc mine Mežica, PE-Jama Pekel, PI-Pivka jama, PO-Postojnska jama, ŠK-Škocjanske jame, ŽU-Županova jama, PPFD expressed in μmol photons/m²/s per cave).](image-url)
Table 2: Bryophytes and pteridophytes in Slovenian show caves (ČR-Črna jama, ID-Mercury mine in Idrija, KO-Kostanjeviška jama, KR-Krška jama, ME-Lead and zinc mine Mežica, PE-jama Pekel, PI-Pivka jama, PO-Postojnska jama, ŠK-Škocjanske jame, ŽU-Županova jama, I-previous studies, II-this study)

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<th>Cave</th>
<th>ČR</th>
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<td><strong>BRYOPHYTA</strong></td>
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<td>Leiocolea bantriensis (Hook.) Jörg.</td>
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<td>Pellia epiphylla (L.) Corda</td>
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<td>Amblystegium sp. Schimp.</td>
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<td>Amblystegium serpens subsp. juratzkanum (Schimp.) Ren. &amp; Card.</td>
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<td>Amblystegium varium (Hedw.) Lindb.</td>
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<td>Barbula unguiculata Hedw.</td>
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<td>Brachythecium sp. Schimp.</td>
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<td>Brachythecium cf. campestre (Müll. Hal.) Schimp.</td>
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<td>Brachythecium mildeanum (Schimp.) Schimp.</td>
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<td>Brachythecium cf. rivulare Schimp.</td>
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<td>Brachythecium velutinum (Hedw.) Schimp.</td>
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<td>Brachythecium velutinum var. speleaeorum Latzel</td>
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<td>Campylium calcareum Crundw. &amp; Nyholm</td>
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<td>Didymodon vinealis (Brid.) R. H. Zander</td>
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<td>Encalypta streptocarpa Hedw.</td>
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<td>Encalypta vulgaris var. obtusa Nees. &amp; Hornsch.</td>
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<td>Eucladium verticillatum (With.) Bruch &amp; Schimp.</td>
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<td>Eucladium verticillatum (With.) Bruch &amp; Schimp. subsp. verticillatum</td>
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<td>Eucladium verticillatum subsp. styriacum (Glow.) J. J. Amann</td>
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<td>Fissidens bambergeri Schimp. ex Milde</td>
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<td>Fissidens bryoides Hedw.</td>
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<td>Fissidens cf. bryoides Hedw.</td>
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<td>Fissidens dubius P. Beauv.</td>
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Comparison of lampenflora among 10 caves and mines based on Bray-Curtis dissimilarity index indicated relatively low similarity except between Postojnska jama and Županova jama (Fig. 2). Two statistical analyses using this index were carried out, on communities of bryophytes and on communities of bryophytes and pteridophytes. Results indicated that there is no pattern; different caves have generally different community of plants. Nevertheless, ferns were not frequent dwellers in Slovenian caves, in this study only five taxa were identified. The most frequently recorded were fern prothalli (0.4, Tab. 2). The most apparent group is Postojnska jama-Županova jama. The cluster Postojnska jama and Županova jama had the highest PPFDs at all sites and the lowest dissimilarity index (0.33 when bryophytes and pteridophytes were included in the study and 0.25 when only communities of mosses were analyzed). This can be attributed to fast growth of lampenflora in Postojnska jama as a result of high PPFDs despite regular physical removal of lampenflora and in Županova jama to con-

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<td>Funaria hygrometrica Hedw.</td>
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<td>Isothecium myosuroides fo. spelaem Grom</td>
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<td>Minium stellare Reichard ex Hedw.</td>
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<td>Oxyrhyynchium hians (Hedw.) Loeske</td>
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<td>Plagiomnium sp. T. J. Kop.</td>
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<td>Plagiomnium affine (Blandow ex Funck) T. J. Kop.</td>
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<td>Plagiomnium rostratum (Schrad.) T. J. Kop.</td>
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<td>Rhynchoasteiella tenella (Dicks.) Limpr.</td>
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<td>Seligeria donniana (Sm.) Müll. Hal.</td>
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<td>Taxiphyllum wissgrillii (Garov.) Wijk &amp; Margad.</td>
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<td>Tortula muralis Hedw.</td>
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<td>Weissia sp. Hedw.</td>
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*PTERIDOPHYTA*

| Asplenium sp. L. | + | - | - | - | + | - | - | - | - | - |
| Asplenium ruta-muraria L. | + | - | - | - | + | - | - | - | - | - |
| Asplenium scolopendrium L. | + | - | - | - | + | - | - | - | - | - |
| Asplenium trichomanes L. | + | - | - | - | + | - | - | - | - | - |
| Cystopteris fragilis (L.) Bernh. | + | - | - | - | + | - | - | - | - | - |
| Cystopteris cf. fragilis (L.) Bernh. | + | - | - | - | + | - | - | - | - | - |
| fern prothallus | + | - | - | - | + | - | - | - | - | - |

Fig. 3: Span of photosynthetic photon flux density for individual species of mosses and ferns identified in lampenflora community in Slovenian show caves. The second quartile (Q₂) is indicated with grey, i.e. 17 µmol photons/m²/s.

DIVERSITY OF BRYOPHYTES IN SHOW CAVES IN SLOVENIA AND RELATION TO LIGHT INTENSITIES
stant, but lower PPFDs and no physical removal of plants since establishing of electric illumination (Tab. 1).

Interestingly, lampenflora from Mežica clustered with Postojnska jama-Županova jama group in both analyses; average PPFD was 0.9 ±0.8 μmol photons/m²/s with lights on 24 hrs per day. This indicates that bryophytes compensated extremely low PPFDs (0.2 – 2.7 μmol photons/m²/s) with longer exposition to light irradiation. Furthermore, in Mežica Cratoneuron filicinum was identified with developed sporophyte at photon fluxes at 2.1 and 2.4 μmol photons/m²/s. In Postojnska jama Brachythecium salebrosum was identified with fully developed sporophyte at PPFD of 4.7 μmol photons/m²/s (Fig. 4A). Low PPFDs at which plants were collected indicate their low light compensation point in caves, equal or higher to the measured values. It is known that in extreme habitats light compensation point of bryophytes is similar to that of algal communities. For example in Antarctic lakes Drepanocladus s.l. had light compensation point of approximately 0.5 μmol photons/m²/s and Calliergon in shallow water around 2.9 μmol photons/m²/s (Glime 2007).

Communities of mosses from Pivka jama and Črna jama were not diverse and were represented by only three and one species, respectively. In these two caves development of moss lampenflora was still in initial phase, and as in 2003 no bryophytes were observed there (Mulec 2005).

Some bryophytes are able to grow over a relatively wide range of light intensities (Glime 2007). Light irradiation at which lampenflora in Slovenian show caves was sampled ranged from 0.2 to 530 μmol photons/m²/s (first quartile Q₁=2, second quartile Q₂=17, third quartile Q₃=55 μmol photons/m²/s). For some taxa PPFDs at which particular organism was identified varied a lot, especially Eucladium verticillatum (1.4-530.0 μmol photons/m²/s), Cratoneuron filicinum (0.2-213.0 μmol photons/m²/s), Rhynchostegium murale (4.7-213.0 μmol photons/m²/s), Fissidens dubius (1.0-200.0 μmol photons/m²/s), Bryum sp. (0.9-180.5 μmol photons/m²/s), Fissidens taxifolius (1.4-150.5 μmol photons/m²/s), Amblystegium serpens (1.0-172.5 μmol photons/m²/s), Brachythecium velutinum (0.8-137.7 μmol photons/m²/s), Fissidens cf. bryoides (0.9-128.9 μmol photons/m²/s), and Brachythecium sp. (0.7-100.3 μmol photons/m²/s). Among ferns Cystopteris cf. fragilis (0.4-160.0 μmol photons/m²/s), Asplenium trichomanes (0.5-160 μmol photons/m²/s) and Asplenium sp. (2.0-128.9 μmol photons/m²/s) had the largest span of PPFD at which they were recorded (Fig. 3). In show caves bryophytes were found close to lamps where also temperature is higher due to heat emissions of lights.

Calcite precipitates accumulating on Eucladium verticillatum termed “eucladioliths” (Dalby 1966) can be found in Slovenian caves, too (Fig. 4B, compare with Fig. 4C).
CONCLUSIONS

In eight Slovenian show caves and two mines equipped with electric illumination 37 taxa of Bryophyta and Pteridophyta were identified. The highest diversity of bryophytes was found in Mežica mine with 16 identified taxa indicating that lighting regime influenced diversity the most.

Light irradiation at which bryophyte lampenflora was recorded started from 0.2 and exceeded 500 μmol photons/m²/s. For some organisms photosynthetic photon flux density at which particular organism grow, varies considerably. For example, PPFD which enables growth of *Eucladium verticillatum* ranged from 1.4 to 530.0 μmol photons/m²/s.

For growth bryophytes compensate low PPFD with longer exposure to light irradiance. In Mežica mine *Crautoneuron filicinum* was identified with developed sporophyte at 2.1 and 2.4 μmol photons/m²/s. Similarly in Postojnska jama *Brachythecium salebrosum* was identified with fully developed sporophyte at 4.7 μmol photons/m²/s.

Using of highly toxic bleach (NaClO) effectively kills lampenflora but has only transitory effect in preventing growth without efficient changes of lighting regime and light quality is thus questionable. Recolonization of lampenflora in caves is rather successful at sites which are exposed to long irradiance period and high PPFDs.

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