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An ecological investigation on lichens and other lithobionts colonizing rock art in Valle Camonica (UNESCO WHS n. 94) addresses preventive conservation strategies

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Abstract:	Environmental control strategies are commonly practiced to limit biodeterioration issues threatening indoor cultural heritage objects, while they are still poorly exploited for the conservation of the outdoor stone heritage surfaces, including rock art. In this study, we evaluated the environmental factors driving the diversity and abundance of lithobiontic communities in the Rock Engravings National Park of Naquane (UNESCO WHS n. 94, Italy). The survey considered 23 rocks which had been cleaned in the last three (3YC) or twelve (12YC) years or from more than 40 years (NRC). A cyanobacteria-dominated biofilm and lichens (37 taxa) were the most widespread and abundant lithobiontic components, prevailing on 3YC-12YC and NRC rocks, respectively. On these latter, a turnover of xerophytic and meso-hygrophytic lichen communities was observed. On 3YC-12YC rocks lichen colonization, if present, was limited to nitrophytic species, including common epiphytes from surrounding trees, and few meso-hygrophytic species, with prevalence of asexual reproductive strategies. Multivariate analyses including environmental parameters (canonical correspondence analyses) indicated the tree cover and the presence of bare or vegetated ground upstream of the rocks, likely prolonging wetness and providing nutrients by water transport, as the factors mostly related to the microbial and lichen recolonization of 3YC-12YC surfaces. On this basis, an experiment on preventive conservation was conducted, consisting of a new cleaning of a strongly recolonized 3YC surface combined with the building of a small wall to protect part of the rock from prolonged water fluxes. The fluorimetric and colorimetric monitoring of the rock surface, done 40 months after this new cleaning intervention, displayed recolonization on the unprotected area only, indicating the potential of preventive conservation strategies also in outdoor environments.

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- 17

16

18 Abstract

19 Environmental control strategies are commonly practiced to limit biodeterioration issues

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- 20 threatening indoor cultural heritage objects, while they are still poorly exploited for the
- 21 conservation of the outdoor stone heritage surfaces, including rock art. In this study, we
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41

42 Keywords

43 biodeterioration, biofilm, cultural heritage, recolonization, nitrophytic community

44

O PELIEZ

45 Introduction

Saxicolous lichens, as well as other lithobionts, are a major threat to stone heritage 46 conservation because of their physical and chemical interactions with mineral substrates, 47 48 promoting weathering processes and thus affecting surface durability (Seaward 2015; Favero-Longo & Viles 2020). On the other hand, at least for some combinations of species, 49 lithologies and climate conditions, bioprotective rather than biodeteriorative effects of lichens 50 were reported (Pinna 2021, and references therein). Besides these negative and/or positive 51 impacts on material properties, lichen colonization influences the aesthetics and legibility of 52 heritage surfaces, with critical consequences when thalli mask meaningful details, as 53 inscriptions or art reliefs (Pinna 2017). In a broader sense, any lithobiontic cover distances the 54 heritage surface appearance from the original author's conception. Therefore, curators of the 55 outdoor stone heritage, particularly in the Latin cultural area, consider as a priority the 56 maintenance of any stone heritage surface in a clean state, i.e. free of lichens and other 57 lithobionts, and manage conservation plans accordingly. Devitalization and mechanical 58 removal of lichen thalli and microbial biofilms are thus routinely included in restoration 59 interventions (Pinna 2017). However, a wide use of synthetic chemicals as biocides, practiced 60 for decades, is now increasingly considered environmentally unsustainable, and new 61 alternative products and/or chemical-free approaches to control lithobionts are incessantly 62 searched for (Cappitelli et al. 2020). 63

Lichenologists, and potentially others, may have different priorities than heritage site curators with regard to the conservation of heritage stone surfaces or of lichens and biodiversity in general (Seaward 2004). Different perceptions of biodeterioration issues generally depend on the type of heritage surfaces affected (a statue, a grave, a church façade, a castle wall, an archaeological ruin) and the local cultural tradition (Favero-Longo & Viles 2020). Moreover, different evaluations may derive from the 'environmental scenery' of each artwork, with the

lithobiontic colonization, although distancing the stone appearance from its original one, 70 71 sometimes contributing to its positive integration with the surrounding natural context. With this regard, Nimis and colleagues (1992) early invoked the possibility of considering lichens 72 as an additional cultural value in certain heritage sites, such as archaeological areas, worth to 73 be preserved and brought to the attention of visitors. 74 75 Lithobiontic colonization and biodeterioration effects deserve particular attention when affecting rock art, as biological growths and the artworks may display a rather similar 76 dimensional extent (i.e. (sub-)millimetric thickness), thus particularly implying conservation 77 issues (Darvill & Batarda-Fernandes 2014; Zerboni et al. 2022). Lichens, in particular, can 78 79 partially mask or fully cover engravings (Tratebas 2004), and were shown to induce physical and chemical deterioration processes on different lithologies bearing rock art, although 80 negative effects on the surface durability were not always recognizable (e.g. Chiari & Cossio 81 2004; Marques et al. 2016). The impact on surface legibility, however, is sufficient to make 82 lichens generally undesirable on engraved stone surfaces, even though their colonization is an 83 84 obvious and unavoidable phenomenon on every rock outcrop (Jung & Büdel 2021) and just lichens are often a prominent and valuable biodiversity component of the environments 85 hosting rock art (Tansem & Storemyr 2021). Treatments with synthetic chemical biocides, in 86 87 combination with mechanical actions and other restoration products as consolidants and water-repellents, have been thus routinely practiced in rock art sites to (i) periodically remove 88 lichens and other lithobionts from engraved surfaces, and (ii) try to prolong the maintenance 89 of the clean state (Tratebas 2004; Paz-Bermúdez et al. 2023). Only recently, in order to reduce 90 the spread of chemicals into the environment, alternative approaches to control lithobionts on 91 92 engraved rocks were assayed, including laser and microwave applications. However, the former seems less effective than traditional biocides and may even increase rock 93 bioreceptivity (Paz-Bermúdez et al. 2023), and the latter needs technical improvements to 94

allow outcrop-scale applications (Favero-Longo et al. 2021). On the other hand, approaches to
prevent recolonization dynamics following cleaning interventions by controlling (micro)environmental parameters, which is a usual and regulated practice (e.g., in Italy, DM
10/05/2001; MIBAC 2001) to limit biodeterioration in indoor environments (Caneva et al.
2008), still appear poorly considered in the case of the outdoor stone heritage, and for rock art
in particular.

In the Rock Engravings National Park of Naquane, heart of the UNESCO site 'Rock 101 Drawings in Valle Camonica' (WHS n. 94, Italy), outcrops hosting the most remarkable 102 engravings have undergone a long series of cleaning interventions (including the application 103 104 of biocides), which were registered since 1980s but started long before (www.irweb.it; Ruggiero & Poggiani-Keller 2014). In the last decades, recolonization dynamics on certain 105 rocks, mostly related to fast spreading of cyanobacterial biofilms, even renewed the necessity 106 of cleaning every few (2-3) years. This makes the management unsustainable in terms of time 107 and costs, but also with regard to the environmental pressure of the repeated biocide 108 109 application and a potential stress on rock surface due to the repeated mechanical treatments. Therefore, a research project started in 2016 to assess critical features of the adopted 110 conservation strategies (e.g., the efficacy of adopted protocols of biocide applications; 111 Favero-Longo et al. 2021), and to explore alternative approaches to better combine cultural 112 and environmental heritage conservation (Ruggiero et al. 2021). In this framework, the 113 present work aims to characterize lithobiontic colonization on the engraved sedimentary rocks 114 of the National Park of Naquane, focusing on the diversity and abundance of lichens on 115 outcrops with different conservation history and environmental conditions. It also gives an 116 117 insight into their physical interaction with the sandstone substrate. The results were used to address a preventive strategy to limit lithobiontic recolonization after cleaning interventions, 118 which was experimentally tested on a selected engraved outcrop. In particular, we tested the 119

hypotheses that: (a) some environmental factors are main drivers of diversity and abundance
of lichens and other lithobionts on recently cleaned surfaces, (b) lichens and other lithobionts
penetrate within the sandstone substrate, and (c) interventions limiting favourable
environmental conditions for lichens may generally hinder the fast lithobiontic recolonization
following cleaning interventions.

125

126 Material and methods

127 *Study site*

The Rock Engravings National Park of Naguane is located in the middle part of Valle 128 Camonica [Capo di Ponte, Brescia, Italy: UTM WGS84: 32T 604400 m E, 5097700 m N], 129 where it was established in 1955 as the first national archaeological park. It extends between 130 400 and 600 m above sea level (a.s.l.) on approx. 14,000 m² of the eastern side of the valley, 131 and hosts the most important groups of prehistoric and protohistorical engravings of Valle 132 133 Camonica. The engravings are distributed on 104 numbered surfaces of sedimentary rock outcrops, dimensionally ranging from few to approx. 250 square meters (e.g. Rock 1, named 134 the "Great Rock of Naquane", with 65 m² of engraved surface; Liborio et al. 2011). In 135 136 particular, engravings are carved in terrigenous sedimentary rocks (Verrucano Lombardo, Upper Permian; Brack et al. 2008) mainly consisting of sandstones/graywackes rich in quartz, 137 feldspars and fragments of volcanic rocks, micro-conglomerates, and mudrocks. Sediments of 138 the Verrucano Lombardo suffered a quite high overburden (several kilometres) during burial 139 which determined a high degree of compaction (documented by the prevalence of long 140 contacts among grains in sandstones) and recrystallization of the clay matrix. The strong 141 diagenetic imprint, in addition to the mineralogical composition of the sand, resulted in a 142 great compactness and hardness and very low porosity of the rock (Supplementary Material 143

Fig. S1). This in turn affected the landscape modelling by fluvial and glacial erosion during 144 Quaternary glaciations giving rise to a remarkable smoothness of rock surfaces. 145 The Park is located in the Cfb zone (C – temperate, f - no dry season b - warm summer, 146 147 according to the Köppen Geiger climate classification; Kottek et al. 2006), with av. 2 °C in winter, 21 °C in summer, and 1000 mm rainfall yr⁻¹ (Ceriani & Carelli 2000; data monitored 148 in the Capo di Ponte monitoring station n. 129, the closest to the Park, in the period 2003-149 2016, available at www.arpalombardia.it/Pages/Meteorologia/Richiesta-dati-misurati.aspx). 150 In terms of land use and forest types, the site is characterized by the occurrence of abandoned 151 chestnut stands (of meso-xeric soils), variously evolved to a mixed broadleaf forest [Betula 152 pendula Roth, Fraxinus ornus L., Populus tremula L., Salix caprea L., Prunus avium (L.) L.], 153 although natural (*Pinus sylvestris* L., as a relic of past submontane pine forests, preceding 154 chestnut cultivation) and planted conifers [Larix decidua Mill., Picea abies (L.) Karst and 155 some exotic species] also widely occur, as well as sparse, xerophytic and acidophytic 156 grassland stands (Ducoli 2012). 157

158

159 *Diversity survey*

160 Lithobiontic communities, and saxicolous lichen diversity in particular, were surveyed in the period between November 2017 and July 2018 on 23 engraved rocks having a different 161 conservation history (information available at www.irweb.it). In particular, 54 plots, 50×50 162 cm, were distributed on the surfaces of: (i) six rocks which were last cleaned in the period 163 2014-2015 (3YC; Rocks 1, 35, 50, 70, 73, 99; n= 19 plots), (ii) four rocks which were last 164 cleaned in the period 2005-2008 (12YC; Rocks 6, 7, 14, 57; n = 8 plots), and (iii) nine rocks 165 (or groups of neighbouring rocks) for which cleaning interventions are not documented in 166 archives registering the conservation history of engravings since the early 1980s (Not 167

Recently Cleaned, NRC; Rocks 2, 4, 8-9, 11, 17-18, , 49, 58, 36-69-96, 74; n= 27 plots). In 168 particular, interventions performed in the period 2005-2008 included mechanical removal of 169 thalli, cleaning with NeoDes 5% or 10%, application of the benzalkonium chloride based 170 product Preventol 3% as preservative, final application of the water-repellents Akeogard CO 171 or Silo 111; interventions performed in the period 2014-2015 included surface washing with 172 low-pressurized water and biocide application of benzalkonium chloride-based biocides. On 173 each rock (or group of neighbouring rocks), three plots (with the exceptions of Rock 1, with 174 six plots because of its strongly larger surface, and of Rocks 7, 14 and 73, with one plot each 175 because of technical constraints) were preferentially positioned in areas visually recognized as 176 representative of the predominant biodeterioration condition(s) affecting the surface legibility, 177 and thus requiring attention from the point of view of heritage conservation. 178 For each plot, the cover of different lithobiontic components -namely bryophytes, lichens, 179 cyanobacteria-dominated biofilms, green algae-dominated biofilms, microcolonial black fungi 180 (MCF)- was visually estimated in the field and checked in the lab on digital images. In the 181 case of biofilms, the extent of microbial mats which determined a visible colour shift of the 182 surface, with respect to the bare rock, was considered. Sampling and microscopic 183 observations allowed to characterize the biofilm(s) of each plot with respect to the dominance 184 of the different microbial components. Cover values were assigned according to the following 185 ordinal scale: 5=>75%, 4=51-75%, 3=26-50%, 2=2-25%; 1=<2% (or diffuse covering, but not 186

187 masking the mineral surface); 0=absence. Moreover, for each plot, lichen diversity was

surveyed using a square grid divided into 25 quadrats (10×10 cm), calculating the frequency

189 of each species as the sum of their occurrences within the grid quadrats and visually

190 estimating their cover through the whole plot.

191 Samples of lichen thalli were collected from each plot, without affecting the rock substrate for

192 conservative reasons, to check field identifications in the lab. Lichen identification was based

on Wirth (1995), Smith et al. (2009) and the online keys published in ITALIC, the 193 Information System of the Italian Lichens, version 07 (see Nimis & Martellos 2020). 194 Nomenclature follows Nimis (2022). Species vouchers are deposited in the Lichen section of 195 the Herbarium Universitatis Taurinensis (TO). Indicator values proposed by Nimis (2022) 196 were considered as reference to express specific ecological ranges with respect to pH of 197 substratum (pH), solar irradiation (IR), aridity (AR) and eutrophication (EU). 198 The plots were also characterized with regard to environmental variables, quantified in the 199 field (estimated in the case of surface micromorphology) and then referred to ordinal scales as 200 follows: aspect (EXP: 3= SW, 2= W, 1= NW, 0= N), inclination (INC: 3= 0-10°, 2= 11-30°, 201 $1=31-50^{\circ}, 0=>50^{\circ}$), surface micromorphology (ROU: 3= rough and/or highly fractured 202 surface, 2= slightly rough and/or moderately fractured surface; 1= smooth surface with few 203 fractures; 0= smooth surface without fractures), tree cover (TRC: 2= tree cover above the plot, 204 1= ground projection of the crown at less than 2 m from the plot, 0= ground projection of the 205 crown at more than 2 m), and distance from bare or vegetated ground upstream of the plot, 206 likely providing nutrients by water transport (GRP: 3 = <1 m, 2 = 1.1 - 4.9 m, 1 = > 4.9 m, 0 =207 absence of bare or vegetated ground upstream of the plot). 208 N.C.

209

Analysis of diversity data 210

The abundance of each lichen *taxon* was calculated in terms of presence through the plots (%) 211

and of average and maxima values of cover (%) and frequency (%) per plot. The relative 212

importance of components of γ -diversity [i.e. similarity (S), relativized richness difference 213

(D), and relativized species replacement (R)] was evaluated for all the plots 214

(NRC+12YC+3YC), and for plots on rock surfaces with a different conservation history 215

considered in combination (NRC+12YC, NRC+3YC, 12YC+3YC) and separately (NRC, 216

12YC, 3YC). The analysis was performed on the matrix of species presence/absence with the 217 218 SDR Simplex software using the Simplex method, as elsewhere detailed (SDR Simplex; Podani and Schmera 2011). An ordination of plots was performed on the basis of frequency 219 data by Principal Co-ordinate Analysis (PCoA: symmetric scaling, centring samples by 220 samples, centring species by species; Ter Braak & Šmilauer 2002). Two Canonical 221 Correspondence Analyses were carried out with the matrices of environmental parameters and 222 223 the cover values estimated for the different lithobiontic components (CCA-I) and the frequencies of lichen *taxa* (CCA-II), in order to partition variation explained by each variable 224 and construct a model of significant variables (biplot scaling for interspecies distances, Hill's 225 226 scaling for inter-sample distances; forward selection of variables option; Monte Carlo permutation test on the first and all ordination axes) (Ter Braak and Verdonschot 1995). The 227 ordinations were performed using CANOCO 4.5 (Ter Braak and Šmilauer 2002). 228 229 Microscopic observation of lithobionts-rock interactions 230 A set of centimetric to decimetric blocks of the site sandstone bedrock, already detached from 231 the outcrops, free of engravings and colonized by lithobionts, were collected to run 232 microscopic observations on the physical interactions of cyanobacterial-dominated biofilms 233 and mature thalli of representative crustose (Verrucaria nigrescens) and foliose 234 (Xanthoparmelia conspersa) lichens with their substrates. Rock fragments (ca. $3-4 \times 2-3 \times 0.5$ 235 cm; n=3-5 per lithobiont) were cross-sectioned, embedded in a polyester resin (R44 Politex-P 236 237 fast, ICR, Reggio Emilia, Italy), polished with silicon carbide paper, and stained with PAS (Periodic acid-Schiff's method; Whitlach & Johnson 1974) to highlight lithobiontic 238 penetration. Sections were observed under reflected light microscopy (RLM) with an 239 Olympus SZH10 microscope in order to quantify the penetration depth reached by the 240 microbial biofilm and the hyphal penetration component of lichens. 241

242

243 *Experiment on preventive conservation*

The possibility of locally limiting environmental conditions recognized as favourable to 244 245 lithobionts, and thus their rapid recolonization after cleaning, was assayed on Rock 70 (WGS84 32T 604380 m E, 5097935 m N), on which different restoration interventions were 246 conducted since the 1980s, the last in 2014 (details in the caption of Supplementary Material 247 Fig. S2). In 2017, after three years only, the whole rock surface was deeply affected by the 248 presence of a cyanobacterial-dominated biofilm and the local occurrence of small lichen thalli 249 (Fuscidea lygaea, Pertusaria flavicans, Phlyctis argena), with the exception of the perimeter 250 of the main engravings that some unknown individual(s) had improperly tried to clean 251 (Supplementary Material Fig. S2A). 252

In the framework of this work, Rock 70 was cleaned again in Summer 2019, with the 253 mechanical removal of the microbial biofilms and the lichens preceded by their devitalization 254 255 with a four-hours poultice application of the biocide BiotinT (N-octyl-isothiazolinone, 7– 10%, and didecyl-dimethyl ammonium chloride, 40–60%, as active principles; CTS, Altavilla 256 Vicentina, Italy). Its effectiveness had been verified by fluorimetric measurements on other 257 outcrops of the Park (Favero-Longo et al. 2021) and further checked on few parcels on Rock 258 259 70 itself (see below). In Autumn 2019, a 10 cm tall and approx. 3 m long wall of bricks, covered and fixed with mortar, was built at 20-30 cm from the upper border of the rock, to 260 limit water fluxes from upstream vegetated and bare ground following rain events. Only the 261 right portion of the rock was left free from the wall protection. It is worth remarking that the 262 wall was built to assay the effect of water control on recolonization dynamics and not as a 263 permanent structure. Moreover, some of the trees bordering the rock outcrop were cut or 264 pruned, to reduce their shading effect on the engraved surface. 265

Measurements of the vitality of the cyanobacterial-dominated biofilm were performed few 266 hours before and one day after the biocide application using a Handy-PEA fluorimeter 267 (Hansatech Instruments Ltd, Norfolk, England; saturating light pulse of 1s, 1500 µmol m⁻²s⁻¹, 268 peak at 650 nm), as described elsewhere (e.g. Favero-Longo et al. 2021). Measures were 269 performed early in the morning, on pre-moistened and dark-adapted surfaces. In particular, 270 measures were distributed on three parcels (approx. 25×25 cm) on different parts of the rock 271 outcrop (n>70 at each measuring time point). Measures on an additional untreated parcel were 272 also collected as control. The basal fluorescence (F_0), which is related to the chlorophyll a 273 content, and the maximum quantum yield of PSII (F_v/F_m) , which is informative on the 274 275 functionality of the photosynthetic process, were monitored as indicators of the microbial viability (Tretiach et al. 2010; Favero-Longo et al. 2021). Potential recolonization after the 276 cleaning intervention was monitored by fluorimetric measures twenty and forty months after 277 the cleaning (i.e. in March 2021, after the limitations due to COVID-19 pandemic, and 278 November 2022), on newly selected parcels, randomly distributed in areas protected by the 279 wall (n=6), out of the wall protection (n=4) and on the uncleaned Rock 71, adjacent to Rock 280 70 (n=3). 281

The fluorimetric monitoring was combined with spectro-colorimetric measures, in order to 282 evaluate the potential deteriogenic effect of lithobiontic recolonization in terms of colour and 283 aesthetic disfiguring. Measures were performed with a portable spectrophotometer (Konica 284 Minolta CM-23d) on target areas of 8 mm (diameter) in geometrical condition d/8 specular 285 component included as setting conditions, using the CIE D65 illuminant and 2° observer, and 286 the CIELAB colour system to process and analyse the spectral data (ISO/CIE 2019). In 287 288 particular, at least five measures were collected for each of ten parcels distributed in areas protected (n=5) and non-protected (n=2) by the wall, and on the adjacent uncleaned Rock 71 289 (n=3), corresponding or adjacent to the parcels used for fluorimetric measures. The L* 290

291 parameter, informative of surface lightness, was considered as reference to recognize a

different development of a dark lithobiontic biofilm (Gambino et al. 2019).

293

294 **Results**

295 Lithobiontic colonization of engraved rock surfaces

All plots displayed a visible lithobiontic colonization with two exceptions, dealing with rocks 296 restored in 2015 and still largely maintaining a clean state after three years. However, total 297 lithobiontic cover and abundance of its components remarkably varied through the different 298 plots and, particularly, with respect to the different conservation history of the rocks. On NRC 299 rocks, a high total cover was a common feature (av. 81.6±6.0% SE), while highly variable 300 301 values were observed for 12YC (av. 55.9±16.9% SE) and 3YC (av. 22.6±9.45% SE) rocks. The NRC cover higher than the 3YC cover was statistically significant (ANOVA, p<0.05). 302 A dark, blackish to red-brownish biofilm was the most widespread and abundant component 303 of lithobiontic communities (Supplementary Material Fig. S3A), with thickness ranging from 304 few microns to millimetres and thus varying from simple 'dirtying' of mineral grains to 305 remarkable masking effects of surface micromorphology and engravings. Microscopic 306 observations showed cyanobacteria as dominant constituents, including filamentous (mostly 307 Stigonema sp. and Scytonema sp.; Supplementary Material Fig. S3B) and, less abundant, 308 309 coccoid (as Gloeocapsa sp. and Chroococcus sp.) species. Black yeasts and meristematic fungi, as well as green algae and primordia of lichen thalli, were also occasionally observed. 310 The dark biofilm was dominant on almost all surveyed surfaces (Fig. 1A), but covered 311 significantly lower areas on 12YC and 3YC rocks (Fig. 1B-C). On these latter, in particular, 312 lithobionts were absent in six out of 19 plots, and cover values higher than 25% only 313 characterized one third of the plots (Fig. 1B). High covers were instead prevalent on 12YC 314

315	rocks (Fig. 1C), displaying the maximum percentage of plots with values higher than 75%,
316	and on NRC (Fig. 1D), where the dark biofilm generally covered the entire surface free of the
317	other lithobiontic components.
318	Greenish biofilms (Supplementary Material Fig. S3E) also occurred on some rocks, including
319	12YC and 3YC, although they never displayed cover values higher than 50% (Fig. 1) and
320	their thickness was generally limited, acting a discolouring rather than a masking effect.
321	Microscopic observations showed filamentous green algae (frequently Microspira sp.) as
322	dominant constituents, together with coccoid species, including free-living Trebouxia sp.,
323	while cyanobacteria only subordinately occurred.
324	Circular colonies of meristematic fungi, of (sub-)millimetric size, but sometimes merging to
325	give crusts of several square decimetres (Supplementary Material Fig. S3C-D), were an
326	additional lithobiontic component on some engraved surfaces. Although their frequency was
327	low as well as their cover values, they were evident on both 12YC and NRC rocks (Fig. 1).
328	Lichens occurred in ten out of 19 plots surveyed on 3YC rocks, but cover values were mostly
329	lower than 2% - specific lichen diversity is considered in the next sub-chapter. On 12YC and
330	NRC rocks, lichens were present in almost all the plots (out of one on 12YC), and cover
331	values were mostly in the 2-25% range (Fig. 1), although in some cases values higher than
332	50% were observed (Supplementary Material Fig. S3F). Bryophytes, and particularly mosses,
333	also occurred in most of the plots, often localized along cracks and fissures (Supplementary
334	Material Fig. S3G). Their cover values were rather negligible on 3YC rocks, and always
335	lower than 25% on 12YC (Fig. 1). On some NRC rocks, they were instead the dominant
336	component, with cover values higher than 50%.

337

338 Lichen diversity

339	A total of 37 saxicolous lichen <i>taxa</i> was recorded through the surveyed plots (Table 1), with
340	prevalence of crustose (59%) with respect to foliose species (38%), although these latter
341	showed higher cover values, and a rather high number of <i>taxa</i> showing asexual reproductive
342	strategy (35%). In particular, a high diversity of yellow-green Xanthoparmelia spp. was
343	found, including five isidiate and two non-isidiate species. However, due to the logistic
344	constraints of identifying each individual, only isidiate and non-isidiate Xanthoparmelia spp.
345	were distinguished in the abundance analyses. For the same reason, other species groupings
346	were considered, including Circinaria caesiocinerea/Aspicilia cinerea and Rhizocarpon
347	disporum/R. reductum, reducing to 30 the final number of taxa considered for the
348	subsequently described analyses.
349	All these 30 <i>taxa</i> were found on NRC rocks, while diversity was lower on 12YC and 3YC (17
350	taxa). Accordingly, SDR analysis performed for the overall plots showed a very high beta-
351	diversity (81.2%), but with richness difference (43.8%) prevailing on replacement (37.5%)
352	(Table 2). Similarity showed a decreasing trend from plots on NRC rocks (28.2%) to those on
353	12YC (22.5%) and 3YC (17.5%), with richness difference appearing mostly important on
354	3YC (46.3%) and replacement more remarkable in 12YC (38.4%). Higher similarity and
355	lower replacement were detected by considering together plots on NRC and 12YC
356	$(S_{NRC+12YC}=25.5\%; R_{NRC+12YC}=25.8)$ with respect to the combinations of plots on NRC and
357	3YC ($S_{NRC+3YC} = 19.4$; $R_{NRC+12YC} = 37.9$) and on 12YC and 3YC ($S_{12YC+3YC} = 12.3$;
358	$R_{NRC+12YC}=41.4$).
359	On NRC rocks, eight taxa displayed the highest occurrence through the plots (37-81%),
360	including both heliophytic-xerophytic (Circinaria caesiocinerea, yellow green
361	Xanthoparmelia spp. with and without isidia, Xanthoparmelia glabrans, Candelariella
362	vitellina, Rhizocarpon disporum) and mesophytic (Caloplaca chlorina, Pertusaria flavicans)
363	species. They all showed high frequency values per plot (av. 8.6- 39.6%), but very different

cover values related to the different growth form, with foliose and continuous crustose thalli 364 (av. cover 0.5-7.0%, but maximum cover of 6.0-50.0%) determining higher cover values 365 than discontinuous crustose thalli (e.g. C. vitellina, P. flavicans: av. cover <0.2%, and 366 maximum up to 2.0%). Other taxa also displayed rather high values of diffusion (15-30% of 367 plots) and frequency, including a group of species commonly found on stone heritage surfaces 368 even in urban environments, as Protoparmeliopsis muralis and Verrucaria nigrescens f. 369 tectorum, and others which are usually associated to the bark rather than to rock substrates, as 370 Candelaria concolor, *Phlyctis argena* and *Physcia adscendens*. These are all nitrophytic 371 species, sharing a high tolerance to eutrophication and, with the exception of *P. muralis*, 372 373 asexual reproductive strategy. Remarkably, the group of usually epiphytic species showed the 374 highest diffusion on 3YC rocks, together with P. flavicans and Fuscidea lygaea, which are meso-hygrophytic species, poorly tolerant to eutrophication, and C. caesiocinerea. On 12YC 375 rocks, lichen diversity was almost completely represented by the taxa dominating NRC rocks 376 (*C. caesiocinerea* > green-yellow *Xanthoparmelia* spp., *C. vitellina* > *C. chlorina* > R. 377 disporum > X. glabrans) and the nitrophytic saxicolous species V. nigrescens and P. muralis, 378 which similarly showed high diffusion, frequency and cover values, while the presence of 379 usually epiphytic species was limited to C. concolor. 380 381 The PCoA extracted four components which explained 65.4% of the total variance and ordinated the plots on the basis of specific frequency data (Fig. 2). Axis 1 (29.1% of total 382 variance) showed a strongly positive correlation with Xanthoparmelia spp. without isidia and 383 C. vitellina, which displayed the highest frequency values, while axis 2 (15.4%) showed a 384 remarkable positive correlation with V. nigrescens and C. chlorina, and negative with Phlyctis 385 386 argena, and axis 3 (13.0%) a positive correlation with Xanthoparmelia spp. with isidia.

387 Accordingly, plots on NRC rocks, with highest abundances of these dominant species, mostly

scattered on the right side of the diagram. Oppositely, plots of 12YC and 3YC rocks scattered

in the left side, likely driven by the relatively lower frequencies of dominant species more

than by the abundance of other subordinate species. It is worth noting that the ten plots

391 without lichens are not represented in the ordination.

392

393 Lithobiontic penetration within the sandstone substrate

394 RLM observations showed a scarce penetration within the sandstone substrate for both the cyanobacterial-dominated biofilm and the considered lichens. The microbial biomass only 395 developed epilithically, with the exception of very limited chasmoendolithic growths, down to 396 397 approx. 500 µm, where slight fractures occurred (Fig. 3A). The hyphal penetration component of *Verrucaria nigrescens* was also poorly pervasive, with a discontinuous occurrence of thin 398 hyphal bundles down to 500 µm within the substrate (Fig. 3C-D). The penetration of 399 Xanthoparmelia conspersa was even poorer, with only a couple of hyphal bundles observed 400 down to 1 mm beneath one of the observed thalli (Fig. 3B). 401

402

403 *Factors conditioning lithobiontic and lichen colonization*

The analysis of cover values estimated for the different lithobiontic groups and environmental variables (CCA-I) extracted four axes which accounted for 100% of species-environmental relationships (Fig. 4A). All canonical axes were significant (Monte Carlo test, P=0.002). The first axis (60.9% of correlation) was positively correlated with surface roughness (ROU, weighted correlation, w.c., 0.89) and negatively with the distance from bare and vegetated

- ground upstream of the plot (GRP, w.c. -0.32), while the second axis (30.4%) was positively
- 410 related with rock inclination (INC, w.c. 0.80) and negatively with tree cover (TRC, w.c. -
- 411 0.23) and GRP (w.c. -0.41). Only ROU and INC were significant conditional factors
- 412 (P=0.002). Plots on NRC rocks scattered in the upper and right part of the diagram, positively

413	related with lichens and mosses, respectively. 12YC and 3YC plots scattered through the
414	whole diagram, including the lower left quadrant, related with cyanobacterial and green algal
415	biofilms.

- 416 The analysis of lichen frequency data and environmental variables (CCA-II) extracted four axes which accounted for 93% of species-environmental relationships (Fig. 4B and S4). All 417 canonical axes were significant (Monte Carlo test, P=0.002). The first axis (36.9% of 418 correlation) was positively correlated with rock inclination (INC; weighted correlation, w.c., 419 0.65) and negatively with the distance from bare and vegetated ground upstream of the plot 420 (GRP, w.c. -0.70). The second axis (32.7%) was positively related with tree cover (TRC, w.c. 421 0.75) and surface micromorphology (ROU, w.c. 0.44) and negatively with surface aspect 422 (w.c. -0.45). All factors, out of surface aspect, showed significant conditional effect according 423 to forward selection, with tree cover displaying the highest value (F = 2.48, P = 0.002), 424 followed by inclination (F = 2.39, P = 0.004), surface micromorphology (F = 2.28, P = 0.006) 425 and distance from the ground (F = 1.71, P = 0.036). 426 427 Given that uncolonized plots do not appear in the factorial map, most of colonized plots on 3YC and 12YC rocks, including those with highest lichen abundance (in terms of total lichen 428
- 429 frequencies), showed positive correlation with tree cover and/or distance from the ground, in
- 430 the space characterized by the most abundant meso-hygrophytic species *F. lygaea* and *P.*
- 431 *flavicans* and the usually epiphytic species. Plots on NRC showing the highest lichen
- abundance mostly scattered in the right lower part of the diagram, in the space characterized
- 433 by the dominant xerophytic species, namely the *Xanthoparmelia* spp. with and without isidia,
- 434 *Candelariella vitellina* and *Rhizocarpon disporum*, and the mesophytic *Caloplaca chlorina*.

435

436 *Control of lithobiontic recolonization by preventive microenvironmental conditioning*

437	Assays of the efficacy of BiotinT against lithobionts on Rock 70, and the cyanobacterial
438	biofilm in particular, showed a significant decrease of F_0 values in the treated parcels
439	(decrease > 80%) with respect to measures performed before the biocide application, and the
440	zeroing of F_v/F_m (Fig. 5A, B). Twenty months after the cleaning intervention, and after two
441	winter seasons, F_0 values quantified on the rock surface protected by the wall were zeroed,
442	while slightly higher values were detected in the unprotected area, suggesting that
443	recolonization was possibly starting. Accordingly, after 20 months more, F_0 and F_v/F_m values
444	quantified on the unprotected surface indicated the recovery of the lithobiontic colonization,
445	while values were still zeroed in the area protected by the wall (with the exception of a single
446	parcel, close to the ground downwards the rock). Lichen recolonization was not observed
447	neither in the protected nor in the unprotected areas of Rock 70.
448	At twenty months after the cleaning, cleaned surfaces protected and unprotected by the wall
449	did not show significant differences in lightness (L*), while uncleaned and unprotected
450	surfaces had lower L* values (Fig. 6). Twenty months later, the rock surfaces unprotected by
451	the wall were significantly darkened (low L* in Fig. 6), with different levels of darkening
452	depending on the proximity to the vegetated ground upwards and the prevalent direction of
453	water fluxes. Conversely, rock surfaces well protected by the wall showed not or just
454	perceivable differences in L*, and uncleaned control surfaces (Rock 71) displayed a smooth
455	darkening (because they were already dark).

456

457 **Discussion**

Approaches to hinder recolonization dynamics following cleaning interventions are still
mostly related to the application of products directly on the heritage surfaces in order to
reduce their bioreceptivity (*e.g.* Pinna et al. 2012; Sasso et al. 2016; Domínguez et al. 2021),

and to the regulation of artificial light regimes (Sanmartín 2021). In the case of rock art, 461 hypotheses and suggestions on a potential conservative effect of reducing the shade created 462 by trees, and redirecting water flow, were formulated (Tratebas 2004), but have been poorly 463 experimentally verified and put into practice (e.g. in the case of Norwegian sites; Bjelland & 464 Kjeldsen 2020). In this work, we show that the characterization of lithobiontic communities in 465 a rock art site and the recognition of environmental factors favouring (re-)colonization 466 dynamics may address preventive strategies based on local (micro-)environmental 467 conditioning, successfully prolonging the maintenance of heritage surfaces in a clean state. 468 The characterization of lichen diversity particularly supported the recognition of factors 469 470 responsible for lithobiontic colonization patterns, confirming the role of lichens as useful indicators in various fields of application, including the conservation of Cultural Heritage 471 (Aptroot & James 2002). 472

473

474 *Lichens and other lithobionts on rocks with different conservation history*

The lack of detailed knowledge on the conservation history of each outcrop in the Naquane
site before the 1980s (further details in the caption of Fig. S3), prevents a full reconstruction
of (re-)colonization patterns in the investigated site. Nevertheless, the abundances of
lithobiontic components through the plots are significantly explained by their different
colonization rates following recent cleaning interventions and some heterogeneity in available
niches.

481 Microbial biofilms, including cyanobacterial ones, were reported as the main lithobiontic

482 component in several rock art sites, and their presence was variously associated to

483 biodeterioration or bioprotection processes -which depend on the lithology and the

484 environmental conditions (Villa et al. 2016)-, and even, in some cases, with the past formation

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of surface crusts which coat the stones and were carved by the engraving activities 485 (Rabacchin et al. 2022; Zerboni et al. 2022). In the case of Naquane, the low porosity and 486 high cohesion of the substrate seem to limit a diffuse endolithic, and more deteriogenic, 487 behaviour of cyanobacteria, which find enough suitable conditions for a rich epilithic growth 488 in the local temperate climate with no dry season (Rubel et al. 2017). The prevalence of 489 cyanobacterial and algal patinas on 3YC surfaces agrees with their ability to colonize rocks 490 faster than lichens (e.g. Lázaro et al. 2008), which are on their turn widespread on 12YC and 491 prominent on several NRC outcrops. In agreement with the succession proposed by Caneva et 492 al. (2008), mosses are also negligible on 3YC and 12YC surfaces, while they are dominant on 493 494 some NRC outcrops. Such different levels of pioneer activity add up to the preference of mosses and lichens for rougher and less steep surfaces with respect to the biofilms, as 495 displayed in CCA-I (Fig. 4A). 496

Levels of direct irradiation and shading were shown to influence the distribution (and 497 deteriogenic impact) of lithobiontic components on building surfaces, with epilithic 498 499 cyanobacteria and green algae dominating shaded sides and lichens prevailing on sunny dry 500 ones (Ariño & Saiz-Jimenez 1996). Moreover, for each component, the different (micro-)environments host different species assemblages, as shown in the cases of the Roman 501 Amphitheater of Italica (Spain; Nimis et al. 1998) and of the engraved schists of the Côa 502 Valley Archaeological Park (UNESCO, Portugal; Marques et al. 2014), where different lichen 503 communities characterized surfaces with different aspect. In the case of Naguane, the EXP 504 factor was not a significant conditional factor neither with respect to the distribution of the 505 different lithobiontic components nor for the different lichen taxa. This is likely because the 506 507 effect of the punctual surface aspect was masked by the general NW exposition of the valley side occupied by the Park. However, different lichen communities were observed in Naguane, 508 with the high beta-diversity values obtained in SDR analysis mostly associated to the turnover 509

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of xerophytic and mesophytic-hygrophytic species, as shown by the PCoA. Such patterns of

511 lithobiontic distribution on heritage stone surfaces were generally related to different orientations and aspect (Aubry et al. 2012; Adamson et al. 2013; Marques et al. 2014). In the 512 case of Naguane, each outcrop was differently shaded by tree cover and exposed to water 513 runoff after rain events (see next sub-chapter). 514 515 Lichen communities on 12YC and 3YC plots mostly show very low cover values and appear as subsets of the richer communities on NRC outcrops. Nevertheless, the higher similarity of 516 12YC and NRC with respect to the NRC-3YC and 12YC-3YC combinations (SDR analysis) 517 indicate that the most pioneer phase of recolonization is already concluded in less than twelve 518 519 years after the cleaning interventions. Species commonly found in synanthropic environments prevail, although some species usually associated to undisturbed conditions persist, as P. 520 *flavicans* and *F. lygaea*. Such pattern reflects the shift observed on several heritage surfaces 521 after cleaning interventions, with nitrophytic, fast-growing species becoming prevalent with 522 respect to originally dominant species (Nascimbene et al. 2009). Persistence of original 523 524 species and, in general, fast recolonization in few years likely relates with the ineffective 525 application of biocides by brush, which generally showed poor effectiveness in the devitalization of crustose species and particularly in dedicated assays recently performed in 526 527 Naquane (Favero-Longo et al. 2021). Such results show the importance of performing effective devitalization treatments to avoid losing the original lichen biodiversity value 528 without obtaining a durable cleaning result. Remarkably, most species on 12YC and 3YC 529 plots show prevalence of asexual reproductive modes (mostly soredia) and/or produce small, 530 highly dispersive ascospores (species of genera Caloplaca s.l., Candelariella s.l., Lecanora 531 532 s.l.), remarking their potential for rapid recolonization and their potential threat to heritage surfaces (Scheidegger & Werth 2009; Morando et al. 2019). It is worth noting that the total 533 diversity of 37 taxa is rather low for the surveyed area, mostly including common species of 534

silicate substrates. This result may depend on the fact that the communities on NRC rocks are
also the product of recolonization processes on the long term of several decades following the
early and, unfortunately, poorly documented cleaning interventions in the area. However, the
comparison with outcrops out of the boundaries of the Park was beyond the aims of this
project and, surprisingly, it may be really difficult to find outcrops in the mid Valle Camonica
which do not host engravings and, thus, did not suffer any human disturbance in recent times.

541

542 *Physical interaction of lichens and other lithobionts with the sandstone substrate*

543 Lichen colonization of engraved outcrops was already deeply considered with respect to the deteriogenic impact in several sites, including the Côa Valley, in the Mediterranean area, 544 where deep hyphal penetration and physical bioweathering were recorded on schists (Marques 545 et al. 2016). Lichens are also dominant on engraved sandstones from the subarctic zone, 546 where their biogeochemical activity was associated to the waning of an original surface red 547 548 colour (e.g. Alta, Norway; Tansem & Storemyr 2020), to the dry semi-arid zone, where physical and chemical degradation processes were microscopically documented (*e.g.* el Morro 549 National Monument, New Mexico; Knight et al. 2004). Although the observations were 550 limited to few cross sections for conservative reasons, the physical interaction of lichens with 551 the examined sandstones appears rather mild, as we observe a poor hyphal penetration even 552 for Verrucaria nigrescens. This common colonizer of heritage surfaces was indeed often 553 reported as a deeply penetrating and impacting species on different lithologies, including 554 other sandstones (Tonon et al. 2021, with refs. therein), although with different intergranular 555 matrices and lower compactness. The hyphal penetration beneath the points of attachment of 556 Xanthoparmelia rhizinae was also negligible, in this case as usually observed on other 557 lithologies (e.g. on gneiss; Favero-Longo et al. 2015). The cyanobacterial biofilm also 558

displayed an epilithic behaviour, differing from observations on other sandstone substrates, in 559 560 which the endolithic growth was prominent (e.g. Büdel et al., 2004; Zerboni et al. 2022). Accordingly, the lithobiontic colonization in Naquane appears as a deteriogenic phenomenon 561 mostly because of surface masking and chromatic disfiguring, while interactions with the 562 substrate responsible for a decreased surface durability seem less important than in other 563 cases. However, we observed a higher hyphal penetration on the same lithology, but on the 564 opposite, ESE-facing, side of the Valley (Favero-Longo et al. 2017), in agreement with the 565 findings that different micro-environmental conditions related to a different surface aspect can 566 imply different bioweathering impacts on stone durability (Marques et al. 2016). 567

568

569 Tree cover and water flow as driving factors and their potential conditioning for preventive
570 conservation

A long period of wetness, due to slow drying or prevailing wind directions, were 571 demonstrated to support lithobiontic colonization on stone materials. Investigations in the wet 572 N-Ireland showed that green algae and lichens colonized north-facing stone blocks (including 573 sandstones) faster and more abundantly than those facing south (Adamson et al. 2013). In 574 Pompeii, surfaces exposed to the prevailing winds during rain events showed richer 575 lithobiontic communities than differently oriented ones (Traversetti et al. 2018). In the case of 576 Naquane, in a similar way, tree shading (TRC) and the presence of bare or vegetated ground 577 above the engraved outcrops (GRP) are factors favouring lithobiontic recolonization after 578 cleaning, according to CCAs. Their significant effect on the water and moisture availability, 579 and the consequent biological dynamics, is confirmed by the prevalent regrowth of meso-580 /hygro-phytic lichen species on 12YC and 3YC surfaces (PCoA). Oppositely, recolonization 581 by xerophytic species on directly exposed rock outcrops seems to require longer times. The 582

abundance of usually epiphytic species as pioneer colonizers on the 3YC and 12YC surfaces 583 further remarks the threats related to the tree proximity, even beyond the shading effect. 584 Such recognition of environmental factors favouring lithobiontic (re-)colonization was 585 586 considered with success in the experiment of preventive conservation conducted on Rock 70, combining some reduction of tree cover with the altering of water flow on an engraved rock 587 outcrop. The development of a phototrophic biofilm and the darkening of the rock surface, 588 quantified by fluorimetric and colorimetric measures, respectively, was significantly related to 589 the absence of the wall protection by prolonged and nutrient-enriched water fluxes. Thus, 590 preventive approaches and the (micro-)environmental conditioning by water flow regulation 591 seem particularly promising to circumscribe surfaces where lithobiontic communities and 592 related biodeterioration effects are hindered and the legibility of engravings is preserved. On 593 other surfaces, the lithobiontic presence may instead be accepted, and possibly exhibited as an 594 additional value of the cultural heritage site. 595

On the other hand, the change of water flows may imply some community shift on the long 596 term, in particular favouring lichens rather than cyanobacterial biofilms (Bjelland and Helberg 597 2006), although lichens have still not (re-)appeared 40 months after the cleaning through the 598 whole outcrop. More generally, the drainage of water or, simply, the altering of water flows 599 imply the addition of non-natural elements in the archaeological natural scenario, as the 600 considered brick wall or other kinds of barriers (Bjelland and Helberg 2006). With this regard, 601 it has to be remarked that the wall considered here is an experimental structure to evaluate 602 603 benefits obtainable with the control of water fluxes. The development of further strategies to obtain similar results without touching the engraved surface is needed. In any case, although 604 605 barriers to water flows may be visually unpleasant, the traditional applications of synthetic biocides to periodically devitalize and remove established lithobiontic communities may 606 imply even a higher impact by affecting the environmental equilibria (Cappitelli et al. 2020). 607

608

609 Conclusions

610 This work characterized the diversity and abundance of lithobiontic communities in the Rock Engravings National Park of Naquane (UNESCO WHS n. 94, Italy), highlighting 611 cyanobacterial biofilms and lichens as the dominant constituents. They both displayed poor 612 penetration within the sandstone substrate, likely because of its high compactness and very low 613 porosity, but they were responsible for chromatic disfiguring and limited the legibility of rock 614 art. Tree cover and the presence of bare and vegetated ground upstream of the rocks resulted as 615 the main drivers of recolonization on surfaces cleaned in the last twelve years, likely prolonging 616 surface wetness after rain events and increasing nutrient availability. Nitrophytic species, 617 including epiphytes from surrounding trees, and few meso-hygrophytic species, mostly 618 producing soredia, were mainly responsible of the rapid lichen recolonization. An experiment 619 of preventive conservation performed on a critical rock, including an effective devitalization of 620 621 lithobionts before cleaning, combined with reduction of tree cover and surface protection from prolonged water fluxes from vegetated ground, prevented recolonization by lichens and other 622 lithobionts for a monitored period of 40 months. By contrast, cleaned surfaces unprotected from 623 prolonged water fluxes showed recolonization, demonstrating the suitability 624 of microenvironmental control strategies to limit and delay biodeterioration issues on the outdoor 625 stone cultural heritage. To make similar preventive approaches practicable, ecological 626 investigations of environmental factors favouring lithobiontic colonization are crucial and, 627 thanks to advanced knowledge on their specific ecological requirements, lichens particularly 628 appear as suitable indicators. 629

630

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812 Figure captions

- 813 Fig. 1. Abundance of different lithobiontic components (CyB, cyanobacterial-dominated
- biofilm; MCF, microcolonial fungi crusts; AlB, green algal-dominated biofilm; Bry,
- 815 bryophytes; Lic, lichens) on the engraved rocks, considering the overall plots together (A) and
- separately for rocks cleaned in the last three years (3YC, B), twelve years (12YC; C) or from
- more than 40 years (NRC; D). , Data are expressed in terms of percentage of plots with cover
- values in the following ranges: >75% (black), 51-75% (dark grey), 26-50% (grey), 2=2-25%
- 819 (light grey), visible cover, but <2% (grey bands), absence of visible cover (white).
- Fig. 2. Ordination of plots on the basis of the specific lichen frequencies (PCoA). Plots are
- 821 differently marked according to the different conservation history of the surveyed rocks
- 822 (NRC, crosses; 12YC, grey squares; 3YC, white squares). Half of plots with highest lichen
- abundance for the NRC and 12YC/3YC categories (in terms of total specific frequencies)
- display a higher symbol size. Species abbreviation in Table 1 (nitrophytic species underlined,
- 825 meso-hygrophytic species in bold).
- Fig. 3. Lithobiontic penetration within the sandstone substrate. A, cyanobacterial biofilm; B,
- 827 Xanthoparmelia conspersa; C, D (inset), Verrucaria nigrescens. Arrows indicate
- 828 cyanobacterial penetration within a fracture (A) and the hyphal penetration component of
- 829 lichens (B, D). Scale bars: 1.0 mm (A), 1.5 mm (B, C), 350 μm (D).
- Fig. 4. Factorial map in the canonical correspondence analysis showing the position of plots
- having a different conservation history with the contributions of lithobiontic covers (A, CCA-
- 832 I) and specific lichen frequencies (B, CCA-II), together with environmental factors (tree
- 833 cover, TRC; surface micromorphology, ROU; inclination, INC; distance from bare or
- 834 vegetated ground upstream, GRP; exposition, EXP). Symbols indicate different lithobionts
- 835 (black circles: lichens, Lich; bryophytes, Bry; cyanobacterial biofilm, CyB; green algal

836	biofilm, AlB; meristematic fungi, MCF), and NRC (crosses), 12YC (grey squares) and 3YC
837	(white squares) rocks. In CCA-II (B), half of plots with highest lichen abundance for the NRC
838	and 12YC-3YC categories (in terms of total specific frequencies) display a higher symbol
839	size; contributions of the different species are separately shown in Fig. S4.
840	
841	Fig. 5. Basal fluorescence (F_0 , A) and maximum quantum efficiency of Photosystem II
842	photochemistry (B, F_v/F_m) quantified on Rock 70 during preliminary biocide assays (July
843	2019; T0, one day before biocide application, T1, one day after biocide application), and 20
844	(March 2021) and 40 (November 2022) months after the cleaning, in areas of the outcrop
845	protected (W) and non-protected (NW) by the wall, and on uncleaned areas as control (U). At
846	each measuring time point, box-plots which do not share at least one letter are statistically
847	different (ANOVA, Tukey's test, $p < 0.05$).
848	Fig. 6. Lightness of the surface (L*) of Rock 70 quantified 20 (March 2021) and 40
849	(November 2022) months after the cleaning in areas of the outcrop protected (W) and non-
850	protected (NW) by the wall, and on uncleaned areas as control (U). At each measuring time
851	point, box-plots which do not share at least one letter are statistically different (ANOVA,
852	Tukey's test, $p < 0.05$).
853	

Table 1. Lichens recorded on sandstone outcrops of the Rock Engravings National Park of Naquane [av. and max cover and frequency values are reported for the plots considered altogether and separately for 3YC, 12YC and NRC outcrops, as well as the % specific occurrence through the plots; growth form (GF): crustose (Cr), foliose (Fo), fruticose (Fr); prevailing reproduction strategy; sexual (S), asexual (A); ecological indicator values from Nimis (2022): pH of the substrate (pH), irradiation (IR), aridity (AR), eutrophication (EU); * *X. conspersa* more frequent, but also *X. tinctina, X. plittii, X. mexicana,* and *X. verrucigera* present; ***X. angustiphylla* more frequent, but also *X. stenophylla* present]

				Ecol	logical	gical indicator			All t	he plot	s (n=27)			3YC ro	cks (n=	19 plots	5)		12)	′C (n=8	plots)			NRC (n= 2		7 plots)	
					valı	ues		(plot %)	Cove	er (%)	Frequ	ency(%)	(plot %)	Cover	(%)	Frequ	ency(%)	(plot %)	Cove	er (%)	Frequ	ency(%)	(plot %)	Cove	er (%)	Freque	ency(%)
Specier	Code	GE	Penr	nH	ID	۸P	511	Occurrence	Av.	Max.	Av.	Max.	Occurrence	Av.	Мах.	Av.	Max.	Occurrence	Av.	Max.	Av.	Max.	Occurrence	Av.	Мах.	Av.	Max.
Acarochora fuscata (Schrad) Arnold	Ac f	Cr	c c	2-4	4-5	2_4	2-4	27	0.0	0.1	0.2	8.0		-	-	-	-						7.4	0.0	0.1	0.4	8.0
Ruellia gethalea (Ach) Th. Er	Rup	Cr	, s	1.2	4-5	4-5	1_2	7.4	0.0	8.0	2.0	56.0	5.2	0.1	1.0	0.4	8.0	125	0.0	0.1	7.0	56.0	7.4	0.0	8.0	1.6	26.0
Buellia stellulata (Taylor) Mudd	Bu c	Cr	5	2-4	4-5	4-5	1-3	1.4	0.2	0.0	2.0	4.0	5.5	0.1	1.0	0.4	0.0	12.5	0.0	0.1	7.0	50.0	27	0.5	0.0	0.1	4.0
Calendara chloring (Flot) H. Olivier	Ca.c	Cr		2.2	2.4	2	2-1	27.9	1 1	20.0	11 1	96.0	-	-	-	-	-	275	5 1	20.0	28 5	96.0	J.7	0.0	6.0	12.9	60.0
Candelaria concolor (Dicks) Stein	Cd c	Cr		3-4	4-5	3-1	3-4	24.1	0.0	0.1	<u> </u>	40.0	21.1	0.0	0.1	3.4	40.0	12.5	0.0	0.1	0.5	4.0	29.6	0.0	0.0	5.8	36.0
Candelariella coralliza (Nyl.) H. Mago	Cn c	Cr	ç	2-3	4-5	4	4-5	19	0.0	0.1	0.1	40.0		-	-	-		12.5	- 0.0		-	4.0	37	0.0	0.1	0.1	4.0
Candelariella vitellina (Hoffm) Müll Arg	Cniv	Cr	s	1-3	3-5	3-4	2-5	33.3	0.0	2.0	19.6	100.0	53	0.0	01	0.6	12.0	37 5	0.0	01	8.0	52.0	51.9	0.0	2.0	36.3	100.0
Chrysothrix sp.	Ch.s	Cr	A	1-2	2-4	1-3	1	13.0	0.0	0.1	0.9	12.0	-	-	-	-	-	37.5	0.0	0.1	3.5	12.0	14.8	0.0	0.1	0.7	8.0
Circinaria caesiocinerea (Malbr) A Nordin Savić & Tibell (+ Asnicilia cinerea (L) Körb)	Cic	Cr	s	2-4	3-5	2-4	2-5	50.0	1.6	40.0	10.8	100.0	10 5	0.0	01	19	32.0	62.5	0.4	2.0	9.5	28.0	74.1	3.1	40.0	17.5	100.0
Cladonia sp.	CLS	Fr	s	4-5	4-5	4	1-3	5.6	0.1	3.0	1.5	32.0	-	-	-	-	-	-	-	-	-	-	11.1	0.2	3.0	3.0	32.0
Euscidea lyagea (W. Mann) V. Wirth & Vězda	Fu.I	Cr	s	1-2	3-4	2-3	1	11.1	0.4	10.0	5.9	100.0	5.3	0.2	3.0	5.3	100.0	12.5	0.0	0.1	0.5	4.0	14.8	0.7	10.0	7.9	96.0
Pertusaria flavicans Lamy	Pe.f	Cr	A	2-3	3-4	2-3	1	25.9	0.1	1.0	8.1	96.0	10.5	0.0	0.1	2.3	24.0	25.0	0.0	0.1	8.0	60.0	37.0	0.1	1.0	12.3	96.0
Phaeophyscia endococcina (Körb.) Moberg	Ph.e	Fo	S	2-3	3-4	1-3	2-3	1.9	0.0	0.1	0.2	12.0	-	-	-	-	-	-	-		-	-	3.7	0.0	0.1	0.4	12.0
Phaeophyscia orbicularis (Neck.) Moberg	Ph.o	Fo	А	2-5	3-5	3-4	4-5	5.6	0.0	1.0	2.5	96.0	10.5	0.0	0.1	5.5	96.0	-	-	-	-	-	3.7	0.0	1.0	1.2	32.0
Phlyctis argena (Spreng.) Flot.	Pl.a	Cr	А	1-2	2-3	2-3	1-2	22.2	0.5	5.0	5.8	84.0	26.3	0.3	4.0	2.5	12.0	-	-	-	-	-	25.9	0.7	5.0	9.8	84.0
Physcia adscendens H. Olivier	Py.a	Fo	А	2-5	4-5	3-4	3-5	7.4	0.0	2.0	1.6	60.0		-	-	-	-	-	-	-	-	-	14.8	0.1	2.0	3.3	60.0
Physcia aipolia (Humb.) Fürnr.	Py.i	Fo	S	2-3	4-5	3	3-4	3.7	0.0	0.1	0.4	20.0	_		-	-	-	-	-	-	-	-	7.4	0.0	0.1	0.9	20.0
Physcia magnussonii Frey	Py.m	Fo	S	3-4	4-5	4-5	3-4	1.9	0.0	0.1	0.1	4.0	-	-	-	-	-	-	-	-	-	-	3.7	0.0	0.1	0.1	4.0
Physconia grisea (Lam.) Poelt	Ps.g	Fo	А	3-4	3-5	3	4-5	1.9	0.0	0.1	0.7	40.0		-	-	-	-	-	-	-	-	-	3.7	0.0	0.1	1.5	40.0
Protoparmeliopsis muralis (Schreb.) M. Choisy s.lat.	Pr.m	Cr	S	2-4	3-5	3-4	3-5	14.8	0.4	18.0	4.7	96.0		-	J- N	-	-	25.0	0.0	0.1	2.0	12.0	22.2	0.9	18.0	8.7	96.0
Rhizocarpon disporum (Hepp) Müll. Arg. (± Rhizocarpon reductum Th. Fr.)	Rh.d	Cr	S	1-3	3-5	2-4	1-3	27.8	0.4	6.0	5.9	56.0	5.3	0.0	0.1	0.2	4.0	25.0	0.9	6.0	10.0	56.0	44.4	0.5	3.0	8.6	40.0
Rhizocarpon geographicum (L.) DC. s.lat.	Rh.g	Cr	S	1-3	3-5	3-4	1-3	7.4	0.0	1.0	0.5	8.0	-	-	- /			-	-	-	-	-	14.8	0.0	1.0	1.0	8.0
Rinodina occulta (Körb.) Sheard	Ri.o	Cr	S	1-2	3-4	2-3	1	5.6	0.0	1.0	0.7	28.0	-	-		-		-	-	-	-	-	11.1	0.0	1.0	1.5	28.0
Rufoplaca gr. arenaria (Pers.) Arup, Søchting & Frödén	Ru.s	Cr	S	2-3	4-5	3-4	2-3	9.3	0.0	2.0	2.0	48.0	5.3	0.0	0.1	0.4	8.0		-	-	-	-	14.8	0.1	2.0	3.7	48.0
Rusavskia elegans (Link) S.Y. Kondr. & Kärnefelt	Rv.e	Fo	S	3-5	4-5	4	3-4	3.7	0.0	1.0	0.6	28.0	-	-	-	-			-	-	-	-	7.4	0.0	1.0	1.2	28.0
Scoliciosporum umbrinum (Ach.) Arnold	Sc.u	Cr	S	1-3	3-4	2-4	1-3	1.9	0.0	0.1	0.1	4.0	-	-	-	-	-	-	-	-	-	-	3.7	0.0	0.1	0.1	4.0
Verrucaria nigrescens f. tectorum (A. Massal.) Coppins & Aptroot	Ve.n	Cr	А	3-5	3-5	2-5	2-5	22.2	0.5	17.0	10.8	100.0	-	-	-	-		62.5	2.4	17.0	34.5	100.0	25.9	0.3	4.0	11.4	100.0
Xanthoparmelia with isidia*	X.is	Fo	А	2-3	3-5	3-4	2-4	29.6	3.6	50.0	13.7	100.0	-	-	-	-	-	12.5	0.6	5.0	7.0	56.0	55.6	7.0	50.0	25.3	100.0
Xanthoparmelia without isidia**	X.ni	Fo	S	2-3	3-5	3-4	2-3	46.3	3.0	45.0	21.6	100.0	5.3	0.0	0.0	1.3	24.0	25.0	1.5	12.0	9.5	72.0	81.5	5.5	45.0	39.6	100.0
Xanthoparmelia glabrans (Nyl.) O. Blanco, A. Crespo, Elix, D. Hawksw. & Lumbsch	Xa.g	Fo	S	2-3	4-5	3	2-3	33.3	0.5	10.0	5.3	80.0	-	-	-	-	-	12.5	0.3	2.0	2.5	20.0	63.0	0.9	10.0	9.8	80.0

Table 2. Percentage contribution from the SDR simplex analyses of lichen communities through the surveyed plots, considered altogether, in combination and separately for NRC, 12YC and 3YC rocks.

	Plots (n)	Similarity (S)	Richness difference (D)	Replacement (R)	R+D (Beta diversity)	S+R (Richness agreement)	S+D -Anti-nest Rich. Id. (Nestedness)		
All plots	54	18.8	43.8	37.5	81.2	65.5	38.5		
NRC+3YC	46	19.4	42.7	37.9	80.6	62.1	39.3		
NRC+12YC	35	25.5	48.6	25.8	74.5	74.2	43.5		
12YC+3YC	27	12.3	46.4	41.4	87.7	58.6	25.9		
NRC	27	28.2	50.5	21.4	71.8	78.6	43.9		
12YC	8	22.5	39.2	38.4	77.5	61.6 64.0	51.7		

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Fig. 1. Abundance of different lithobiontic components (CyB, cyanobacterial-dominated biofilm; MCF, microcolonial fungi crusts; AlB, green algal-dominated biofilm; Bry, bryophytes; Lic, lichens) on the engraved rocks, considering the overall plots together (A) and separately for rocks cleaned in the last three years (3YC, B), twelve years (12YC; C) or from more than 40 years (NRC; D). , Data are expressed in terms of percentage of plots with cover values in the following ranges: >75% (black), 51-75% (dark grey), 26-50% (grey), 2=2-25% (light grey), visible cover, but <2% (grey bands), absence of visible cover (white).

169x125mm (300 x 300 DPI)



Fig. 2. Ordination of plots on the basis of the specific lichen frequencies (PCoA). Plots are differently marked according to the different conservation history of the surveyed rocks (NRC, crosses; 12YC, grey squares; 3YC, white squares). Half of plots with highest lichen abundance for the NRC and 12YC/3YC categories (in terms of total specific frequencies) display a higher symbol size. Species abbreviation in Table 1 (nitrophytic species underlined, meso-hygrophytic species in bold).

169x168mm (300 x 300 DPI)



Fig. 3. Lithobiontic penetration within the sandstone substrate. A, cyanobacterial biofilm; B, Xanthoparmelia conspersa; C, D (inset), Verrucaria nigrescens. Arrows indicate cyanobacterial penetration within a fracture (A) and the hyphal penetration component of lichens (B, D). Scale bars: 1.0 mm (A), 1.5 mm (B, C), 350 μ m (D).

137x101mm (500 x 500 DPI)



Fig. 4. Factorial map in the canonical correspondence analysis showing the position of plots having a different conservation history with the contributions of lithobiontic covers (A, CCA-I) and specific lichen frequencies (B, CCA-II), together with environmental factors (tree cover, TRC; surface micromorphology, ROU; inclination, INC; distance from bare or vegetated ground upstream, GRP; exposition, EXP). Symbols indicate different lithobionts (black circles: lichens, Lich; bryophytes, Bry; cyanobacterial biofilm, CyB; green algal biofilm, AlB; meristematic fungi, MCF), and NRC (crosses), 12YC (grey squares) and 3YC (white squares) rocks. In CCA-II (B), half of plots with highest lichen abundance for the NRC and 12YC-3YC categories (in terms of total specific frequencies) display a higher symbol size; contributions of the different species are separately shown in Fig. S4.

325x169mm (300 x 300 DPI)



Fig. 5. Basal fluorescence (F0, A) and maximum quantum efficiency of Photosystem II photochemistry (B, Fv/Fm) quantified on Rock 70 during preliminary biocide assays (July 2019; T0, one day before biocide application, T1, one day after biocide application), and 20 (March 2021) and 40 (November 2022) months after the cleaning, in areas of the outcrop protected (W) and non-protected (NW) by the wall, and on uncleaned areas as control (U). At each measuring time point, box-plots which do not share at least one letter are statistically different (ANOVA, Tukey's test, p < 0.05).

136x59mm (500 x 500 DPI)



Fig. 6. Lightness of the surface (L*) of Rock 70 quantified 20 (March 2021) and 40 (November 2022) months after the cleaning in areas of the outcrop protected (W) and non-protected (NW) by the wall, and on uncleaned areas as control (U). At each measuring time point, box-plots which do not share at least one letter are statistically different (ANOVA, Tukey's test, p < 0.05).

89x63mm (300 x 300 DPI)

An ecological investigation on lichens and other lithobionts colonizing rock art in Valcamonica (UNESCO WHS n. 94) addresses preventive conservation strategies

Declaration of interests

☑ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

□ The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Torino, 23th February 2022

Faithfully

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Species	Code	GF
Acarospora fuscata (Schrad.) Arnold	Ac.f	Cr
Buellia aethalea (Ach.) Th. Fr.	Bu.a	Cr
<i>Buellia stellulata</i> (Taylor) Mudd	Bu.s	Cr
Caloplaca chlorina (Flot.) H. Olivier	Ca.c	Cr
Candelaria concolor (Dicks.) Stein	Cd.c	Cr
Candelariella coralliza (Nyl.) H. Magn.	Cn.c	Cr
Candelariella vitellina (Hoffm.) Müll. Arg.	Cn.v	Cr
Chrysothrix sp.	Ch.s	Cr
<i>Circinaria caesiocinerea</i> (Malbr.) A. Nordin, Savić & Tibell (± <i>Aspicilia cinerea</i> (L.) Körb.)	Ci.c	Cr
Cladonia sp.	Cl.s	Fr
Fuscidea lygaea (W. Mann) V. Wirth & Vězda	Fu.l	Cr
Pertusaria flavicans Lamy	Pe.f	Cr
Phaeophyscia endococcina (Körb.) Moberg	Ph.e	Fo
Phaeophyscia orbicularis (Neck.) Moberg	Ph.o	Fo
Phlyctis argena (Spreng.) Flot.	Pl.a	Cr
Physcia adscendens H. Olivier	Py.a	Fo
Physcia aipolia (Humb.) Fürnr.	Py.i	Fo
Physcia magnussonii Frey	Py.m	Fo
Physconia grisea (Lam.) Poelt	Ps.g	Fo
Protoparmeliopsis muralis (Schreb.) M. Choisy s.lat.	Pr.m	Cr
Rhizocarpon disporum (Hepp) Müll. Arg. (± <i>Rhizocarpon reductum</i> Th. Fr.)	Rh.d	Cr
Rhizocarpon geographicum (L.) DC. s.lat.	Rh.g	Cr
Rinodina occulta (Körb.) Sheard	Ri.o	Cr
Rufoplaca gr. arenaria (Pers.) Arup, Søchting & Frödén	Ru.s	Cr
Rusavskia elegans (Link) S.Y. Kondr. & Kärnefelt	Rv.e	Fo

Scoliciosporum umbrinum (Ach.) Arnold	Sc.u	Cr
Verrucaria nigrescens f. tectorum (A. Massal.) Coppins & Aptroot	Ve.n	Cr
Xanthoparmelia with isidia*	X.is	Fo
Xanthoparmelia without isidia**	X.ni	Fo
Xanthoparmelia glabrans (Nyl.) O. Blanco, A. Crespo, Elix, D. Hawksw. &		
Lumbsch	Xa.g	Fo

Ecological indicator values					All	the plots (n=	27)	
	E			25	e (plot %)	Cove	er (%)	Freque
					currence	Av.	Мах.	Av.
Repr.	рН	IR	AR	EU	Ö			
S	3-4	4-5	3-4	3-4	0.0	0.0	0.1	0.2
S	1-3	4-5	4-5	1-3	0.0	0.2	8.0	2.0
S	3-4	4-5	4	1-2	0.0	0.0	0.1	0.1
А	2-3	3-4	3	3-4	0.0	1.1	30.0	11.1
А	3-4	4-5	3-4	3-5	0.0	0.0	0.1	4.1
S	2-3	4-5	4	4-5	0.0	0.0	0.1	0.1
S	1-3	3-5	3-4	2-5	0.0	0.1	2.0	19.6
А	1-2	2-4	1-3	1	0.0	0.0	0.1	0.9
S	2-4	3-5	2-4	2-5	0.0	1.6	40.0	10.8
S	4-5	4-5	4	1-3	0.0	0.1	3.0	1.5
S	1-2	3-4	2-3	1	0.0	0.4	10.0	5.9
А	2-3	3-4	2-3	1	0.0	0.1	1.0	8.1
S	2-3	3-4	1-3	2-3	0.0	0.0	0.1	0.2
А	2-5	3-5	3-4	4-5	0.0	0.0	1.0	2.5
А	1-2	2-3	2-3	1-2	0.0	0.5	5.0	5.8
А	2-5	4-5	3-4	3-5	0.0	0.0	2.0	1.6
S	2-3	4-5	3	3-4	0.0	0.0	0.1	0.4
S	3-4	4-5	4-5	3-4	0.0	0.0	0.1	0.1
А	3-4	3-5	3	4-5	0.0	0.0	0.1	0.7
S	2-4	3-5	3-4	3-5	0.0	0.4	18.0	4.7
S	1-3	3-5	2-4	1-3	0.0	0.4	6.0	5.9
S	1-3	3-5	3-4	1-3	0.0	0.0	1.0	0.5
S	1-2	3-4	2-3	1	0.0	0.0	1.0	0.7
S	2-3	4-5	3-4	2-3	0.0	0.0	2.0	2.0
S	3-5	4-5	4	3-4	0.0	0.0	1.0	0.6

S	1-3	3-4	2-4	1-3	0.0	0.0	0.1	0.1
А	3-5	3-5	2-5	2-5	0.0	0.5	17.0	10.8
А	2-3	3-5	3-4	2-4	0.0	3.6	50.0	13.7
S	2-3	3-5	3-4	2-3	0.0	3.0	45.0	21.6
s	2-3	1-5	3	2-3	0.0	05	10.0	53
J	2-3	+-J	5	2-3	0.0	0.5	10.0	5.5

		3YC r	ocks (n= 19	plots)		
ncy(%)	(plot %)	Cove	er (%)	Frequ	ency(%)	(plot %)
Max.	Occurrence	Av.	Max.	Av.	Max.	Occurrence
8.0	-	-	-	-	-	-
56.0	5.3	0.1	1.0	0.4	8.0	12.5
4.0	4	-	-	-	-	-
96.0	0	-	-	-	-	37.5
40.0	21.1	0.0	0.1	3.4	40.0	12.5
4.0	-	6	-	-	-	-
100.0	5.3	0.0	0.1	0.6	12.0	37.5
12.0	-	-	2	-	-	37.5
100.0	10.5	0.0	0.1	1.9	32.0	62.5
32.0	-	-	-	-	-	-
100.0	5.3	0.2	3.0	5.3	100.0	12.5
96.0	10.5	0.0	0.1	2.3	24.0	25.0
12.0	-	-	-	-) -	-
96.0	10.5	0.0	0.1	5.5	96.0	-
84.0	26.3	0.3	4.0	2.5	12.0	-
60.0	-	-	-	-		-
20.0	-	-	-	-	- 4	-
4.0	-	-	-	-	-	-
40.0	-	-	-	-	-	-
96.0	-	-	-	-	-	25.0
56.0	5.3	0.0	0.1	0.2	4.0	25.0
8.0	-	-	-	-	-	-
28.0	-	-	-	-	-	-
48.0	5.3	0.0	0.1	0.4	8.0	-
28.0	-	-	-	-	-	-

4.0	-	-	-	-	-	-
100.0	-	-	-	-	-	62.5
100.0	-	-	-	-	-	12.5
100.0	5.3	0.0	0.0	1.3	24.0	25.0
80.0	-	-	-	-	-	12.5

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12YC	Crocks (n=8	plots)			NRC	ocks (n= 27	plots)
Cove	er (%)	Freque	ency(%)	plot %)	Cove	er (%)	Freque
Av.	Мах.	Av.	Max.	Occurrence (Av.	Мах.	Av.
-	-	-	-	7.4	0.0	0.1	0.4
0.0	0.1	7.0	56.0	7.4	0.3	8.0	1.6
-	-	4	-	3.7	0.0	0.1	0.1
5.1	30.0	28.5	96.0	44.4	0.6	6.0	13.8
0.0	0.1	0.5	4.0	29.6	0.0	0.1	5.8
-	-	-		3.7	0.0	0.1	0.1
0.0	0.1	8.0	52.0	51.9	0.2	2.0	36.3
0.0	0.1	3.5	12.0	14.8	0.0	0.1	0.7
0.4	2.0	9.5	28.0	74.1	3.1	40.0	17.5
-	-	-	-	11.1	0.2	3.0	3.0
0.0	0.1	0.5	4.0	14.8	0.7	10.0	7.9
0.0	0.1	8.0	60.0	37.0	0.1	1.0	12.3
-	-	-	-	3.7	0.0	0.1	0.4
-	-	-	-	3.7	0.0	1.0	1.2
-	-	-	-	25.9	0.7	5.0	9.8
-	-	-	-	14.8	0.1	2.0	3.3
-	-	-	-	7.4	0.0	0.1	0.9
-	-	-	-	3.7	0.0	0.1	0.1
-	-	-	-	3.7	0.0	0.1	1.5
0.0	0.1	2.0	12.0	22.2	0.9	18.0	8.7
0.9	6.0	10.0	56.0	44.4	0.5	3.0	8.6
-	-	-	-	14.8	0.0	1.0	1.0
-	-	-	-	11.1	0.0	1.0	1.5
-	-	-	-	14.8	0.1	2.0	3.7
-	-	-	-	7.4	0.0	1.0	1.2

-	-	-	-	3.7	0.0	0.1	0.1
2.4	17.0	34.5	100.0	25.9	0.3	4.0	11.4
0.6	5.0	7.0	56.0	55.6	7.0	50.0	25.3
1.5	12.0	9.5	72.0	81.5	5.5	45.0	39.6
0.0	2.0	25	20.0	C 2 0		10.0	0.0
0.3	2.0	2.5	20.0	63.0	0.9	10.0	9.8

ncy(%)
Лах.
2
8.0
36.0
4.0
60.0
36.0
4.0
100.0
8.0
100.0
32.0
96.0
96.0
12.0
32.0
60 0
20.0
4.0
40.0
96.0
40.0
8.0
28.0
48.0
28.0

4.0		
100.0		
100.0		
100.0		
80.0		

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Plots (n)	Similarity (S)	Richness difference (D)	Replacement (R)
54 46 35 27 27 8	18.8 19.4 25.5 12.3 28.2 22.5	43.8 42.7 48.6 46.4 50.5 39.2	37.5 37.9 25.8 41.4 21.4 38.4
	Plots (n) 54 46 35 27 27 8 19	Plots (n) Similarity (S) 54 18.8 46 19.4 35 25.5 27 12.3 27 28.2 8 22.5 19 17.7	Plots (n) Similarity (S) Richness difference (D) 54 18.8 43.8 46 19.4 42.7 35 25.5 48.6 27 12.3 46.4 27 28.2 50.5 8 22.5 39.2 19 17.7 46.3

R+D (Beta diversity)	S+R (Richness agreement)	S+D -Anti-nest Rich. Id. (Nestedness)	
81.2 80.6 74.5 87.7 71.8 77.5 82.3	65.5 62.1 74.2 58.6 78.6 61.6 64.0	38.5 39.3 43.5 25.9 43.9 51.7 27.1	
		SC.	