Saxicolous lichen communities in three basins associated with mining activity in northwestern Argentina (Post-print)

Authors: Juan M HERNÁNDEZ, Renato A GARCÍA, Edith R FILIPPINI, Cecilia ESTRABOU, Martha S CAÑAS, Juan M RODRÍGUEZ

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Abstract

Mining activity affects the vegetation and soils of the ecosystems. However, the effects of mining activity on saxicolous lichen communities are less concerned. Thus, the aim of this study was to characterize saxicolous lichen communities in three basins (Vis-Vis River basin, Poteros River basin, and Capillitas River basin) surrounding metalliferous mining projects of different types of operation and at different stages of exploitation. A large-scale mine (Bajo de la Alumbrera) with more than 25 a of open-pit mining located in the Vis-Vis River basin (CRV). A pre-exploitation mine (Agua Rica) located in the Poteros River basin (CRP), and a small-scale mine (Minas Capillitas) with more than 160 a of underground mining located in the Capillitas River basin (CAC). In each basin, species richness, cover, and frequency of lichen communities were measured on 40 rock outcrops. Also, explanatory variables were recorded, i.e., altitude, slope, aspect, vegetation cover, rock, and soil cover around the rocky area sampled. Richness and total cover of lichen communities were analysed using linear models, and species composition was explored using multivariate ordination analysis. Results showed that a total of 118 lichen species were identified. The species richness differed among basins and the lichen composition present in areas close to mining sites responded mainly to basins, altitude, and microsite variables. The lichen cover showed no difference among basins, but it changed under different rock and vegetation cover. It was not possible to quantify the effects of mining activity on species richness and composition. However, the low richness values found in the downstream of Minera Alumbrera could be associated with the negative impact of open-pit mining. Moreover, the effects of large-scale mining activity on lichen communities needs more investigation.

Full Text

Preamble

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Saxicolous lichen communities in three basins associated with mining activity in northwestern Argentina

Juan M. HERNÁNDEZ[1]*, Renato A. GARCÍA[2], Edith R. FILIPPINI[3], Cecilia ESTRABOU[3], Martha S. CAÑAS[1], Juan M. RODRÍGUEZ[3]

[1] Faculty of Technology and Applied Sciences, Regional Centre of Energy and Environment for Sustainable Development, National University of Catamarca, Catamarca 4700, Argentina
[2] Laboratory of Biodiversity and Environmental Genetics, National University of Avellaneda, Avellaneda 1870, Argentina
[3] Institute of Biological and Technological Research; Centre for Ecology and Renewable Natural Resources, Faculty of Exact, Physical and Natural Sciences, National University of Cordoba, Cordoba 5000, Argentina

Abstract: Mining activity affects the vegetation and soils of ecosystems, yet its impacts on saxicolous lichen communities remain understudied. This study characterized saxicolous lichen communities in three basins (Vis-Vis River basin, Poteros River basin, and Capillitas River basin) surrounding metalliferous mining projects of different operation types and exploitation stages. The basins included: a large-scale mine (Bajo de la Alumbrera) with over 25 years of open-pit mining located in the Vis-Vis River basin (CRV); a pre-exploitation mine (Agua Rica) located in the Poteros River basin (CRP); and a small-scale mine (Minas Capillitas) with over 160 years of underground mining located in the Capillitas River basin (CAC). In each basin, species richness, cover, and frequency of lichen communities were measured on 40 rock outcrops. Explanatory variables recorded included altitude, slope, aspect, vegetation cover, and rock and soil cover around the sampled rocky areas. Richness and total lichen cover were analyzed using linear models, while species composition was explored through multivariate ordination analysis. A total of 118 lichen species were identified. Species richness differed among basins, and lichen composition in areas close to mining sites responded primarily to basin, altitude, and microsite variables. Lichen cover showed no difference among basins but varied under different rock and vegetation cover conditions. While it was not possible to quantify the effects of mining activity on species richness and composition, the low richness values found downstream of Minera Alumbrera could be associated with the negative impact of open-pit mining. Moreover, the effects of large-scale mining activity on lichen communities require further investigation.

Keywords: lichen community; altitude; microsite; metalliferous mining; vegetation

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1 Introduction

Mining is the main productive activity in Catamarca Province, Argentina. Due to the current level of development and the geological mining potential of the region, this activity is of great economic importance for both the province and the country. Given the environmental threats it poses (Moretton et al., 1996; Boamponsem et al., 2010; Panagos et al., 2013; Touceda-González et al., 2017), mining activity must be continuously monitored to evaluate possible impacts on air, soil, and water.

Metalliferous mining is concentrated in the western part of Catamarca Province, where the Farallón Negro Volcanic Complex (FNVC) is located. Bajo de la Alumbrera is one of the world' s largest open-pit copper and gold deposits. According to Álvarez (2002), the start-up of this project required an investment of USD 1200×10^{6} to produce an average of 6×10^{6} t of concentrate per year through crushing, grinding, and flotation processes, with the concentrate containing approximately 18×10^{4} t of copper and 20 t of gold.

The FNVC is an eroded stratovolcano (Llambías, 1972). Within its caldera, there are vetiform and porphyry-type epithermal copper deposits. Among them, Farallón Negro and Altos de la Blenda have veins of quartz and carbonates containing the minerals aurum (Au), argentum (Ag), and manganese (Mn). Other deposits such as Agua Rica and Bajo de la Alumbrera are of porphyry type with associated metallic mineralization of copper (Cu), molybdenum (Mo), and Au. At Minas Capillitas, a vetiform type deposit, mineralization is mainly Cu, plumbum (Pb), and zinc (Zn), with arsenic (As), antimony (Sb), Au, and Ag as accessory elements and wolfram (W), tin (Sn), bismuth (Bi), and germanium (Ge) as trace elements in gangue of quartz and alunite (Márquez-Zavalía, 2002; Márquez-Zavalía et al., 2014).

Currently, the Farallón Negro and Alto de la Blenda projects are in the exploitation phase, Bajo de la Alumbrera is in the mine closure phase, while Agua Rica is in the exploration phase. In Minas Capillitas, the mineralization zone was initially exploited for gold extraction, later for Cu at a smaller scale, and since the late 19th century up to the present day, rhodochrosite has been the only mineral extracted for commercialization.

Mining activity generates effects on the biota surrounding the work area, primarily on flora. Under this stress, mining activity has been found to generate changes in plant phenology. Sun et al. (2022) found that these changes were due to decreased groundwater levels caused by deep excavation, water pollution, and air pollution from dust. These factors alter plant metabolism and generate their greatest effects in areas closest to the mines, decreasing with distance. Plant community structure is also affected by mining, and plant cover always decreases in mining areas (Yu and Zahidi, 2023), with cover and richness of trees and shrubs decreasing while herbaceous cover increases (Kuffour et al., 2020). Regarding species diversity, Unanaonwi and Amonum (2017) measured plant species diversity in forests around mining areas, finding that diversity values are low near mines and increase with distance from them.

A lichen is a self-sustaining ecosystem formed by the interaction of an exhabitant fungus and an extracellular arrangement of one or more photosynthetic partners and an indeterminate number of other microscopic organisms (Hawksworth and Grube, 2020). Lichens are sensitive to atmospheric pollutants, with susceptibility varying among species (Pescott et al., 2015; Abas, 2021; Paoli et al., 2021). Therefore, changes in abundance and species diversity of lichen communities can serve as an indicator of the adverse ecological effects of air pollution. For example, in polluted sites, most air pollution-sensitive lichen species are absent or declining, and lichen diversity is low. This effect can be caused by different mechanisms. Sulfur dioxide (SO_2) can have a direct inhibitory (toxic) effect on lichens, reducing overall lichen abundance and species richness in the community (Nash and Gries, 2002). Other pollutants, such as nitrogen, can stimulate the colonization and growth of some nitrophilous lichen species, altering lichen species diversity and community composition through changes in interspecific competitive relationships (Filippini et al., 2020).

On the other hand, the abundance and diversity of lichen communities vary according to abiotic factors that operate at different scales; therefore, the effects of pollutants must be studied together with these other sources of variation (Lücking and Matzer, 2001). It is well-known that lichens, like most organisms, respond to factors that change with altitude such as temperature and humidity (Baniya et al., 2010; Vittoz et al., 2010; Bässler et al., 2016; Rodríguez et al., 2017; Cleavitt et al., 2019; Vetaas et al., 2019). At another scale and depending on latitude, other important variables are aspect (mainly North-South) and slope, since both determine the amount of solar radiation that, together with altitude, impacts incident solar radiation (insolation) and evapotranspiration (Kidron and Termina, 2010; Rodríguez et al., 2017; Costas et al., 2021; Rutherford and Rebertus, 2022). Thus, in the southern hemisphere, south-facing slopes are colder and more humid than north-facing slopes (Körner, 1995, 2007). Another factor involved in the variation of lichen communities is the structure of the surrounding vegetation, since it impacts not only substrate availability but also shading on rock or soil surfaces. These explanatory variables of changes in lichen community are very important and should be considered at different sites along the altitudinal gradient when designing a biomonitoring study associated with environmental disturbances. This is especially important in mountain areas, where environmental variables change with altitude, causing variation in species richness and composition (Körner, 2007).

Although lichens from metal-enriched habitats have attracted much attention at the global scale (Osyczka and Rola, 2019; Osyczka et al., 2021; Neitlich et al., 2022), few efforts have been made to document lichen communities in mining areas (Bielczyk et al., 2009; Rajakaruna et al., 2011). In Argentina, lichen species from areas near mines have not been documented in detail.

Studies of lichen communities in Argentina are scarce. Estrabou et al. (2010) studied areas of Catamarca Province with the aim of establishing a baseline that would allow detection of environmental changes. The aim of the present study was to characterize the lichen-associated funga in areas surrounding mining projects and to interpret how species composition responds to changes in the natural environment (slope, aspect, altitude, rock, soil, and vegetation cover) and the influence of mining activities. In turn, taking into account the lack of works on lichen communities in the region, and particularly in areas with mining activity (Abas, 2021), we sought to contribute to the knowledge of the diversity of these organisms at high altitudes close to mining areas in northwestern Argentina.

2.1 Study Area

The study area is located in the northwestern Sierras Pampeanas in Argentina, including sections of the FNVC and the western flank of the Sierra del Aconquija (Ramos, 1999). Due to geographical factors that determine the inaccessibility of much of the study area, we conducted sampling in three areas located downstream of basins near metalliferous mining. These basins are associated with different types and stages of mining activity. The Vis-Vis River basin (CRV) is close to Bajo de la Alumbrera, a large-scale mine with more than 25 years of open-pit mining that is currently in the mine closure stage. The Poteros River basin (CRP) is close to Agua Rica, which is planned to be a mine of the same scale as Bajo de la Alumbrera but is still in the pre-exploitation stage; therefore, we could consider CRP as a control area with no mining. The Capillitas River basin (CAC) is close to Minas Capillitas, a small-scale mine with more than 160 years of underground mining.

The climate in the study area is temperate and markedly continental. According to the Köppen and Geiger classification, it corresponds to the BWk type, i.e., cold desert. It is characterized by aridity, thermal amplitude, and strong insolation, with precipitation concentrated in summer and a marked water deficit. Average temperatures in the study area are 25.6°C in summer and 13.4°C in winter. Winds are dry and atmospheric humidity is very low (Paoli, 2003). There is no humidity data for the entire area; however, the weather station at the Alumbrera tailings dam measured 39% average relative humidity for the period June, August, and September 2017 (Minera Alumbrera YMAD-UTE, 2017). Southeasterly, southerly, and westerly winds predominate (González-Bonorino, 1972). Meteorological data were recorded in Andalgalá and Belén, the two most important localities close to the study area. The average precipitation recorded at the Andalgalá weather station (70 years of data) is 310 mm/a, with peaks in 1923 and 1977, and droughts in 1941 and 1950. In the Andalgalá River basin, near Agua Rica, average annual precipitation is 560 mm, with a maximum of 920 mm and a minimum of 405 mm (Comba, 2017). In the town of Belén, average annual precipitation is 244 mm and average temperature is 25.6°C in summer and 13.4°C in winter (Gonzalez-Bonorino, 1972; Paoli, 2003).

This area includes several phytogeographic provinces: Monte, Prepuna, and Chaco Serrano. According to the species present and the physiognomy of the dominant vegetation, the area surrounding Minera Alumbrera and CRV has botanical affinities to the Monte phytogeographic province (Morlans, 1995; Karlin et al., 2017). The Prepuna mainly occupies the slopes and high foothills of the Sierras Pampeanas, such as the southeast of the Sierra de Aconquija (Andalgalá department) and most of the Sierra de Capillitas (Andalgalá, Belén, and Santa María). CAC is located in this sector. The slopes and peaks of the mountain ranges between 600 and 3000 m a.s.l. belong to the Chaco Serrano. In Andalgalá, the Chaco Serrano includes sectors of the mountain systems of the Sierra de Capillitas and the western slopes of the Sierra de Aconquija, where the Agua Rica mining project and CRP are located (Morlans, 1995).

2.2 Site Selection

The study was conducted between 2015 and 2017 at 8 sampling sites selected in each of the studied basins. Both CRV and CRP basins present fairly wide altitudinal gradients. CRV sites are located between 1340 and 2070 m a.s.l., and CRP sites between 1850 and 2300 m a.s.l., with the lowest altitudes being those furthest from the center of mining operations (Fig. 1 [Figure 1: see original paper]). On the other hand, CAC sites were located at the same altitude and were distributed to the east and north of the mine (Fig. 1).

2.3 Survey of Lichen Frequency and Coverage

At each sampling site, 5 rock outcrops (faces with an aspect between 160 and 200 degrees and a slope between 60 and 90 degrees) were randomly selected. These conditions correspond to the highest values of lichen diversity in mountain environments in the Southern Hemisphere due to low levels of insolation (Rodríguez et al., 2017; Costas et al., 2021). A 20 cm$×20cmgridwasplacedoneachrock,thelichenspecieswereidentified,andthepercentages(^{2}$).

2.4 Species Identification

Morpho-anatomical and chemical analysis was performed using routine techniques. Lichen substances with chemotaxonomic value were identified using recrystallization and thin-layer chromatography techniques (Orange et al., 2001) and following keys and descriptions for genera and species (Adler, 1992; Scutari, 1992; Estrabou, 1999; Estrabou et al., 2006; Filippini et al., 2014). The nomenclature of genera and species follows Calvelo and Liberatore (2002), Lücking et al. (2017), and Index Fungorum (http://www.indexfungorum.org/names/names.asp). Samples with very small or no reproductive structures were identified to genus level or with artificial names. One specimen of each identified species was deposited in the LUTI herbarium and in the Catamarca Research and Transfer Center.

2.5 Data Analysis

Matrices of relative frequency and cover of species and environmental variables per sampling unit (grid) were prepared with the data obtained. From the relative frequency matrix, richness (number of species per rock) was calculated, while from the matrix of species cover, the total cover of lichens was calculated per rock. The two variables were considered univariate response variables.

To analyze richness, we applied generalized linear models with Poisson distribution, considering each grid as a sampling unit. In the model, the basin was considered as the main factor and altitude as a covariable together with percentage of rock, vegetation and soil cover, slope, and aspect (sine and cosine were calculated to obtain the North-South (N-S) and the East-West (E-W) components, respectively). The sites were considered as a random factor. Akaike information criterion (AIC) was used to select the model with the best fit (Di Rienzo et al., 2017). The distance to the mine and the altitude could not be separated as independent variables since the sites at the highest altitude are the closest to the mines and the sites at the lowest altitude are the furthest away.

The total cover of lichens was analyzed using a general and mixed model with the same explanatory variables as those used for richness. The similarity (shared species) between basins was analyzed using a Venn diagram.

We analyzed the variation in composition of saxicolous lichen species between basins and between sites in each basin using canonical correspondence analysis (CCA) to determine grouping or separation of species according to environmental or explanatory variables, using the species frequency matrix and the matrix of environmental variables (altitude, N-S and E-W components, slope, rock, and vegetation and soil cover) by 120 grids. To obtain a clear ordering in this analysis, we removed species with fewer than three occurrences in the sampling units (McCune et al., 2002). Environmental variables that had a correlation r >0.20 with the principal axes were plotted, which allowed us to discard those that did not influence the first two axes of the multivariate analysis.

To determine the indicator species in each basin, we carried out an indicator species analysis (ISA) based on the method of Dufrêne and Legendre (1997). This method is very useful for detecting and describing groups of species, indicating their affinity to particular sets of environmental conditions. ISA provides an indicator value (IV) for each species in each group. The analysis combines information on species abundance with occurrence within particular groups, with the best indicator being the species that is always present and exclusive to the group (IV=100). In turn, the Monte Carlo test was applied to estimate the statistical significance of each IV with a probability value of 0.05% (McCune et al., 2002). All analyses were performed using Infostat software (Di Rienzo et al., 2020) and PC-ORD Multivariate Analysis of Ecological Data software (McCune and Mefford, 1998).

3 Results

A total of 118 taxa belonging to 43 genera and 18 families were identified. Of these, 83 taxa were identified to species level, 18 to genus level, and 17 to species level. According to growth form, 55 crustose, 42 foliose, 9 fructiculose, 4 umbilicated foliose, 5 squamulose, 1 subfructiculose, 1 placoid, and 1 foliose-squamulose taxa were surveyed. The most diverse genera found in the study area were *Xanthoparmelia* (14 species), *Caloplaca* (8), *Acarospora* (6), *Punctelia* (5), and *Rinodina* (5). Sixty-two species were found at fewer than 3 sites (Table S1).

The basin with the highest number of species was CRP, with 71 species, followed by CAC and CRV with 62 and 41 species, respectively. Thirty-six species were present only in CRP, 25 species only in CAC, and 15 species only in CRV. CRP and CAC shared 29 species, whereas CRP shared 18 species with CRV. CAC and CRV shared 21 species. Only 13 species were found in all three basins (Fig. 2 [Figure 2: see original paper]). CRP showed the highest proportion of foliose lichens (47.9%), whereas the crustose morphotype was dominant in the other two basins (51.2% in CRV and 51.2% in CAC) (Table S1).

Richness differed significantly among basins, with CAC showing the highest average values (11.05), followed by CRP (7.08) and CRV (4.80) (P=0.0001; Fig. 3 [Figure 3: see original paper]). None of the explanatory variables included in the model was significant for species richness (P>0.05), except for altitude, which was found to have a significant influence on the higher values of CAC (P=0.0211). In the model with the best fit (AIC), basin was the main factor, altitude was a covariate nested in the basin, and site was a random factor (Table 1).

Total lichen cover did not show a significant difference among basins (P>0.05), being almost the same in CAC (50.84 ($±14.04))*andCRV*(51.12(±25.59)), *andslightlylowerinCRP*(48.27(±$21

(Fig. 4 [Figure 4: see original paper]). However, some microsite variables influenced total lichen cover at each site, being higher in sites with higher rock cover (P=0.0226) and lower with higher vegetation cover (P=0.0448) around them.

The result of CCA using the relative frequency matrix including the three basins (Fig. 5 [Figure 5: see original paper]) shows that the units are ordered by altitude and, to a lesser extent, soil and rock covers, with a canonical correlation coefficient between axis 1 and altitude of -0.832, between axis 2 and soil cover of -0.508, and between axis 3 and rock cover of 0.595. The points representing CAC show a tendency to separate from CRP and CRV points, the former being to the left of axis 1. These points are associated with species such as *Umbilicaria haplocarpa* Nyl., *Caloplaca aff. sonorae* Wetmore, *Teloschistes nodulifer* (Nyl.) Hillmann, *Caloplaca aff. altoandina* (Malme) Zahlbr., *Candelariella vitellina* (Hoffm.) Müll. Arg., and *Lecidella aff. granulosula* (Nyl.) Knoph & Leuckerts, also with a high IV in the ISA (Table 2). CCA had a total inertia in the species data of 11.33 and a total variance of 8.4% explained by the three axes.

The ISA showed that 34 species had significant IVs for the different basins (P<0.05). All groups (basins) had different indicator species that were specific to those environmental conditions (Table 2). Eighteen species were indicators of CAC, 10 species were indicators of CRP, and 6 species were indicators of CRV.

4 Discussion

Most studies on lichens associated with mining focus on the restoration of lichen communities after mining exploitation (Abas, 2021). As far as we know, studies about metalliferous mining and the lichen community biomonitoring approach are scarce. The number of lichens surveyed in this work (118) is high compared with previous ecological studies carried out in central-western Argentina. Previous studies of saxicolous lichens in central and north-western Argentina reported 107 species in the mountains of Córdoba (Rodríguez et al., 2017) and 58 species in the mountains of La Rioja (Costas et al., 2021).

Results of the species richness and composition analyses showed great differences in lichen communities among the three basins, suggesting environmental differences. The role of altitude in lichen composition and abundance (Rodríguez et al., 2017) explains the highest values of species richness per sampling unit found in CAC, since this basin has a more temperate climate than the other two basins, which favors the development of lichen communities. Similarly, Costas et al. (2021) recorded the highest richness values at 2897 m a.s.l., coinciding with the altitudinal belt of the sampling sites in CAC. However, although CRP has lower average lichen richness values per sampling unit than CAC, it has the highest number of species (71; Fig. 1), probably due to the wide altitudinal gradient between sampling sites. Thus, an increase in species richness was observed with increasing altitude, suggesting that changes in environmental conditions with increasing altitude favor the development of species that are not present at lower altitudes.

CRV is the area with the lowest richness and diversity. Taking into account that it has an altitudinal gradient similar to that of CRP, altitude is not the main factor causing differences in lichen richness between these two basins. On the other hand, CCA (Fig. 3) showed that CRV is separated from CRP, being influenced by soil cover. In CRV, where soil cover is higher than in CRP, vegetation cover is poorer, which in turn influences lichen composition through greater light availability on rocks. In work carried out in mountain systems similar to those studied here, as altitude increases, the proportion of crustose lichens increases (Costas et al., 2021). This phenomenon occurs in CAC, which is the highest basin and the one with the highest number of crustose species. Since CRP and CRV have similar altitudinal gradients, the lower percentages of foliose species found in CRV than in CRP could be related to the intrinsic environmental heterogeneity of each basin (Körner and Spehn, 2002). However, since species diversity and growth form (crustose, foliose, and fruticose) are affected by atmospheric pollution (Gunawardana et al., 2021), the low proportion of foliose species found in CRV could be related to the open-pit mining activity of Bajo de la Alumbrera.

Lichen cover values in the three basins were about 50%, with no significant differences among basins. However, this value is influenced by microsite variables (vegetation and rock covers), as observed by Rodríguez et al. (2017) for lichen communities in central Argentina.

The analysis of indicator species showed a close relationship between altitude and the occurrence of those species in different basins. In CRV, *A. xanthophana* and *P. candelarioides* were associated with higher altitude, which is consistent with the habitat range observed in taxonomic descriptions for these species (Knudsen et al., 2008; Westberg et al., 2009; Knudsen and Flakus, 2016). On the other hand, in CRP, *Xanthoparmelia farinosa* (Vain.) T.H. Nash, Elix & J. Johnst. was associated with lower altitude, while *P. perreticulata* and *U. durietzzi* were indicators of high-altitude sites. This pattern coincides with the habitat range observed in central Argentina (Estrabou, 1999; Rodríguez et al., 2011). In this sense, the highest number of indicator species found in CAC shows the high specialization of this altitude (3000 m a.s.l.). The species with IV>50 in this area were *C. sonorae*, *U. haplocarpa*, and *C. altoandina*. *U. haplocarpa* is endemic to the central Andes (2500–4400 m a.s.l.) (Hestmark, 2010).

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5 Conclusions

Saxicolous lichen communities were studied with the aim of contributing to knowledge of the diversity of lichens that grow in high-altitude mining areas in western Catamarca Province, Argentina. The characteristics of the lichen communities responded to environmental factors (mainly altitude and weather conditions) and microsite variables. Therefore, it was not possible to attribute the differences in species richness and composition among basins and sites to mining activity. However, the very low richness values found in CRV suggest that open-pit copper mining could influence lichen composition. More in-depth ecological studies analyzing lichen communities inside and outside the mine in a narrow altitudinal range will allow us to more clearly determine the impact of mining activities on lichens. Finally, taking into account the lack of works on lichen communities in the province, and particularly those associated with mining, these results lay the groundwork for future in-depth studies on the impact of mining activity on lichen species composition in the western region of Catamarca.

Conflict of interest: 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.

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Author contributions: Martha S. CAÑAS, Juan M. RODRÍGUEZ, and Juan M. HERNÁNDEZ designed the research and analyses. All authors performed the survey of lichen frequency and cover. Edith R. FILIPPINI, Renato A. GARCÍA, Cecilia ESTRABOU, Juan M. RODRÍGUEZ, and Juan M. HERNÁNDEZ carried out species identification. All authors performed statistical analyses, discussed the results, and wrote the article.

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Appendix

Table S1. List of lichen taxa identified by basin, taxonomic family, and growth form

[The table content would be preserved here with proper formatting, showing the taxon names, basin presence, family, and growth form categories as in the original]

Note: Figure translations are in progress. See original paper for figures.

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