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Copertina: Paolo Azzella

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Bioprotection of Stone Monuments under Warmer Atmosphere

Antonio GÓMEZ-BOLEA[1] & Juan Carlos PEÑA RABADÁN[2]

[1]*Universitat de Barcelona: Departament de Biologia Evolutiva, Ecologia i Ciències Ambientals - Institut de Recerca de Biodiversitat (IRBio) - FluVAlps Research group*

[2]*Servei Meteorològic de Catalunya. Generalitat de Catalunya & FluVAlps Research group Universitat de Barcelona*

Abstract: Biofilms, including lichens, are present in all stone surfaces exposed to the environment. Crustose saxicolous lichens, when they are alive, it has been found that can act protectively, even after death, the patina they left continues to protect the stone surface from erosion. In arid regions, the extreme temperature can act as a limiting factor for the life of lichens. In these regions of southern Europe is where the protective cover of lichens possibly disappears.

Résumé: Les biofilms, y compris les lichens, sont présents sur toutes les surfaces en pierre exposées à l'environnement. Les lichens encroûtants saxicoles, lorsqu'ils sont vivants, peuvent être protecteurs après leur mort, la patine qu'ils ont laissée continue de protéger la surface de la pierre de l'érosion. Dans les régions arides, la température extrême peut agir comme un facteur limitant pour la vie des lichens. Dans ces régions du sud de l'Europe, la couverture protectrice des lichens peut disparaître.

Key-words: lichens, saxicolous, stone temperature, future scenarios.

Mots-clés: lichens, saxicoles, température de la pierre, scénarios futurs.

1. Stone colonization and succession

When a new stone surface is exposed to the atmosphere, starts a new colonization by microorganisms, both in natural or manmade induced conditions. In the first case, cyanobacteria, green algae, mosses and lichens were the settlers on the stone surfaces in the new volcanic Surtsey Island, after 3 year of their formation (Brock, 1973). Colonization has also been studied on the new exposed surfaces of the rock after retreating glaciers (Hoppert *et al*., 2004). These authors found that the primary colonization starts with black fungi (Aureobasidiomycetes), after 2 years of the exposition to the atmosphere, followed by terrestrial unicellular green algae, epilithic cyanobacteria and finally, after 12 years, they found differentiated lichens.

Differences time of colonization, until lichens are formed, can be explained by several factors, namely: climatic, dry deposition from the atmosphere and type of rock, among the main. On manmade stone, one of us (AGB) found that colonization in Barcelona city was fast. After one year, surface of sand-lime mortar, were strongly colonised by dematiaceous fungi, which developed evident mycelia on the mortar surface, also were observed algae colonies, mainly *Stichococcus bacillaris* and *Trebouxia*-like. After 3 years, little thalli of lichens *Verrucaria nigrescens* and *Lecania turicensis* were observed.

About colonization on stone monuments, there are numerous publications (Scheerer *et al*., 2009). The first colonizing microorganisms will be different according to: nature of the stone, climate and quality of the atmosphere.

For many climatic regions in the world, on the vertical or sub-vertical stonewalls seems that lichens are end of the succession in the colonization. Micro-colonial fungi appeared to precede lichens in colonizing recently fractured, exposed rock surfaces (Palmer *et al*., 1990). Finally, the epilithic lichen thalli develop and grow until they swell and detach themselves from the rock, again leaving the surface of the rock available to be re-colonized. However, endolithic lichens stop their growth when their thalli come into contact, and form like a puzzle on the stone surface (fig. 1 and fig. 2).

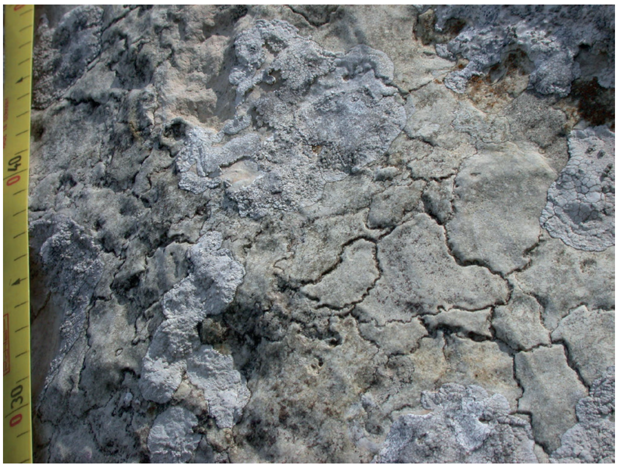
2. Erosion *versus* bioprotection of stone surfaces

This section is easier to explain if we consider colonization and succession, by biofilms and lichens, of the stone surfaces as a soil formation process (paedogenesis). In the layman's mind, the "soil" is a very concrete thing, namely, the "dirt" on the surface of the earth. To the scientist, the soil is a natural body, differentiated into horizons of mineral and organic constituents, usually unconsolidated, of variable depth, which differs from the parent material below in morphology, physical properties and constitution, chemical properties and composition, and biological characteristics (Jenny, 1994). The soil formation is a function of few variables namely: parent material, climate, organisms, topography and time.

Many works have been published on the weathering of the stone surface by biofilms (Scheerer *et al*., 2009). In a review, Chen *et al*. (2000) group numerous articles on biodeterioration, according to the type of alterations that the lichens produce on the stone: physical or chemical alterations. The same authors, in a last section, recognize that lichens may play a role in protection of rocks against weathering.

From observation of Ariño *et al*. (1995), on the protective role of crustose lichen thalli on the rock surfaces, many works have been published on this topic. Even models of lifespan, for crustose lichens on calcareous surfaces, have been proposed (McIlroy de la Rosa *et al*., 2013a). These models suggest that the episodic event when bioprotective lichen cover is removed from a rock surface is potentially when most geomorphological 'work' is done on surfaces with extensive lichen coverage. Chen *et al*. (2000) consider lichen protection from two aspects: i) lichens thalli as barrier, shielding the substrate rock from external environments and buffering the effects of physical and chemical weathering agents and ii) lichens, as transformers of substrate, can produce a patina of oxalate, providing hardness and insolubility to the stone surface. Furthermore, not only lichens protect the surface of the rock, green algae can also protect the rock surface from weather. Cutler *et al*. (2013) found evidences that green biofilms (without species identification) might have a broadly bioprotective role of the stone surfaces that had been exposed in Belfast for around 100 years.

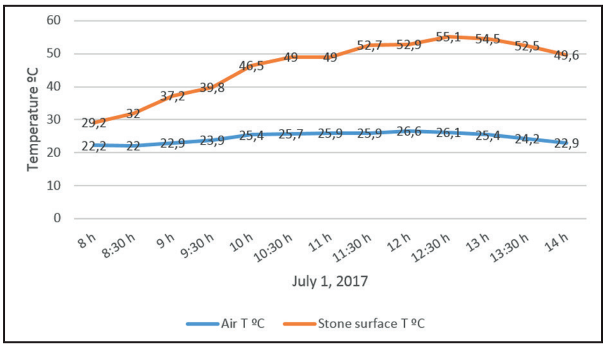
1. - Alive endolithic thalli of *Pyrenodesmia alociza*.
Thalle endolithique vivant de Pyrenodesmia alociza.



2. - Surface of the stone engraved by dead lichen thalli.
Surface d'une pierre gravée par des thalles morts de lichens.

For the stone monuments, the stone surface would be the parental material (bedrock) of "soil" and the "vegetation" would be the biofilm, including lichen thalli. On the stone surfaces, exposed to the atmosphere, really we found a micro-soil. In this context, hyphae of fungi, algae, bacteria and cyanobacteria fix and stabilize mineral particles, avoiding erosion. In spite of the primary deteriorative effect on their substratum by the organisms, long-term endolithic growth also involves mechanisms that stabilize and preserve the rock surface. A tightly woven cellular network may strengthen the colonized stone (Hoppert *et al*., 2004).

From this point of view, the disjunction between biodeterioration and bioprotection of the stone surface is superfluous. Remember that always the vegetation cover protect soil from the erosion. Vegetation imparts inertia to a landscape by resisting both the inception and cessation of erosion, modulating the dynamics of the exogenous forcing. Vegetation also reduces drainage density and highlights the transient and variable nature of erosionally active channel extent (Collins *et al*., 2004).



3. - Temperature changes during the UTC hours of a day in July. *Changements de température durant les heures UTC d'un jour de Juillet*.

3. Warmer atmosphere and crustose saxicolous lichens

Our hypothesis is that the expected increase of temperature can kill biofilms and lichens, that are protect the surface of stone monuments. This would expose the stone surfaces to rapid erosion.

3.1. What is the maximum temperature that lichens can withstand?

Lichen has two main components: the photobiont and the mycobiont. The photobiont can be algae (eukaryotes) or cyanobacteria. The mycobiont, in crustose saxicolous lichens, is a filamentous ascomycete. We reviewed bibliographic data for each group of organisms and finally for the lichen.

The acid-resistant and heat-resistant unicellular alga *Cyanidium caldarium* (Tilden) Geitler, currently in the Cyanidiaceae family (Rhodophyta) (Guiry & Guiry, 2017), show the upper temperature limit for the existence between 55 - 57ºC. Doemel & Brock (1970) studied aquatic and terrestrial populations from over 150 acid thermal areas from USA, Italy, New Zealand and Japan, and in no location was *C. caldarium* found at a temperature above 57ºC.

Bell (1993) in a minireview, about crypto-endolithic algae of hot semiarid lands and deserts, says that sandstones conduct heat into the matrix of the rock and therefore, endolithic organisms endure higher temperatures than they experience on the surface. Internal temperatures of 47ºC have been measured in Arizona sandstones.

Temperature tolerance of rock-inhabiting meristematic fungi was studied by Sterflinger (1998). In culture media, the maximum growth was at 32ºC and most fungi show lethal temperatures between 45ºC and 65ºC, and only for one black yeast, lethal temperature was 75ºC.

Tansey & Brock (1972) working with thermophilic fungi, in laboratory conditions and different culture media, found an upper temperature limit for fungi able to grow near 60 ºC.

Temperatures studies of the survival and growth of microcolonial rock fungi (Palmer *et al*., 1987) showed that many of them can tolerate exposure to temperatures of 70-80°C for as long as 21 days.

Palmer *et al*. (1990) found that, in East Oregon, the highest rock temperature recorded, where crustose lichens live, was 57 °C, during a period of two years.

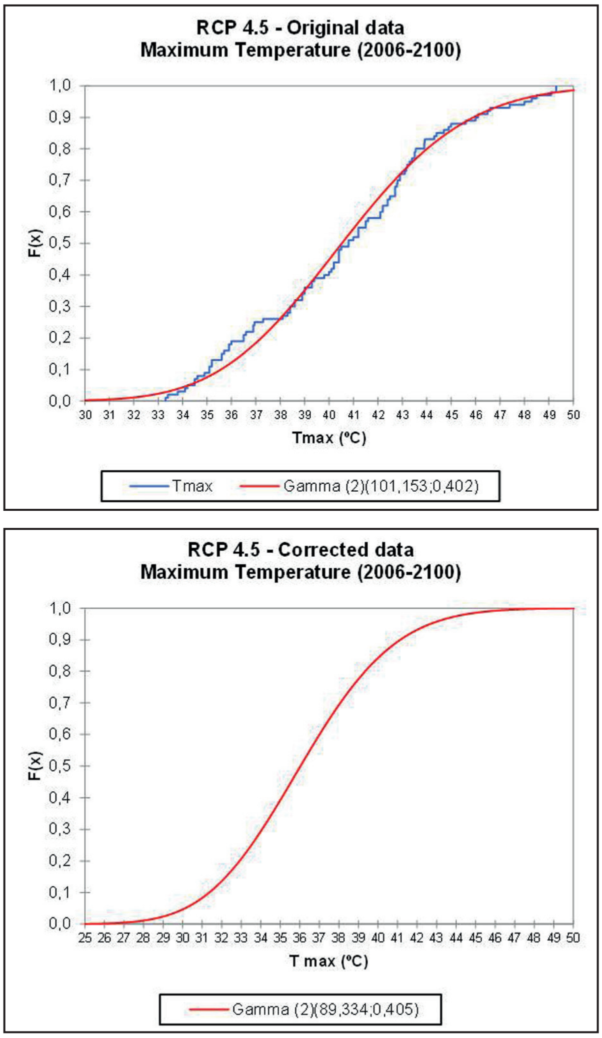
McIlroy de la Rosa *et al*. (2013b) studied lichen cover and temperature in the Monastery of Cartuja (Granada, Spain). On the stairwell of this monument, the maximum summer temperature recorded, on stone surface, for zone with 56% lichens cover was 43.9ºC, very similar to the 44.9ºC maximum recorded for zone with 3% lichens cover. Instead average stone surface temperatures of 20ºC was found in the first case, while the second case the average temperature was 23ºC. They conclude that the average stone surface temperatures, over the course of one year studied, seem to determine the presence or absence of lichen coverage on stonework.

3.2. Can be reached lethal temperature on the stone surface, in natural conditions?

Maximum daytime rock temperatures usually exceeded air temperatures by 10-20°C during the warmer months (Palmer *et al*., 1990).

We found, in July, maximum temperature on stone surface (grey schist), without lichens, of 55.1ºC, when the air temperature was 26.1ºC (fig. 3).

We can inferred that when air temperature is above 40 ºC, on stone surfaces temperature can reach more than 70ºC. This temperature is used in the process named Pasteurization, which uses the application of heat to destroy microorganisms.



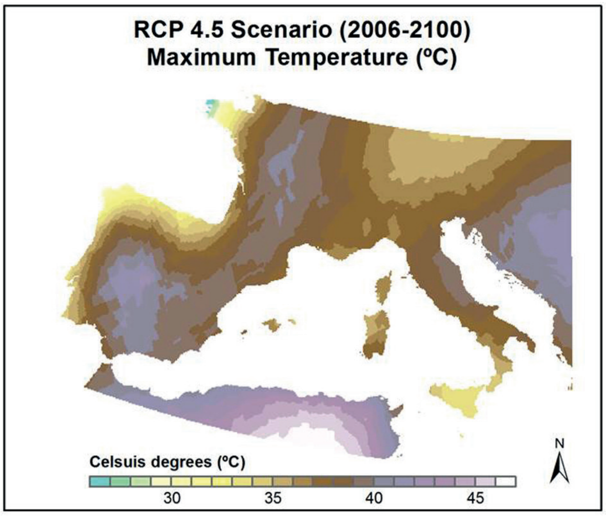
4. - RCP 4.5 scenario original data and gamma distribution (up) and gamma distribution for the corrected data (bottom).
Données originales du scénario RCP 4.5 et distribution Gamma (en haut) et Gamma corrigée (en bas).

4. In the future, what regions can be reaching lethal temperature?

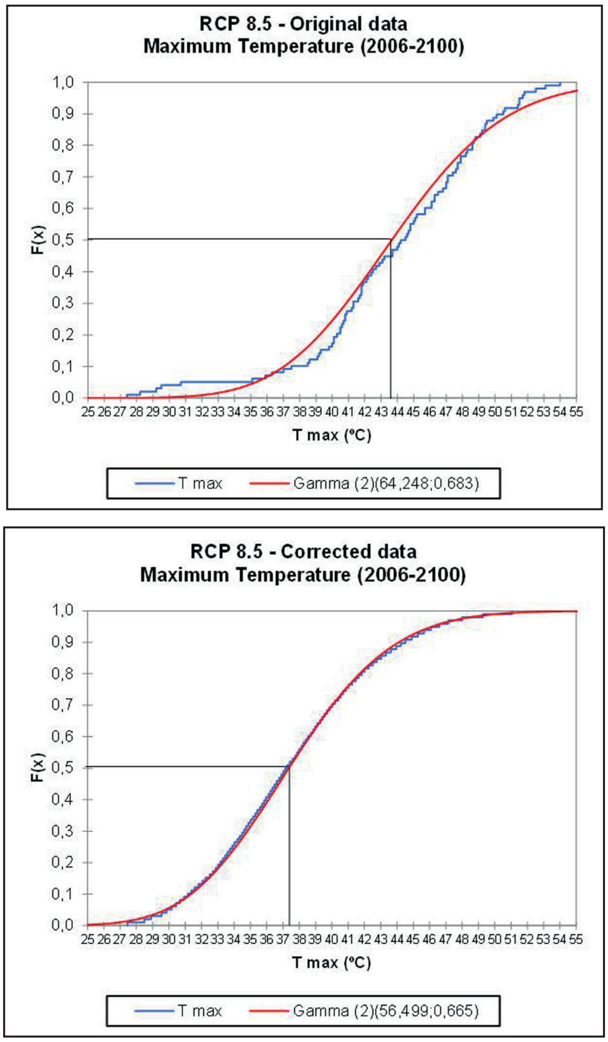
Climate change must influence the temperature by increasing the average concentration of pollutants and aerosols. This change will favour a higher temperature, changes in precipitation patterns, reduction of the mixing layer that prevents vertical movements in the atmosphere, and the greatest number of atmospheric stability synoptic situations.

The future temperature scenarios should be assessed within a framework with integrated weather forecast (Wood *et al*., 2004). Consequently, it is necessary to update the currently available climatic simulations in order to include impacts on air quality, using regional climatic models coupled with high-resolution space chemical transport models. Long-term trends indicate that emissions controls have successfully reduced concentrations of pollutants in recent years and in some areas but with an increase in developing regions linked to strong economic activity. The projection in the future depends, therefore, on the control policies especially of the primary pollutants for which the regional climatic models gives results based on the emission scenario (Cheng *et al*., 2007).

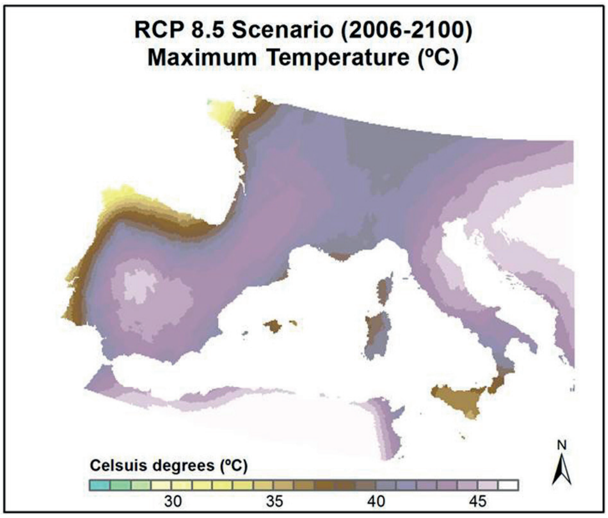
The Max Planck Institute Earth system model was used to study the maximum temperature in two future scenarios (RCP 4.5 and RCP 8.5) during



5. - RCP 4.5 scenario. Maximum temperature distribution over the south of Europe.
Distribution des températures maxima sur le sud de l'Europe selon le scénario RCP 4.5.



6. - RCP 8.5 scenario original data and gamma distribution (up) and gamma distribution for the corrected data (bottom).
Données originales du scénario RCP 8.5 et distribution Gamma (en haut) et Gamma corrigée (en bas).



7. - RCP 8.5 scenario. Maximum temperature distribution over the south of Europe.
Distribution des températures maxima sur le sud de l'Europe selon le scénario RCP 8.5.

the 21st century. The domain used was [11.3ºW: 20.6ºE] – [34.5ºN: 49.4ºN]. The model was calibrated given the climate variability in the future scenarios, using the Quantile-Quantile mapping transformation (Q-Q; Amengual *et al*., 2012).

The RCP 4.5 is based on an emissions scenario keeping and corrective measures of the present time.

The bias observed in the original data of the model was corrected by Q-Q method using the Gamma distribution (Thom, 1958) of two parameters (k, beta) to adjust the data time-series. Highlight the values of the south of Italy and the island of Sicily below the expected values.

The corrected RCP 4.5 scenario (fig. 4) shows a mean of maximum temperature over the domain analyzed around 4ºC less than the RCP 4.5 original scenario (40.5ºC to 36ºC). These results are used to map the maximum temperature over the 21th Century.

The distribution of maximum temperature from 2006 to 2100 (fig. 5) shows temperature greater than 40ºC in center and south of Iberian Peninsula, interior and south of France, east of the Italic Peninsula, and the Adriatic Peninsula. Values greater than 45ºC only affect the south of the domain analyzed (North Africa).

The RCP 8.5 is based on an emissions scenario without kind of control.

The same procedure is used: the bias observed in the original data of the model was corrected by Q-Q method using the Gamma distribution of two parameters k and beta to adjust the data time-series. As in the RCP 4.5 scenario, below-expected values are observed in in the southern tip of Italy and Sicily.

The corrected RCP 8.5 scenario (fig. 6) shows a mean of maximum temperature over the domain analyzed around 6ºC less than the RCP 4.5 original scenario (43.5ºC to 37.5ºC, around 1.5ºC greater than the mean of the RCP 4.5 scenario). These results are used to map the maximum temperature over the 21th Century.

The distribution of maximum temperature from 2006 to 2100 (fig. 7) shows temperature greater than 40ºC in the most of southern Europe. Values greater than 45ºC affect interior of Iberian Peninsula, central part of Italic Peninsula, Adriatic Peninsula and North Africa.

5. Conclusion

Crustose saxicolous lichens protect stone surface of monuments, mainly in southern regions of Europe, where climate condition are warmer. In the future this bioprotection may disappear if saxicolous lichens die and are unable to recolonize stone surfaces due to the high temperatures they can reach.

Further investigation of the response and resistance of saxicolous lichens to hot temperatures and exposition time, would be necessary.

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