International Biodeterioration & Biodegradation 96 (2014) 157–165

Contents lists available at ScienceDirect

International Biodeterioration & Biodegradation

journal homepage: www.elsevier.com/locate/ibiod

Review

Biological colonization patterns on the ruins of Angkor temples (Cambodia) in the biodeterioration vs bioprotection debate

F. Bartoli [a,*], A. Casanova Municchia [a], Y. Futagami [b], H. Kashiwadani [c], K.H. Moon [d], G. Caneva [a]

[a] Roma Tre University, Department of Science, Viale Marconi 446, 00146, Rome, Italy
[b] National Research Institute for Cultural Properties, Tokyo, 13-43, Ueno Park, Taito-ku, Tokyo, 110-8713, Japan
[c] Department of Botany, National Museum of Nature and Science, 4-1-1, Tsukuba, Japan
[d] National Institute of Biological Resources, Environmental Research Complex, Incheon, 404-170, Republic of Korea

ARTICLE INFO

Article history:
Received 23 May 2014
Received in revised form
23 September 2014
Accepted 26 September 2014
Available online

Keywords:
Stone conservation
Algae
Cyanobacteria
Lichens
Mosses
Archaeological site conservation

ABSTRACT

The biological colonization present on the temples of the UNESCO World Heritage site of Angkor is wide and relevant, but a debate on its biodeteriorative and bioprotective effects is now developing. We investigated the biological patterns observed on two temples (Ta Nei and Ta Keo) exposed to different microclimatic conditions, in order to assess the damage caused by the communities present on the stone. We analyzed the penetration (depth and spread) into the stone, and the degree of decohesion of seven communities (green algae, cyanobacteria, lichens and mosses). The microscopic analyses highlighted a clear interaction between organism and stone, displaying a trend of increasing harmfulness from the community of the green algae (*Trentepohlia)* up to the moss communities. All the lichen communities show biodeterioration abilities: the *Pyxine community* seems more aggressive than the *Lepraria* and *Cryptothecia* communities, and more also than the cyanobacterial communities. The positive effects of the lichen cover in reducing dangerous evaporation processes cannot outweigh the negative effects of their hyphal penetration. Light forest cover seems beneficial for the conservation of the Angkor monuments since it reduces evaporation processes, but further studies should be carried out so as to find an optimal balance between contrasting factors.

Contents

* Corresponding author. Tel.: +39(6)57336374; fax: +39(6)57336321.
E-mail address: flavia.bartoli@uniroma3.it (F. Bartoli).

http://dx.doi.org/10.1016/j.ibiod.2014.09.015

Introduction

Stone biodeterioration involves numerous interactions between organisms, substrates and climates, giving rise to a variety of biodeterioration patterns (Caneva and Salvadori, 1989; Warscheid and Braams, 2000; Caneva et al., 2009). It is well known that biological colonization of stone monuments is always influenced by a favorable climate, so comparative analyses of colonization phenomena occurring in different climatic contexts have been undertaken in order to identify tendencies and correlations on a macroclimatic scale (Danin and Caneva, 1990; Warscheid et al., 1996; Gaylarde and Gaylarde, 2005; Caneva and Pacini, 2009).

Several studies deal with general processes of stone deterioration or the biological identification of communities observed on monuments in tropical areas such as India, Sri Lanka, Indonesia, Thailand, and Philippines (Lee and Wee, 1982; Sadirin, 1988; Aranyanak, 1992; Chihara et al., 1992; Tripathi et al., 1997; Kumar and Kumar 1999; Uchida et al., 1999; Adhikary, 2000; Crispim et al., 2006; Gaylarde et al., 2012), and Central and South America, in particular Mexico, Guatemala, Honduras, Cuba, and Brazil, (De Miguel et al., 1995; Ortega-Morales et al., 1999, 2005; Caneva et al., 2005; Ramírez et al., 2010), while there are very few, which deal with tropical Africa. However, despite the intense biological growth characteristic of tropical environments, there is a lack of studies that focus on the interaction between organisms and substrate with the aim of describing the relevant action of organisms on the monuments.

Many authors have shown that substrate weathering, where the biological cover meets the rock surface, can be substantially accelerated by the growth of several organisms (Rodrigues, 1991; Nimis et al., 1992; Seaward, 1997; Silva et al., 1997; Adamo and Violante, 2000; Chen et al., 2000). These authors have gone on to emphasize the aggressive action of these populations, in particular of lichen populations, which are able to penetrate deep into the substrate with the fungal hyphae and can also produce high levels of chelating substances, which have the power to extract ions from the substrate (Siever and Woodford, 1979; Prieto et al., 1994; Prieto Lamas et al., 1995; Wierzchos and Ascaso, 1996; Adamo et al., 1997).

However, the dual role of organisms, which colonize the surface as biodeteriogens or bioprotective, and how this dual role effects conservation strategies, is still being debated. Several authors take the view that organisms, especially lichens, should not be removed from stone surfaces in certain conditions because the biodeterioration they cause is less damaging than physic-chemical processes due to weathering (bioprotection effect) (Ariño et al., 1995; Fiol et al., 1996; Grondona et al., 1997; Mottershead and Lucas, 2000; Carter and Viles, 2003, 2005; Concha-Lozano et al., 2012; De la Rosa et al., 2012).

The debate on biodeterioration vs bioprotection seems particularly relevant to the archaeological site of Angkor, where Khmer temples that had been abandoned for many centuries suffer from a wide range of biological colonization due to dense forest cover (Delvert, 1963; Uchida et al., 1999; Warrack, 2000; Warscheid, 2000; Warscheid and Leisen, 2011; Caneva et al., 2012; Gaylarde et al., 2012).

The Angkor archaeological park (Cambodia), inscribed on the UNESCO World heritage List in 1992, includes about forty temples built over a period of six hundred years (9th–15th centuries) (Warrack, 2000). The park is distributed over 400 km^2 in the plain around the Tonle Sap (Great lake), characterized by a tropical monsoon climate with distinctive rainy and dry seasons.

The archaeological park has been studied, but mainly from a floristic point of view. The lichen flora of this area has appeared in taxonomic studies by several authors (Nakanishi et al., 2010; Moon et al., 2011, 2013; Schumm and Aptroot, 2012; Aptroot et al., 2013). At present, a total of 63 species are known in Cambodia, mainly (45) from collection around Siem Reap: 19 species grow on rocks. Among the 63 species of lichen flora, 50 species in 42 genera discovered around the investigation area, are reported for the first time in Cambodia, including a few unidentified species (Moon et al., 2011, 2013, 2014). There are 19 species of moss flora in 14 genera and 11 families of Bryopsida (Higuchi, 2009), at Ta Nei 9 species in 8 genera of bryophytes and 3 species in 2 genera of liverworts were recorded.

National Research Institute for Cultural Properties, Tokyo (NRICPT), in cooperation with the Authority for the Protection and Management of Angkor, and the Siem Reap Region (APSARA National Authority) in 2001 selected for study the Ta Nei temple, which had previously been chosen for conservation studies and training courses by ICCROM (Warrack, 2000). The choice of this temple, built in the reign of Jayavarman VII (around the end of the 12th-beginning of the 13th centuries), was due to its relatively small size and its decentralized position in the shade of forest canopy cover, making it representative of base-case studies of stone conservation in shady environmental conditions (Futagami, 2009). Previous studies have shown the presence on stones of a rich micro- and macroflora constituted by communities (listed following the phytosociological style, see Westhoff and Van Der Maarel, 1978) of algae and cyanobacteria (respectively *Trentepohlietum*, *Scytonemo-Gloeocapsetum)*, of lichens (*Leprarietum*, *Cryptothecietum*, *Pyxinetum*), mosses and higher plants, corresponding to different local ecological conditions (Caneva et al., 2012).

In opposite condition seems to be the Ta Keo temple, built in the reign of Jayavarman V (10th century) which is, in a cleared area of the archaeological park, and it suffers for the severe weathering underlined by André et al. (2011). This weathering has been caused by aggressive microclimatic conditions related to the complete cutting down of the forest canopy over recent decades (Chihara et al., 1992). Now it also displays lower levels of biological colonization, often limited to wide black patinas of cyanobacteria and lichen communities. On the basis of a comparison of the observed rate of weathering of this temple and that of the temples covered in vegetation, some authors (André et al., 2008, 2011) have concluded that most biological colonizations, and especially lichens, have a bioprotective action.

In this paper, the harmfulness of the biological colonization patterns which can be observed in these two temples exposed to different microclimatic conditions in the Angkor archaeological park was investigated, in order to assess the biodeterioration damage caused by the different communities found on the stone and therefore contribute to the on-going debate.