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Original article

Exploring ecological relationships in the biodeterioration patterns of Angkor temples (Cambodia) along a forest canopy gradient

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ABSTRACT

Various biological communities colonize the Khmer temples in Angkor (Cambodia), which had lain abandoned for many centuries. These biodeterioration patterns change in response to different environmental conditions, and the aim of this study is to quantify their frequency and ecological characteristics according to a forest canopy gradient. The descriptive and multivariate statistical analysis applied to data collected from the four temples in the study identifies various biological communities along with a temple-specific ecological succession. The initial pioneer community is primarily composed of a reddish biofilm of the green alga *Trentepohlia* sp., and it occurs in xeric and shady environmental conditions, becoming dominant in forested areas. Cyanobacteria biofilm, consisting of species belonging to the genera *Scytonema* and *Gloeocapsa*, sometimes in combination with the lichen *Endocarpon* sp., prevails in xeric and sunny conditions. With the progressive increase of the availability of edaphic water, typical of forested areas, various lichen communities are able to establish themselves (dominated by *Lepraria*, *Pyxine coralligera* and *Cryptothecia subnidulans* respectively), followed by moss and higher plant communities. Understanding these relationships appears to be a very useful way of identifying the best microclimatic conditions for stone conservation.

1. Research aims

This paper is aimed at providing a contribution to the modeling of changes in biological colonization on the stone temples of Angkor in relation to the gradients of the most important limiting environmental factors. In particular, we wish explore the ecological relationships between different biodeterioration patterns found growing on monuments, by tracing a forest canopy gradient.

2. Experimental

2.1. Introduction

The biodeterioration of materials is closely related to the chemical and physico-chemical nature of the substrate, as well as to the features of the surrounding environment [1–5]. The influence of the lithotype in relation to its bioreceptivity is related in particular to the differential porosity, and has been confirmed in many cases in Mediterranean and temperate climates [6,7].

In wet and warm tropical climatic conditions, such as those in Mesoamerica and Southern Asia, where the temperatures, as well as the water input, are usually high, abandoned monuments are widely colonized by various biological communities as a result of favourable environmental conditions [8–11].

The time factor is also relevant, and colonizing organisms vary in relation to the length of time that a site is abandoned, until the final stage of growth of forest communities, which simultaneously favour further biological colonization [12,13].

Biological colonization can also change according to different microclimatic conditions, to local protection of the stone from direct rainfall, or with elevated exposure to sunlight [14,15]. These appear to be limiting factors in that they are present in minimal or maximal quantities with respect to the tolerance of an organism; such differences in threshold limits, above or below which growth is inhibited, vary greatly between organisms, and explain the principle changes in the composition of

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communities over space and time, resulting in an ecological succession [16,17].

In accordance with these general tendencies, the Khmer temples in Angkor (Cambodia), after being abandoned, starting from the XVI century, began to be colonized by different biological communities until the development of a luxuriant forest. It is possible to observe a variety of biodeterioration processes at these sites, which have been described in a number of studies [18–21], that focus mainly on an analysis of community biodiversity and problems of stone biodeterioration, or, on general ecological aspects [22]. These papers highlight as the biodeterioration effects concern to physic-chemical alteration due to the penetration of the adhesion structure (rhizoids, roots and hypha) resulting in disaggregation and loss of stone materials. With regard to the conservation of the Khmer temples, some authors [21–24], however underlines the positive effects of forest cover and of the biological colonization in stabilizing the microclimate, preventing the negative effects of overheating and ventilation, and regulating moisture on the sandstone. The importance of a better knowledge of the relations among forest canopy and biodeterioration pattern was emphasized in a previous contribution [25].

2.2. Characteristics of the study area

Cambodia's Angkor Period (9th–15th century) refers to the time in which the capital was located in this area. Angkor Thom, the capital of King Jayavarman VII, was built around the end of the 12th century. At first the temples were built with bricks, and later with soft fine-grained sandstone weakly cemented together with clay and calcite having a porosity of about 13–19%. Laterite, on the other hand, was used only as filler within walls, pavements and platforms [26].

The macroclimate of the site is characterized by tropical monsoon with a short rainy season, a prolonged dry season, and irregular but generally plentiful rainfall (between May and mid-October) which amounted to a total of approximately 1200 mm, as shown by the thermo-pluviometric diagram and calculated according to methods proposed by Bagnouls-Gaussen [27] and Walter and Leith [28] (Fig. 1).

Microclimatic conditions vary widely between forest and cleared areas, and four temples were chosen according to their different forest cover and microclimatic conditions: Ta Prohm was

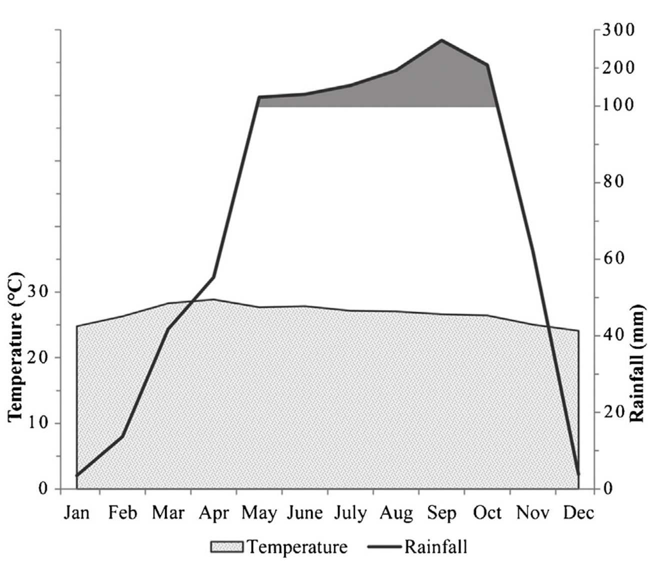

Fig. 1. Bagnouls-Gaussen diagram of the average temperature (°C) and rainfall (mm) for three years (2006, 2007, 2008), in the archaeological area of Angkor (Cambodia).

selected for the presence of a dense forest canopy, giving rise to humid and shady conditions; Ta Nei and Bayon temples, for their partly shady conditions and relatively humid environment, and Ta Keo as an example of sunny and dry conditions, due to local deforestation [29–31] (Fig. 2).

Microclimatic data was collected from 2001 to 2013 by the National Research Institute for Cultural Properties, Tokyo (NRICPT) from the interior and the exterior of the enclosure of the Ta Nei Temple [32,33]. Detailed information on average temperatures is given in Fig. 3a; monthly maximum and minimum temperatures varied between 29–36 °C and 18–25 °C respectively. Fluctuation in daily temperature was smaller in the rainy season than in the dry season. Annual average Relative Humidity was around 80%, between 45% and 90% in the dry season, and between 75% and 90% in the rainy season (Fig. 3b). In the absence of forest cover (inside enclosure of Ta Nei), monthly average solar radiation values went from a minimum of around 2–6 MJ/m^2 from December to January, to a maximum of around 10–16 MJ/m^2 from March to July, some variations were registered between one year and another (Fig. 3c).

According to the data obtained from January to June 2012, the temperature inside the enclosure (non-forested) was 0.5–2.5 °C higher than that outside the enclosure (Fig. 4a)(forested), and relative humidity inside was 0–9 points lower than that outside (Fig. 4b). Differences were wider in daytime than at night. Solar radiation inside the enclosure is stronger than outside (Fig. 4c).

2.3. Materials and methodologies

2.3.1. Identification and estimation of biodeterioration patterns in different ecological conditions

Field surveys were carried out in the archaeological area during the dry seasons between 2010 and 2012 in order to analyze the different biodeterioration patterns, their frequency, and their distribution in relation to environmental factors. Specifically, the phytosociological method [34] was used to ascertain the nature and extent of each biodeterioration pattern observed on the temple's outer surfaces. The following scale was used to indicate extent of coverage for each species: + = 0.5; 1 = 1–5%; 2 = 5–25%; 3 = 25–50%; 4 = 50–75%; 5 = 75–100%. As is usual in vegetation studies, these values were obtained through visual observations in the field, which were facilitated by their easily recognizable phenomenology. We considered for each temple the 4 expositions, and the possible variations due to the lighting changes caused by the shadowing of forest canopy (16 average values for a total of 40 relieves). The data collected in the field was evaluated according to the Braun-Blanquet cover-abundance scale. In order to proceed with the statistical analysis, this data has been converted into ordinal transformations in accordance with the scale of van der Maarel [35]. Finally, we converted the van der Maarel scale into decimal values (Table 1).

Samples were collected and analysed with an optical microscope (Olympus BX41) to carry out the observations necessary for their identification trough analytic keys, as described in Caneva et al. [22], and in Bartoli et al. [25].

2.3.2. Statistical analysis

The data was analyzed using two different multivariate statistical analysis procedures: (i) Hierarchical Cluster Analysis (HCA) and (ii) Principal Components Analysis (PCA). These analyses were used to identify the latent patterns in terms of spatial similarity (HCA) and relationships between variables (PCA) observed between the selected indicators of biodeterioration based on the ecological communities found in each of the four temples. Similarity between variables and objects (temples) was examined separately using hierarchical clustering based on Euclidean distance and Ward's agglomeration rule. A factor analysis based on principal components extraction (PCA) was run on the available data matrix