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Environmental history of the northern Maya Lowlands: Evidence from a karstic lake

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Landscape transformation by Maya civilization represents one of the most significant anthropogenic environmental changes in the pre-colonial Americas. Using lake sediments, we address how the evolution of a karstic lake has been affected by human–environment interactions over the last 8300 years.

The Maya civilization developed and thrived in the region of the Yucatan Peninsula (México, Guatemala, and Belize) from ~4000–500 yr BP (before present). The Puuc region, located at the northwest of the peninsula, was a key area for human settlements, as it harbors some of the most productive soils in the Maya lowlands (Fig. 1). In this region, Maya settled from ~2800 yr BP, and some city-states persisted until the early 11th century (Dunning et al. 2013; Hoggarth et al. 2016). Although today it represents the driest zone of the peninsula, the Puuc region was one of the most densely populated areas during Maya times. These human settlements probably exerted substantial impacts on perennial water sources given the regional vulnerability to water stress. Sediments in karstic aquatic ecosystems widespread across the Yucatan Peninsula (lakes and sinkholes) represent natural archives to investigate human-environment interactions by using different proxies. Lake Yalahau is the largest lake in the northern Yucatan Peninsula and is located relatively close to three major Maya cities from the Puuc region (Fig. 1). There are also archaeological remains of a civic ceremonial center at the northwest of the lake. Thus, the multi-proxy record of Lake Yalahau provides an excellent opportunity to understand the effect of natural stressors and human activities on the lake system over the last 8300 years in the Puuc region.

We recovered a 560-cm-long sedimentary sequence from the deepest part of Lake Yalahau using a modified Livingstone piston corer. Here, we used elemental concentrations and geochemical analysis of organic matter to explore mechanisms of underlying changes in lake evolution. A principal component analysis (PCA) was applied to elemental and geochemical proxy data to summarize environmental variability through time in Yalahau. This technique summarizes the geochemical signals in principal components (PC) that are interpreted as representing climatic and/or environmental drivers, and can be used to infer the environmental evolution of the lake throughout the different cultural stages of the Maya civilization. Major geochemical trends of Lake Yalahau were described in terms of changes in erosion in the catchment (PC1) and lake productivity (PC2) (Fig. 2). Detrital elements (iron and rubidium) were located along negative PC1 values, while authigenic elements (calcium and strontium) were located along positive PC1 values. Negative PC1 scores are associated with an increase in the input of detrital elements to the lake caused by high erosion in the catchment area. Negative correlation of calcium carbonate with total organic carbon in Lake Yalahau suggests that $CaCO_3$ concentrations are influenced by lake productivity. As CO_2 increases, as a product of oxidation of organic matter, it lowers pH in the hypolimnion and promotes calcite dissolution in sediments (Dean 1999). Elements associated with poorly oxygenated conditions (sulphur) and high lake primary productivity (total organic matter) were characterized by negative values in PC2, while calcium carbonate concentrations were associated with positive PC2 scores. Thus, negative PC2 scores were interpreted as an increase in primary productivity in Lake Yalahau. Our findings point to anthropogenic activities and regional climatic variability as the main triggers of the lake evolution trends over the last 8300 years.

Maya Archaic (8300–4000 yr BP)

The infilling of Lake Yalahau and other lakes in the northern Yucatan Peninsula started at around 8000 yr BP. This process was probably related to regional sea-level rise and a higher moisture availability during the early Holocene in the Northern Hemisphere (Haug et al. 2001; Milliken et al. 2008). PC2 positive scores suggest low productivity conditions in Lake Yalahau (Fig. 2). Humid conditions prevailed at the end of the early Holocene, enabling the establishment of deciduous forests in the northwest of the Yucatan Peninsula (Leyden 2002). This vegetation cover probably protected the soil from erosive agents, explaining the low erosion rates observed in Yalahau from 7000–4000 yr BP through soil stabilization (Koinig et al. 2003). Archaeological remains indicate the presence of hunter-gatherers in the Maya Lowlands during the Archaic period (Hoggarth et al. 2016). However, pollen records show relatively pristine vegetation during this period, implying anthropogenic effects on the environment would have been minimal or limited in their spatial extent (Leyden 2002).

Maya Preclassic (4000–1700 yr BP)

Evidence of the first permanent settlements in the Puuc region dates to the Middle Preclassic (Hoggarth et al. 2016). In Lake Yalahau, decreasing PC1 scores indicate increasing erosion probably associated with land-use changes (Fig. 2). The input of allochthonous nutrients, in turn, resulted in increased lake productivity reflected in

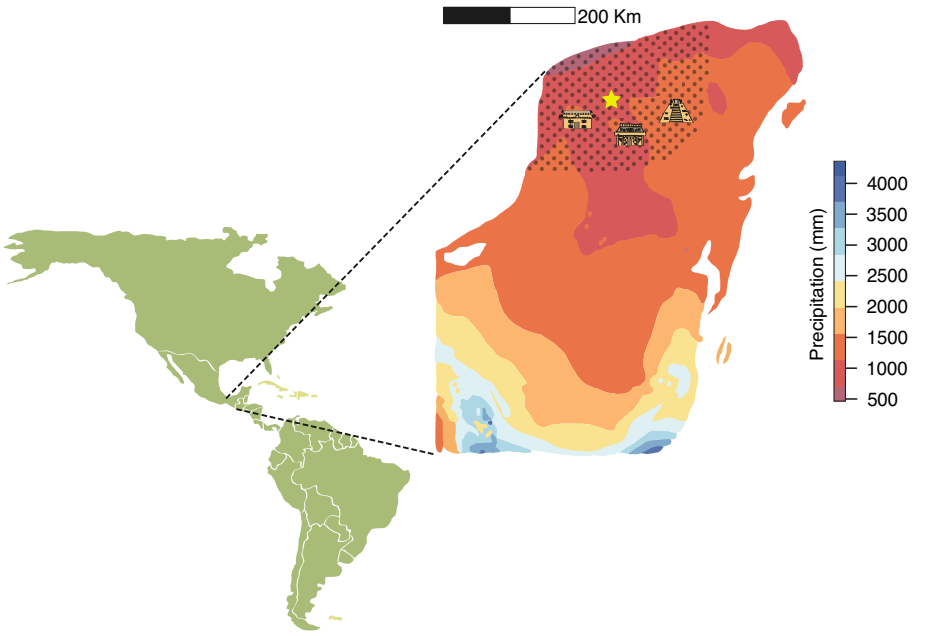

Figure 1: Location of the Yucatan Peninsula showing the modern mean annual rainfall distribution (Fick and Hijmans 2017). The Puuc region (marked dotted area) and Lake Yalahau (yellow star). Buildings symbolize main archaeological sites from the Puuc region, from left to right: Oxkintok, Uxmal, and Chichén Itzá (Illustrations by Ariadna Valenzuela-Zuñiga).

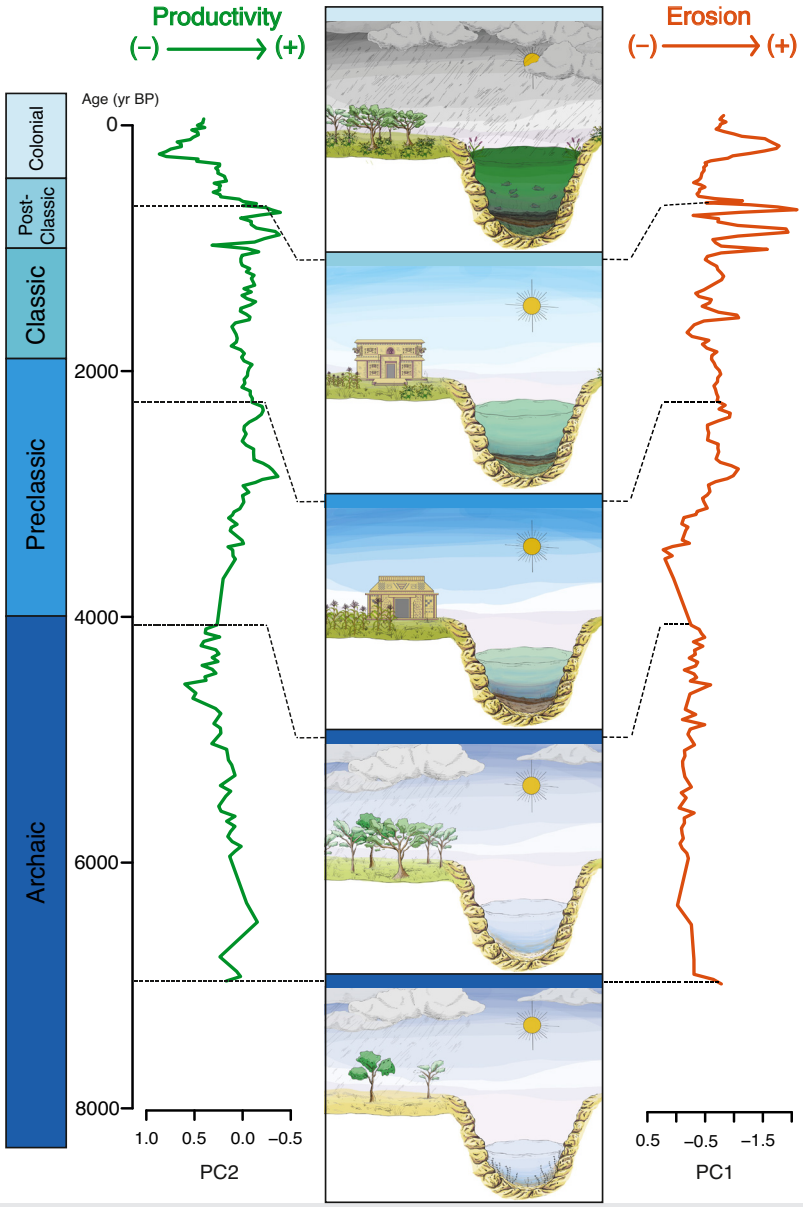

Figure 2: Paleoenvironmental synthesis of Lake Yalahau over the last 8300 years based on changes in productivity (PC2 scores) and erosion (PC1 scores). The Maya chronology is shown on the left side (Illustrations by Ariadna Valenzuela-Zuñiga).

changes in PC2 scores. The evidence suggests that deforestation and agriculture were extensive practices throughout the Yucatan Peninsula during the Preclassic (Anselmetti et al. 2007; Leyden 2002; Wahl et al. 2006). Also, lake sediments recorded several pronounced regional droughts (Hodell et al. 2001) that coincide with changes in vegetation cover in Yalahau during the middle to late Preclassic.

Maya Classic (1700–1000 yr BP)

During the Classic period, increased erosion in the basin and eutrophication of Lake Yalahau are indicated by both negative PC1 and PC2 scores. These findings coincide with the development of "classic" Puuc architecture in city-states near the lake (i.e. Uxmal), corresponding to a large-scale human occupation of the region (Dunning et al. 2013). Regional paleoclimate records from speleothems and lake sediments show successive droughts during the Terminal Classic that coincide with societal collapse of some city-states in the southern Maya Lowlands (Hodell et al. 2001; Medina-Elizalde et al. 2010). However, archaeological evidence shows an apogee of Puuc sites during the Terminal Classic period. Puuc settlements developed urban reservoirs (aguadas) and underground cisterns (chultunob) for water storage. These water management strategies may have allowed the Puuc populations to deal with droughts better than in other areas of the Maya Lowlands (Dunning et al. 2013; Hoggarth et al. 2016).

Maya Postclassic (1000–400 yr BP)

Regional paleoclimate records indicate a severe drought during the early Postclassic that coincides with the decline of construction of monuments and hieroglyphic inscriptions at the Puuc urban centers (Dunning et al. 2013; Hodell et al. 2001; Medina-Elizalde et al. 2010). Hoggarth et al. (2016) suggest a shift in occupation to sites along the coast and nearby freshwater ecosystems such as lakes and rivers during the Postclassic period. The access to perennial water resources, such as those provided by Lake Yalahau, could favor settlements around the lake. During this interval, productivity and erosion rates increased, reaching their maximum throughout the Yalahau record. Also, an increase in tropical hurricanes in this interval would explain enhanced soil erosion and allochthonous sediment input into the lake (Schmitt et al. 2020).

Colonial (400 yr BP–Present)

Our record indicates that the last 400 years have been characterized by high erosion rates and a substantial decrease in productivity in Lake Yalahau. These patterns have been associated with increased regional moisture availability and high cyclonic activity (Medina-Elizalde et al. 2010; Schmitt et al. 2020). Environmental degradation associated with human activities coupled with droughts and hurricane effects could explain a decline in the population throughout the Puuc region at the end of the Postclassic period and during Colonial times (Dunning et al. 2013; Schmitt et al. 2020).

Our study illustrates the importance of studying the evolution of these karstic lakes to understand long-term environmental changes in the Maya Lowlands. The sedimentary record of Lake Yalahau shows that anthropogenic environmental degradation may have been one of the main drivers of ecological change since the Preclassic period in the Puuc region. Further archaeological and paleolimnological studies, focused on the human–impact proxies (i.e. pollen and charcoal) and responses of karstic lakes to anthropogenic degradation, will contribute to a better understanding of human–environment interactions in the Maya Lowlands.

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