Chapter 10
Holocene Paleoecology and Paleoclimatology of South and Southeastern Mexico: A Palynological and Geospatial Approach

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Abstract Reconstruction of Holocene paleoecological conditions and paleoclimate of an area with high biological diversity and a variety of climatic conditions like southern and southeastern Mexico is complex. This region is characterized by vegetation types ranging from tropical forest to high mountain vegetation. Additionally, this region was inhabited by the ancient Maya culture, which shaped the landscape for several millennia. Previous paleoecological studies from this region were focused on the Maya culture-environment relationships, to decipher natural and human-induced deforestation. These studies also aimed to understand the effects of climatic regional forcing (El Niño-Southern Oscillation (ENSO), Intertropical Convergence Zone (ITCZ), and North Atlantic Oscillation (NAO) on the natural vegetation. In this chapter we review the paleoecological results and present a new geospatial approach to analyze past precipitation and tropical forest distribution of the Yucatán Peninsula from 1 AD to 1700 AD in 100-year intervals. The geospatial analysis revealed heterogeneity in spatial patterns of precipitation and tropical forest extension during the Late Preclassic, Terminal Classic, and

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Medieval Warm Period to Little Ice Age transition. The dry periods of the Middle and Late Holocene in the Yucatán Peninsula and southern Mexico can be chronologically placed in the following intervals: 4700–3600 cal year BP, 3400–2500 cal year BP, 2300–2100 cal year BP, 1900–1700 cal year BP, 1400–1300 cal year BP, 730 cal year BP, and 560 cal year BP. We conclude that this region requires additional studies with strong chronological framework due to its heterogeneous environmental conditions.

Keywords Geospatial approach · Tropical forest cover · Holocene · Paleoecology · Ancient Maya

Introduction

Southern and southeastern Mexico covers a vast area with variable climate, biodiversity, and physical conditions. This region includes the states of Chiapas, Tabasco, Campeche, Yucatán, and Quintana Roo. The landscape is diverse and it includes lowland as well as mountain ecosystems. The mountains in Chiapas have elevations up to 4000 m asl and pine-oak highland forests dominate the landscape. Other vegetation types, like mesic mountain forests and wet and dry tropical forests, and mangroves cover different altitudinal ranges of this region (Fig. 10.1). This diverse vegetation and climatic mosaic offers an excellent opportunity to understand ecological variability during the Holocene in an area of high biodiversity, endemism, and with a long history of use by the human societies (Islebe et al. 2015b).

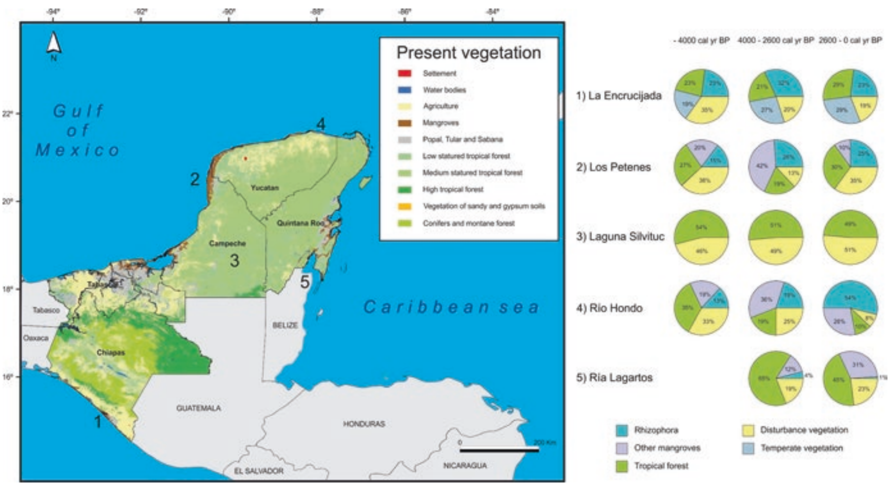

Fig. 10.1 Percentage pie plots of the main sampled vegetation types in different sites across southern and southeastern Mexico during key intervals of the Holocene

From a conservation point of view, this region has major protected areas like the Lacandon rainforest in Chiapas and the Calakmul Biosphere Reserve in Campeche, which represent the northernmost distribution of neotropical forests. The studies of paleoecology of southeastern Mexico, Belize, and lowland Guatemala over the Holocene have a major scientific objective, i.e., to understand the relation of ancient Maya culture with the environment and to decipher their cultural demise (Brenner et al. 2002b; Cowgill et al. 1966). One of the key questions is how the sustainable ancient Maya culture managed their natural resources (Lentz et al. 2014), and these paleoecological studies provided clues to understand the past land use changes.

Palynological research in the wider region was fostered by Leyden (1984) to understand vegetation changes in lowland Guatemala from the Pleistocene to Holocene transition. Later, several relevant palynological studies were published by Crane (1996), Leyden et al. (1998), Islebe et al. (1996), and Dunning et al. (1998), among other studies, to analyze the interactions between vegetation and environment. This growing paleoecological knowledge over the past 50 years in southeastern Mexico allowed a better understanding of the past environmental variability (Islebe et al. 2015a). Paleopalynology in a highly diverse area also depends on accurate identification of fossil pollen grains as more than 8000 plant species can be actually found in southern/southeastern Mexico. Therefore, the accurate pollen identification depends on available bibliography and studies on pollen morphology (Palacios-Chávez et al. 1991) and the correlations between the present plant communities and pollen rain (Correa-Metrio et al. 2011; Escarraga-Paredes et al. 2014; Islebe et al. 2001) and Chiapas (Domínguez-Vázquez et al. 2004). From a paleoclimate view, the regional climate forcings like ENSO (El Niño-Southern Oscillation) and ITCZ (Intertropical Convergence Zone) had conspicuous effect on vegetation (Haug et al. 2001, 2003) and were detected by high-resolution palynology (Aragón-Moreno et al. 2018a). In this chapter, we focus on fossil pollen as a proxy for paleoecological and paleoclimatological reconstruction. We also present a geospatial model of precipitation and vegetation change of the Yucatán Peninsula covering the last 1700 years.

Present Climate

Present climate conditions are complex due to the geography of the region. The ITCZ defines two main seasons of the southern Mexico: a rainy season between May and November and a dry season between December and April (Vela-Peláez et al. 2018). Seasonality is strong and the dry season can extend to May. For the Yucatán Peninsula and areas under the influence of the Gulf region, cold arctic air incursion between December and March is known. Those polar continental air masses can provide an additional amount of precipitation during the winter months (Islebe et al. 2015a). The amounts of precipitation vary enormously in southern and southeastern Mexico. In the Yucatán Peninsula, the annual precipitation ranges from

500 to 1600 mm, along a north-south gradient. An east-to-west gradient of the Yucatán Peninsula shows that precipitation along the coast of the Gulf of Mexico is around 600–800 mm annually, while the precipitation along the Caribbean is higher due to influence of the jet streams (Muñoz et al. 2008). Most of the precipitation falls during summer and autumn. The main sources of humidity are the westerlies and the Caribbean low-level jet (CLLJ; Aragón-Moreno et al. 2018a). Mean annual precipitation in Tabasco is between 1000 and 2000 mm (Gama et al. 2011), and climate of this part is mainly driven by conditions of the Gulf of Mexico. The state of Chiapas presents a complex precipitation regime, as the orographic factors play an important role in the central highlands. Mean annual precipitation ranges from 600 mm along the drier Pacific coast to more than 3000 mm in the high-central mountain ranges and some parts of the Lacandon area (Román-Cuesta et al. 2004). Mean annual temperature in the Yucatán Peninsula varies between 24 and 26 °C, and similar values are recorded for the Tabasco and the low-lying parts of Chiapas. Mean annual temperature of Pacific coastal Chiapas is around 25 °C, while at elevations above 3000 m, mean annual temperature drops below 10 °C. An important climatic factor in south and southeastern Mexico is the El Niño-Southern Oscillation (ENSO). During El Niño periods, the amount of precipitation decreases strongly between June and August in the Yucatán Peninsula and along the Pacific coast of Chiapas (Aragón-Moreno et al. 2018a). It is estimated that the precipitation decreases by 30 and 50% during El Niño years in the region (Mendoza et al. 2007; O'Hara and Metcalfe 1995). A stronger North Atlantic high-pressure center during the winter causes stronger trade winds, and it causes cool sea surface temperatures in the tropical Atlantic. The cooler SSTs in the Caribbean Sea reduce the amounts of spring precipitation. Additionally, south and southeastern Mexico is affected by hurricanes formed in the Pacific Ocean as well as in the Caribbean Sea between June and November (Sánchez-Sánchez et al. 2015).

Holocene Paleoecology

The climate drivers are diverse, and climate of this geographical area is under the influence of the ITCZ (Brenner et al. 2002a), ENSO, North Atlantic high, and change in insolation (Douglas et al. 2015; Hodell et al. 2001). The early postglacial climatic conditions are still not well understood, but the available research indicates establishment of present-day potential vegetation types at around 9000 cal year BP. The late Pleistocene environmental history was reconstructed from several sediment cores of the Lake Pet*é*n-Itzá located in the lowland Guatemala (Correa-Metrio et al. 2012; Hodell et al. 2008). Few paleoecological records date back until the Early Holocene, and they are available from the coastal Chiapas and the Yucatán Peninsula. The Middle Holocene was generally characterized by conditions of increased humidity in Mexico and Central America. Evidences came from cores collected from the highland as well as lowland lacustrine cores (Marchant et al. 2009). The Middle Holocene was also relevant as humans started influencing the natural environment and became a major driver of the ecological change (Leyden 2002). The Late Holocene was reconstructed in several studies using different proxies in the southern Mexico (Table 10.1). All these proxy records, generally, have a common trend toward drying conditions and a decrease in precipitation. Humans played a major role in the landscape transformation, and many scholarly discussions analyzed this topic from a variety of disciplines (Gunn et al. 2017; Lentz et al. 2015).

Early Holocene (10–7 ka BP)

The Early Holocene is not well represented in paleoecological records of the southern Mexico. From the Lake Petén-Itzá in the lowland Guatemala, the palynological analysis of Leyden (1984), Hodell et al. (2008), and Islebe et al. (1996) provided some clues to environmental conditions of the Early Holocene. Increased humidity and temperature allowed geographical expansion of the tropical forest species, and

Table 10.1 Paleoecological studies from southeastern Mexico focused on Middle to Late Holocene. The sites marked with an asterisk are included in the geospatial modeling

Site, state	Proxy	Reference
Rio Hondo, Quintana Roo	Pollen, geochemistry	Aragón-Moreno et al. (2018a)
El Palmar, Quintana Roo*	Pollen	Torrescano-Valle and Islebe (2012)
Lake Cobá, Quintana Roo	Pollen	Leyden (2002), Leyden et al. (1998)
Puerto Morelos, Quintana Roo*	Pollen	Islebe and Sánchez (2002)
Lakes, Quintana Roo*	Pollen, modeling	Carrillo-Bastos et al. (2010)
Ría Lagartos, Yucatán*	Pollen	Aragón-Moreno et al. (2018b), Aragón-Moreno et al. (2012)
Ría Lagartos, Yucatán*	Pollen, modeling	Carrillo-Bastos et al. (2013)
Lake Silvituc, Campeche*	Pollen	Torrescano-Valle and Islebe (2015)
Lake Silvituc, Campeche	Pollen, modern analogues	Vela-Peláez et al. (2018)
Los Petenes, Campeche	Pollen, geochemistry	Gutiérrez-Ayala et al. (2012), Roy et al. (2017)
El Triunfo Reserve, Chiapas	Pollen	Joo-Chang et al. (2015)
Lagunas de Montebello, Chiapas	Pollen	Franco-Gaviria et al. (2018)
Lake Najá, Chiapas	Pollen	Domínguez-Vázquez and Islebe (2008)
Yucatán Peninsula	Pollen rain vegetation	Islebe et al. (2001) Correa-Metrio et al. (2011), Escarraga-Paredes et al. (2014)
Chiapas	Pollen rain vegetation	Domínguez-Vázquez et al. (2004)

it resulted in development of the tropical forest. The main pollen taxa indicate development of the Moraceae and *Brosimum* in those tropical forests (Islebe et al. 1996; Leyden 1984). The Early Holocene records from the Quintana Roo (Carrillo-Bastos et al. 2010) do not provide insight about the forest development. Tropical forest taxa in general were higher during the Early Holocene compared to the Middle and Late Holocene.

Middle Holocene and Late Holocene (Last 7 ka)

The Middle Holocene and Late Holocene are characterized by several studies using different approaches and proxies. Response to the 4.2 ka event was identified in the mangrove sediments of the Yucatán Peninsula (Aragón-Moreno et al. 2018a), and it demarcated the initiation of recently defined Meghalayan Stage/Age by Walker et al. (2019). This climate anomaly caused disruption of the westerlies and Asian Summer Monsoon. Disruption of the westerlies had a strong influence on precipitation distribution along the eastern Yucatán Peninsula.

Joo-Chang et al. (2015) presented a palynological study from an extensive mangrove area in the Pacific coast of Chiapas. The area was dominated by *Rhizophora mangle* stands in a mosaic of mangrove vegetation with *Avicennia germinans* and *Laguncularia racemosa*. These mangrove species responded to a decadal-/centennial-scale ITCZ variability, as well as to the coupling of ITCZ and ENSO. Increased ENSO activity from 3500 cal year BP to 2400 cal year BP resulted in higher *Rhizophora mangle* representation, with a sudden drop at 2400 cal year BP (Joo-Chang et al. 2015). Similar environmental changes were observed in different areas of the tropical North Atlantic, e.g., in the Bahamas and Haiti, pointing to a common climatic driving mechanism (Higuera-Gundy et al. 1999; van Hengstum et al. 2018).

A highland pollen record from Chiapas covers the Late Holocene (Franco-Gaviria et al. 2018). Like other records, this pollen record also showed climate conditions changed toward increasing drying trend. Moist oak-dominated montane forests increased after 600 cal year BP. Domínguez-Vázquez and Islebe (2008) presented a pollen record from the Lacandon area in Chiapas. A protracted drought was identified between 1200 and 700 cal year BP, while taxa from moist montane forests increased from 700 cal year BP onward. Pine forests dominated the landscape during the drought intervals, while the montane forest taxa increased their presence during the wetter phases.

Several studies reported the Middle Holocene paleoecology of the Yucatán Peninsula. All those studies observed evidence of drier environmental conditions around 5000 cal year BP, which in turn reflected in the changing tropical forest taxa composition and their diversity (Aragón-Moreno et al. 2018a; Carrillo-Bastos et al. 2010). The tropical forest taxa, mainly Leguminosae and Moraceae, decreased, and pollen of disturbance taxa increased, e. g., Poaceae, Asteraceae, and Malvaceae. Similar conditions of drying trends were found at 5000 cal year BP at Lake Puerto

Arturo of Guatemala (Wahl et al. 2014). A paleoecological study from the Lake Silvituc, southern Yucatán Peninsula, showed the response of vegetation to different drivers like climate and human-induced changes (Torrescano-Valle and Islebe 2015). Vegetation near the watershed changed from a closed to an open vegetation type, with characteristic taxa of disturbed or secondary conditions like Poaceae, Asteraceae, and other herbs. However, the local vegetation reacted to regional variability of precipitation as the near-shore plant communities changed, and specific aquatic taxa appeared, e.g., *Typha* and *Nymphaea*. The sediments of Lake Silvituc is one of the few available paleoecological records showing the influence of volcanic activity in this region. The detected tephra were related to volcanic eruptions of the El Chichón volcano (Nooren et al. 2016).

A Geospatial Approach to Understand Late Holocene Vegetation Change of the Yucatán Peninsula

One of the major points of interest is the understanding of geographical extension of the drought which affected the Late Holocene vegetation distribution. Under this view, we chose several pollen records with adequate chronology to develop a geospatial model (Table 10.1). All the radiocarbon dates were calibrated, and the vegetation maps were built with the ArcGIS 9.3 extension applying ILP (polynomial interpolation technique). The ILP follows a deterministic approach, and it uses values measured at different points inside an area to create a continuous surface (Wadsworth and Treweek 1999). We used the methodology detailed in Carrillo-Bastos et al. (Carrillo-Bastos et al. 2012) and chose local interpolation for polynomials because this does not imply normal distribution of the data and the predictive errors were smaller. The prediction was carried out with a power function of (p) = 2 and under the option of search for the ideal influence for each distance (IDD). These parameters produced surfaces with a smaller prediction error. Extrapolations were calculated to the rest of studied geographical areas and graphed in Fig. 10.2. The thematic layers were added after the paleo-vegetation reconstruction was developed at different chronological sequences. In this case, the geographical distribution of dry tropical forest and present-day mean annual precipitation changes were added to the geospatial modeling. Considering the available chronologies and information about paleo-vegetation changes, the thematic paleo-precipitation maps were reconstructed for the intervals of every 100 years, starting at 1 AD until 1700 AD (Figs. 10.2 and 10.3). The blue-green colors indicate higher reconstructed precipitation levels and the yellow-brownish colors indicate lower precipitation levels. For different time intervals, the information about the change in precipitation compared to the present-day precipitation levels can be drawn. Drier conditions were observed between 200 and 300 AD in the southern and northern Yucatán Peninsula. Drier conditions during this interval were also inferred from a beach ridge, and diatom record was obtained from the Tabasco state (Nooren et al. 2018). This dry interval

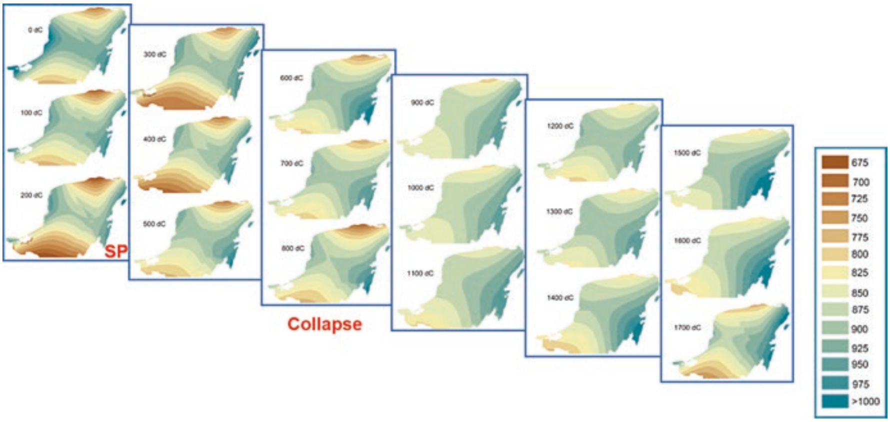

Fig. 10.2 Precipitation reconstruction for the interval 1–1700 AD. Modeled precipitation values are expressed in mm (SP = Late Preclassic drought)

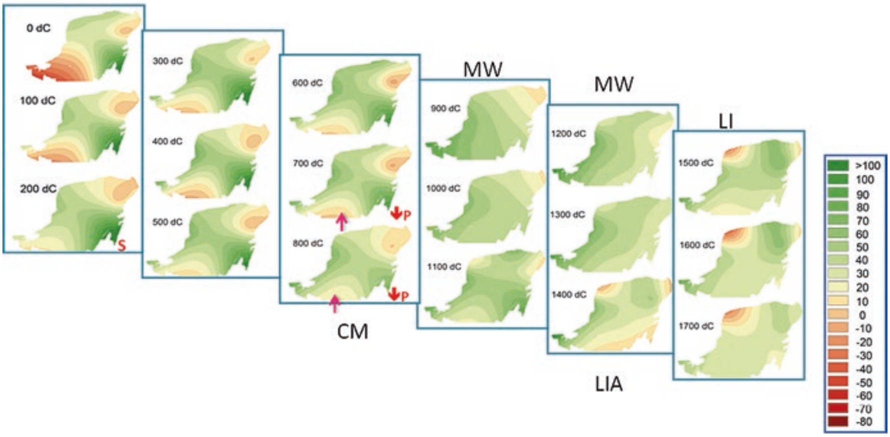

Fig. 10.3 Tropical forest cover reconstruction for the interval 1–1700 AD (CMD Classic Maya drought, MWP Medieval Warm Period, LIA Little Ice Age, P precipitation)

falls within the Late Preclassic drought (Ebert et al. 2017). Many Maya cities were abandoned during this arid period. The reduction in precipitation during the Late Preclassic drought was estimated between 25 and 35% compared to present-day precipitation values. Other recent modeling estimated a reduction of 31% of mean annual precipitation. The regional precipitation values increased between 500 and 700 AD. After 800 AD and within the period of Maya classic droughts, the precipitation reduced, and the southern Yucatán Peninsula received mean annual precipitation between 725 and 850 mm. The general precipitation reduction compared to present precipitation values was at least 20–40% between the Preclassic and Classic periods. The reduction in mean annual precipitation was less pronounced compared to values of the Late Preclassic drought. The following Medieval Warm Period (MWP; 1000–1200 AD) received generally more precipitation compared to the Classic Maya droughts. The Little Ice Age was characterized again by reduced precipitation in the southern, western, and northern Yucatán Peninsula. The eastern part of the Yucatán Peninsula, however, seemed to be less affected by climate conditions of the Little Ice Age.

Figure 10.3 summarizes the paleo-vegetation changes between 1 and 1700 AD. The green to dark red color scales indicate openness of the tropical forest. The past and present tropical forest distributions have been related to mean annual precipitation. Tropical forest conditions were different around 1 AD, presenting a match with a drought period, and it was also detected in the recent modeling of past vegetation (Vela-Peláez et al. 2018). The southwestern and northeastern Yucatán Peninsula vegetations were the most affected, and the open dry forest was the dominant vegetation. During the Late Preclassic drought, the dominant forests in the south and northwest were sub-deciduous forest types with Fabaceae pollen taxa. Vegetation composition in the south, central, and northern peninsula during the Classic Maya droughts was the dry forest types. However, this data modeling did not observe complete regional deforestation in the 100-year time windows. However, the densely populated parts of the southern part of the Yucatán Peninsula and Guatemala, most likely, had some local deforestation. These changes in forest composition were not only driven by climate but also by change in landscape induced by the ancient Maya culture (Islebe et al. 2018). Between 900 and 1100 AD, the forest cover increased on eastern side of the Yucatán Peninsula. Relatively fast forest recovery was also observed at Lake Petén-Itzá during this interval (Mueller et al. 2010). The forests recovered in 80-year period. Projection in the eastern side of the Yucatán Peninsula indicated less affectation in the paleo-vegetation map, suggesting sufficient moisture availability for the tropical forests in this part of the peninsula.

Outlook

The ITCZ, NAO, and ENSO were the main drivers of the Holocene ecological changes in the southern and southeastern Mexico. The southward shift of the ITCZ was related to decreased precipitation in the Yucatán Peninsula, and this was driven by changes in insolation (Haug et al. 2001; Steinhilber et al. 2009). Vegetation responded to those changes at decadal/centennial and millennial scales (Aragón-Moreno et al. 2018a). Response to those changes was evidenced in the pollen spectra recorded on local and regional scales, and it reflected changes in plant communities and exhibited their resilience. Higher precipitation during the Early Holocene was provided by increased jet stream activity and establishment of the CLLJ (Caribbean low-level jet) (Pollock et al. 2016). The geospatial approach of understanding past precipitation and forest distribution also helped to decipher causal changes of landscape, namely, the climate-driven versus human-induced land use changes and the response of vegetation to these changes. This approach needs additional paleoecological data and robust chronological control to define specific areas that probably changed under a variable precipitation scenario. The geospatial approach also helped to understand changes in forest distribution at specific ecotones, e.g., the change from deciduous to sub-deciduous dry forest and wetland to forest transitions, which under past climate conditions responded quickly in species turnover.

Major vegetation change of the Holocene in southern Mexico was recorded during 5500–4000 cal year BP, 3500–2000 cal year BP, and protracted droughts of the Maya Terminal Classic Period (Carrillo-Bastos et al. 2013). Also the intervals of increased precipitation were considered as a driver of vegetation change. The driest period in the southern Yucatán Peninsula was constrained at 2600 cal year BP, and the pollen records indicated a clear decrease in forest type and cover. The forest recovery was observed on a decadal and centennial scale of nearly 80 years. Estimates of precipitation reduction during the Terminal Classic are variable. They were around 50% (Evans et al. 2018) based on the isotope values and ranged up to 35% based on the pollen modern analogues (Vela-Peláez et al. 2018). However, the estimates of precipitation must consider the geographical coverage, as precipitations in southern Mexico and the Caribbean are at present highly variable.

Southern Mexico covers a large biodiverse region, and most of the paleoecological studies were carried out in tropical forests, mangrove ecosystems, and several highland lakes. Additional sediment cores with adequate dating control are required to obtain a complete picture of past vegetation dynamics and climate variability in this region.

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