

Spatial and temporal distribution of palaeoclimatic records in the Maya Area

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ABSTRACT

Palaeoclimatic research has been performed in the Maya Area (MA), using mainly lake sediment cores and speleothems. Most of the studies have been performed in the lowlands, leaving the highlands unexplored. Lake sediments records contain a diversity of proxies (e.g. Mineralogy, isotopes, pollen, charcoal, diatoms, chemicals, magnetic susceptibility, among others) and temporal resolution, making them frequently not easy to compare and leaving numerous gaps of information. Practically all stalagmites are focused on using $\delta^{18}\text{O}$ as a proxy of effective rainfall during the Maya periods, having only some explored the role of palaeostorms and hurricanes as well as the paleoclimatology of the pre-Maya and modern periods. In this review paper, the location and temporal frame of palaeoenvironmental records of the MA and their proxies are presented, showing the zones and periods that possess environmental information and assessing their resolution. The comparison shows that more high-resolution records with a multi-proxy approach covering most of the Holocene are needed to understand the climate change in different zones of the MA. Finally, the geographic distribution of the diverse recorded hydroclimate responses based on the records is presented for three critical moments in the Maya History that have been associated with dry periods in the Great Maya Droughts hypothesis. This geographic perspective shows that dry events were not presented in all the MA during these moments although they were vastly recorded in both high- and lowlands. The geographic perspective also shows a negligible drought effect in the central lowlands for the Maya Hiatus period, where this cultural phenomenon was identified first. But signals of droughts are presented in other zones of the MA for this period. The distribution of the drought signal also shows that sites that thrived during the Maya Collapse period were in the regions that suffered the strongest droughts, whilst many sites that were abandoned were in regions rich in hydric resources. Explanations are reviewed for these contradictions. Finally, the works towards the development of mathematical models of the environmental variables are briefly reviewed, pointing out the lack of a proper computational model that has been fed by the palaeoclimatic data developed by the records in the MA.

Keywords: Palaeoclimatic-records; Maya-Cultural-Area; Maya-Collapse; Lake-cores; speleothems; environmental-proxies.

RESUMEN

La investigación paleoclimática se ha llevado en el Área Maya (AM), con el uso de espeleotemas y sedimentos lacustres principalmente. La mayoría de los estudios han sido conducidos en las tierras bajas, dejando el altiplano inexplorado. Los registros de sedimentos lacustres contienen una diversidad de indicadores (mineralogía, isótopos, polen, carbón vegetal, diatomeas, entes químicos, susceptibilidad magnética, etc.) y una resolución temporal que frecuentemente no permite su fácil comparación y deja cuantiosos espacios vacíos de información. Prácticamente todas las stalagmitas se enfocan en usar el $\delta^{18}\text{O}$ como indicador de lluvia efectiva durante los periodos mayas. Solo algunas espeleotemas han explorado el papel de las tormentas y los huracanes, así como la paleoclimatología de los periodos pre-Maya y modernos. En este artículo de revisión se presentan los marcos temporales y espaciales de los registros paleoambientales del AM al igual que sus indicadores. Así se evalúan las zonas geográficas y los periodos que cuentan con información paleoambiental, así como la resolución de ésta. La comparación muestra que más registros de alta resolución con un enfoque que utilice varios indicadores cubriendo la totalidad del Holoceno es necesaria para entender el cambio climático en las diferentes zonas del AM. Finalmente, la distribución geográfica de las diversas respuestas hidroclimáticas grabadas en los registros es presentada para tres momentos críticos de la historia maya que han sido asociados con periodos secos en la hipótesis de las grandes sequías mayas. Esta perspectiva geográfica muestra que las sequías no estuvieron presentes en toda el AM, sin embargo fueron registradas en la mayoría de las áreas tanto en las tierras bajas como en el altiplano Maya. La perspectiva geográfica también muestra un efecto de sequía insignificante en las tierras bajas centrales durante el período de Hiato Maya, donde este fenómeno cultural se identificó por primera vez. Sin embargo, se presentan señales de sequía en otras zonas del AM para este periodo. La distribución de la señal de sequía también muestra que los sitios que prosperaron durante el periodo de Colapso Maya estaban en las regiones que sufrieron las sequías más fuertes, mientras que muchos sitios que fueron abandonados estaban en regiones ricas en recursos hídricos. Se revisan las explicaciones a estas contradicciones. Finalmente, se revisan brevemente los trabajos hacia el desarrollo de modelos

matemáticos de las variables ambientales, y se señala la falta de un modelo computacional adecuado que se haya alimentado de los datos paleoclimáticos desarrollados por los registros del AM.

Palabras clave: registros paleoclimáticos; área Maya; colapso Maya; núcleos lacustres; espeleotemas; indicadores ambientales.

INTRODUCTION

Palaeoenvironmental studies across the Maya Area (MA) have been performed mostly to know the natural environmental changes (including climate) and the human impact on the environment across centuries, as well as to study the natural agents that might have driven and modulated the development of the Maya civilisation. Since the appearance of processual archaeology in the 1970's, environmental reconstruction studies have also been considered part of the archaeology work (Sabloff, 1994). On this wise, archeobotany, zooarchaeology, sedimentology and soil science started to be routine studies in the Maya archaeological research (Sabloff, 1994). The findings in this research fields (bones, plants, combustion features, etc.) are seen as cultural material for contextualizing human behaviour, even though they potentially can give information about paleoclimates. Because of this and their low ability for tracing sub-centennial climate changes, the link between archaeological research and palaeoclimatic studies were still scarce in the MA.

The first attempt to analyse the climate change was made by Cowgill *et al.*, (1966) in Petenxil Lake, Guatemala, using pollen as a proxy. Since then, until January 2022, 82 Holocene records have been produced across the MA, including lake cores, speleothems, corals, tree rings, and cave sediments. During the 1960's, 70's and 80's, the purpose of palaeoclimatic reconstruction was to clarify the context where the Maya lived, which meant mainly to know what kind of vegetation and crops existed during the Maya History, since this knowledge was barely covered by the recently decoded ancient Maya texts (Demarest, 1976; Grube *et al.*, 2012; Johnson, 2013).

In those years, a detailed palynological and geochemical examination was carried out on sediment cores obtained from several sites in the Peten district in Guatemala, as a part of the Central Peten Historical Ecology Project (CPHEP) (Deevey, 1977; Deevey *et al.*, 1979; Vaughan *et al.*, 1985; Wiseman, 1985). Since the inception of the CPHEP, other studies have looked at the regional vegetation history using pollen in Quexil (Leyden, 1984; Rice and Rice, 1984; Rice *et al.*, 1983; Vaughan *et al.*, 1985), Salpeten (Brenner *et al.*, 2002a, 2002b), Macanche, Yaxha (Rice *et al.*, 1983), and Sacnab (Rice *et al.*, 1983; Vaughan *et al.*, 1985), covering the complete Holocene. Most of these studies had centennial or multi-decadal resolution and were dated by uncalibrated radiocarbon (Brenner *et al.*, 2002c).

The inflexion point in palaeoclimatic studies was the publication of the Great Maya Droughts (Gill, 2000). Gill (2000) proposed a series of recurrent droughts in the MA and other Mesoamerican areas as events that triggered, enhanced or played a role during various socio-political changes in the Mesoamerican history. For the MA, he proposed that strong droughts were present during the socio-political changes suffered during the Maya Abandonment (1800 BP to 1750 BP) when settlements from the Gulf coast to the Pacific coast were emptied; the Maya Hiatus (1414 BP to 1360 BP) when a demographic collapse and halting construction were observed mainly in the central lowlands; and the Maya Collapse (1190 to 1140 BP) when a massive reconfiguration of the politics and migration occurred. In this paper, the time frames for the Maya Abandonment and the Maya Hiatus proposed by Gill (2000) are used, whilst the period established for the Maya Collapse is based on Grube *et al.*, (2012) and

Douglas *et al.*, (2016b), who argued that the collapse started 50 years before the first massive drought at 1140 BP inferred by Gill (2000). It has to be highlighted that the first drought during the collapse has been observed around 740 BP in some palaeorecords (Evans *et al.*, 2018; Webster *et al.*, 2007). Gill (2000) based his hypothesis mainly on the findings of the sediments of Lake Chichancanab where layers of gypsum were indicative of strong droughts during the time of the collapse (Hodell *et al.*, 1995, 2005a).

Since the last decades of the XX century, the improvements in analytical techniques allowed a better resolution in the palaeolimnological records. In particular, the advent of new detectors in ICP-QMS and XRF equipment, with its improved precision and smaller sample sizes, began a new era in palaeoclimatology in general (Bernal *et al.*, 2010), *e.g.* isotopic analysis on *P. coronatus* in Chichancanab and the sinkhole Aguada X'Caamal in the Yucatan Peninsula, (Mayab) used these improvements (Hodell *et al.*, 1995, 2005a). Oxygen and carbon isotopes ratios had been barely used before during the XX century (*e.g.* Covich and Stuiver, 1974).

In addition, these improvements found their counterparts in geochronology; when the advent of the Accelerator Mass Spectrometry, AMS allowed a smaller amount of sample for radiocarbon dating. In addition, U-series became a reliable dating method for many carbonates (or evaporites) samples of Quaternary age with unprecedented minor uncertainties (Andersen *et al.*, 2004; Bernal *et al.*, 2006; Mortimer *et al.*, 2002). To date, the U-series method has just been applied to speleothems in the case of the MA.

A remarkable case is the research on the lake Peten Itza which has been studied mainly in this century, developing one of the most complete multi proxy records (Bush *et al.*, 2009; Correa-Metrio *et al.*, 2012; Curtis *et al.*, 1998; Escobar *et al.*, 2012; Hillesheim *et al.*, 2005; Hodell *et al.*, 2008; Mueller *et al.*, 2009; Pérez *et al.*, 2011, 2013; Schüpbach *et al.*, 2015).

This paper presents a summary of 82 Holocene palaeoenvironmental studies performed in the MA until January 2023. I reviewed the published research mainly in English and Spanish. The purpose is to present the spatial and temporal distribution of the palaeoenvironmental records and their proxies in the MA. In this way, this geographic perspective allows us to highlight periods, areas, and proxies which study needs to be strengthened. In addition, I assess which records have a high resolution in their proxies as well as summarise the dating methods applied. Finally, I present a spatial distribution of the records that support or undermine the presence of environmental events, linked to droughts, during critical moments of Maya History such as the Maya Abandonment (1800 BP to 1750 BP), the Maya Hiatus (1414 BP to 1360 BP), and the Maya Collapse (1190 to 1140 BP). The aim of this work is to contribute to a spatial and temporal perspective of the palaeoclimatic research and their major results developed in the MA for the Holocene and in particular to the three critical historical Maya moments in terms of the presence or absence of droughts, presenting a complete picture of the diversity of the results, as is suggested by Beach *et al.*, (2015) and Marchant *et al.*, (2004). This paper does not explain the drivers and processes of the diversity of results, since the complexity of such an argument would require the collaboration of people of different research-subjects and the support of computational models like the ones creates in PHYDA (Baek *et al.*, 2019; Steiger *et al.*, 2018; Tejedor *et al.*, 2021a, 2021b), otherwise the argument would be mainly speculative. However, to put major results from a geographical perspective during a specific time frame is the first step towards a computational model.

Finally, this work expects to help in planning a better approach for future research, focusing on regional questions that may contribute to the general MA perspective, since financial and time resources are usually constrained.

TYPES OF PALAEOCLIMATIC RECORDS IN THE MA

The studies presented here are often linked to climate changes during the Holocene. The kind of palaeoclimatic records used in the MA are

- Lake records, which are based on sediment cores.
- Speleothems, which are sedimentary deposits of secondary carbonates developed in caves due to the changes of pressure of CO₂ infiltrating water, creating stalagmites, stalactites among other formations.
- Cave sediment records, which are sediments deposited inside a cave and due to the characteristic of caves, are less susceptible to weathering and diagenesis than sediments in open areas.
- Tree rings which are formed in the trunk according to the seasonal environmental changes of temperature or humidity.
- Seasonal Swamp records, which are similar to the lake sediments, are based on cores taken from seasonal swamps or wetland inland environments. Because their formation differs from lake records and their sampling can also be different from them, they are classified apart.
- Corals, which are marine animals living in colonies and developing hard skeletons annually.

Every kind of record, or archive, can potentially be studied using a set of palaeoenvironmental proxies such as pollen, the elemental, ionic and molecular chemical composition (including pigments), mineral composition, textural composition, charcoal content, the kind and amount of microfauna, diatoms, the isotopic composition such as $\delta^{18}\text{O}$ of bulk carbonates or the $\delta^{18}\text{O}$ of exoskeleton of a particular taxon, density changes, magnetic susceptibility (μ) and the colour or light response (e.g. reflectance) of the record. It has to be highlighted that the same proxy in two different places can indicate different phenomena depending on the context. Sometimes it could indicate different phenomena in the same place if the environmental conditions changed drastically (e.g. Mills *et al.*, 2017), as in the isotope record from Sinkhole Aguada X'Caamal (Hodell *et al.*, 2005a).

Bhattacharya *et al.*, (2017); Bhattacharya and Coats (2020); Harvey *et al.*, (2021); Lozano *et al.*, (2015); Metcalfe *et al.*, (2000, 2015) have presented a spatial distribution of the Holocene palaeoclimatic records in Mexican Mesoamerica and Central America, including some records of the MA. In Figure 1, I have taken their work much further, showing the spatial distribution of the 82 different Holocene records in the MA. Some records on the Pacific Coast and the Gulf of Mexico are in mangrove zones. Therefore, they are classified as permanent swamps, e.g. site Cerritos 2 in the La Encrucijada Biosphere Reserve (Joo-Chang *et al.*, 2015), Manchon (Neff *et al.*, 2006), Los Petenes (Gutiérrez-Ayala *et al.*, 2012); however, due to their characteristics related to palustrine environments, I classified them as lake sediment cores instead of wetlands.

In the case of the seasonal wetlands, the Cobweb Swamp records in Belize were developed in areas inside artificial channels developed by the Maya (Jones, 1994), which are dry today, while the records at Akab Muclil and Cob are wetlands in flood plains (Kylander *et al.*, 2012; Pohl *et al.*, 1996). A similar case happens in records obtained from sediments deposited in artificial reservoirs for keeping water (chultunes) in Aguada Mucal and adjacent reservoirs (Lentz *et al.*, 2022). In addition, records at El Infierno (Castanet *et al.*, 2022), El Laberinto and El Ramonal adjacent to Calakmul were developed from sediments (colluvium) deposited in seasonal swamps (Gunn *et al.*, 2002).

The lakes Atitlan (Newhall *et al.*, 1987) (not to be confused with Lake Amatitlán), Ayarza (Poppe *et al.*, 1985) and Petexbatum (Dunning *et al.*, 1997) (Figure 1 black circles) were sites where palaeoclimatic

studies were intended. However, the presence of inverted radiocarbon dates and indecipherable stratigraphy prevents a reliable chronology. However, I present these failed records since they help us understand the lack of palaeoenvironmental records in these areas.

Fourteen records were developed using speleothems (Akers *et al.*, 2016, 2019; Kennett *et al.*, 2012; Frappier *et al.*, 2002, 2007, 2014; Medina-Elizalde and Rohling 2012; Medina-Elizalde *et al.*, 2016a,b; Pollock *et al.*, 2016; Ridley 2014; Ridley *et al.*, 2015; Serrato Marks *et al.*, 2021; Smyth *et al.*, 2011, 2017; Warken *et al.*, 2021; Webster *et al.*, 2007; Wiseman 1985), in two occasions, two speleothems come from the same site, e.g. Río Secreto (Medina-Elizalde *et al.*, 2016b; Serrato Marks *et al.*, 2021) and Yok Balum, (Kennett *et al.*, 2012; Lechleitner *et al.*, 2015) but covering different periods.

Tree rings (Anchukaitis *et al.*, 2013), corals (Gischler *et al.*, 2008; Horta-Puga and Carriquiry, 2012) and cave sediments (Polk *et al.*, 2007) have been also developed in the area (Figure 1), but covering only recent years.

The palaeoenvironmental records developed in the MA are compared to the location of the Maya archaeological sites (Figure 1 white triangles). It can be observed that most of the palaeoclimatic studies have been performed in zones of high-density archaeological sites, e.g. the Peten region, the Lamanai region and the Riviera Maya. However, there are high-density regions of archaeological sites with small numbers of palaeoclimatic studies, such as the Comitán region in the Northern Maya Highlands, the Puuc and Chenes regions in the Mayab and the area of the north coast of the Mayab. It has to be highlighted the distribution of archaeological sites, which are mostly near of water bodies, including sinkholes.

Regions with a low density of archaeological sites tend to have small number of paleoclimatic records. These regions are the flood plains in Tabasco, the centre of the Northern Maya Lowlands (the Coahuah Region), the Southern Maya Lowlands, and the Southern Maya Highlands. For instance, the Lake Kail record in the highlands suggests that effective rainfall increasing trend at the Millennial scale have an opposite tendency compared to the lowlands (Stansell *et al.*, 2020). After comparing the nearest Rey Marcos record (a speleothem), which indicates a trend to less meteoric rainfall, it is inferred from Lake Kail less evaporation in the highlands. This tendency needs to be confirmed in other lakes of the highlands. The lack of studies in the Maya part of El Salvador and Honduras is probably due to the political situations in these countries since the Cold War period, however archaeological research in contrast has been conducted even in war zones in Guatemala (Webster 2002), so the lack of studies there might be for unknown reasons beyond politics.

It has to be highlighted that the archaeological sites do not necessarily reflect the distribution of the Maya settlements since undiscovered sites may exist. In addition, the Maya settlements, were not equally populated, and most of them were just populated during a particular period. In this way, most Maya settlements were located in the Highlands and Southern Lowlands during the Preclassic period, in the Central Lowlands (including the Peten Region) during the Classic period, and in the Northern Lowlands (practically all the Mayab) during the Postclassic period (Sharer and Traxler 2005).

Lake sediments are well distributed in all the regions where paleoclimatic research has been carried out. However, many studies are concentrated in the Peten region (Central Lowlands) of northern Guatemala, probably due to a large number of lakes in that region and the existence of the CPHEP (Figure 1).

Finally, it has to be highlighted that soils as palaeoclimatic records are not the subject of this paper due to their frequently lack of decadal or centennial resolution and the superimposition of weathering signals on the original climatic ones (Targulian and Goryachkin 2004), which

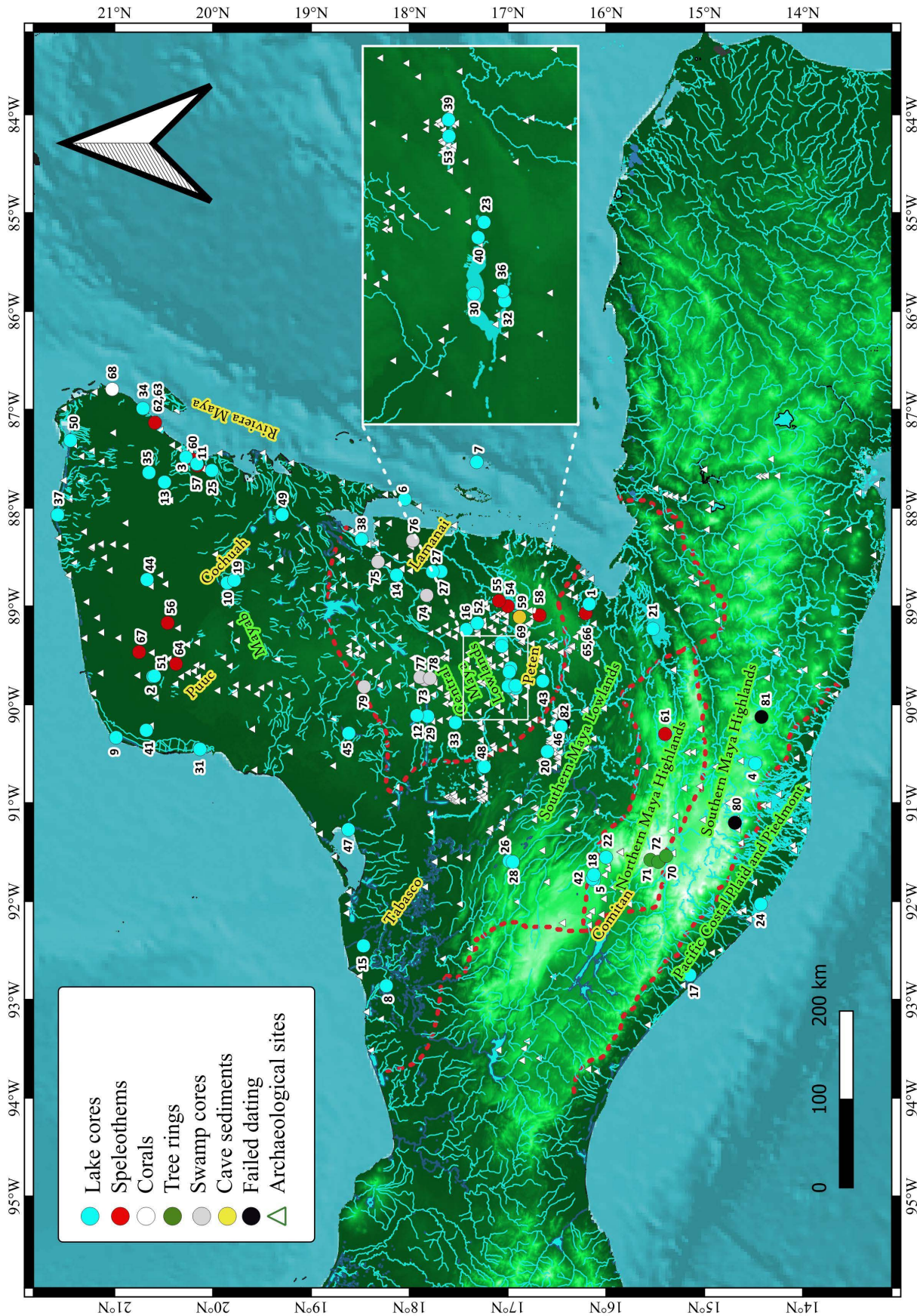


Figure 1. Palaeoenvironmental records in the Maya Area (MA) for the Holocene. The colour indicates the kind of record; lake sediment cores, speleothems, tree rings, swamp or wetland sediment cores and cave sediments. The map also shows the sites where efforts to develop a palaeoclimatic record failed. Records with a resolution better than 20 years are indicated (+). The numbers indicate the name of the studied site listed in Tables 1 to 4. Red dotted lines indicate the borders between subareas inside the MA proposed by Sharer and Traxler, (2005). The location of archaeological sites is based on Ford *et al.*, (2009). Map produced using QuantumGIS 3.28.4. An alternative Figure is presenting using the archaeological sites compiled by Witschey and Brown, (2010). An alternative Figure s1 (Supplementary Material) is presenting using the archaeological sites compiled by Witschey and Brown, (2010).

made them bad candidates for tracing climatic changes that occurred for some decades such as the droughts proposed for Mesoamerica. However, soils have contributed to giving clues about the resilience of some regions to the droughts as well as to suggest an alternative explanation to the Maya Collapse; the over exploitation of the soil with intensive agriculture, which was proposed in early years by Cook (1921), Cooke (1931) and Morley (1946).

Soil science works have been established that agriculture was intense in the Central Lowlands, depositing massive amounts of inorganic sediments into the lakes (Anselmetti *et al.*, 2007; Mueller *et al.*, 2010). This inorganic sediment called the Maya Clay is a ubiquitous multiphase anthropogenic induced colluvium in the Peten lakes: Tuspan; Quexil; Sacnab; Petenxil; and Peten Itza (Vaughan *et al.*, 1985) and in the wetlands in the Central Lowlands, *e.g.* at Los Bajos (Dunning *et al.*, 2002). The Maya Clay has been claimed as a stratigraphic marker of the Mayacene, an early Anthropocene analogue in the region (Beach *et al.*, 2015). Soil degradation also has been observed in some parts of the Southern Maya Lowlands (Faust, 2001) and the Mayab (Sedov *et al.*, 2007). In some sites, some degree of soil degradation has been observed (Beach *et al.*, 2006), whilst in other sites, it has been observed that the Maya were aware of the degradation and attempted to stop it (Dunning *et al.*, 1998).

Soil research has also traced changes in vegetation and the humid regime in regions with small number of palaeoclimatic records such as the floodplains of Tabasco, distinguishing even between the vegetation that existed during the last phase of the pedogenesis using carbon isotopes and the one existed for the complete formation of the soil (Solís-Castillo *et al.*, 2013, 2014, 2015).

LAKE SEDIMENT RECORDS IN THE MA

Most palaeoenvironmental records have been produced using sediment cores extracted from lakes in the MA. All the lakes still have water, and no dry palaeo-lakes have been studied in the area. The Blue Hole (Gischler and Storz, 2009), a sinkhole (cenote) in the continental platform merged into the Caribbean Sea, is worthy of note due to the sedimentation process that existed there, including the inclusion of coral debris. Lake records contain a range of different proxies.

I developed a database containing these records (Table 1 and Figure 2), summarising the proxies used and the dating method. The proxies were classified into eleven categories: density; isotopes; fauna; algae (diatoms); pollen; charcoal; elemental and molecular chemical composition (including proxies of a trophic index, *e.g.* P, S and N); magnetic susceptibility (μ); in- and organic carbon content; mineral composition; and sedimentology.

All the proxies related to chemical composition were put into a single category, except for the inorganic and organic carbon content analysed by loss on ignition in most records. In this way, the elemental and molecular composition, mineralogy and proxies of the trophic index were put together in Figure 2. But mineralogy is still a category apart in Table 1. The spatial distribution of these records has been compiled (Figure 2) using the combined version of these chemical proxies.

The multiproxy approach was applied in most records (Figure 2). However, the records with isotopic composition as a proxy usually did not use pollen as proxy, making a comparison between changes in the surrounding vegetation and changes in the effective or meteoric rainfall, or water balance difficult. A relatively recent exception to this is the research of Wahl *et al.*, (2014) and Stansell *et al.*, (2020).

Most lake records were developed from actual lakes (Figure 2), while a small number of records have been taken from sinkholes with

groundwater (cenotes or aguadas), for instance Aguada X'Caamal (Hodell *et al.*, 2005a), Chumkopo (Brown *et al.*, 2014), Yaal Chac (Metcalf *et al.*, 2022) and Cenote Muyil (Sullivan *et al.*, 2022). This lack of studies on cenotes is interesting since the sinkholes play an essential role in the theory of the Maya droughts developed by Gill (2000), but it has to be considered that classic cenotes do not tend to accumulate sediments in contrast to aguadas (Guzmán, 2017; Hodell *et al.*, 2005a; Lopez-Maldonado and Berkes, 2017). This issue also reflects the fact that despite the critical role of cenotes in the ancient Mayan texts and archaeology, they are present in no more than 33 % of the MA (Perry *et al.*, 2002).

Pollen is the most commonly used proxy. Therefore, most sites have a record of vegetation changes, and it is followed by in- and organic carbon content (%C in Figure 2). Therefore, many records can indicate carbonate precipitation and productivity changes, respectively. Elemental, ionic and molecular chemical abundances are the third most used proxy.

Depending on the specific chemical entity used, these proxies usually give information about the terrigenous input into the lakes and the degree of erosion around the lake, among other properties. A special mention is the use of the molecule of stanol in the Lake Itzan used as a proxy of human impact (Keenan *et al.*, 2021) and the use of pigments as proxy of the quality of water in lake Amatitlán (Waters *et al.*, 2021). In the case of the texture as a proxy, only a number of the records are listed where the publication discusses changes in the texture, *e.g.* Encrucijada (Joo-Chang *et al.*, 2015) Laguna de Términos (Gunn *et al.*, 2012), Yaxha (Brenner 1983), Yaloch (Mueller *et al.*, 2009; Wahl *et al.*, 2013) Peten Itza (Curtis *et al.*, 1998; Mueller *et al.*, 2009, 2010) Blue Hole (Schmitt *et al.*, 2021), Muyil (Sullivan *et al.*, 2022), Izamal (Duarte *et al.*, 2021), Vista Alegre in Hollbox (Glover *et al.*, 2022) but it is possible that some records indirectly present such changes (*e.g.* describing the mineralogy) although they do not discuss them. These textural changes usually indicate changes in the source of the sediments or the energy of the flow.

Along with texture, density is a less used proxy, and this might be due to the difficulties of finding a direct environmental driver of the changes in density. The case of Chichancanab is a particular exception, where the changes in density are substantial and linked with major precipitation of evaporites (specifically gypsum), which implies the presence of dry periods (Hodell *et al.*, 2005b). The presence of gypsum in this lake studied by a multy approach (Curtis *et al.*, 1996; Douglas *et al.*, 2014; Hodell *et al.*, 2001, Aimers and Hodell, 2011) was used to infer the water level of the lake during the megadroughts presented during the Maya Collapse (Evans *et al.*, 2018).

Finally, another aspect to consider is the low number of records containing charcoal as a proxy compared to a large number of pollen records. This issue might be related to the potentially poor preservation of charcoal in hard water (Braadbaart *et al.*, 2009) present in many of the lakes in the MA (Cervantes-Martinez *et al.*, 2002; Gondwe *et al.*, 2010; Pérez-Ceballos *et al.*, 2012). However, no major challenges have been reported in the records that have used charcoal as an environmental proxy, *e.g.* the charcoal record in Basil Jones (Birmingham *et al.*, 2021). This is also supported by the charcoal preserved in the ancient hearths found in submerged caves in Aktun Ha (López-Martínez *et al.*, 2020). Where hard water effects on dates has been reported, indicating that the cave system possess hard water despite its interconnection with seawater (Gabriel *et al.*, 2009).

Lake records which environmental reconstruction could not be associated to an absolute age (Table 2) due to inverted radiocarbon dates and unclear stratigraphy (Figure 1 black circles, Figure 2 blue dots with a red x) contain pollen records and faunal assemblages. In the case of the cores extracted at Atitlan and Ayarza, the lakes are in a

Table 1. Palaeoenvironmental records based on lake sediments. The different kinds of chemicals analysed (including elements used as trophic index proxies in blue; in- and organic carbon content are excluded), fauna and algae studied, and material used for isotopic analysis is displayed. Also dating method, age model type and mean resolution of the proxy with more samples is shown. Pollen (including aquatic pollen), charcoal, density, in- and organic carbon and magnetic susceptibility analyses are excluded since this information is in Figure 4.3. The category "No Transformation" indicates the records that do not develop an age model although dated, presenting the results against depth.

Location	Isotopes	Bio-proxies	Chemicals (including Trophic index)	Mineral proxies	Reference	Dating method	Core length (cm)	Number of dates	Age model type	Dated material	Mean resolution (years)
1	Agua Caliente				Walsh <i>et al.</i> , 2014	^{14}C	123	4	Polynomial	Charcoal, single twig	121
2	Aguada X'Caamal	<i>D. stevensoni</i> $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$, <i>P. coronatus spinose</i> $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$			Hodell <i>et al.</i> , 2005a	^{14}C	413.5	10	Second-order polynomial equation	Charcoal, wood, and seeds	8
3	Aktun Ha	$\delta^{13}\text{C}_{\text{org}}$, <i>C. ilosvayi</i> $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$	Foraminifera, thecamoebians, ostracods		Gabriel <i>et al.</i> , 2009	^{14}C	61	5	No transformation	Three twigs, one shell, one charcoal	47
4	Amatitlán		N%, C/N, N/P Pigments		Velez <i>et al.</i> , 2011; Waters <i>et al.</i> , 2021	^{14}C	701	11	BACON	Charcoal	19
5	Balammetik		Diatoms	Al, Ti, Mn, and Ca, P	Caballero <i>et al.</i> , 2020	^{137}Cs , ^{210}Pb	70	3	Piecewise-linear model	Bulk sediments	1
6	Basil Jones				Birmingham <i>et al.</i> , 2021	^{14}C	350	9	Piecewise-linear model using CLAM	Plant Macrofossil	50
7	Blue Hole	Bulk sediment $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$,			Gischler <i>et al.</i> , 2008; Schmitt <i>et al.</i> , 2021	^{14}C	600	11	Piecewise-linear model	Organic residue	24
8	Cantemual		Diatoms	Si, Fe, S, Ca, Sr, Br	Nooren, 2017	^{14}C , correlation with <i>L. Cometa</i>	325	5	No applicable	Organic residue	3
9	Celestun	Organic Matter $\delta^{13}\text{C}$,	Foraminifera	C/N	Hardage <i>et al.</i> , 2021	^{14}C , ^{210}Pb	290	22	BACON	Basal peta, terrestrial micro-organics	100
10	Chichan-canab	<i>P. coronatus</i> $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ plant wax δD		Plant wax lipids, Wgt % S	Gypsum Covich and Stuiver, 1974; Curtis <i>et al.</i> , 1996; Douglas <i>et al.</i> , 2014; Hodell <i>et al.</i> , 1995, 2001, 2005a	^{14}C	260	14	Polynomial model	Wood, plant waxes, terrigenous macrofossils	5
11	Chumkopo				Brown <i>et al.</i> , 2014	^{14}C , ^{137}Cs	103	4	No transformation	Leaf, twig, and bulk organic	68
12	Chumpich			Ti, K, Fe and Ca	Islebe <i>et al.</i> , 2022; Torrescano-Valle <i>et al.</i> , 2019	^{14}C	220	4	BACON bayesian model	No reported	Centennial
13	Coba	Ostracods $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$	Diatoms	Cl, and Ca, Mg, K, Fe, Na	Leyden <i>et al.</i> , 1998; Whitmore <i>et al.</i> , 1996	^{14}C , TL, OSL	880	8	No transformation	Ostracods, mud, wood	176
14	de Cocos		Ostracods, <i>Pyrgophorus sp.</i>	Al, Ti, Na	Bradbury <i>et al.</i> , 1990	^{14}C	500	1	No transformation	Organic material	117
15	Cometa				Nooren, 2017	^{14}C , Tephra layers	425	1	Piecewise-linear model	No applicable	3
16	Ek'Naab			Alumino-silicates	Wahl <i>et al.</i> , 2019	^{14}C	698	6	Piecewise-linear model using CLAM	Non-aquatic plants, wood, and seed	14
17	Encrucijada			Glass shards	Joo-Chang <i>et al.</i> , 2015	^{14}C	600	4	Linear regression	Wood, leaves remains, bulk organic sediment	52
18	Esmeralda, Chiapas			Zr, Sr, Fe, Ca	Franco-Gaviria <i>et al.</i> , 2019, 2020	^{14}C	600	4	BACON	Pollen extract	21
19	Esmeralda, Coahuah	<i>P. coronatus</i> $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$		K/Sr, Ca, Ti/Sr, Br, Fe/Zr	Martinez-Dyrzo <i>et al.</i> , 2022	^{14}C	380	5	BACON CLAM	Bulk sediment	1
20	Itzan			Stanol, C	Keenan <i>et al.</i> , 2021	^{14}C	570	9	4th-order polynomial	Plant fragments	40
21	Izabal			Ca, Al, Ti	Duarte <i>et al.</i> , 2021	^{14}C	760	10	BACON	Terrestrial wood fragmets	50

Table 1 (cont.). Palaeoenvironmental records based on lake sediments. The different kinds of chemicals analysed (including elements used as trophic index proxies in blue; in- and organic carbon content are excluded), fauna and algae studied, and material used for isotopic analysis is displayed. Also dating method, age model type and mean resolution of the proxy with more samples is shown. Pollen (including aquatic pollen), charcoal, density, in- and organic carbon and magnetic susceptibility analyses are excluded since this information is in Figure 4.3. The category "No Transformation" indicates the records that do not develop an age model although dated, presenting the results against depth.

Location	Isotopes	Bio-proxies	Chemicals (including Trophic index)	Mineral proxies	Reference	Dating method	Core length (cm)	Number of dates	Age model type	Dated material	Mean resolution (years)
22 Kail	Bulk sediment $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$				Harvey <i>et al.</i> , 2021; Stansell <i>et al.</i> , 2020	^{14}C , ^{210}Pb	545	43	BACON	Charcoal, Leaf	5
23 Macanche			Ca, Mg, and Fe, P		Brenner, 1983; Vaughan <i>et al.</i> , 1985	^{14}C	420	No reported	No transformation	Organic and calcareous material	Multi-decadal
24 Manchon Swamp			Ca, Sr, Mg, Na, and transition elements		Neff <i>et al.</i> , 2006	^{14}C	620	7	Piecewise-linear model age-depth model tool from Calib© 6.1.1;	botanical constituents	55
25 Muyil					Sullivan <i>et al.</i> , 2022	^{14}C	1200, 1250	12	Bayesian age model	Plant material	5
26 Naja					Dominguez and Islebe, 2008	^{14}C	340	6	Piecewise-linear model	Bulk sediments samples	59
27 New River Lagoon, Lamanai Hill-bank	Bulk sediment $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$, <i>Cochliopina</i> sp. and <i>Pyrgophorous</i> sp. $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$	Diatoms			Metcalfe <i>et al.</i> , 2009	^{14}C , ^{210}Pb	1381	8	Polinomial	Organic material and gastropods	56
28 Ocotlito		<i>C. ilosvayi</i> , <i>D. stevensoni</i> , <i>Potamocypris</i> sp.	Sr, Ti, Ca, Mg, Na, K and Cl, SO_4^{2-} , N %		Diaz <i>et al.</i> , 2017	^{14}C	900	8	Piecewise-linear model	Organic material, charcial, pollen extract	14
29 Paixban	$\delta^{13}\text{C}$ of Organic material				Wahl <i>et al.</i> , 2016	^{14}C	600	10	Clam model	plant material, wood, seed	Multi-decadal
30 Peten Itza	<i>Cochliopina</i> sp. $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$	<i>P. coronatus</i>	Ca %, Pigments, Stanol, Ti, Fe, Al		Anselmetti <i>et al.</i> , 2007; Bush <i>et al.</i> , 2009; Correa <i>et al.</i> , 2012; Curtis <i>et al.</i> , 1998; Escobar <i>et al.</i> , 2012; Hillesheim <i>et al.</i> , 2005; Hodell <i>et al.</i> , 2008, 2012; Mueller <i>et al.</i> , 2008; Perez <i>et al.</i> , 2013, 2011; Schüpbach <i>et al.</i> , 2015	^{14}C	550	25	Polynomial CLAM 2.2	Leaf, charcoal, wood	108
31 Los Petenes			Fe, K, Ca and Ti		Gutierrez-Ayala <i>et al.</i> , 2012; Torrescano-Valle <i>et al.</i> , 2019	^{14}C	220	6	Piecewise-linear model age from Calib© 6.1.1. BACON Bayesian model	Bulk organic material	40
32 Petenxil		sponge spicules, Cladocera, Tubellaria, Insects, Diatoms, algae	Alkaline elements, halogens, Al, Si, Ti, V, Rb, Ce, La, and Sa, P		Cowgill <i>et al.</i> , 1966	^{14}C		4	No transformation	Organic material	Centennial
33 Puerto Arturo	<i>P. coronatus</i> $\delta^{18}\text{O}$				Wahl <i>et al.</i> , 2014, 2016	^{14}C	728	11	Third orden Polinomial model CLAM 2.2	Charcoal, plant fragments, wood, and insect	28
34 Puerto Morelos					Islebe and Sanchez, 2002	^{14}C	190	2	Piecewise-linear model	Unidentified organic material	22
35 Punta Laguna	<i>C. ilosvayi</i> $\delta^{18}\text{O}$, <i>P. coronatus</i> $\delta^{18}\text{O}$				Curtis <i>et al.</i> , 1996	^{14}C	630	9	Piecewise-linear model	Wood, aquatic gastropods	14

Table 1 (cont.). Palaeoenvironmental records based on lake sediments. The different kinds of chemicals analysed (including elements used as trophic index proxies in blue; in- and organic carbon content are excluded), fauna and algae studied, and material used for isotopic analysis is displayed. Also dating method, age model type and mean resolution of the proxy with more samples is shown. Pollen (including aquatic pollen), charcoal, density, in- and organic carbon and magnetic susceptibility analyses are excluded since this information is in Figure 4.3. The category "No Transformation" indicates the records that do not develop an age model although dated, presenting the results against depth.

Location	Isotopes	Bio-proxies	Chemicals (including Trophic index)	Mineral proxies	Reference	Dating method	Core length (cm)	Number of dates	Age model type	Dated material	Mean resolution (years)
36 Quexil	Bulk Sediment $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$		Ca, Mg, and Fe, P		Leyden, 1984; Rice and Rice 1983, 1990; Vaughan <i>et al.</i> , 1985	^{14}C	904	6	No transformation	Organic mud, lacustrine organism	-71
37 Río Lagartos					Aragon-Moreno <i>et al.</i> , 2012; Carrillo-Bastos <i>et al.</i> , 2013; Torrescano-Valle <i>et al.</i> , 2019	^{14}C	190	4	Piecewise-linear model	Bulk organic material	60
38 Río Hondo			Ca, Fe, Ti		Aragon-Moreno <i>et al.</i> , 2018	^{14}C	797	7	Piecewise-linear model	Bulk organic material	14
39 Sacnab			P	SiO_2 , $\text{Al}_x(\text{SiO}_2)_x$	Rice and Rice, 1983; Vaughan <i>et al.</i> , 1985	^{14}C	630	3	No transformation	Organic material	204
40 Salpeten	<i>P. globula</i> $\delta^{18}\text{O}$, Plant wax $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$		Ca, Mg, Fe, plant wax lipids, P		Brenner <i>et al.</i> , 2002; Leyden, 1984, 1987; Rosenmeier <i>et al.</i> , 2002, 2016	^{14}C	350	17	Fourth-order polynomial model	Wood, charcoal, seeds	10
41 San José Chulchaca	Ostracods $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$, <i>P. coronatus spinose</i> $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$	Diatoms	Cl, and Ca, Mg, K, P		Whitmore <i>et al.</i> , 1996; Hodell <i>et al.</i> , 2005	^{14}C	110	8	No transformation	Mud	196
42 San Lorenzo		Cladocea	Ti, Ca, Sr, Fe, Mn, Zr, Rb, K		Franco-Gaviria <i>et al.</i> , 2019, 2020	^{14}C	670	4	BACON 2.2	Plant remains, charcoal, wood	5
43 Santa Ana la Vieja					Cowgill and Hutchinson, 1966	correlation with Pentexil	23	0	No transformation	No apply	multi-decadal
44 Sayaucil	Ostracods $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$, planorbid gastropods $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$	Diatoms	Cl, Ca, Mg, and K, P		Whitmore <i>et al.</i> , 1996	^{14}C	613	5	No transformation	Mud	206
45 Silvituc (Noh)					Torrescano-Valle and Islebe, 2015; Vela-Pelaez <i>et al.</i> , 2018	^{14}C	135	6	Piecewise-linear model age-depth model tool from Calib© 6.1.1;	Bulk organic material	152
46 Tamarindito		Gastropods	P	Fe_2O_3 , SiO_2	Dunning <i>et al.</i> , 1997	^{14}C	235	5	Piecewise-linear model	Organic material	676
47 Laguna de Terminos Río Candelaria Panlao			Al, B, Ba, Ca, K, Mg, Na, Si, Sr, transition elements		Gunn <i>et al.</i> , 2012, 2019; Torrescano-Valle <i>et al.</i> , 2012	^{14}C	290	8	No transformation	Organic	170
48 Tuspan	<i>C. ilosvayi</i> $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$, $\delta^{13}\text{C}_{\text{org}}$	<i>Cytheridella</i> sp., <i>Candonopsis</i> sp., Diatoms	Ca%, Ti%, Si, S, K, Mn, Fe, and Al, P and S	Smectite, chlorite, halloysite	Fleury <i>et al.</i> , 2015; Nooren <i>et al.</i> , 2018	^{14}C	975	14	CLAM model	Vegetal macro remains, charcoal, wood	6
49 Tzib	<i>Pyrgophorus</i> sp. $\delta^{18}\text{O}$ <i>Assimineia</i> sp. $\delta^{18}\text{O}$				Carrillo-Bastos <i>et al.</i> , 2010, 2012	^{14}C	250	2	Extrapolated line with an additional CALIB 5.0.2 date	Bulk organic material	322
50 Vista Alegre Holbox					Glober <i>et al.</i> , 2022	correlation with sea levels high-stands	165	0	No transformation	distinctive horizons correlated	Centennial
51 Yaal Chack			Fe, Ti, Br, Ca Pigments		Metcalf <i>et al.</i> , 2021	^{14}C	300	9	Piecewise-linear model	Organic material	Multi-decadal
52 Yaloch	$\delta^{13}\text{C}_{\text{org}}$			Alumino silicate %	Wahl <i>et al.</i> , 2013	^{14}C	397	10	Composite of two polynomial regressions	Organic material	8
53 Yaxha			P	SiO_2 , $\text{Al}_x(\text{SiO}_2)_x$	Brenner, 1983; Rice and Rice, 1983	^{14}C	630	3	No transformation	Organic material	204

volcanic crater. Considering that both volcanos are in an active margin, the presence of inverted radiocarbon dates might be explained by earthquakes (Poppe *et al.*, 1985). The hydraulic system at Petexbatum, the other failed record, is connected with lake Tamarindito, which has a well-established record (Dunning *et al.*, 1997). In this way, the lack of dates at Petexbatum could be compensated.

SPELEOTHEM RECORDS IN THE MA

Only fourteen records have been developed in the MA based on speleothems (Table 3) (Figure 3). These records were dated by uranium-series which can potentially have tiny uncertainties and does not need to be calibrated like radiocarbon since the parental nuclides are not cosmogenic, often allowing a very reliable chronology to be developed (Bernal *et al.*, 2010), which has been valuable considering the issue of old carbon in karstic lakes for ¹⁴C dating.

Some speleothems have a chronology established with numerous dated points, which possess relatively minimal uncertainties, e.g. the speleothems at Macal Chasm (Akers *et al.*, 2016; Webster *et al.*, 2007) and Rey Marcos (Winter *et al.*, 2020), although correction for the presence of detrital material is typically applied (Bernal *et al.*, 2006, 2010). Speleothems can also potentially be annually layered, allowing high-resolution chronologies to be established, similar to

those using varves in lakes. Unfortunately, only the speleothems at Actun Tunich Muknal Cave (Frappier *et al.*, 2007), Chan Hol Cave (Stinnesbeck *et al.*, 2017) and Naharon Sinkhole (Warken *et al.*, 2021) had continuous layers, but they do not cover the period of the Maya civilisation.

In contrast, speleothems can present some degree of diagenesis, which is evident by the presence of aragonite (Dominguez-Villar *et al.*, 2017). In this case, the speleothems function as an open system that loses nuclides, resulting in unreliable dates.

Although practically any kind of speleothem could be used for environmental reconstruction (Fairchild *et al.*, 2006), stalagmites are the only kind of speleothem used for this purpose in the MA. All the speleothems were studied using stable isotopes (except the stalagmite at Chaltun Ha which used fluorescence), and all of them used $\delta^{18}O$ except for the stalagmite Yok-G which used the $\delta^{13}C$ as a proxy.

Figure 3 shows the proxies used on speleothems. Only the speleothems found at Macal Chasm (Webster *et al.*, 2007), Chen Ha (Pollock *et al.*, 2016) and Naharon (Warken *et al.*, 2021) used both carbon and oxygen isotopes as environmental proxies. In the case of Yok Balum, both isotopes are referred to but were used in different stalagmites (Jamieson *et al.*, 2016; Kennett *et al.*, 2012; Lechleitner *et al.*, 2015).

The $\delta^{18}O$ is a meteoric rainfall amount proxy in the speleothems at low latitudes because inside a cave, the gradient temperature between seasons is negligible, precipitation amount is generally considered the

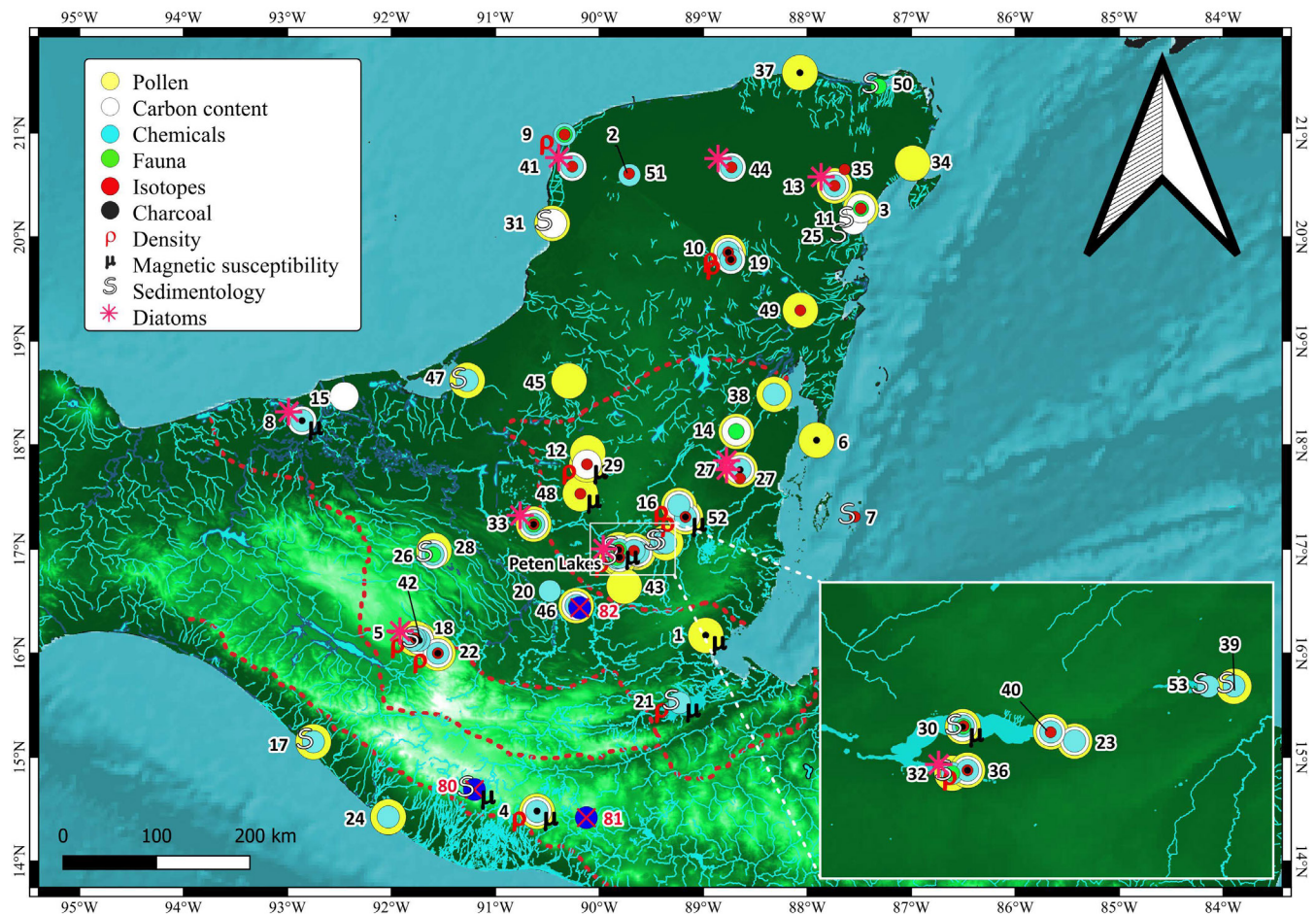


Figure 2. Location of studies that used lake sediments as environmental records indicating the different proxies involved (see legend). Although I divided the different chemical proxies into various categories (see Table 1), we unified all in a single category for presenting their spatial distribution. The numbers indicate the name of the studied site listed in Table 1. Borders (red dotted lines) indicate the different sub-areas in the MA referred in Figure 1. Map produced using QuantumGIS 3.28.4.

Table 2. Palaeoenvironmental records based on lake sediments, which were unable to develop an age model.

Num.	Location	Kind of record	Reference	Dating method	Dated material
80	Atitlan lake	Lake sediments	Newhall <i>et al.</i> , 1987	Undated	No specified
81	Ayarza lake	Lake sediments	Poppe <i>et al.</i> , 1985	Frequent turbidites represent half of the material making impossible to date it	Bulk sediment
82	Petexbatum	Lake sediments	Dunning <i>et al.</i> , 1997	Inversed dates and indecipherable stratigraphy	No specified

Table 3. Palaeoenvironmental records based on speleothems presenting the proxy studied, its temporal resolution, the name of the rock and the environmental signal recovered (a proxy of). The table also shows information related to the age model, such as the dating method, number of dating samples, age model type and dated material.

Location	Proxy	Reference	Dating method	Size of speleothem (cm)	Number of dating samples	Resolution	Age model type	Name of rock sample	Dated material	Proxy of
54 Actun Tunichil Muknal cave	$\delta^{18}\text{O}$	Frappier, 2002; Frappier <i>et al.</i> , 2007	^{137}Cs , layer counting	2.6	12	Sub-seasonal	Piecewise-linear model	ATM7	Organic material	ENSO, hurricanes
55 Box Tunich cave	$\delta^{18}\text{O}$	Akers <i>et al.</i> , 2019	U-series, ^{14}C , ^{210}Pb	9.3	9	8 years	Piecewise-linear model Chronological Tuning	BZBT	Calcite, Organic Material	Palaeoprecipitation
56 Chaltun Ha sinkhole	Fluorescence	Frappier <i>et al.</i> , 2014	layers counting	16.9	layers counting	Annual	Piecewise-linear model	CH-1	Calcite	Flooding events
57 Chan Hol cave	$\delta^{13}\text{C}$, $\delta^{18}\text{O}$	Stinnesbeck <i>et al.</i> , 2017	U-series	7.2	17	Centennial	Piecewise-linear model	CH-7	Calcite	Palaeoprecipitation
58 Chen Ha cave	$\delta^{13}\text{C}$, $\delta^{18}\text{O}$	Pollock <i>et al.</i> , 2016	U-series	100	11	Sub-annual	Linear interpolation model	CH04-02	Calcite	Palaeoprecipitation
59 Macal Chasm cave	$\delta^{18}\text{O}$, $\delta^{13}\text{C}$, luminescence, reflectance	Akers <i>et al.</i> , 2016; Webster <i>et al.</i> , 2007	^{14}C	93.6	16 of U-Th, 8 of ^{14}C , 2 of ^{210}Pb	Byannual TCP, 4 and 15 years modern, 20 years paleoindian and pre-classic	Piecewise-linear model, Bacon age-depth model	MC-01	Calcite	Palaeoprecipitation, cultivation and soil use
60 Naharon Sinkhole	$\delta^{13}\text{C}$, $\delta^{18}\text{O}$, Mg/Ca, Sr/Ca, Ba/Sr	Warken <i>et al.</i> , 2021	U-series, ^{14}C	11	18	Decadal	Piecewise-linear model	NAH14	Calcite	Palaeoprecipitation
61 Rey Marcos cave	$\delta^{18}\text{O}$	Winter <i>et al.</i> , 2020	U-series		20	Decadal	COPRA	GU-RM1	Calcite	Palaeoprecipitation
62 Río Secreto cave	$\delta^{18}\text{O}$	Medina-Elizalde <i>et al.</i> , 2016	U-series	31	13	8 years	Piecewise-linear model	Itzamna	Calcite	Palaeoprecipitation
63 Río Secreto cave	$\delta^{13}\text{C}$, $\delta^{18}\text{O}$, Mg/Ca, Sr/Ca	Serrato Marks <i>et al.</i> , 2021	U-series	80	15	Annual	COPRA	RS1	Calcite	Palaeoprecipitation
64 Vaca Perdida cave	$\delta^{18}\text{O}$	Smyth <i>et al.</i> , 2017, 2011, 2010	U-series	45	14	16.6 years	Piecewise-linear model	VP-10-1	Calcite	Palaeohumidity
65 Yok Balum cave	$\delta^{13}\text{C}$	Ridley <i>et al.</i> , 2015	cycles of $\delta^{13}\text{C}$, U-series	365	18	Monthly	Piecewise-linear model	Yok-G	Aragonite	Hurricanes
66 Yok Balum cave	$\delta^{18}\text{O}$	Kennett <i>et al.</i> , 2012; Lechleitner <i>et al.</i> , 2015; Maya <i>et al.</i> , 2012	U-series	41.5	40	Subannual	Piecewise-linear model	Yok-1	Calcite	Palaeoprecipitation
67 Tzabnah cave	$\delta^{18}\text{O}$	Medina-Elizalde <i>et al.</i> , 2010; Medina-Elizalde and Rohling, 2012	U-series and layers counting	44.1	12	2.3 years	Piecewise-linear model	Chaac	Calcite	Palaeohumidity

biggest driver of rainfall $\delta^{18}\text{O}$ values (Fairchild *et al.*, 2006; Lachniet and Patterson 2009). In this way, compared with modern instrumental records, it was possible in some cases to estimate the amount of ancient rainfall for the stalagmite, as at Tzabnah (Medina-Elizalde *et al.*, 2010), as well as to reconstruct the occurrence of hurricanes (Medina-Elizalde *et al.*, 2016b).

The speleothem at Macal Chasm and Naharon were the only ones where other proxies besides isotopes were used. In Macal Chasm, the greyscale (reflectance) and U.V. stimulated luminescence were used as proxies of humidity (Akers *et al.*, 2016) since the density of the precipitate carbonated is driven by the humidity and the incorporation of detrital material (Webster *et al.*, 2007). Likewise, Mg/Ca, Sr/Ca, and Ba/Ca were used in Naharon (Warren *et al.*, 2021).

It has to be highlighted that the speleothems have a very high resolution in the environmental isotopic signal in most cases. This kind of resolution is only also achieved in tree rings (Douglas *et al.*, 2016a), varved sediments (Cuven *et al.*, 2011) or lake sediment records studied by XRF (Davies *et al.*, 2015). In the case of lakes, even if a high-resolution isotopic signal is reached, the residence time of their waters modulate the length of the environmental signal. In this way, an isotopic signal tends to reflect the signal of a period of 10 years in small-medium hydrologically closed lakes (e.g. Lake Tilo Ethiopia, Lake Golhisar, Turkey) and 100's years in large lakes (e.g. Lake Malawi, Lake Turkana, Turkey) (Leng *et al.*, 1999). Is still unknown the residence

time in many of the closed lakes of the MA (Pérez *et al.*, 2013). A similar scenario might happen in the signals from stalagmites, where the residence time is the time that water flows through the soils and the epikarst, this is particular important for the Mg/Ca ratio (Fairchild *et al.*, 2006). Studies in the Rio Secreto cave system in the Mayab suggest that most speleothem signals represent the annual amount of weighting isotopic composition related to rainfall (Lases-Hernandez *et al.*, 2019). Whilst the residence time at Aktun Tunichil Muknal was 3 months according to the differences between Hurricanes signals observed in the speleothem and the instrumental record (Frappier *et al.*, 2007).

Finally, palaeoclimatic studies involving speleothems have been performed mainly in Belize (Figure 3). Whilst some records were developed in the Mayab. The stalagmite collected at Rey Marcos cave is the only record in the Highlands and Guatemala (Winter *et al.*, 2020). Table 3 summarises the proxies and dating method using on the MA speleothems.

ADDITIONAL RECORDS IN THE MA

The Punta Nizuc record (Table 4) is the only one based on studying corals (Horta-Puga and Carriquiry 2012), however it only covers a small recent period. Therefore, reef corals based records seem unsuitable for paleoclimatic reconstructions in the MA.

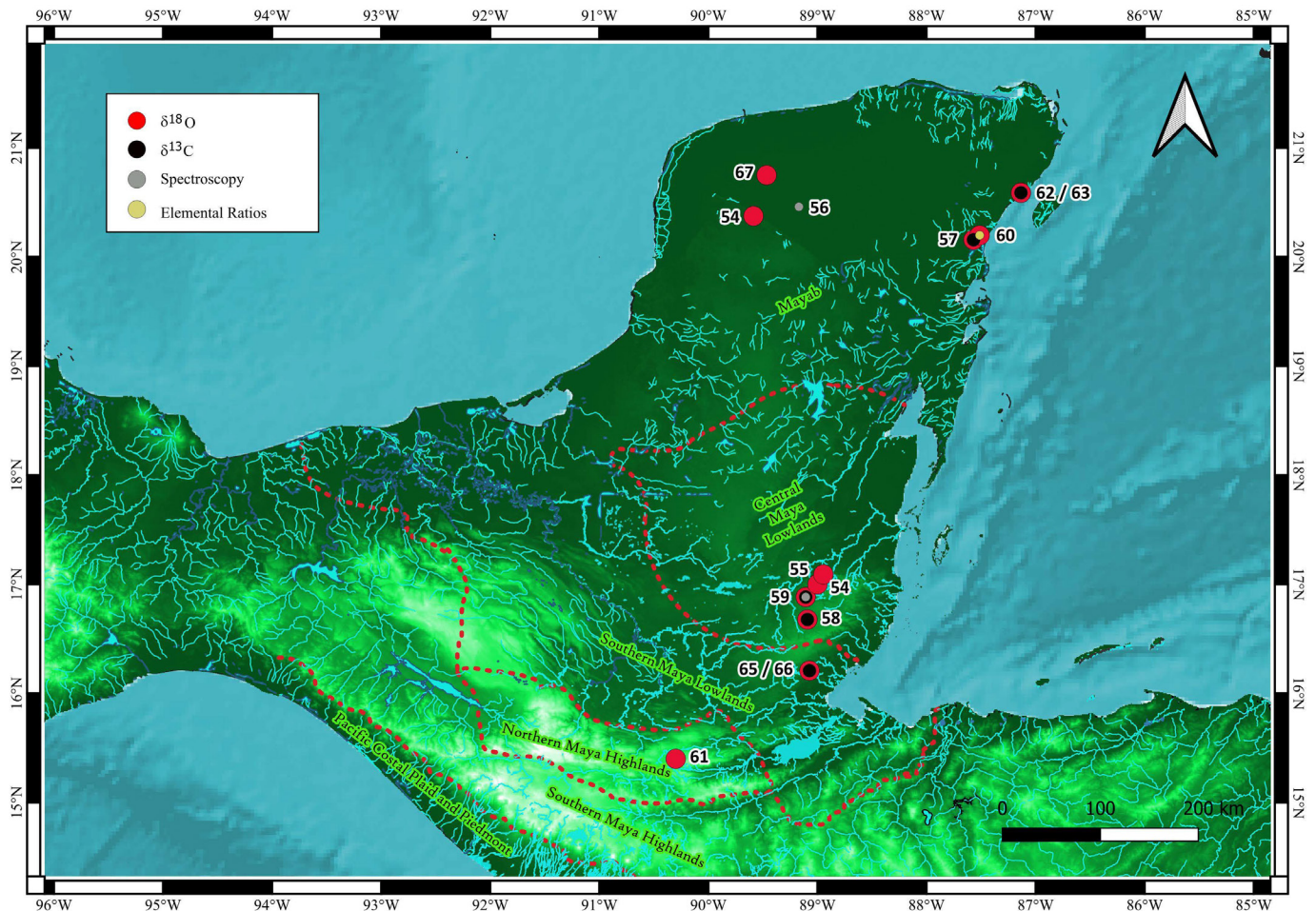


Figure 3. Location of studies that used speleothems as environmental records. The map also shows the spatial distribution of the proxies studied in each speleothem (see legend). The numbers indicate the name of the studied site listed in Table 3. Borders (red dotted lines) indicate the different sub-areas in the MA referred in Figure 1. Map produced using QuantumGIS 3.28.4.

The only research that has used tree rings in the MA (Table 4) was performed in Puerta del Cielo, San Juan Mountain and Bosque del Rancho in the Southern Highlands in Guatemala (Figure 4, green circles). This small number of records is probably a consequence of several factors. First of all, there have been few studies on trees in the region because it has generally been assumed that trees in the lowland tropics do not form annual rings, unlike trees in higher-latitude or higher-altitude regions that cease growth completely in winter (Douglas *et al.*, 2016a).

This idea is supported by the lack of a significant gradient of temperature between winter and summer; therefore, the rings reflect seasonal changes in precipitation. However, it has been shown that trees still produce rings at low latitudes. Besides, as in other parts of North America, the vegetation in the highlands is composed of the cloud forest of coniferous trees due to the high elevation that produces more temperate climates. The issue with the dendroclimatological records is not the lack of tree rings but the preservation of the old trees (Douglas *et al.*, 2016a).

Second, it is unlikely that many living trees in the Maya area are older than a few hundred years (the same applies in general for tropical ecosystems), restricting the time frame over which climate variability in the region could be studied by this method (Douglas *et al.*, 2016a). Therefore, the chance to find dendroclimatological records contemporary with the Mesoamerican periods is meagre.

The current stage of dendroclimatology research in the MA makes this kind of record unsuitable for reconstructing climates during the Mesoamerican periods. Some dendrochronological archives in the Cultural Archaeological Areas of Aridoamerica, (American Southwest) and the centre of Mesoamerica, evidently outside the MA, has been used to sustain the hypothesis of the Maya Droughts (Stahle *et al.*, 2011). However, the location of these records makes them very problematic since they were exposed to different climate regimes. However, if the climate dynamics between them are known, linking the different areas might be possible.

The records based on sediment cores or discrete sediment samples from profiles from seasonal wetlands (*e.g.* sediments from archaeological profiles) used pollen as a proxy for vegetation, while three of them, Ramonal, Laberinto (Gunn *et al.*, 2002) and Akab Muclil (Krause *et al.*, 2019), used the elemental composition of the sediments. Akab Muclil is the only record to use an isotopic proxy, $\delta^{13}\text{C}_{\text{organic}}$ (Table 4).

Most wetland records are located in the southern part of the Mayab near the Central Lowlands border (Figure 4 grey circles). Another unusual record in the MA is the one based on cave sediments at Ixchel Reflection Cave (Polk *et al.*, 2007) (Figure 4 yellow circle) where $\delta^{13}\text{C}$ was compared to a similar proxy in the speleothem of Macal Chasm (Webster *et al.*, 2007), showing similar trends interpreted as variations of humid and dry conditions (Polk *et al.*, 2007). Table 4 summarises the proxies used on these records.

TEMPORAL FRAMEWORK OF PALAEOCLIMATIC RECORDS IN THE MA

I developed a list of records spans in the MA. As the chronology of the lake sediment records is mainly based on radiocarbon dating. I created a list of the assigned age for the bottom and top points of the entire record extrapolated from the applied age model (I used the extreme assigned ages of this interval, instead of the median ages). The sources of material for dating are mentioned, as well as the number of dates obtained (Table 1). It is not mentioned if a record's age model used a hard water error correction since this step is not always described even in records with high carbonate content in karst areas. This issue is more commonly addressed in the records produced in the Mayab for the last 15 years, normally searching terrestrial material for dating, which is not influenced by old carbon.

The dating method used in the record is also shown (*e.g.*, radiocarbon, U-series, layers counting, etc) (Tables 1–4). As well as age

Table 4. Palaeoenvironmental records not based-on speleothems or lake sediments. The table also shows information related to the resolution of the proxies studied as well as the age model (dating method, age model type and dated material).

Num.	Location	Kind of Record	Reference	Dating method	Age model type	Dated material	Mean resolution (years)
68	Punta Nizuc Reef	Coral	Horta-Puga and Carriquiry, 2012	Layer counts	Linear regression	Coral	Annual
69	Ix Chel Reflection cave	Cave sediments	Polk <i>et al.</i> , 2007	Radiocarbon	Piecewise-linear model	organic material	Centennial
70	Bosque del Rancho	Dendroclimatology	Anchukaitis <i>et al.</i> , 2013	Crossdating	Piecewise-linear model	Trees	Annual
71	Puerta del cielo	Dendroclimatology	Anchukaitis <i>et al.</i> , 2014	Crossdating	Piecewise-linear model	Trees	Annual
72	San Juan Mountain	Dendroclimatology	Anchukaitis <i>et al.</i> , 2015	Crossdating	Piecewise-linear model	Trees	Annual
73	Aguada Mucal, Brisa Rservoir, Fidelia Reservoir, Little Tom Reservoir	Artificial reservoir	Lentz <i>et al.</i> , 2022	Archeo-Stratigraphic correlation	Linear model	Organics	Decadal
74	Akab Muclil	Seasonal swamp	Krause <i>et al.</i> , 1919	Radiocarbon	Piecewise-linear model	Organics	Centennial
75	Cob Swamp	Seasonal swamp	Pohl <i>et al.</i> , 1996	Radiocarbon	No transformation	Organics	Centennial
76	Cobweb	Seasonal swamp	Jones <i>et al.</i> , 1994	Radiocarbon	No transformation	Organics	Centennial
77	Laberinto	Seasonal swamp	Gunn <i>et al.</i> , 2012	Radiocarbon	No transformation	Organics	Centennial
78	Infierno	Seasonal swamp	Castanet <i>et al.</i> , 2022	Radiocarbon	No transformation	Organics	Centennial
79	Ramonal	Seasonal swamp	Gunn <i>et al.</i> , 2002	Radiocarbon	No transformation	Organics	Centennial

models, which were constructed by diverse algorithms by the authors of the respective research, including linear and polynomial regression, piecewise-linear models, and Bayesian statistics-based models, including those generated in CLAM or Bacon software. Many records attributed the date of the core collection to the top of the core without assuming any removal of material and a continuous sedimentation process. Many records attribute an age of 0 BP at the top even though the discrepancies between the year of collection and the assigned age 0 BP, (1950 AD) were not always negligible. Some records have no age model assigned, leaving the measured ages as a point of comparison besides the depth. Only some records had the opportunity to use an actual tephra layer of known provenance for dating, e.g. records at Guatemala, Tabasco and Campeche (Nooren, 2017; Stansell *et al.*, 2020). Other dating methods used, such as ²¹⁰Pb, are also specified in Table 1. The published radiocarbon dates were uncalibrated for the records published before the 1990s. Therefore, I calibrated these dates using the IntCal13 calibration Curve in OxCal, when it was possible. The year of coring, length of the record and spatial sampling interval of the proxy with most samples is also noted (Tables 1–4).

The sampling temporal resolution of the record was calculated using these two last parameters and the chronology assigned by the authors of every record, following the formula

$$R = SD \frac{Om - Ya}{Do} \quad (1)$$

where *R* is the obtained resolution, *SD* is the sampling distance of the proxy with most samples, *Om* is the oldest measured date, *Ya* is the assigned date at the top, *Do* is the depth of the oldest date. In this way, it was possible to establish which records have a resolution better than 20 years, which will be considered high resolution records (Figure 5, lines with a + sign). These high resolution records are important since they would have potentially registered events such as decadal droughts, ENSO signals, and even hurricanes (if the residence time is also lower than 20 years), which could be revealed using spectral analyses such as wavelets (Coutino *et al.*, 2021; Lachniet *et al.*, 2004; Medina-Elizalde *et al.*, 2016a, 2016b; Nooren *et al.*, 2018; Pollock *et al.*, 2016; Serrato Marks *et al.*, 2021) The variance analyses in high resolution records are also useful to test the residence time of the system (Pollock *et al.*, 2016). The time frames covered by every palaeoenvironmental record in the MA is displayed first by groups (Figure 5, colour indicates the record type); the wetland records, lake sediment records, speleothems, cave sediments, corals and tree rings. And second by alphabetical order.

However, where records have longer chronologies, e.g. Chichancanab (Covich and Stuiver 1974), I constrained the period of the record to the time frame that has been studied using a group of proxies. Figure 5 also shows a dotted line for the major part of the period studied at Aguada X'Caamal, representing when this sinkhole functioned as an open system, making its studied proxy ($\delta^{18}O$) unreliable as a proxy of evaporation-precipitation ratio for that period (Hodell *et al.*, 2005a).

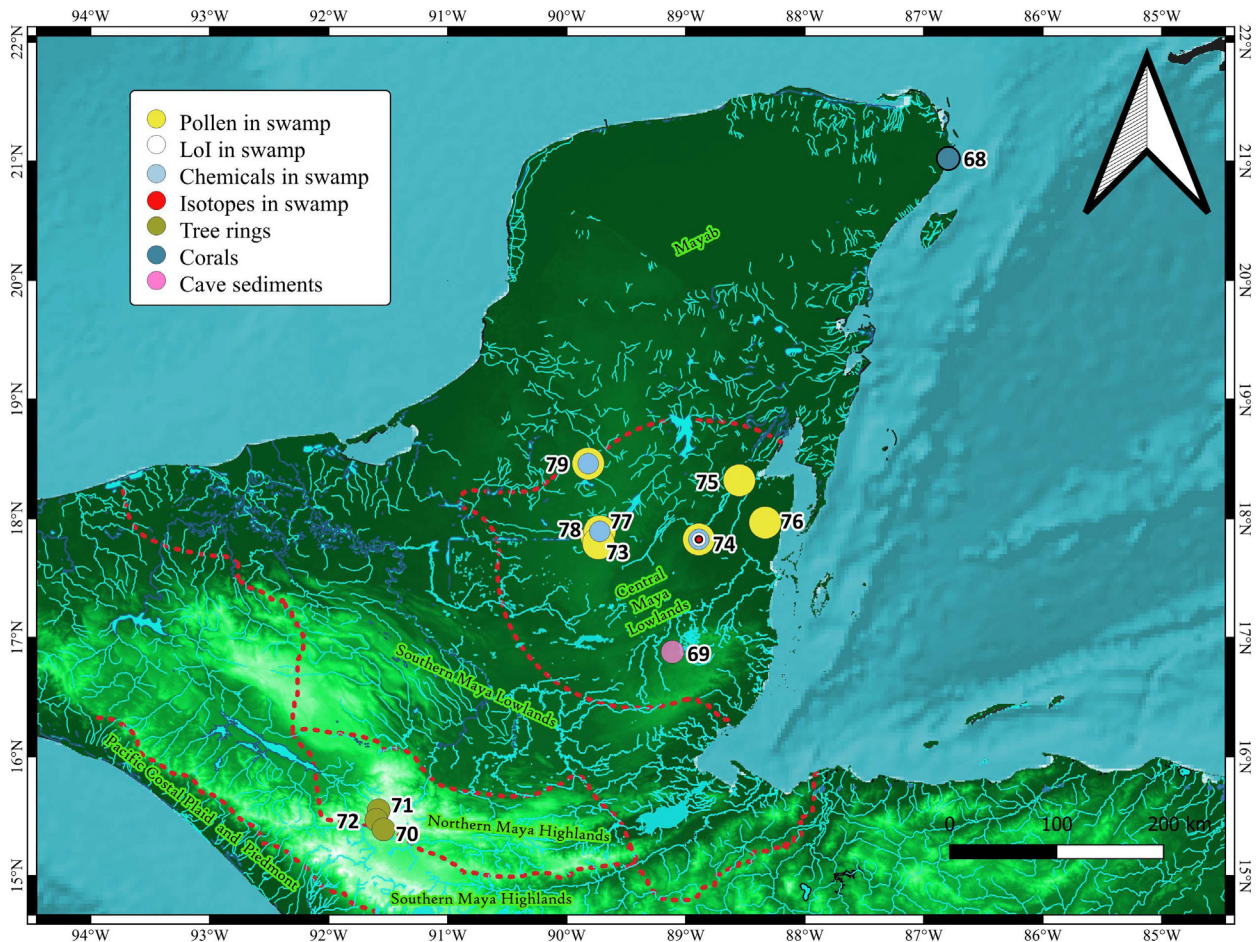


Figure 4. Location of studies that used swamp and wetland cores as well as tree rings, corals and cave sediments (see legend). The map shows the proxies used in every swamp record such as pollen, LoI, chemicals and stable isotopes (see legend). The numbers indicate the name of the studied site listed in Table 4. Borders (red dotted lines) indicate the different sub-areas in the MA referred in Figure 1. Map produced using QuantumGIS 3.28.4.

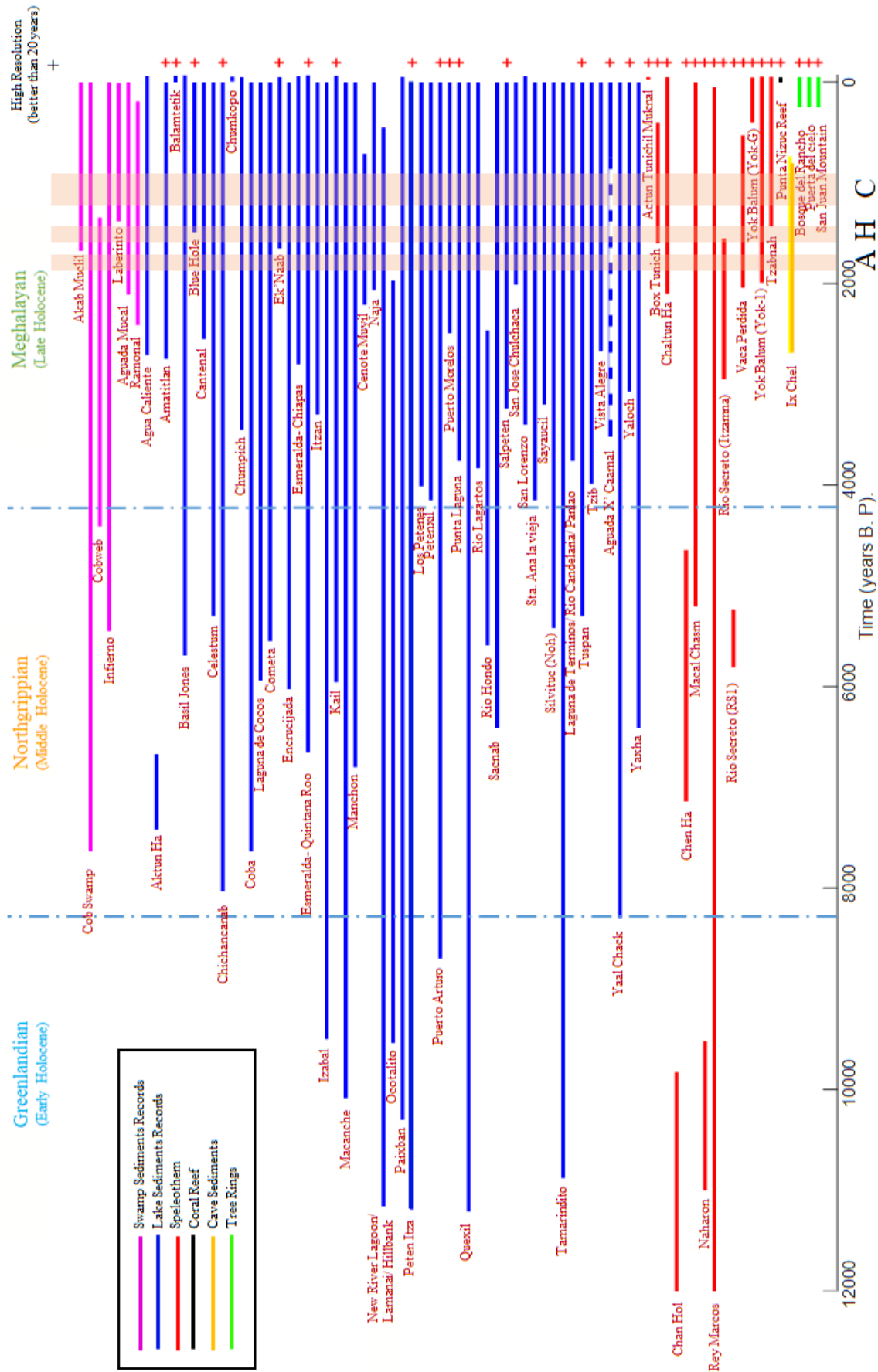


Figure 5. Time frame of the different records of the MA; temporal swamp (pink), lake (blue), speleothems (red), cave sediments (yellow), corals (black) and tree rings (green). Unpublished lake records are in pale blue. The letter indicates the critical periods during Maya History, the Maya Abandonment (A), the Maya Hiatus (H) and the Maya Collapse (C). The symbol (+) indicates the records with at least one proxy with a resolution better than 20 years. The numbers indicate the name of the studied site listed in Tables 1 to 4. Borders (red dotted lines) indicate the different sub-areas in the MA referred in Figure 1.

Some records share the same chronology, since one is stratigraphic correlated with the other instead to develop its own absolute chronology for instance, the records at Santa Ana La Vieja and Petenxil (Cowgill *et al.*, 1966).

Most records cover only a part of the Holocene (Figure 5). Only 12 records cover the Greenlandian Stage. The number increases to 32 for the Northgrippian Stage, while the Meghalayan stage is the time frame that contains most records; 74.

The speleothem, coral and tree rings tend to have a better resolution than lake sediments. However, these records only cover a small fraction of the Holocene. The exception is the speleothem in the Rey Marcos cave, which covers all the Holocene (Winter *et al.*, 2020). However, this record is in the highlands. In summary, despite the relatively large number of records, the MA still needs to have records that cover longer time frames, high resolution, and more of a multiproxy approach.

In an alternative display of the time frame covered by the records by latitude, the central lowlands possess the major concentration of high resolution records, excluding the Peten region, followed by the Belize caves (Supplementary Material, Figure S2). Whilst the Pacific Coast does not have any high resolution record.

RELEVANT PALAEOCLIMATIC RECORDS OUTSIDE THE MA

The MA covers an extension of approximately 400000 km². Therefore, the use of palaeoclimatic records outside this area to indicate the presence of a drought presents major challenges and is problematic from the epistemic point of view. The use of external palaeoclimatic records for supporting the Mayan drought is more complicated when they come from Southern Central America, *e.g.* the speleothem recovered at Chilibrillo Cave in eastern Panama (Lachniet *et al.*, 2004) or central Mesoamerica, *e.g.* the speleothem collected at Juxtahauca Cave (Lachniet *et al.*, 2012) or Diablo Cave (Bernal *et al.*, 2011), both in Guerrero. For example, the use of records in central Mesoamerica to support the Mayan drought hypothesis is problematic since they are immersed in different climates, although they are all in the same summer rainfall regime, so a shift in the overall drivers of this could give a coherent signal. For instance, substantial changes in settlement patterns also happened there at the time of the Maya Collapse at the end of the Mesoamerican Classic Period (Carrasco 2001; González-José *et al.*, 2007).

Most of the palaeoclimatic records in central Mesoamerica indeed register recurrent droughts through the Mesoamerican periods, but they are not linked to societal Collapse on the same scale that occurred in the MA. The drought is not seen as a driver of the societal Collapse in central Mesoamerica, although it has been established that drought played a role to some degree in the decline of Teotihuacan as a major power, one of the most populated cities in the world at that time (Lachniet *et al.*, 2017).

The use of palaeoclimatic records outside the MA for supporting the drought hypothesis is only justified if the drought was a manifestation of a climate event of planetary or transoceanic proportions. The fact that a series of civilisations in north-western South America presented a collapse, *e.g.* the Mochica Tiwanaku culture at a similar time around 1000 BP (deMenocal 2001), supports the idea of a subplanetary climate event. The end of the Tang dynasty in imperial China due to a decrease in the intensity of summer monsoons at the time of the Maya Classic Collapse could be connected to the same climatic event, (Yancheva *et al.*, 2007).

The most accepted explanation of a climatic event of subplanetary proportions, which could have caused droughts in parts of Mexico,

Central America, the northern part of South America and over China, is the displacement of the Intertropical convergence zone. Related to this, the most cited record outside the MA presented linked to the droughts during the Maya Collapse at the Terminal Mesoamerican Classic period is the titanium record of the marine sediments collected from the Cariaco basin of the coast of Venezuela (Haug *et al.*, 2001, 2003). The titanium content through the record is a proxy of the displacement of the Intertropical Convergence, Zone, ITCZ. Since the movement of the ITCZ responds to solar insolation in a similar way that the Bermuda High, a displacement to the south of the highest north latitude position of the ITCZ might have coincided with a displacement to the south of the Bermuda High, causing drier trade winds over the MA. The Cariaco record is frequently used to compare with local studies in the MA for distinguishing between regional patterns and sub-planetary patterns of the hydrological balance despite its considerable distance from the Maya area and lack of correlation in modern climatology.

PRESENCE OF DROUGHTS IN THE TIME OF THE MAYA ABANDONMENT

The spatial distribution of the 57 palaeoclimatic records that cover the period of the Maya Abandonment at the end of the Preclassic Mesoamerican period, shows the records that register an event associated to a dry event (a drought registered in a proxy related to rainfall, a change to drier forest or a change in vegetation that cannot be explained by anthropogenic forcing, or changes in the precipitation of secondary carbonates or evaporites) (Figure 6).

There are also records that possibly suggest a drought event (Figure 6). For example, this is the case at Lake Sayucil, Laguna de Cocos, Macanche and Petenxil, where at least one proxy related to rainfall or anthropogenic activity suggests a drought or/and lack of anthropogenic activity, respectively (*e.g.* no presence of *Zea mays*). The problem with these records is their lack of resolution. For instance, the pollen record at Lake Yaloch did not record any *Zea mays* and has a decrease in Poaceae, but such crops reappear after the period of the Maya Hiatus, indicating that the region was not abandoned at all or re-occupied (Wahl *et al.*, 2013). The asterisk symbol indicates that the existence or possible existence of a dry event appears in the record but is not discussed by the authors.

Records that do not signal a drought are found in the central Lowlands of the Peten region (Figure 6). Naja is the only record that does not present a drought signal in the inland area (Domínguez-Vázquez and Islebe, 2008), but this is possible to the sampling resolution in its pollen record. In contrast, most records show a dry climatic signal at the Maya Abandonment, including records in the highlands, *e.g.* Lakes San Lorenzo and Esmeralda in Chiapas (Franco-Gaviria *et al.*, 2018, 2020), Lake Kail (Stansell *et al.*, 2020) or Lake Amatitlán (Velez *et al.*, 2011), while all the speleothems in Belize and the Mayab indicate a very dry period.

Most high resolution records (14 of 17), which concentrate in the Riviera Maya and the Central Lowlands (Figure 6, plus sign) support the presence of a drought for the Maya Abandonment, the exception are the records at Peten Itza, Petenxil, Sacnab, Naja and Puerto Morelos.

Despite the resolution and approach, most records point out the presence of a dry period during the Maya Abandonment. In the works around El Mirador and Nakbe, Dahlin found evidence of habitation of seasonal swamps around 1800 BP (Dahlin, 1990) supporting this. The presence of records without drought signals in the Peten might be explained by the great amount of hydric sources in this area. However, the archaeological evidence infers that the population levels were

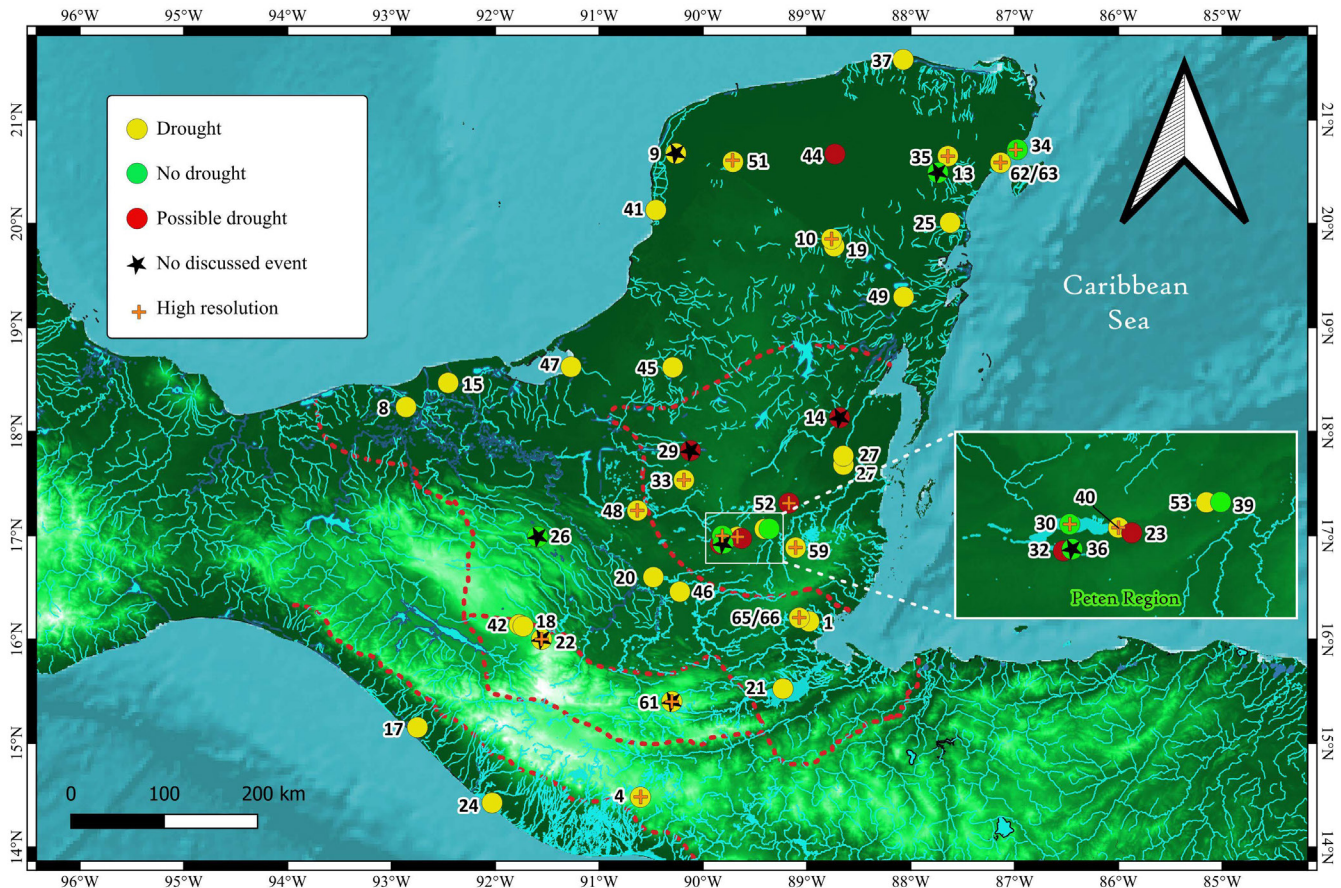


Figure 6. Spatial distribution of the environmental signal at the moment of the Maya Abandonment. The records indicating a possible drought are not conclusive and have an insufficient temporal resolution for observing decadal variations. The asterisk indicates that a stressful climatic event is observed in the record, but the authors do not discuss it. Records with a resolution better than 20 years are indicated (+). The numbers indicate the name of the studied site listed in Tables 1 to 4. Borders indicate the different sub-areas in the MA referred in Figure 1. Map produced using QuantumGIS 3.28.4.

truncated in this area, and population around the lakes maintained a smooth development (Gill, 2000). Another aspect to consider is the size and depth of the Peten Lake, as well as its connection with tributary rivers. This has an impact on the residence time which modulates the length of the signal that can be extracted. In this way, even if the sampling resolution of geochemical or isotopes proxies were annual, no major changes could be traced if the residence time of the lake studied is 10 or even 100 years (Leng and Marshall 2004). Even so, some records like the Ca/Ti, Fe and Al of Peten point out a tendency to dry conditions around this period (Mueller *et al.*, 2009). But more research is needed according to the authors. At the centennial scale, climate has been the major driver of vegetation change according to the Peten Itza records (Correa-Metrio *et al.*, 2012; Hodell *et al.*, 2008), this might suggest that records based of pollen where changes of vegetation have been only linked to anthropogenic activities in this period might be associated in an important part to climatic changes. The presence of unequivocally proxies of dry conditions both in the highlands and the lowlands support this last interpretation.

Unfortunately, the Maya abandonment would require more research in Preclassic sites for comparing previous levels of population and the use of natural resources before the Maya Abandonment. This period has been less studied since many of the research in the southern lowlands, which contain most of the Preclassic Maya sites, is financially supported by the New World Archaeological Foundation, which by religious beliefs tends to avoid the study of the early Preclassic period.

The new research at Aguada Fenix in the flood plains of Tabasco (Inomata *et al.*, 2020) probably will bring light to the environmental history of this time.

PRESENCE OF DROUGHTS IN THE TIME OF THE MAYA HIATUS

The spatial distribution of the 60 palaeoclimatic records at the moment of the Maya Hiatus according to the presence or absence of a drought, shows that most sites without signals of droughts are in the southern and central lowlands (Figure 7), including records at Lamanai and the stalagmite of Macal Chasm. Paradoxically, the concept of the Maya Hiatus was conceived based on the story of monuments and stelae constructions at Tikal (Drew, 2015; Moholy-Nagy, 2003), which was a big city in this region. Records in the Northern Mayab near the Caribbean Sea and near the flood lands of Tabasco near the Gulf of Mexico also do not show signals of a drought. This supports the idea that these two regions have more hydric resources than the MA which make them more resilient. It has to be highlight that some signals of drought are also associated to human agency such as the vegetation change in the pollen of Chumpich (Islebe *et al.*, 2022; Torrescano-Valle *et al.*, 2019).

The map also includes the records where the signal is ambiguous but could indicate a possible drought, *e.g.* Sayucil $\delta^{18}\text{O}$ (Whitmore *et*

al., 1996) or the interruption of the anthropogenic impact on the lake, e.g. Laguna de Cocos (Bradbury *et al.*, 1990), and Lake Yaxha (Brenner, 1983). Almost all speleothems growing at this period suggest a drought at the moment of the Maya Hiatus, except for Macal Chasm (Akers *et al.*, 2016). This indicates that the lack of drought signals in the central lowlands records is not always related to the lack of high resolution in records, since stalagmites in the MA have similar resolution. However, the epikarst at Macal Chasm could have a major residence time, cushioning a drought signal. This mechanism is unlikely due to the permeability of the epikarst in the MA, long residence times in karst system have not been reported until now. Despite Macal Chasm, the only high resolution records (Figure 7, plus sign) that do not register a drought during the Maya Hiatus are at Peten Itza and Yaloch.

Fewer lake records show the presence of droughts during the Hiatus in comparison to the abandonment and the collapse periods, which might suggest that the drought was less intense than those in the other two periods, which agrees with the observations in the stalagmites at Yok Balum (Kennett *et al.*, 2012) and Box Tunich (Akers *et al.*, 2019). Another interesting point is the presence of droughts at the Highlands except for the record at Amatitlán (Velez *et al.*, 2011). The asterisk symbol again indicates that a signal of drought appears in the record but is not discussed by the authors.

The absence of drought signal in many of the records around Tikal, where this concept was developed, indicates that the cultural hiatus at Tikal was not direct driven by droughts. However, the presence of

droughts in other regions of the MA could have had an impact on the trade networks from which Tikal depended. For example, the Maya Hiatus marks the end of the human impact on Lake San Lorenzo in the highlands according to the human impact index reconstructed from its pollen record (Franco-Gaviria *et al.*, 2018), even though the archaeological record suggests an occupation of the surroundings (e.g., at Chinkultic) until the Postclassic period (Navarrete, 2007). This might suggest that the lower human impact was a consequence of the disruption of the trade networks, where Chinkultic might have provided crops and wood to other regions.

Finally, the eruption of the volcano El Llapango in El Salvador in 1414 years BP is the most probable driver of the drought (Demarest, 2004). This dated eruption supports the presence of a drought event in the MA. Therefore, the cultural hiatus might have been only a local cultural phenomenon at Tikal, but in terms of the environmental history, it was a climate event that affected many zones of the MA.

PRESENCE OF DROUGHTS IN THE TIME OF THE MAYA COLLAPSE

The spatial distribution of the 61 palaeoclimatic records based on speleothems and lake sediments that cover the period of the Maya Collapse at the end of the Classic Mesoamerican Archaeological period (Figure 8) shows six records without a signal related to a drought or a

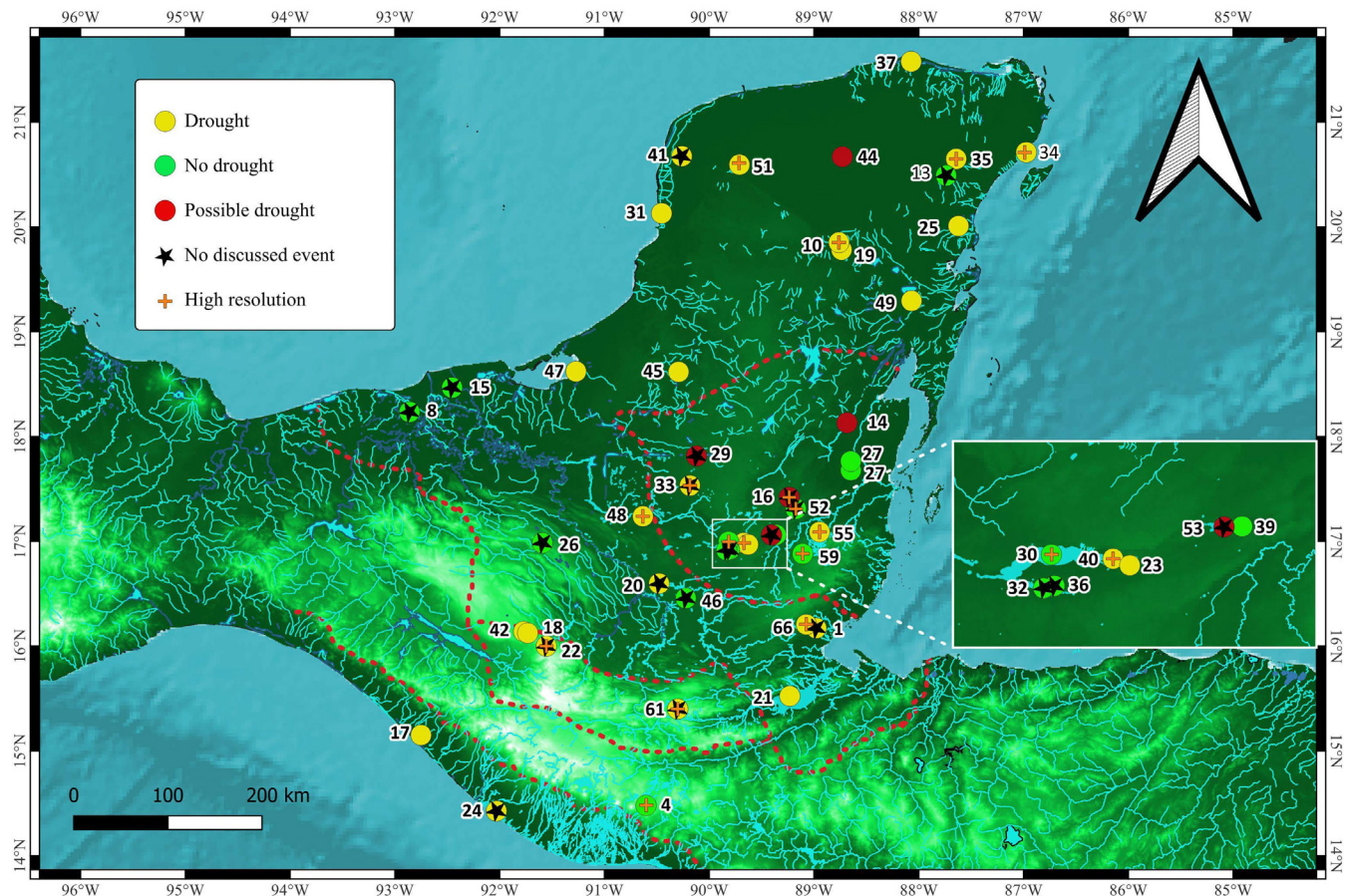


Figure 7. Spatial distribution of the environmental signal at the moment of the Maya Hiatus. The records indicating a possible drought are not conclusive and have an insufficient temporal sampling resolution for observing decadal variations. The asterisk indicates that a stressful climatic event is observed in the record, but the authors do not discuss it. Records with a resolution better than 20 years are indicated (+). The numbers indicate the name of the studied site listed in Tables 1 to 4. Borders indicate the different sub-areas in the MA referred in Figure 1. Map produced using QuantumGIS 3.28.4.

change of vegetation again concentrated in the central lowlands; Peten lakes (Cowgill *et al.*, 1966, Leyden *et al.*, 1993, Mueller *et al.*, 2009, Schüpbach *et al.*, 2015, Vaughan *et al.*, 1985), Paixban (Wahl *et al.*, 2016), the region of Lamanai (Metcalf *et al.*, 2009) and in the southern lowlands in the flood plains of Tabasco; Cometa and Cantemul (Nooren, 2017). This is explained by the vast amount of hydric resources of these regions. In contrast, twenty-nine records recognise a drought event or a vegetation change. According to this, the drought effects not only happened at the lowlands, contrary to what has been argued but also in the highlands, where the impact was important.

Again, the asterisk indicates an apparent dry event in the record that is not discussed. This is the case of the record of Tusan, whose chronology ends at the moment of the Collapse (Fleury *et al.*, 2015).

Other than a pollen-based record, the other records that show a drought is based on a tendency to relatively high values in the $\delta^{18}\text{O}$, significant precipitation of evaporates, or changes in sedimentation rate. Most speleothems in the lowlands indicate a dry period between 1140 to 1040 BP (810 – 910 years A.D.), therefore the drought started around a half-century after the first step of the Collapse, the invasion of Tikal over Calakmul (Grube and Schubert 2015).

If the droughts were not the primary drivers of the Collapse, the insights provided by the 33 records, including 16 high resolution (Figure 8, plus sign), indicate that the drought existed during the Maya

Collapse and may, therefore, have played a role in it. However, at the same time, the existence of records that do not show any signal related to a drought indicates that regional variables were able to cushion the effect of a drought (which depends on the sensitivity of the system). Another separate issue is if the drying was sufficient to disrupt agricultural and other human activities, from which some particular proxies depends (e.g. charcoal production, pollen, sedimentation rate).

There are also records where a proxy marks the existence of a drought, but the pollen record does not indicate changes in vegetation (Figure 8). For example, in the lake sediment record of Coba, physical proxies indicate lower lake levels and an increase in salinity, suggesting a drought. However, the pollen record indicates a presence of *Zea mays* during and after the Collapse during the Terminal Classic Mesoamerican period (Leyden *et al.*, 1998; Whitmore *et al.*, 1996). Thus perseverance of *Zea mays* is congruent with the archaeological and historical record that shows that the city of Coba did not collapse. Dry conditions might have offered favourable conditions for agriculture of *Zea mays* in subareas of the MA that used to suffer severe floods, e.g. Puerto Arturo (Wahl *et al.*, 2014). However, this was not the case around Coba (Leyden *et al.*, 1993). Thus, the perseverance of *Zea mays* here might suggest an adaptation to the droughts. The record in Lake Itzan also suggest a drought, but its proxy based on stanol also shows that humans activity continue (with a diminished population) even

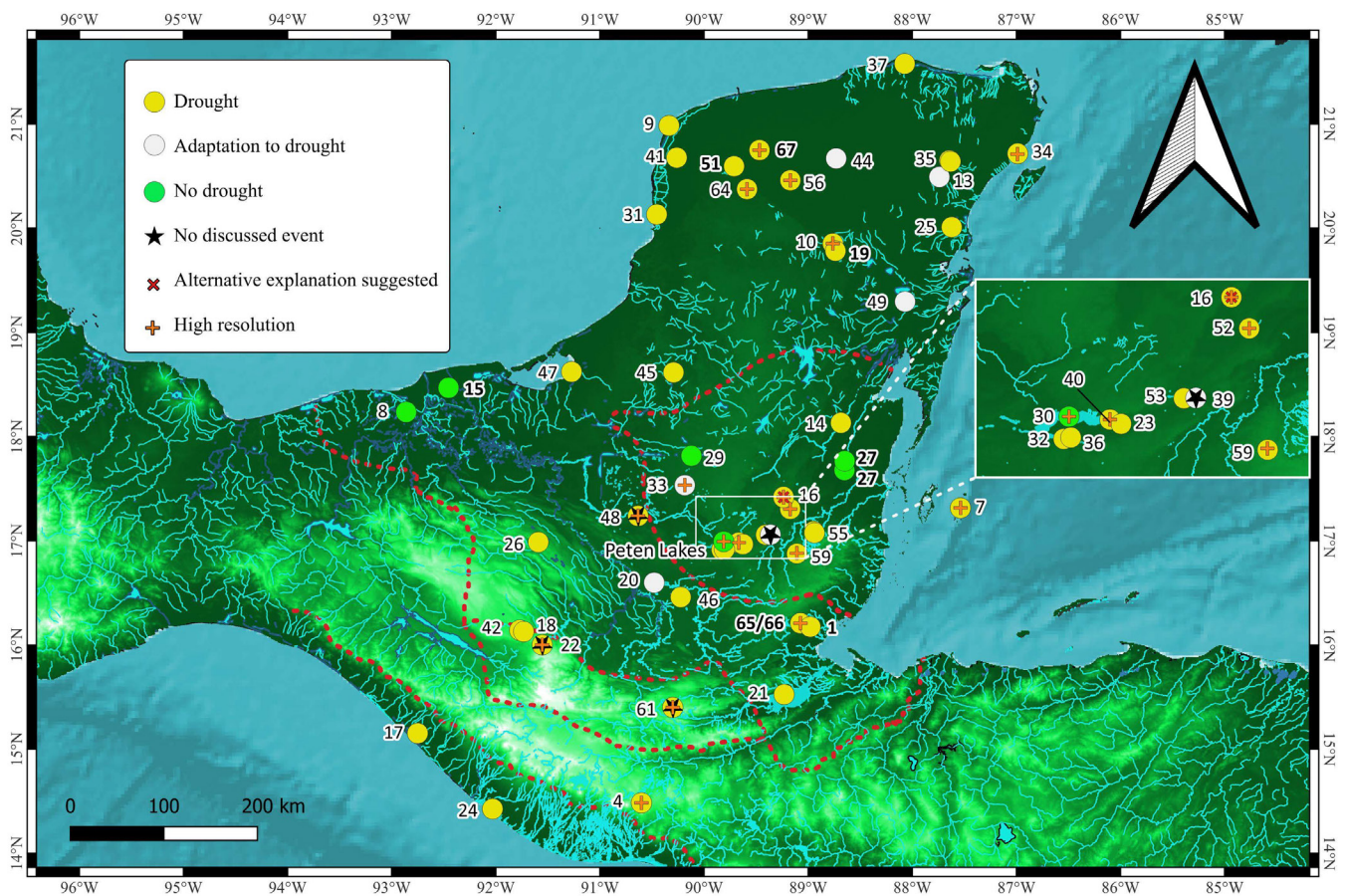


Figure 8. Spatial distribution of the environmental signal at the moment of the Maya Collapse. The records indicating a possible drought are not conclusive and have an insufficient temporal sampling resolution for observing decadal variations. The asterisk indicates that a stressful climatic event is observed in the record, but the authors do not discuss it. The label "Adaptation to droughts" indicates sites where the physical proxies indicate the presence of droughts, but the pollen record does not show a change in vegetation, including the preservation of crops like *Z. mays*. Records with a resolution better than 20 years are indicated (+). The numbers indicate the name of the studied site listed in Tables 1 to 4. Borders indicate the different sub-areas in the MA referred in Figure 1. Map produced using QuantumGIS 3.28.4.

though the archaeological record suggests a complete abandon of the near sites (Keenan *et al.*, 2021).

In the MA, changes in the vegetation are commonly linked to anthropogenic activity besides climate change, since agriculture promotes the clearance of extensive hectares of forest, the introduction of species like *Zea mays* (e.g. Carrillo-Bastos *et al.*, 2010; Wright *et al.*, 1996) or proliferation of the genus *Cucurbita* or *Poaceae* (e.g. Aragón-Moreno *et al.*, 2012; Gutiérrez-Ayala *et al.*, 2012; Kennett and Beach, 2013; Pohl *et al.*, 1996), or the diminishing of some particular kind of forest for obtaining wood (Franco-Gaviria *et al.*, 2018). Therefore, the interpretation of changes in the vegetation surrounding a lake has to be undertaken very carefully, and it has to be supported by additional proxies.

There are perhaps more palaeoclimatic records with signals for the Maya Collapse than other periods because the purpose of many studies in the MA focused on this issue. High resolution records indicate at least three severe droughts during the Collapse (Evans *et al.*, 2018), sometimes intercalated with periods of floods (Smyth *et al.*, 2017). According to Hodell *et al.*, (1995) and Webster *et al.*, (2007), these three drought events happened at 1140, 1090 and 1028 years BP based on lake sediments from Chichancanab in the Mayab or 1196–1152, 1079 and 1057–1028 years BP according to the speleothem from the Macal Chasm, at the Central Maya Lowlands (discrepancies fall inside the uncertainty of the age models used in the different records).

The diverse results show that the intensity of the droughts varied across the MA according mainly to the presence of hydric resources, the altitude and probably the interaction between the ITCZ, the trade winds and the high Bermuda High pressure system in Summer and the Nortes in Winter, which influence zones might have been diverse, complexed and different from what it has been seen in the instrumental epoch. In this way, Evans *et al.*, (2018) inferred a reduction up to 47 % of rainfall compared to the present amount based on oxygen isotopes of gypsum in Chichancanab, whilst Medina-Elizalde *et al.*, (2010) calculated a decrease of precipitation up to 35 % during the most severe dry periods at 1125 BP and 1020 BP based on the oxygen isotopes in the stalagmite at Tzabnah. However, the reduction of rainfall over Palenque would have never made water scarce in the Maya Southern Lowlands (Beach *et al.*, 2008; Iannone 2014; Harrison 1993), but none calculation has been performed for these areas.

The geographic perspective of the signals related to droughts for the Maya Collapse suggest a quasi-ubiquitous decrease of the precipitation in the MA, where the absence of drought signals in some regions just means that locally its effect was negligible. The geographic perspective highlights that many of the immigration areas during the Collapse such as the Puuc Region (Grube and Schubert, 2015) and the Cochuah Region (Shaw, 2015), where Chichancanab is located, presented also signals of severe droughts. These areas were not particularly more attractive in terms of hydric resources than the emigration zones such as those around the Usumacinta River or the Central Lowlands (Demarest, 2014; Webster, 2002), which in contrast contain records pointing out that the effects of the droughts were imperceptible there. This contradiction between cities that were abandoned whilst other cities thrived during the collapse in rich and poor of hydric resources areas, respectively, and the intensity of the droughts indicates that we still do not know how critical the droughts were for changes in vegetation (and perhaps vice versa), how critical were for the quality of water (Waters *et al.*, 2021), and how these changes impacted the human life (Douglas *et al.*, 2016a). In addition, there are only a few studies of human bones, and too few animal bone and shell records for assessing a critical impact of droughts on humans and wildlife at the time of the Maya Collapse (Beach *et al.*, 2015) and few studies involve the availability of food plant sources during the droughts (Fedick and Santiago

2022). Douglas *et al.*, (2016a) suggest that more research about regional changes in soils would help to clarify the resilience to the droughts, but the lack of resolution of these archives does not seem sufficient for this.

In this way, the geomorphology variables, including the distribution of the superficial water bodies and the access to groundwater, as well as the patterns of the winds and rainfall in summer and winter still need to be reconstructed using GIS and climatic models such as PHYDA for having a better regional perspective. In addition, the socio-dynamics of the Maya communities needs more aspects to be investigated to have a better picture of the drivers of the migrations, that determined the abandon and thriving of the sites, including the available technology to keeping water for long periods. Until now the geographic perspective indicates whereas a water decrease was indeed present for the Collapse that is not enough to explain the settlement patterns during these times. An interested environmental hypothesis for explaining this contradiction is the possible increase of Saharan Dust to the Mayab due to the droughts, which trajectory nowadays covers the Mayab (Kutralam-Muniasamy *et al.*, 2021; Liu *et al.*, 2008), where the Tikul Hills (Puuc Region) would have been the first barrier to catch the dust. This might have provided nutrients to the soils, as it does in the Amazonas (Goudie and Middleton 2001; Nogueira *et al.*, 2021; Swap *et al.*, 1992), making the Puuc and Cochua regions more attractive for agriculture. In addition, another hypothesis based on the studies on L. Amatitlán in the Maya highlands explores a possible a shift in agriculture practices and/or the construction of channels in response to the droughts which might have been impacted the quality of water caused by the presence of cyanotoxin in water bodies due to the proliferation of cyanobacterias (Waters *et al.*, 2021). This hypothesis is congruent with the observations of low-quality water in sites at the lowlands such as Tikal (Lentz *et al.*, 2020), three rivers regions (Luzzadder-Beach and Beach, 2008), and L. Sayucil (Whitmore *et al.*, 1996). Therefore, this might explain the abandon of areas rich in hydric sources.

PROBLEMS OF THE RECORDS TO RECONSTRUCT THE ENVIRONMENTAL HISTORY OF THE MA

The comparison between records presents two major problems. For one side the synchronism of the signals between records is questionable, since age models were dated by different methods, and the uncertainties deepens not only of this but in the amount of absolute dates studied. On the other side, each record contains proxies which ability to trace climate changes depends on the sampling resolution and the residence time of the analyte in the system. Because these reasons, it is important to eliminate the uncertainties that exist between records, which might make their climatic signals difficult to compare. If it is possible, the method developed by Breitenbach *et al.*, (2012) for developing age models can be applied to old and new records to homologate and make the climatic signals between records synchronic in terms of dating, making them comparable for tracing short temporal signals. Despite these problems, the geographic perspective showing the presence or absence of signals related to droughts in a particular time frame and emphasising which records are high resolution, is still valid.

FINAL COMMENTS

Although 82 records have been produced for the MA, this paper shows that as Beach *et al.*, (2015), Aimers and Hodell, (2011), and Douglas *et al.*, (2016a) suggest it is still necessary new high-resolution, multiproxy, accurately dated records. This new research must involve

the development of proxies such as the stanol for the human impact, pigments for the quality of water and chemical ratios that help to understand the presence of aerosols either volcanic ash or Saharan dust. Yancheva *et al.*, (2007) highlighted that the droughts in the MA were a manifestation of a planetary climatic event, therefore their duration was the same in the MA, even though their effects in terms of intensity were perceived different in every subregion.

The new records must have components that help to separate the anthropogenic signals from the natural climate signals, if it is possible. They must reach the same highest sampling resolution, equalizing the time frame covered by the environmental signal according to the residence time of the system. These records must feed data for mathematical models (Douglas *et al.*, 2016a) such as those in PHYDA, that can take in consideration volcanic eruptions, aerosols (such as the Sahara Dust and wildfires) and insolation (Baek *et al.*, 2019; Steiger *et al.*, 2018; Tejedor *et al.*, 2021b,a). Until now, mathematical models have been constrained to hydroclimatic variables (Collard *et al.*, 2021) and tend to constrain big areas that do not allow the details of the resilience between subregions in the MA (Bhattacharya and Coats 2020; Bhattacharya *et al.*, 2017).

In contrast, many theoretical models incorporating climatic patterns tend to be geographic comparison between climatic records or logic diagrams between variables showing loops and feedbacks, but no computational models. In this way, archaeological and soil data is added to these models, pointing out the contradictions between them, when deterministic causation cannot be appealed. Most of these models are constrained to localities (Dahlin, 2002; Kennett *et al.*, 2022; Pruffer *et al.*, 2022). Some of them are constrained for the Mayab (Hodell *et al.*, 2007), the lowlands (Bhattacharya *et al.*, 2022; Douglas *et al.*, 2015, 2016b; Gill *et al.*, 2007; Kennett *et al.*, 2012; Lucero *et al.*, 2011; Me-Bar and Valdez, 2003), or the high lands (Harvey *et al.*, 2021). But none has been performed for the whole MA. Many of these models tend to forget the human agency. Until now, most of the papers that incorporate an environmental explanation (droughts or soil depletion) of the abandonment, hiatus or collapse in regional terms have not included mathematical models, or over interpreted the archaeological finds or added western conceptions. For example, warfare has been argued for the collapse as a result of the droughts, although the archaeological record, despite epigraphy has not found signs of warfare.

CONCLUSIONS

This paper has presented a summary of the 82 palaeoclimatic records in the MA. The spatial and temporal areas covered by records and their proxies have been presented graphically, highlighting the distribution of high resolution records and the information gaps related to the scarcity of records or the lack of proxies in some areas. Most of the records (74) covered the late Holocene, in contrast less of the half (32) cover the Middle Holocene and only a few (12) cover the Early Holocene. The speleothem at Rey Marcos and the records at Peten Itza are the only two records that constrain the whole Holocene. Although the record a Quexil encompasses also the all Holocene, it is a low resolution pollen record with not good quality on dating. This summary can help to plan new research in the MA.

The mayor environmental results of the records available were compared to test the hypothesis of the mega-droughts proposed by Gill (2000), presenting a spatial distribution of the signals associated to droughts for the Maya Abandonment, the Maya Hiatus, and the Maya Collapse. The spatial distribution supports the idea that these historical events are linked to dry regional environmental conditions. However, the intensity of the dry conditions was different in specific areas, and

some of these areas might have had specific conditions to cushion the dry conditions. The Maya Central Lowlands had more hydric resources to cushion dry events during the three critical historical events. The drought presented for the Maya Hiatus was the less intense dry period based on the number of records that present drought signals.

The geographic perspective indicates a decrease of water incoming during the Maya Abandonment. The geographic perspective also highlights that a dry regime existed during the Maya Hiatus in most part of the MA, but not in the Central Lowlands where this cultural phenomenon was identified. This indicates that the Maya Hiatus was not triggered by the climate conditions in the central lowlands. But the dry conditions in other areas of the MA might have played a role in its cultural Hiatus.

The geographic perspective indicates that dry conditions indeed existed in all the MA during the time of collapse. However, the cities that collapsed were in areas where the climate records indicate negligible dry conditions due to the vast amount of water sources (regions such as the Peten lakes, Belize and the flood plains of Tabasco). In contrast, regions, that suffered a strong decreasing of rainfall in the Mayab, such as the Puuc or Cochuah regions, thrived. This contradiction between the collapse and flourishing of Maya cites and the cushioned and severe droughts indicates that the droughts were not the only important environmental factor in the abandon and migration phenomena presented during the Collapse. Factors such as the productivity of soils and the quality of water might have been also played a role.

Finally, more high-resolution records with a multi-proxy approach covering most of the Holocene, and a synchronous dating are needed to generate mathematical models, that can help to understand better the environmental and climate change in different zones of the MA.

SUPPLEMENTARY MATERIAL

Figures S1 and S2 can be downloaded at <www.rmccg.unam.mx> in the abstract's preview page of this paper.

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