



Evidence for highly variable land use but a stable climate in the southwest Maya lowlands

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Abstract. The lowland Maya of Mesoamerica were affected by multiple environmental stresses throughout their history, and
10 are experienced a major demographic and political decline, or collapse, during a period of inferred intense multidecadal
drought, between approximately 1200- and 1000-years BP. The complex interactions between climate and society in the
Maya lowlands are generally not well understood. We combine carbon and hydrogen isotopic analyses of leaf wax *n*-alkanes
with quantification of faecal stanols and polycyclic aromatic hydrocarbons from a lake sediment core from the southwest
lowlands to assess whether 1) palaeoecological evidence of land use is related to population change; and 2) whether
15 population and land use are linked to changing precipitation. Our data reveal a transition from generally more intense fire use
and C₄ plant agriculture during the Preclassic (3500-2000 BP) to dense populations and reduced fire use during the Classic
(1600-1000 BP). This is consistent with other evidence for a more urbanised and specialised society in the Classic. We do
not find evidence for drought in the hydrogen isotope leaf wax record (δD_{lw}), implying that local drought was not a primary
driver of observed variability in land use or population change.

20 1 Introduction

The lowland Maya of Mesoamerica experienced a major demographic and political decline, sometimes referred to as a
collapse, during a period of intense multidecadal drought, between approximately 750 and 900 CE (Hodell et al. 1995;
Rosenmeier et al. 2002; Aimers 2007; Medina-Elizalde et al. 2016). The effects of environmental and climatic change on
ancient societies are generally not well understood and remain incompletely understood in the Maya lowlands. Itzan, an
25 ancient population centre in the south-west Maya lowlands (Johnston 2001; Johnston et al. 2006), is in the relatively small
catchment of Laguna Itzan, where a sediment core has been previously described (Breckenridge 2000; Douglas et al. 2018;
Keenan et al. 2021). We applied different geochemical proxies to the same core to reconstruct how precipitation, fire and



agriculture varied over time, and we compare these with previously published stanol data on human waste and demographic change.

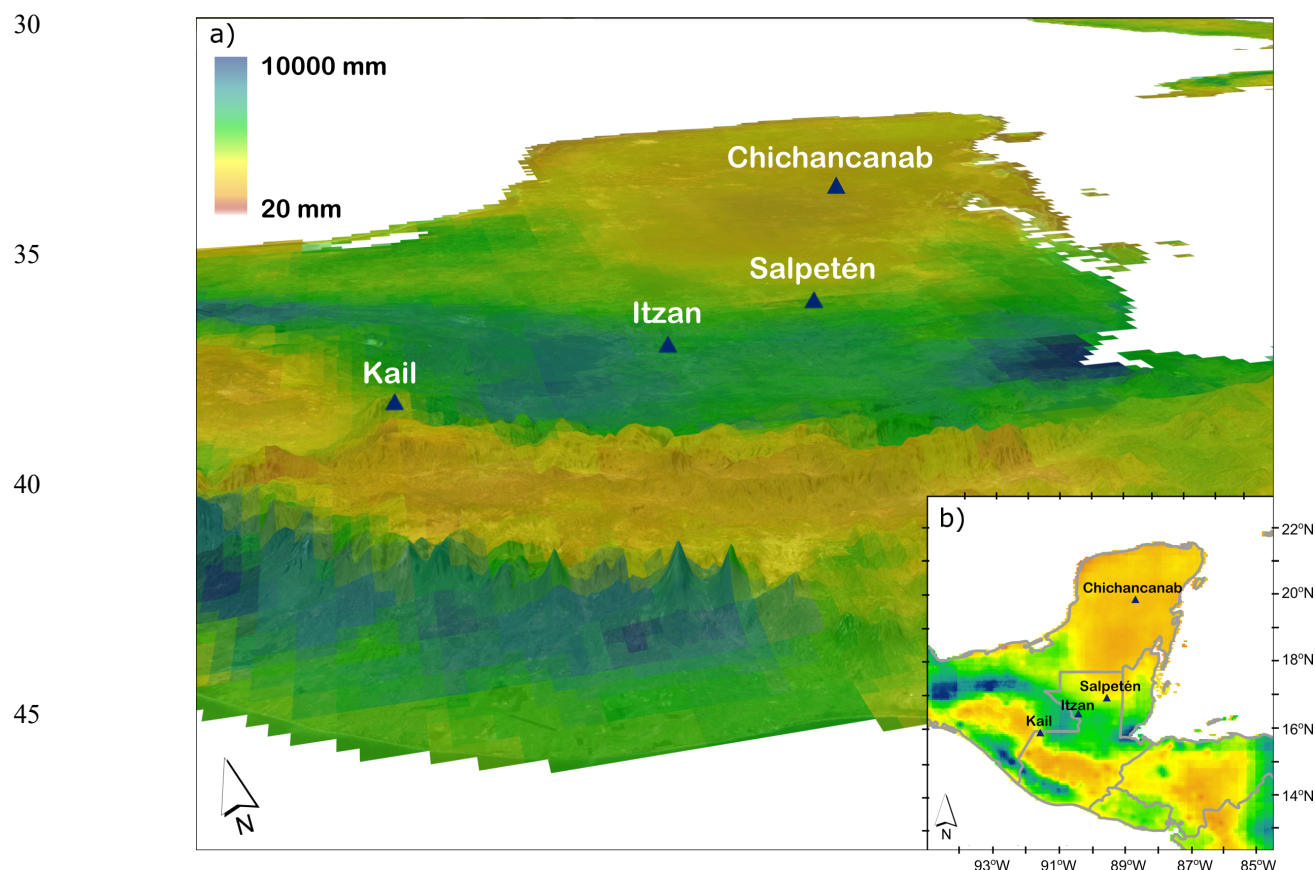


Figure 1. a) 3D relief and rainfall map of Central America with location of Itzan and Lakes Chichancanab, Salpetén, and Kail. Colours are an average of annual summed precipitation in mm (CHIRPS: Climate Hazards Center InfraRed Precipitation with Station data) between 1989 and 2019. b) Regional map of the Maya area is inset bottom right.

Polycyclic aromatic hydrocarbons (PAHs) are produced from the incomplete combustion of organic matter in conditions of oxygen depletion and can be preserved in lake sediments, where their concentration can be used as a proxy for past fire frequency and intensity (McGrath et al. 2003; Conedera et al. 2009; Denis et al. 2017). In this study PAH analyses are applied to understand the timing and extent of fire used for local agricultural land clearance or building. Fire was used as a method of deforestation, and in the use of swidden, or slash-and-burn, agriculture (Brittingham et al. 2019). Leaf wax lipids are synthesised by plants as chemical barriers, to inhibit water loss, and to provide protection from disease and UV light (Diefendorf & Freimuth, 2017). Leaf waxes record the stable carbon isotope ratio ($\delta^{13}\text{C}$) of vegetation, which is strongly



60 influenced by the photosynthetic pathway of the plant, namely differentiating C₃ plants (most trees, shrubs, and forbs) and C₄ plants, which include many tropical grasses, such as maize, which the Maya cultivated (Wright & White, 1996; Feakins & Sessions, 2010). Plants waxes also record the isotopic composition of hydrogen (δD) in plant tissue ((Sachse et al. 2021; Sachse et al. 2015). Precipitation δD in the low-elevation tropics is largely determined by the amount of rain, such that with increased rainfall, the δD is lower (Sachse et al. 2015; Niedermeyer et al. 2016; Douglas et al. 2015). This water is used in

65 the biosynthesis of leaf waxes, thereby preserving isotope composition, although it is subject to a large biosynthetic fractionation factor that can vary between plant groups (Sachse et al. 2015). In the lowlands, spatial variation in the δD_{lw} of leaf waxes appears to be strongly controlled by soil water evaporation, and, therefore, past variation is likely a combined effect of precipitation isotope variability and soil water evaporation (Douglas et al. 2015).

70 We combine these new data with previously published palaeoclimate records for Lakes Chichancanab and Salpetén (Fig. 1; Douglas et al. 2015), and faecal stanols as a proxy for human population (Keenan et al. 2021). PAH concentrations may have increased with increasing leaf wax $\delta^{13}C_{lw}$, as land was cleared for maize agriculture (McGrath et al. 2003; Sluyter & Dominguez, 2006). We also hypothesised that agricultural expansion, indicated by increasing $\delta^{13}C_{lw}$ values, and population growth, indicated by increased concentrations of faecal stanols, occur in response to amenable climate conditions, indicated

75 by decreasing δD_{lw} values. Further, we hypothesised that Terminal Classic population decline was associated with more positive δD_{lw} values, which indicate dry climate conditions indicative of drought, as seen in other areas of the Maya lowlands.

2 Results

We identify five events distinguished by changes in the four proxy records (Fig. 2). Event 1, at 4000 years BP, prior to

80 archaeological or molecular evidence of human presence, is marked by a pulse of enriched $\delta^{13}C_{lw}$. Event 2, characterised by evidence of fire, potentially for land clearance, at 3200 years BP, coincides with a smaller 1 ‰ shift to more positive $\delta^{13}C_{lw}$ values and an increase in coprostanol, a marker for human population. There is no consistent relationship between δD_{lw} and $\delta^{13}C_{lw}$ in the record, but the second major peak in $\delta^{13}C_{lw}$ (-30 ‰) at 2900 years BP (Event 3) is coeval with the wettest period in the record, and it precedes a ~900-year period of fluctuating $\delta^{13}C_{lw}$ values and inputs of coprostanol. The interval of

85 highly variable land use and coprostanol concentrations culminates at 1900 years BP with the most positive $\delta^{13}C_{lw}$ values (-25 ‰) and Total PAH concentrations of 3.1 $\mu g g^{-1}$ OC, marking Event 4, and it is followed by a ~500-year period of low coprostanol and PAH concentrations. Coprostanol input then increases gradually peaking at 1100 years BP (Event 5) co-eval with a $\delta^{13}C_{lw}$ peak of -25‰ and 1.7 $\mu g g^{-1}$ OC Total PAH. The Terminal Classic, between 1140-1000 years BP, is marked by

an abrupt decline in coprostanol and PAHs and more negative $\delta^{13}\text{C}_{\text{lw}}$. The variability of the δD_{lw} record defined by maximum
90 versus minimum is only 22 ‰ at Itzan, whereas it is 44 ‰ at Chichancanab and 55 ‰ at Salpetén to the northeast (Fig. 3).

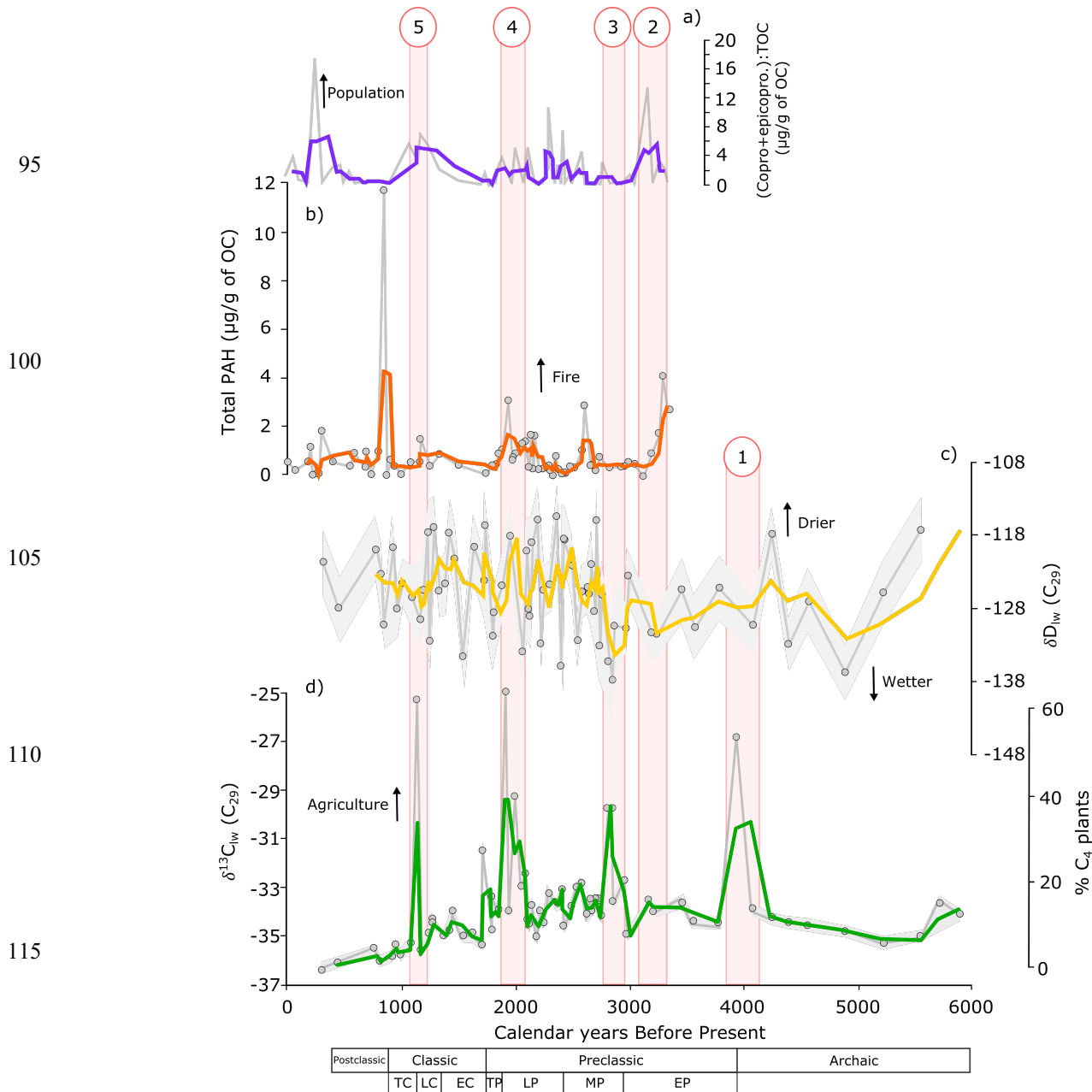


Figure 2. a) Coprostanol concentrations normalised to organic carbon ($\mu\text{g/g}$ of OC), with raw data in grey and the purple
120 line represents a 100-year moving average; b) Total PAH in grey with red a moving average ($\mu\text{g/g}$ of OC); δD_{lw} of C_{29} n-



alkanes in grey and yellow a moving average (‰); and d) $\delta^{13}\text{C}_{\text{lw}}$ of C_{29} n-alkanes in grey with moving average in green (‰) with % C_4 plants from a mixing model. For δD_{lw} and $\delta^{13}\text{C}_{\text{lw}}$ the grey envelope is the pooled standard error. Note that not all samples analysed for $\delta^{13}\text{C}_{\text{lw}}$ could be analysed for δD_{lw} . 5 “events” have been identified based on peaks that deviate from the baseline record as well as peaks that co-occur across different proxies and are shown as pink bars. Maya time periods are shown below. TC=Terminal Classic; LC=Late Classic; EC=Early Classic; TP=Terminal Preclassic; LP=Late Preclassic; MP=Middle Preclassic; EP=Early Preclassic.

3 Discussion

3.1 Progressive changes in modes of land use over time

Enriched $\delta^{13}\text{C}_{\text{lw}}$ in Event 1 could relate to major changes in catchment vegetation during a particularly short period of occupation. That this peak was short-lived suggests that the population was likely itinerant, possibly mobile hunter gatherers (Inomata et al. 2015). *Zea mays* L., maize pollen, is found in southeast Mexico near the mouth of the Usumacinta River by 5000 years BP (Sluyter & Dominguez, 2006), and carbon isotopes of human skeletons suggest that maize was a staple in Belize between 4700- and 4000-years BP (Kennett et al. 2020). This is the first evidence of an Archaic (pre-agricultural) population in the southwest lowlands, and possibly in the southern lowlands. Event 2, characterised by evidence of fire, potentially for land clearance, at 3200 years BP coincides with a small 1 ‰ shift to more positive $\delta^{13}\text{C}_{\text{lw}}$ values and an increase in coprostanol concentrations, a marker for human population (Keenan et al. 2021; Vachula et al. 2019; D’Anjou et al. 2021; Keenan et al. 2022). Thus, this period was a time of significant landscape change in the catchment of Itzan. The change in $\delta^{13}\text{C}_{\text{lw}}$ shows that burning for land clearance was not always associated with extensive C_4 plant domestication or agriculture, and that space may have been cleared for the construction of communal building projects or for C_3 plant crops, for example, or potentially to attract deer to the forest edges. Prior to the development of agriculture, non-sedentary peoples have in some places aggregated to engage in the construction of Neolithic public works, for example in Europe such as Stonehenge, Southern Arabia, Ohio and the American Southwest. Highly short-lived population aggregation at Itzan may have been for the construction of public works. Archaeological evidence reveals temporary agglomeration of significant numbers of people at the nearby sites of Ceibal and Aguada Fénix at this time (Inomata et al. 2017; Inomata et al. 2019). Event 3 indicates population variation and periodic burning. Overall, this pattern is suggestive of populations moving in and out of the area, with variable degrees of associated burning and land clearance, and possibly different farming techniques and subsistence strategies with variable dependence on maize agriculture. Comparable pulses in building and economic activity nearby are inferred at Ceibal (Inomata et al. 2020). The most positive $\delta^{13}\text{C}_{\text{lw}}$ values (-25 ‰) occur during Event 4 suggesting significant agricultural activity, and the Total PAH concentrations of $3.1 \mu\text{g g}^{-1}$ OC suggest significant burning. Again, these peaks are short-lived and are followed by a ~500-year period of low coprostanol and PAH concentrations, indicative of



depopulation and minimal land use. This hiatus in coprostanol and PAH input coincides with the pan-lowland Early Classic collapse and regional population decline.

Following this period, population then increased gradually, peaking at 1100 years BP (Event 5), which is also the local and regional population maximum inferred by archaeological evidence (Johnston 2004). Notably, C₄ plant coverage declined during the early part of the Classic (1750-1300 BP), when human population was increasing, indicating there is not a linear relationship between C₄ plant agriculture and catchment population density. This may imply that agriculture was intensified in the catchment around the time that population peaked. Lower $\delta^{13}\text{C}_{\text{lw}}$ values than the preceding period, except for the peak at 1100 years BP, suggests decreased agricultural production, despite Classic population growth. A similar reduction in coprostanol, despite the population maximum inferred by archaeological evidence, was discussed in Keenan et al. (2021) and explained as the result of a transition in agricultural strategy, including efforts to reduce soil erosion. Similar strategies have been observed elsewhere, for example at Tikal, such as ridge and furrow cultivation, the use of vegetation along the margins of water sources, intensive dooryard gardening and orchards, and extensive farming in outfield areas (Fedick et al. 2024). Except for the PAH peak at 900 years BP, PAH levels never reached pre-1900 years BP levels again. This could imply that most forest had already been cleared prior to the Classic and/or that fire was not a method for land clearance during the Classic, despite larger populations and a $\delta^{13}\text{C}_{\text{lw}}$ peak of -25‰ indicative of significant, albeit short-lived, C₄ plant agriculture. The likely explanation is that fire was no longer a key component of agricultural production during the Late Classic and fits with the narrative of agricultural intensification described above. Later input of PAHs may, therefore, have been more protracted because of low intensity burning. The Terminal Classic, between 1140-1000 years BP, is marked by an abrupt decline in coprostanol and PAHs and more negative $\delta^{13}\text{C}_{\text{lw}}$, suggesting site abandonment, cessation of fire use and agriculture. This period was a time of major societal restructuring across the lowlands, hypothesised to be in response to a regional drought, although there is no significant shift in the $\delta\text{D}_{\text{lw}}$ record (Hodell et al. 1995; Rosenmeier et al. 2002; Keenan et al. 2021). This response was the same across different sites. C₄ plant agriculture and fire appear to be most prevalent during the Preclassic and may be a signal of shifting cultivation. High variability may imply different groups with different land use strategies, or variable land use by the same group. Conversely, for much of the Classic period fire and C₄ plants are lower despite sustained population. This might reflect the employment of more efficient agricultural strategies following the recognition of soil degradation and/or the necessity to sustain growing populations. This variability in land use does not appear to be related to climate variability in any clear or consistent way, given the relatively muted climate variability recorded at Itzan. In this sense, Itzan contrasts with other sites where climate has been seen to drive societal and land use change (Rosenmeier et al. 2002; Hodell et al. 2001; Hodell et al. 2008).

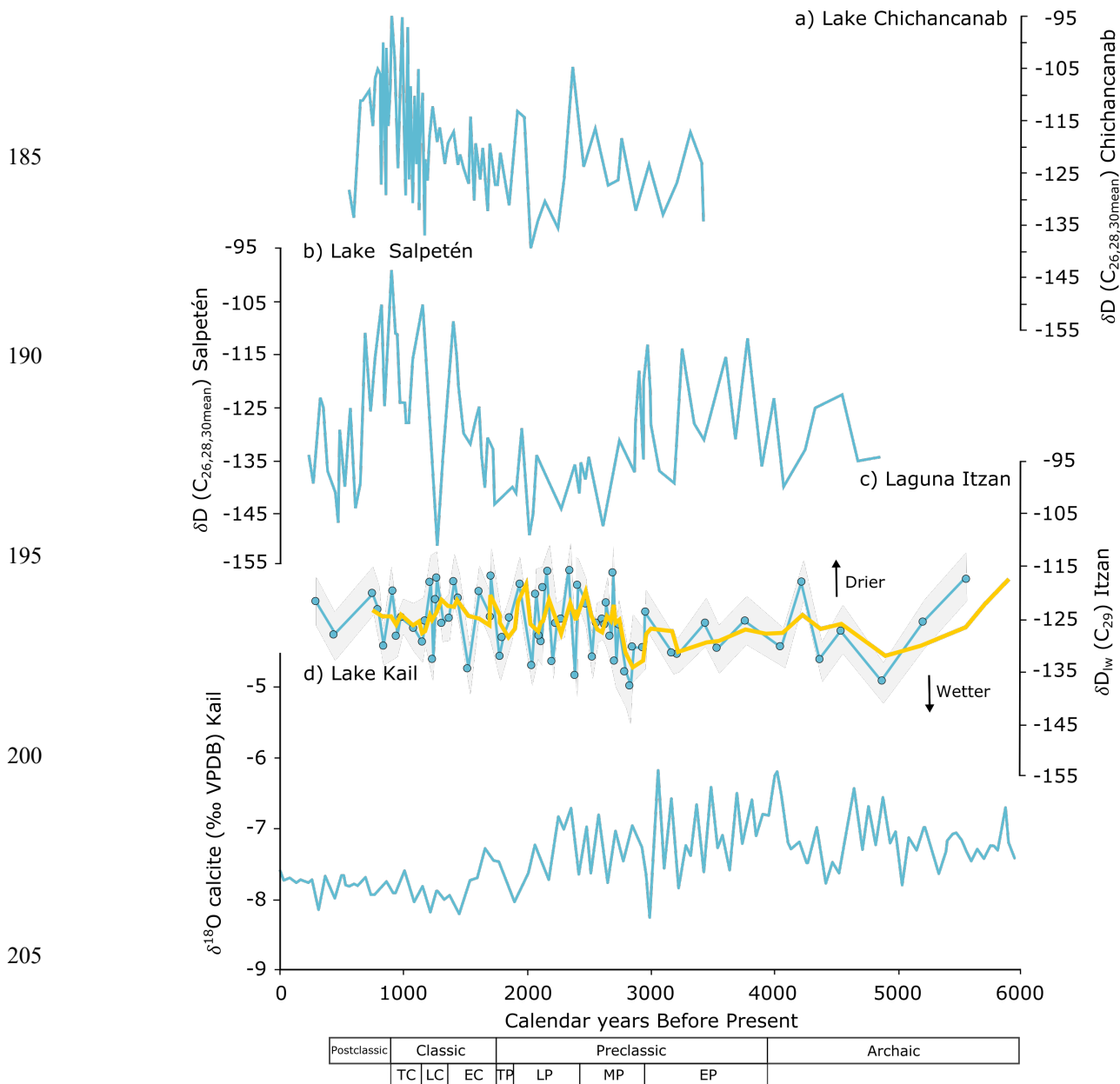


Figure 3. δD_{lw} (‰) of leaf wax n -alkane records as proxies for palaeohydrological change moving southwards from a) Lake Chichancanab; to b) Lake Salpetén; to c) Laguna Itzan; to d) Lake Kail. Maya time periods are shown below. TC=Terminal Classic; LC=Late Classic; EC=Early Classic; TP=Terminal Preclassic; LP=Late Preclassic; MP=Middle Preclassic; EP=Early Preclassic.



3.2 Relatively stable climate in the southwest lowlands

215 Despite a major restructuring of society, there is no evidence for drought in the δD_{lw} record at Itzan. Other palaeoclimate records suggest that climate change was not uniform across Central America or within the Maya lowlands (Stansell et al. 2020; Winter et al. 2020; Duarte et al. 2021). Precipitation variability in Guatemala is thought to be controlled by changes in moisture availability associated with Atlantic and Pacific basin ocean-atmosphere dynamics and sea surface temperatures. Differences in precipitation records may be explained partially by latitude; however, Itzan is only 95 km southwest of

220 Salpetén. We suggest that differences in climate variability on small spatial scales could also be explained by local climate related to distance to the Cordillera. There is a band of high precipitation overlying Itzan that is controlled by the Caribbean low-level jet and orographic precipitation as it is lifted over the Cordillera (Cook & Vizzy, 2010). A $\delta^{18}O$ record from Lake Kail (Fig. 3d) in the highland region similarly shows no signs of a Terminal Classic drought and is relatively muted in terms of climate variability (Stansell et al. 2020). This contrasts with precipitation to the northeast, which may have been

225 controlled more strongly by convection and, therefore, relative differences in land and ocean temperatures. In addition, it has been proposed that Maya deforestation could have reduced convective precipitation (Cook et al. 2012), and it is possible that this effect was less important in areas more strongly influenced by orographic precipitation. Finally, small changes in the zone of seasonal subsidence that causes relatively dry conditions in the northern Yucatan Peninsula might have affected Lake Salpetén but would have been less likely to influence Laguna Itzan (Fig. 3). Significant differences in modern rainfall

230 today support the idea of spatial heterogeneity in the past, and proximity to the Cordillera may drive these patterns (Fig. 1). Orographic “gaps” result in localised wind jets and affect precipitation, resulting in less climate variability in the southwest lowlands (Baldwin et al. 2021). Our data suggest that the southwest Maya lowlands had less extreme drying or climate variations than other regions, which is intriguing as this region is thought to have been where collapse began (Douglas et al. 2016).

235 Despite the lack of evidence for local drought, population does decline at Itzan, pointing to a regional interdependency related to drought elsewhere (Keenan et al. 2021). Societal upheaval in the central lowlands, including inter-polity warfare, the collapse of royal dynasties and regional political hierarchies, population dislocations, and the disruption of regional economies and inter-regional exchange, almost certainly would have had significant pan-lowland repercussions. Complex

240 and spatially variable patterns of climate change across the Maya lowlands would have exasperated the effects, resulting in a complex mosaic of social, political, and environmental outcomes. For example, the Rio de la Pasión catchment, within which Itzan lies, was not completely de-populated following the Terminal Classic population decline. Small inputs of coprostanol and PAHs suggest the presence of smaller numbers of people, although the largest PAH peak in the record, at 840 years BP, may be the result of wind-blown deposition from forest fires in dry landscapes to the north or locally (Vachula et al. 2022).



245 Increasingly negative $\delta^{13}\text{Cl}_w$ values until -36.5 ‰ suggest forest recovery to greater extents than at any point in the record, in the absence of large populations and deforestation.

4 Conclusions

This study reveals the changing land use over 3300 years reflecting the process of urbanisation – a decrease in fire use and movement of maize agriculture outside of the lake catchment. Secondly, our data suggest that the southwest Maya lowlands had less extreme drying or climate variations than other regions. This is important because some archaeologists propose this is where collapse began (Douglas et al. 2016) and if drought did not occur strongly, then it implies that it was not a precipitating cause of depopulation or collapse. A lack of temporal and spatial high-resolution palaeo-records in the region limit our ability to fully test the hypothesis of drought-related collapse in the southwest Maya lowlands, and similar multi-proxy work in the future could help us better understand the evolution of climate and society through time.

Methods

Sediment cores from Laguna Itzan in the southwest Maya lowlands were collected in 1997 and described by Breckenridge (2000). Two overlapping cores totalling 5.7 m of sediment were collected in 10.1 m water depth near the western shore of the lake, close to the deepest point of the lake (16.598° N, 90.4784° W). The core has been stored refrigerated at the LacCore facility at the University of Minnesota Twin Cities. The core was sub-sampled to obtain a temporal resolution of approximately 50–100-year intervals, without reference to sediment lithology. These samples were subsequently freeze-dried to remove water. Dried sediment samples were ground, weighed, added to a PTFE tube and extracted using a CEM MARS 6 microwave extractor with 10 mL of 9:1 dichloromethane:methanol. This ratio of solvents was selected after testing various methods for their extraction efficiencies using lake sediment samples (Kornilova & Rosell-Melé, 2003; Battistel et al. 2015). The MARS 6 oven was heated to 80 °C and held at that temperature for 20 minutes. The contents of the PTFE tube were then transferred to a centrifuge vial, centrifuged and the Total Lipid Extract (TLE) was transferred to an evaporating vial. 3 mL of 9:1 dichloromethane:methanol was added twice more to the centrifuge tube to ensure complete removal of extracted material. The TLE was evaporated and split into 2 fractions (a non-polar fraction and a polar fraction) using silica gel chromatography. The pipette columns consisted of 5 cm of silica gel, and 1 cm of sodium sulphate. 15 mL of hexane was eluted to collect the non-polar hydrocarbon fraction and 15 mL of methanol was eluted to collect the remaining neutral and polar fractions. The hydrocarbon fraction was analysed using gas chromatography with a flame ionisation detector (GC-FID) with a TRACE TR-5 GC Column (60 m × 0.25 mm) at McGill University in sequence with known standards for fluoranthene, pyrene, benzo[b]fluoranthene, benzo[e]pyrene, and benzo[ghi]perylene (Sigma-Aldrich). The polar fraction was saponified and the same sample aliquots were used to produce the previously published stanol record. The *n*-alkane



hydrogen and carbon isotope measurements were made using a Thermo Delta V Plus Isotope Ratio Mass Spectrometer (IRMS) coupled to a Thermo GC-IsoLink at McGill University, which uses a Thermo TG5Ms column (60 m × 0.25 mm × 0.25 μm). Compound-specific isotope values were calibrated to the V-SMOW and V-PDB scales using a set of n-alkane standards (Mix A6) that were measured offline in references to international standards at Indiana University (arndt.schimmelmenn.us/compounds.ht). The Mix A6 standards were used to calibrate both hydrogen and carbon isotope measurements for n-alkanes and were analysed at least twice daily. Laboratory standards were also analysed to monitor for instrumental drift and assess measurement reproducibility. The laboratory standards were derived from extracts of maple (*Acer* sp.) leaves collected on the campus of McGill, with synthetic alkanes (Sigma-Aldrich) added to enhance the C₂₂ and C₃₀ n-alkane concentrations. Laboratory standards were run after every 3 samples to check for instrumental drift. Only the C₂₉ n-alkane was consistently resolved throughout the core, and therefore we focus on this measurement. C₂₉ production is linked to terrestrial trees (Bliedtner et al. 2018; Aichner et al. 2018). Measurement uncertainty was estimated through replicate or triplicate analysis of each sample. Isotope data are presented as the mean of double or triple replicates with a pooled standard error shown in grey envelope (Polissar & D'Andrea, 2014; Fig. 2). The analytical standard error ranged from 3.1 to 4.4‰ for δD_{lw} measurements and is 0.25‰ for δ¹³C_{lw} measurements.

The age model for the PAHs and faecal stanols, is based on an age model created using ¹⁴C ages of terrestrial macrofossils (Douglas et al. 2018; Keenan et al. 2021) from the cores calibrated using IntCal13 (Douglas et al. 2018; Reimer et al. 2013) using a 4th-order polynomial fit with the Classical Age-Depth Modeling (CLAM) software in R (Blaauw 2010). The average age uncertainty (95% confidence interval) of the chronology is 100±30 years. The age model for the leaf wax n-alkanes is based on compound specific radiocarbon dating of n-alkanoic acids from the Itzan core. The use of the age chronology based on n-alkanoic acids from Itzan for the n-alkanes assumes that the n-alkanoic acids were produced at the same time as the n-alkanes. Because of the potential residence time of leaf waxes in sediments for up to thousands of years, this chronology is more accurate for understanding isotopic variation in leaf waxes than the age model determined from terrestrial macrofossils found in sediments (Douglas et al. 2016; Douglas et al. 2014). As we are interested in the climate at the point of formation and as it has been shown that waxes can take up to thousands of years to be deposited in lake sediments, it is necessary to use the compound specific radiocarbon age model for the waxes. For the stanols and PAHs it might also be the case that there is some long-term soil storage, but in the absence of compound specific ages we assume low residence times before deposition, and include 100-year moving averages. Faecal stanol concentrations agree broadly with population change inferred from archaeological evidence (Johnston 2006). Furthermore, for concentration measurements of PAHs and stanols, our focus is the flux to the lake at a given point in time. Therefore, the relevant time for the paleoclimate signal is the time of deposition (terrestrial macrofossil age model), whereas for the n-alkane isotope data it is the time of molecule formation (compound



specific age model). However, we acknowledge that long-term soil storage of stanols or PAHs would complicate their records, and that some of the PAH and $\delta^{13}\text{C}_{\text{lw}}$ peaks could potentially overlap, and this question deserves future attention.

Data availability

310 Data in this manuscript are available here <https://doi.org/10.6084/m9.figshare.29497826.v1>

Author contribution

Benjamin Gwineth: Conceptualization, Methodology, Investigation, Validation, Visualization, Writing - Original Draft;
Kevin Johnston: Resources, Writing - Review & Editing; Andy Breckenridge: Resources, Writing - Review & Editing; Peter
315 M. J. Douglas: Conceptualization, Supervision, Funding acquisition, Writing - Review & Editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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