












Drought-Induced Civil Conflict Among the Ancient Maya

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The influence of climate change on civil conflict and societal instability in the premodern world is a subject of much debate, in part because of the limited temporal or disciplinary scope of case studies. We present a transdisciplinary case study that combines archeological, historical, and paleoclimate datasets to explore the dynamic, shifting relationships among climate change, civil conflict, and political collapse at Mayapan, the largest Postclassic Maya capital of the Yucatán Peninsula in the thirteenth and fourteenth centuries CE. Multiple data sources indicate that civil conflict increased significantly and generalized linear modeling correlates strife in the city with drought conditions between 1400 and 1450 cal. CE. We argue that prolonged drought escalated rival factional tensions, but subsequent adaptations reveal regional-scale resiliency, ensuring that Maya political and economic structures endured until European contact in the early sixteenth century CE.

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Archeological and historical studies have proposed linkages among global climate change, societal instability, violent conflict, and sociopolitical collapse^{1–7}, but also instances of resilience, transformation and sustainability in the face of climate pressures^{8–10}. The influence of climate change on civil conflict in the last century has also been the focus of compelling statistical studies^{11,12}, and an important nexus for debate, revealing the importance of human agency and unexpected, non-linear relationships between climate and human behavior^{13–19}. Longer-term climatic, archeological, and historical records can contribute to these contemporary debates, but demand a rigorous transdisciplinary framework that bridges natural and social systems^{8,18}. We report a singular case study of the complexities of the natural and social systems at the Postclassic Maya capital of Mayapan (1200–1450 calendar year [cal.] CE) throughout its history and its ultimate demise. This occurred in the context of drought, civil conflict, and the collapse of the regional state. A period of political balkanization after 1450 cal. CE preserved complex organizational institutions and fostered a resilient, peninsular-wide market economy observed at European contact in the early 16th century CE. We examine climate stresses to Mayapan's local and regional subsistence and economic systems, and the behaviors of human actors that included political violence within these dynamic social and political transformations.

Climate assessment reports of the intergovernmental panel on climate change (IPCC) evaluate risk and model vulnerability during the last century at regional and global scales²⁰. Long-term climate reconstructions reveal that some climate variations in the past were of significantly greater magnitude than those experienced in the last 100 years. Furthermore, current and future anthropogenic influences are projected to amplify the severity of extreme events in the water cycle and lead to more intense and prolonged droughts than those that impacted agricultural productivity in the recent past^{21,22}. Archeological and historical records are well-suited for examining past societal effects of climate crises over long-term cycles. Such effects in Pre-Columbian Mesoamerica may have included migration, demographic decline, geographic shifts in centers of political power, and warfare. We focus on the latter, specifically the initiation and consequences of societal conflicts that coincided with climate impacts on the agrarian food base and regional political economy. These subsistence and related economic foundations are well-known from the archeological record and from memories of descendant peoples in early Colonial period European accounts¹². The magnitude and duration of the climate impacts in the northern Yucatán Peninsula (Mayapan) may have transcended established mechanisms to overcome modest inter-annual rainfall fluctuations²³, given the limitations of cumbersome transport and the long-term storage of maize, the primary staple grain^{2,24}.

The Maya region offers the breadth and depth of archeological, historical, and climate records essential for studying correlations between social change and fluctuating climate conditions. Here, we compare the archeological and ethnohistorical evidence for civil conflict with local and regional records of climate change at the last large Pre-Columbian Maya capital city of Mayapan (1200–1450 cal. CE, Fig. 1). Multiple studies have shown that patterns of political formation, consolidation, and fragmentation of Maya states were cyclical well before Mayapan became a Postclassic Period political center. From the middle of the first millennium BCE until Mayapan's emergence, kingdoms formed, consolidated, or expanded their domains of subjects, then ultimately fragmented at the same time that new centers emerged to dominate the landscape^{25–28}. Large cities first appeared along the western edges of the Maya region by 1000–800 cal. BCE²⁹ and numerous monumental centers and networks of villages developed in the heart of the Maya Lowlands by 500 cal. BCE³⁰. One of

the largest state capitals in all of Maya prehistory (in terms of monumentality), El Mirador, was established between 100 cal. BCE and 250 cal. CE²⁷. The Lowlands region was dotted with kingdoms large and small, amidst a densely populated countryside of towns and villages throughout the Classic period, with the Late Classic Period (600–800 cal. CE) witnessing the emergence of the largest number of competing states in the southern lowlands. Shifting centers of influence and the most dramatic sequential disintegration of these cities occurred during the Terminal Classic period, between 800 and 1000 cal. CE, with climate change argued to be a contributing factor to increasing conflict^{2,31–34}. During this interval, the towns and cities of the northern and coastal peninsula (e.g., Uxmal, Chichen Itza, Aventura) were magnets for Maya settlement, in turn experiencing political and demographic decline that coincide with multiple lines of evidence for drought during the eleventh century cal. CE^{10,35,36}. But northern and coastal Maya populations subsequently recovered quickly and the political capital of Mayapan arose and governed from at least 1100 to 1450 cal. CE³⁷. Mayapan provides an appropriate test case for exploring the causes and impacts of civil conflict because of its temporal proximity to European Contact, and retrospective, Colonial-Period documentary accounts provide additional evidence that can be evaluated with chronological (radiocarbon [¹⁴C] dates) and human osteological data.

Mayapan emerged as a regional capital on the Yucatán Peninsula, following the demise of Chichen Itza between 1000 and 1100 cal. CE^{38,39}. Numerous political families, smaller polities, and substantial populations endured through the fall of the Chichen Itza polity. Many of these entities were reintegrated into the Mayapan confederacy, especially those concentrated in the northwest region of the peninsula³⁵. Historical sources indicate that the most influential nobility came from the houses of the Cocom, the Xiu, and the Chel (among others) who governed the polity as members of Mayapan's ruling council^{40,41}. These lords established the city's monumental center, replete with its principal pyramid, the Temple of K'uk'ulkan, and a nucleated set of other temples, colonnaded halls, and shrines covered in murals and sculptures that reflect the city's mythical foundations^{39,42}. Densely settled residential zones extend from the center in all directions within the city's 9.1 km-long circumferential wall, which encloses an area of 4.2 km², and housing sprawls at least a half kilometer beyond this boundary (Fig. 1)⁴³. Twelve formal gates in the wall directed pedestrian traffic into and out of the city; the wall was clearly a defensive feature⁴³. The monumental and settlement zones were founded with the intent of establishing a new political capital. Population aggregation and recruitment across the Yucatán peninsula, and occasionally beyond, persisted throughout Mayapan's history as indicated by strontium isotopes in human teeth⁴⁴. Subject peoples were summoned to move to the city to provide all manner of services⁴¹. Human remains are ubiquitous at the archeological site, which was once home to 15–20,000 inhabitants who were sustained by household gardens and orchards, hunting, and rain-fed maize agriculture, supplemented by trade³⁷. Dietary stable isotope studies indicate heavy reliance on maize, a crop that was highly sensitive to periodic droughts, given the limitations for long-term grain storage^{44,45}.

In this work, we use a transdisciplinary approach that combines archeological, historical, and paleoclimate datasets to examine the dynamic interactions of climate change, civil conflict, and political collapse at Mayapan during the 14th and 15th centuries CE. We use generalized linear modeling to demonstrate that increases in traumatic injuries evident in the bioarcheological record strongly correlate with drought conditions between 1400 and 1450 cal. CE. We argue that prolonged drought escalated rival factional tensions that ultimately resulted in the

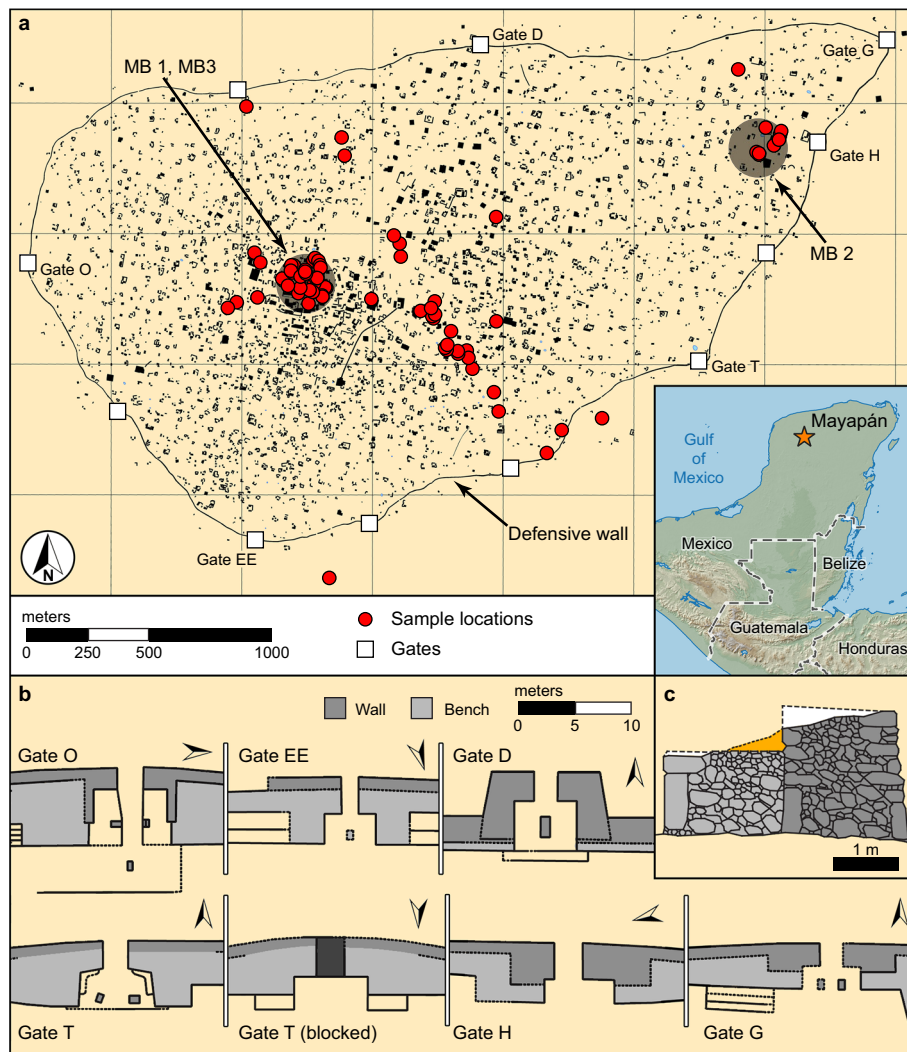


Fig. 1 Map of Mayapan. **a** Layout of the city showing housing complexes, the defensive wall, formal gates, and the locations of skeletal samples (red dots). **b** Gate and wall configurations adapted from⁴³. **c** Cross-section of the tiered double-wall construction surrounding Mayapan. MB, Mass Burial.

abandonment of the city, but that Maya political and economic structures endured regionally until European contact in the early 16th century CE.

Results

Integration of archeological and historical observations. We used accelerator mass spectrometry (AMS) to ¹⁴C-date purified bone collagen from 205 human skeletons to develop a high-temporal-resolution history of population fluctuations at Mayapan (Fig. 2c; also see Methods and Supplementary Note 4). We then integrated these data with archeological, historical, osteological, and paleoclimatological data to explore relations between periods of societal stability or fragility, and drought. These data indicate a rural population in the vicinity of this location from the Middle Preclassic (~1000 cal. BCE) through the Colonial Period. After the establishment of the Postclassic capital by 1150 cal. CE, there was rapid nucleation of populations starting ~1200 cal. CE that continued through 1320 cal. CE (Fig. 2c).

According to retrospective historical documents, Mayapan was a militaristic state that raided its peninsular enemies and took war captives destined for slavery or sacrifice. Historical records can be biased, so we used archeological, osteological, and radiocarbon data to establish the timing of a series of events recorded historically using the Maya K’atun calendar^{4,40}. These intervals

include: 1) a period of “terror and war” [1302–1323 cal. CE], 2) an interval of “inquisition against members of the Xiu nobility” [1361–1381 cal. CE]; 3) decentralization and population decline [1382–1401 cal. CE], 4) massacre of the Cocom noble family [1440–1461 cal. CE] and 5) political demise of the regional state and abandonment of the city [post-1450 cal. CE] (Fig. 2a–d).

Incorporating regional climate & paleoclimate records. To investigate linkages between these events and climate, we compared the records of cultural change to local and regional paleoclimate records. Modern rainfall on the northwestern Yucatán Peninsula is marked by a strong north-south gradient, from a minimum of 450 mm yr⁻¹ at Progreso on the northwest coast, to 1000 mm yr⁻¹ at Mérida, and 1150 mm yr⁻¹ at Abala, near Mayapan (Supplementary Fig. 1). A pronounced west-to-east increase in precipitation across the northern peninsula, a consequence of the prevailing easterly winds heading inland (westward) from the Caribbean water source, also exists. Rainfall is highly seasonal, with the wet season lasting from May to October. Northern Yucatán lies within the main North Atlantic hurricane belt and a single storm event can contribute a substantial proportion of annual precipitation for that year. Farming in the region depends heavily on the timing of the onset,

duration, and total effective rainfall of the wet season⁴⁶. Although short-term droughts tend to be spatially and temporally patchy in northern Yucatán⁴⁷, more protracted droughts during the historic period are evident in documentary and paleoclimate archives^{48,49}.

Those extended dry intervals of the Colonial Period caused well-documented crop failures, severe famines, and high mortality that destabilized the economy and led to periodic dispersal of populations from towns in the northern Yucatán⁴⁸.

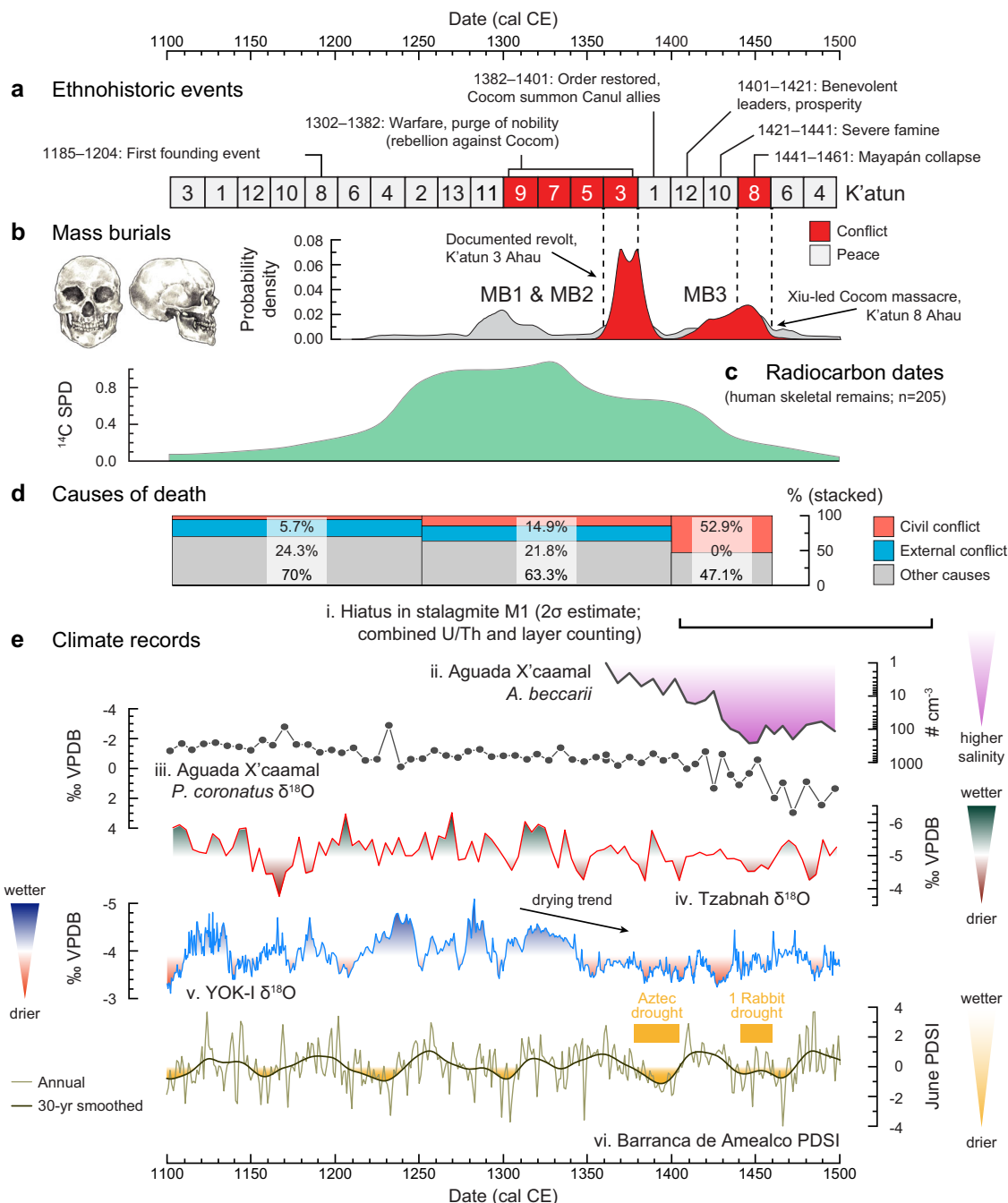


Fig. 2 Culture and climate records. **a** Retrospective events recorded historically using the Maya K'atun calendar, highlighting intervals of conflict and peace within Mayapan^{40,41}; **b** Summed probability distributions of AMS- ^{14}C -dated human skeletons from mass burials MB1, MB2, and MB3 as an independent measure of internal conflict (OxCal Code and model provided in Supplementary Code 2); **c** Summed probability distribution of directly AMS- ^{14}C -dated human skeletal remains from Mayapan as a population size estimate⁸⁸ (see methods and Supplementary Discussion 4; Code available in Supplementary Code 1); **d** Osteological data indicative of internal or external conflict and other causes. The sample included 35 individuals <18 years of age, 142 individuals ≥ 18 years of age (of which 48 are males, 49 are females and 45 are adults of indeterminate sex), and 28 individuals of unknown age (see Supplementary Discussion 3 and Supplementary Data 1). **e** Local and regional climate records. (i) Estimated age ($\pm 2\sigma$) of the hiatus for Mayapan stalagmite M1 (this study). (ii) Abundance of the benthic foraminifer *Ammonia beccarii* in the sediment profile from Aguada X'caamal⁹⁰ with an updated time scale (this study). (iii) Oxygen isotope record of the snail *Pyrgophorus coronatus* from the same core⁹⁰. (iv) Oxygen isotope record from the Chaac speleothem from Tzabnah Cave, Tecoh, Yucatán⁵³; (v) Oxygen isotope record from stalagmite Yok-I from Yok Balum Cave, Belize²; (vi) Palmer Drought Severity Index (PDSI) inferred from tree ring record from Barranca de Amealco, Mexico⁶¹. All unpublished datasets plotted are provided in Supplementary Data 2 and the Source Data File. U/Th, Uranium/Thorium, MB, Mass Burial.

Rainfall over the Yucatán Peninsula is derived mainly from the Caribbean, Atlantic, and Gulf of Mexico sources, and only occasionally from the Pacific². Summer wet season rainfall dynamics on the peninsula are influenced by the Caribbean Low-Level Jet (CLLJ), an easterly trade wind system. Variability of the CLLJ depends on the position and strength of the Bermuda High⁵⁰, meridional sea level pressure (SLP), and sea surface temperature (SST). Stronger trade winds, caused by a high meridional SLP gradient, result in lower SSTs and drier conditions on the Yucatán Peninsula. The sea-level pressure gradient between the Caribbean and the eastern Pacific links the region in a complex fashion with the inter-tropical convergence zone (ITCZ) and the El Niño-Southern Oscillation (ENSO) system in the Pacific^{51,52}, influencing Yucatán moisture dynamics indirectly. Such linkages tend to occur in the wet season, prior to El Niño events⁵¹, which reduce tropical depressions and hurricanes in the study region. Outside the rainy season, winter *nortes* occasionally bring rainfall and cold, windy weather from the Gulf of Mexico⁴⁶.

The YOK-I speleothem $\delta^{18}\text{O}$ record² shows a series of wetter intervals between 1100 and 1340 CE, an interval when populations at Mayapan were growing (Fig. 2e). A drying trend that began after 1340 CE is inferred from YOK-I $\delta^{18}\text{O}$ data and is consistent with the more local, but lower-resolution Chaac speleothem $\delta^{18}\text{O}$ record from Tzabnah Cave in Tecoh, located ~12 km north of Mayapan (Supplementary Note 1)^{53,54}. The mid-14th-century drying trends are consistent with a growth hiatus between 1397 and 1427 CE (2σ confidence interval) identified here in a stalagmite (M1) collected from a cave located directly below the central Plaza at Mayapan, and analyzed for the present study (Supplementary Notes 1 and 2; Supplementary Data 1). One explanation for cessation of growth is that the climate became so dry at Mayapan that drip water stopped reaching the stalagmite and calcite deposition ceased. When deposition resumed about 1600 CE, the stalagmite mineralogy changed from calcite below to aragonite above the hiatus. At Aguada X'caamal, a small sinkhole ~27 km west of Mayapan, the $\delta^{18}\text{O}$ and salinity of the lake water increased abruptly at 88 cm in the core, corresponding to a date of 1345–1458 CE (2σ confidence interval; Supplementary Note 2). Stable isotope and faunal changes in Aguada X'caamal coincide approximately with the detected hiatus and mineralogical transition from calcite to aragonite in stalagmite M1 from beneath Mayapan.

Population Dynamics and Civil Conflict. Summed probability distributions (SPD) of directly radiocarbon-dated human skeletal material (Fig. 2c, Supplementary Fig. 14, Supplementary Note 4) from Mayapan show steady population growth and nucleation starting ~1100 cal. CE and a peak between 1200 and 1350. Populations started to decline after ~1350 cal. CE and were very low by 1450 cal. CE. This is consistent with both the K'atun 1 Ahau (1382–1401 cal. CE) depopulation and the K'atun 8 Ahau (1441–1461 cal. CE) depopulation and abandonment of Mayapan, mentioned in multiple historical sources (e.g., Fray Diego de Landa and the Books of Chilam Balam of Chumayel, Tizimin, and Mani)⁴⁰. Public artistic programs and historical records also suggest greater interaction with Aztec populations from Central Mexico during that time, initially through Mexican mercenaries and traders⁵⁵. At the same time, the Cocom lineage aligned itself with Canul allies at the end of the 14th century, associated with internal disputes with their Xiu rivals (Fig. 2a)⁴⁰.

Mayapan's cityscape contains varied and numerous funerary deposits, as well as extra-funerary deposits, interpreted as mass

graves (Supplementary Note 3; Supplementary Data 2). Multiple individuals were often interred together in household graves, and ossuaries containing the secondary deposits of skeletal material exist within the monumental center, as well as in high-status houses in the residential zone^{56–58}. In contrast, other large deposits of human remains in the monumental center (e.g., Round Temple Complex) likely represent sacrificed (or otherwise killed) war captives from polities targeted by the Mayapan state elsewhere on the peninsula (beyond the northwest stronghold of the confederacy). One such deposit was found in an alleyway next to the site's iconic Round Temple, which contained the crania and long bones of 25 individuals who were directly AMS-¹⁴C-dated to 1302–1362 cal. CE (Supplementary Note 3). Three of the individuals suffered perimortem cranial trauma and cut marks on some of the bones, indicating postmortem dismemberment and defleshing, likely caused by intentional desecration^{56,57,59}. These mortuary deposits may correspond to historical references of conflict and strife waged on the Yucatán Peninsula between 1302 and 1362 cal. CE⁴⁰, during a period when Mayapan's monumental landscape was fully built and when its population and regional influence were at their peak.

Another type of mass grave in the city is unlike either funerary features or deposits of the remains of war captives. Rather, it is indicative of violence experienced by individuals who were likely high-status residents of Mayapan. These two shallow mass graves also exhibit desecration of human and ritual pottery remains (deity effigies); both are adjacent to ceremonial edifices. Both features date to the late 14th century (1350–1400 cal. CE; Supplementary Note 3). One is in the center of the city by Temple Q-80 (MB1; Q.79; 10 individuals; Supplementary Fig. 9) and the other is next to the Itzmal Ch'en temple and colonnaded hall, part of an outlying ceremonial group near the far eastern gates of the city wall (MB2; 20 individuals; see Fig. 1)^{37,57}. Both MB1 and MB2 are shallow graves that contain multiple, mostly disarticulated individuals who were buried along with smashed pottery (Chen Mul Modeled censers). Four of the individuals in MB1 suffered violent deaths, as indicated by stone knives embedded in their scapula, rib cage, or pelvis⁶⁰. The bones of ~20 individuals in MB2 were chopped into pieces and burned. Both observations are consistent with historical records for the late 14th century CE, which indicate that one faction of the government persecuted, tortured, and executed rival factions. Following this turmoil, sources suggest a restoration of order and several decades of relative stability just before and after 1400 CE⁴⁰. Direct AMS ¹⁴C dates on 10 individuals from MB1-MB2 are statistically indistinguishable from one another, with a modeled age of 1360 to 1400 cal. CE. This coincides with a major central Mexican drought in the Aztec-controlled highlands (1378–1404 cal. CE)⁶¹, which was the most extreme dry episode since 771 cal. CE. The historical records of massacres at Mayapan also correspond with the population decline that is evident in the decreasing number of directly AMS ¹⁴C-dated individuals (Fig. 2c), as well as evidence for the destruction and abandonment of some buildings around the same time as MB1 and MB2³⁷. Remnant populations persisted in the city, but new architectural construction was much reduced as violence increased.

The last recorded mass burial at Mayapan (MB3) flanks the northern staircase of the Temple of K'uk'ulkan, and is the best candidate for the Xiu-led massacre of members of the Cocom family that resulted in the city's collapse and ultimate abandonment. The skulls and isolated limbs of nine individuals, many of them children ($n = 7$), were found mixed with debris from building collapse (Supplementary Note 3). Two of these individuals show evidence for violent death in the form of

perimortem rib puncture wounds, consistent with a massacre. Direct AMS- ^{14}C measurements indicate that they were killed after 1400 cal. CE. Radiocarbon dates for six of these individuals are statistically indistinguishable and suggest a single massacre between 1440 and 1460 cal. CE. Mitochondrial DNA indicates that these individuals shared strong maternal genetic affinities and were potentially related on the maternal line⁴⁴. Remarkable agreement between the historical accounts of this politically charged, divisive event and the calibrated radiocarbon dates on physical remains suggests that MB3 pertains to the violent battle and destruction of Mayapan in K'atun 8 Ahau (1441–1460 CE). This and other historical references are increasingly corroborated by paleoclimatic, paleoenvironmental, and archaeological datasets, dated using AMS ^{14}C and U-Th series methods. Like Mayapan's ultimate demise, drought and famine are also described in the Book of Chilam Balam of Mani (Fig. 2; 1441–1460 CE)⁶².

Fisher's exact tests (one-tailed) were used to compare counts of deaths from internal conflict during Mayapan's occupation (Fig. 2). Results show significant differences between numbers of deaths in the following intervals: Early to Middle (1100–1400 cal. CE) $p = 0.053$; Early to Late (1100–1500 cal. CE) $p < 0.001$; Middle to Late (1250–1500 cal. CE) $p = 0.002$ (Fig. 2D). Population decline and violence coincided with a marked period of drying indicated by greater oxygen isotope values in the YOK-I (Belize) and nearby Chaac speleothem-based paleoclimate records, a shift to greater $\delta^{18}\text{O}$ values in snails from a sediment core taken in nearby Aguada X'caamal, and the abrupt rise in the abundance of the euryhaline benthic foraminifer *A. beccarii* in the X'caamal profile (Fig. 2; Supplementary Note 2). In the context of drought, leaders of political units who had belonged to the Mayapan confederacy returned to their home territories after the dissolution of the regional state. They headed numerous smaller polities across the peninsula, some of which were quite powerful and prosperous at the time of Spanish contact⁶³.

Discussion

The period of depopulation at Mayapan also overlapped with the drought of *1 Rabbit* (1454 cal. CE) that caused severe famine in Aztec Central Mexico (Fig. 2)⁶⁴. That famine followed closely on the heels of a devastating series of climate disasters that affected Central Mexico in 1446, especially, starting in 1450 cal. CE. Impacts of those Central Mexican droughts on the Maya region remain unclear, but surely, lucrative long-distance trade with Central Mexico would have been temporarily disrupted⁶⁵. Trade was an especially important livelihood for a populous network of towns across the peninsula, extending from the Gulf Coast to the Caribbean. Significant fluctuations in local rainfall, especially in the form of extreme droughts, invariably affected agricultural productivity, despite the significant investment of Mayapan and its contemporary cities and towns in extensive agrarian farming, intensive cultivation of orchards and gardens, and complementary activities of hunting, fishing, and husbandry of domestic turkeys and deer³⁷. Spatial differences in rainfall, soil depth, surface water, and elevation gave rise to diverse local production opportunities and histories in the Maya Lowlands⁶⁶, and importantly, differences in relative vulnerability to short-term or local climate variations. Variability in the development of water management and intensive agricultural systems also occurred in the lowlands, although such investments are generally more limited in the northwest and central Yucatán compared to other zones^{67–71}. Short-lived, temporary crises were systematically addressed by exchanges

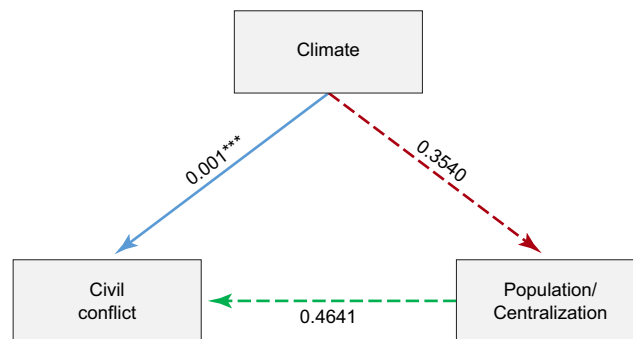


Fig. 3 Summary of model results. The diagram compares the direction and significance of general linear modeled relationships between climate, population, and civil conflict. P -values are given for each relationship, with asterisks denoting significance. Dotted lines show non-significant relationships. Colors correspond with model fit plots in Supplementary Fig. 15.

with adjacent peninsular regions of food, an important commodity sold in Pre-Columbian and Contact Period Maya marketplaces^{72,73}.

We used Generalized Linear Modeling (GLM) to examine the relationships among climate change, fluctuations in population size/nucleation (SPD), and osteological data indicative of internal conflict during Mayapan's entire occupational history (~1100–1450 cal. CE; Fig. 3, Supplementary Note 3, Supplementary Figs. 15–16). Osteological data from directly radiocarbon-dated human skeletal material (associated with civil conflict) were compared with local/regional climate data. Model results show a significant increase in internal conflict associated with drought conditions (Tzabnah, $p = 0.0001$; YOK-I; $p = 0.0033$; Fig. 3, Supplementary Table 2). Comparisons of climate and population size/nucleation during this same interval reveal a non-significant relationship, suggesting population dynamics were largely structured by phenomena other than local precipitation. A multivariate GLM, comparing climate records to conflict with SPD as an interaction term, rejects the hypothesis that climate only has a direct effect on internal conflict when population numbers are high.

Despite the lack of association between climate and population throughout the occupational sequence, we do find a significant relationship between drought and population decline when we examine the period between 1350 and 1430 cal. CE, i.e., the time when the most substantial population decline occurred ($p = 0.0065$; Supplementary Fig. 16). Results indicate that both climate drying and population decline or dispersal correspond to the dramatic increase in civil conflict near the end of the Mayapan occupational sequence. Finally, we also explored the relationship between warm summer/fall sea-surface temperatures in the Cariaco Basin (Venezuela)⁷⁴ and conflict, argued to be related to increased warfare in the Maya region at the end of the Classic Period (~700–900 CE)⁷⁵, but found no significant relationship ($p = 0.65$).

Our findings support Mayapan's storied institutional collapse between 1441 and 1461 cal. CE, a consequence of civil conflict driven by political rivalry and ambition, which was embedded in the social memory of Yucatecan peoples whose testimonies entered the written record of the early Colonial Period⁴¹. Our data indicate that institutional collapse occurred in the environmental context of drought and conflict within the city. Vulnerabilities of this coupled natural-social system existed because of the strong reliance on rain-fed maize agriculture, lack of centralized long-term grain storage, minimal opportunities for irrigation, and a sociopolitical

system led by elite families with competing political interests, from different parts of the Yucatán Peninsula. We argue that long-term, climate-caused hardships provoked restive tensions that were fanned by political actors whose actions ultimately culminated in political violence more than once at Mayapan. Direct radiocarbon dates and mitochondrial DNA sequences from the remains of individuals in the city's final mass grave suggest they were family members of the heads of state (the Cocombs), ironically and meaningfully laid to rest at the base of the Temple of K'uk'ulkan, the iconic principal temple and ritual center of Mayapan. Our results suggest that rivalry among governing elites at Mayapan materialized into action in the context of more frequent and/or severe droughts. Comparatively, such climate challenges present a range of opportunities for human actors, from the development of innovative adaptations to the stoking of revolution^{5,18,76}. These climate hardships and ensuing food shortages would have undermined the city's economic base and enabled the Xiu-led usurpation. The unifying and resilient institutions that held the Mayapan state together until ~1450 CE were ultimately eroded, the confederation dissolved, and the city largely abandoned.

As a counterpart to strong archeological, historical, and climatic evidence for civil conflict and institutional collapse at Mayapan, we explored different pathways for resilience and societal transformation to regional climate change⁸. Mobility was an important component of social change as people dispersed from Mayapan to other parts of the Yucatán Peninsula⁷⁷. This was a common indigenous response, observed historically during drought periods when Maya people abandoned Spanish towns and dispersed to settlements in the unsubdued frontier to the south^{48,78,79}. The social and political landscape of the Yucatán Peninsula was also reorganized into a network of smaller states that were politically independent, but economically interwoven. Prosperous coastal towns, first observed by Spaniards,⁶³ took advantage of a variety of freshwater features^{69,70} and marine resources that provided opportunities for subsistence and economic diversification. Maritime commerce thrived, with large canoes carrying salt, chocolate and other commodities around the peninsula⁸⁰. At the time of European contact, the Yucatán Peninsula was divided into 15 states⁶³, some with developed hierarchies and kings (*halach winik*) and others more loosely organized; bureaucratic systems ranking nobles according to an array of religious and political titles⁸¹. The conflict between states occurred and each state had military leaders who could quickly mobilize armies, but there is little historical evidence for civil conflict within each state. Ironically, climatic impacts caused by drought and related pestilences continued in northern Yucatán with little respite in the century following Mayapan's fall⁴⁸. Yet economic, social, and religious traditions persevered until the onset of Spanish rule, despite the reduced scale of political units, attesting to a resilient system of human-environmental adaptations⁶³.

Overall, we argue that human responses to drought on the Yucatán Peninsula during the 15th century CE were complex. On the one hand, drought stimulated civil conflict and institutional failure at Mayapan. However, despite decentralization, intervals of mobility, temporary impacts to trade, and political reorganization in the region, a resilient network of small Maya states persisted and was encountered by Europeans in the early 16th century⁶³. These complexities are important as we attempt to evaluate the potential success or failure of modern state institutions designed to maintain internal order and peace in the face of future climate change. Recent regional climate records and modeling results suggest drier conditions in Central America are associated with global warming^{82,83}. Food insecurity, social

unrest, and drought-driven migration are already of considerable concern in parts of Mexico and Central America. Our transdisciplinary work highlights the importance of understanding the complex relationships between natural and social systems, especially when evaluating the role of climate change in exacerbating internal political tensions and factionalism in areas where drought leads to food insecurity.

Methods

The primary bioarchaeological data for this paper derives from Instituto Nacional de Antropología e Historia (INAH)-Yucatán's projects in the excavation and restoration of Mayapan's monumental zone (directed by Carlos Peraza Lope). Additional data originate from salvage archeological work conducted by Peraza Lope for INAH along the Merida-Chetumal highway that crosses through the Mayapan site, as well as National Science Foundation-supported collaborative research in the settlement zone. Permits were issued by the INAH-Consejo de Arqueología for excavation and the export of samples for analysis in the US (C.A.401-36/2172, issue date: October 21, 2009; 401-3-10492/11554, AA-53-09 A/ 3989, issue date: November 5, 2009; C.A.401-36/0028, issue date: January 19, 2010; C.A.401-36/1223, issue date: July 13, 2010; 401-3-7328, AA-40-10 A/ 948, issue date: August 10, 2010; 401-3-1016, AA-01-16, issue date: February 5, 2016). All work was conducted with local Yucatecan archeologists, field crews, support staff, and the community of Telchaquillo, located 1 km north of the archeological site of Mayapan. All excavation, including the excavation of human remains, was done with community permission and participation. All human remains that fall under the auspices of the Instituto Nacional de Antropología e Historia of Mexico (Yucatan) are stored at a permanent repository located at the laboratory of the Proyecto INAH Mayapán, Telchaquillo, Yucatán, Mexico. Samples associated with the Carnegie Institution of Washington excavations are curated at the laboratory of the Centro INAH Yucatán, Mérida, Yucatán, Mexico.

Radiocarbon dating. We report 211 AMS ¹⁴C dates from 205 sets of human remains excavated at Mayapan (see Supplementary Data 2). Bone collagen for AMS ¹⁴C analysis was extracted and purified using the modified Longin method with ultrafiltration⁸⁴. Samples with low collagen yields were processed using amino acid hydrolysis and XAD purification⁸⁵. Physically cleaned samples were demineralized and gelatinized. Crude gelatin yields were recorded and the gelatin was ultra-filtered, retaining >30 kDa molecular weight gelatin. Carbon and nitrogen concentrations and stable isotope ratios were measured at the Yale Earth Systems Center for Stable Isotopic Studies facility with a Costech elemental analyzer (ECS 4010) and a Thermo DeltaPlus Advantage isotope ratio mass spectrometer, respectively. Sample quality was evaluated by % crude gelatin yield, C%, N%, and C:N ratio. Ultrafiltered gelatin (~2.1 mg) was combusted for 3 h at 900 °C in vacuum-sealed quartz tubes with CuO and Ag wire. Graphitization and AMS ¹⁴C measurements were done at the Keck Carbon Cycle Accelerator Mass Spectrometer facility and the Penn State University Accelerator Mass Spectrometer Laboratory. The ¹⁴C ages were corrected for mass-dependent fractionation using measured ^δ¹³C values and compared with backgrounds and known-age secondary standards. All dates were calibrated in OxCal version 4.4⁸⁶ using the IntCal20 curve⁸⁷.

Summed probability distributions. To estimate population centralization at Mayapan, we used the rcarbon package⁸⁸ in the R environment to generate summed probability distributions (SPDs) on calibrated radiocarbon dates from our sample of 205 dated human skeletal remains. We then compared our SPDs to a Monte-Carlo simulation of a null exponential growth model (see Supplementary Note 4) to identify general population centralization trends as well as periods of time when our SPD significantly deviated from the expected null values⁸⁹. Higher- or lower-than-expected density of observed SPDs for a particular year indicates a local divergence of the observed SPD from the fitted exponential growth null model, and the significance of these deviations can be used to assess the goodness-of-fit using a global test.

Generalized linear model-centralization. We fit generalized linear models (GLMs) with a binomial distribution and log link appropriate to proportional data and quasi-likelihood estimation to account for overdispersion. To generate the GLM comparing the Mayapan SPD (response variable) to the YOK-I ^δ¹⁸O and Tzabnah ^δ¹⁸O data (predictor variables), we derived summed probability values and paired them with ^δ¹⁸O values for every year both data were available. To pair SPD values with internal conflict data, we averaged values for the 2σ ¹⁴C probability distribution for each individual. For example, if an individual had a 2σ ¹⁴C range of AD 1100–1175, all SPD values from that temporal range were averaged. The resulting GLM was generated in the R programming environment.

Generalized linear model-conflict. A GLM with a binomial distribution and log link appropriate to proportional data and quasi-likelihood estimation to account for overdispersion was estimated to compare precipitation with individual deaths from civil conflict. To do this we averaged the YOK-I and Tzabnah ^δ¹⁸O values for

the 2σ ^{14}C probability distribution for each individual. The resulting dataset contains a sub-sample of 183 individuals, each with a death from civil conflict and YOK-I and Tzabnah $\delta^{18}\text{O}$ designation, which was uploaded into the R programming environment to generate the GLMs.

Reporting summary. Further information on research design is available in the Nature Research Reporting Summary linked to this article.

Data availability

All source data generated in this study are provided in the Supplementary Information/Source Data file. Osteological/Bioarchaeological data was generated at the University of New South Wales, Australia (Stanley Serafin; s.serafin@unsw.edu.au). All human remains that fall under the auspices of the Instituto Nacional de Antropología e Historia of Mexico (Yucatán) are stored at a permanent repository located at the laboratory of the Proyecto INAH Mayapan, Telchaquillo, Yucatán, Mexico. Samples associated with the Carnegie excavations are stored at the laboratory of the Centro INAH Yucatán, Mérida, Yucatán, Mexico. All sample requests should be made to INAH (Carlos Peraza; cperaza_yuc@hotmail.com). AMS radiocarbon data was produced at the Pennsylvania State University Accelerator Mass Spectrometry Facility (current contact is Brendan Culleton; bjc23@psu.edu). The speleothem and associated data were generated at Cambridge University (David Hodell; dah73@cam.ac.uk). Source data are provided with this paper.

Code availability

All R code generated for the SPD and statistical analyses and OxCal code used for chronological modeling are available as Supplementary Data files.

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References

- Zhang, D. D., Brecke, P., Lee, H. F., He, Y.-Q. & Zhang, J. Global climate change, war, and population decline in recent human history. *Proc. Natl Acad. Sci. USA* **104**, 19214–19219 (2007).
- Kennett, D. J. et al. Development and disintegration of maya political systems in response to climate change. *Science* **338**, 788–791 (2012).
- Davis, M. *Late Victorian Holocausts: El Niño Famines and the Making of the Third World*. (Verso, 2002).
- Masson, M. & Peraza, L. C. Militarism, Misery, and Collapse. in *Kukulcan's Realm: Urban Life at Ancient Mayapan* 521–540 (University Press of Colorado, 2014).
- Parker, G. *Global Crisis: War, Climate Change, & Catastrophe in the Seventeenth Century*. (Yale University Press, 2013).
- Megadrought and Collapse*. Vol. 1 (Oxford University Press, 2017).
- Weiss, H. et al. The genesis and collapse of third millennium north mesopotamian civilization. *Science* **261**, 995–1004 (1993).
- Degroot, D. et al. Towards a rigorous understanding of societal responses to climate change. *Nature* **591**, 539–550 (2021).
- Degroot, D. Climate change and society in the 15th to 18th centuries. *WIREs Clim. Change* **9**, (2018).
- Turner, B. L. & Sabloff, J. A. Classic period collapse of the central maya lowlands: insights about human-environment relationships for sustainability. *Proc. Natl Acad. Sci. USA* **109**, 13908–13914 (2012).
- Burke, M., Hsiang, S. M. & Miguel, E. Climate and conflict. *Annu. Rev. Econ.* **7**, 577–617 (2015).
- Hsiang, S. M., Burke, M. & Miguel, E. Quantifying the influence of climate on human conflict. *Science* **341**, 1235367–1235367 (2013).
- Theisen, O. M., Gleditsch, N. P. & Buhaug, H. Is climate change a driver of armed conflict? *Climatic Change* **117**, 613–625 (2013).
- Couttenier, M. & Soubeyran, R. Drought and civil war in Sub-Saharan Africa. *Economic J.* **124**, 201–244 (2014).
- Ash, K. & Obradovich, N. Climatic stress, internal migration, and syrian civil war onset. *J. Confl. Resolut.* **64**, 3–31 (2020).
- Gleick, P. H. Water, drought, climate change, and conflict in Syria. *Weather, Clim., Soc.* **6**, 331–340 (2014).
- Karnieli, A., Shtein, A., Panov, N., Weisbrod, N. & Tal, A. Was drought really the trigger behind the Syrian Civil War in 2011? *Water* **11**, 1564 (2019).
- Selby, J., Dahi, O. S., Fröhlich, C. & Hulme, M. Climate change and the Syrian civil war revisited. *Political Geogr.* **60**, 232–244 (2017).
- Selby, J. Climate change and the Syrian civil war, Part II: the Jazira's agrarian crisis. *Geoforum* **101**, 260–274 (2019).
- Shukla, P. R. et al. *IPCC: Climate Change and Land: an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems*. (2019).
- Collins, M. et al. Long-term Climate Change: Projections, Commitments, and Irreversibility. in *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* (Cambridge University Press, 2013).
- Williams, A. P., Cook, B. I. & Smerdon, J. E. Rapid intensification of the emerging southwestern North American megadrought in 2020–2021. *Nat. Clim. Change*. <https://doi.org/10.1038/s41558-022-01290-z> (2022).
- Fedick, S. L. & Santiago, L. S. Large variation in availability of Maya food plant sources during ancient droughts. *Proc. Natl Acad. Sci. USA* **119**, e2115657118 (2022).
- Kennett, D. J. et al. Early isotopic evidence for maize as a staple grain in the Americas. *Science Advances* (2020).
- Marcus, J. The peaks and valleys of ancient states: an extension of the dynamic model. in *Archaic States* 59–94 (School of American Research, 1998).
- Masson, M. A. Maya collapse cycles. *Proc. Natl Acad. Sci. USA* **109**, 18237–18238 (2012).
- Ebert, C. E., Peniche May, N., Culleton, B. J., Awe, J. J. & Kennett, D. J. Regional response to drought during the formation and decline of Preclassic Maya societies. *Quat. Sci. Rev.* **173**, 211–235 (2017).
- Kennett, D. J. & Marwan, N. Climatic volatility, agricultural uncertainty, and the formation, consolidation and breakdown of preindustrial agrarian states. *Philos. Trans. R. Soc. A* **373**, 20140458 (2015).
- Inomata, T. et al. Monumental architecture at Aguada Fénix and the rise of Maya civilization. *Nature* **582**, 530–533 (2020).
- Pugh, T. W. & Rice, P. M. Early urban planning, spatial strategies, and the maya gridded city of nixtun-ch'ich', petén, guatemala. *Curr. Anthropol.* **58**, 576–603 (2017).
- Douglas, P. M. J. et al. Drought, agricultural adaptation, and sociopolitical collapse in the Maya Lowlands. *Proc. Natl Acad. Sci. USA* **112**, 5607–5612 (2015).
- Hodell, D. A., Curtis, J. H. & Brenner, M. Possible role of climate in the collapse of Classic Maya civilization. *Nature* **375**, 391–394 (1995).
- Haug, G. H. et al. Climate and the collapse of Maya civilization. *Science* **299**, 1731–1735 (2003).
- Webster, D. *The fall of the ancient maya: solving the mystery of the maya collapse*. (Thames & Hudson, 2002).
- Hoggarth, J. A. et al. The political collapse of Chichen Itza in climatic and cultural context. *Glob. Planet. Change* **138**, 25–42 (2016).
- Ringle, W. M. et al. Lidar survey of ancient Maya settlement in the Puuc region of Yucatan, Mexico. *PLoS ONE* **16**, e0249314 (2021).
- Masson, M. & Peraza Lope, C. *Kukulcan's Realm: Urban Life at Ancient Mayapan*. (University of Colorado Press, 2014).
- Andrews, A. P., Andrews, E. W. & Castellanos, F. R. The Northern maya collapse and its aftermath. *Anc. Mesoam.* **14**, 151–156 (2003).
- Millbrath, S. & Peraza Lope, C. Revisiting mayapan: Mexico's last Maya capital. *Anc. Mesoam.* **14**, 1–46 (2003).
- Roys, R. L. Literary Sources for the History of Mayapan. in *Mayapan, Yucatan, Mexico* 25–86 (Carnegie Institution of Washington, 1962).
- Landa, D. de. *Relaciones de las Cosas de Yucatan*. Vol. 18 (Harvard University Press, 1941).
- Proskouriakoff, T. Civic and Religious Structures of Mayapan. in *Mayapan Yucatan Mexico* (eds. Pollock, H., Roys, R., Proskouriakoff, T. & Smith, A. L.) Vol. 619 87–164 (Carnegie Institution of Washington, 1962).
- Russell, B. W. Fortress mayapan: defensive features and secondary functions of a postclassic maya fortification. *Anc. Mesoam.* **24**, 275–294 (2013).
- George, R. Postclassic population aggregation, urban diet, and genetic diversity at the political capital of Mayapan. (The Pennsylvania State University, 2020).
- Kennett, D. J., Masson, M., Serafin, S., Culleton, B. & Peraza Lope, C. War and Food Production at the Postclassic Maya city of Mayapan. In: *The Archaeology of Food and Warfare: Food Insecurity in Prehistory* 161–192 (Springer, 2016).
- Mardero, S., Schmock, B., Christman, Z., Metcalfe, S. E. & De la Barreda-Bautista, B. Recent disruptions in the timing and intensity of precipitation in Calakmul, Mexico. *Theor. Appl. Climatol.* **140**, 129–144 (2020).
- De la Barreda, B., Metcalfe, S. E. & Boyd, D. S. Precipitation regionalization, anomalies and drought occurrence in the Yucatan Peninsula, Mexico. *Int J Climatol* **40**, 6474 <https://doi.org/10.1002/joc.6474> (2020).
- Hoggarth, J. A., Restall, M., Wood, J. W. & Kennett, D. J. Drought and Its Demographic Effects in the Maya Lowlands. *Curr. Anthropol.* **58**, 82–113 (2017).
- Mendoza, B., García-Acosta, V., Velasco, V., Jáuregui, E. & Díaz-Sandoval, R. Frequency and duration of historical droughts from the 16th to the 19th

- centuries in the Mexican Maya lands, Yucatan Peninsula. *Climatic Change* **83**, 151–168 (2007).
50. Oster, J., Warken, S., Sekhon, N., Arienzo, M. & Lachniet, M. Speleothem paleoclimatology for the Caribbean, Central America, and North America. *Quaternary* **2**, 5 (2019).
 51. Giannini, A., Kushnir, Y. & Cane, M. A. Interannual variability of caribbean rainfall, ENSO, and the Atlantic Ocean. *J. Clim.* **13**, 297–311 (2000).
 52. Centro de Ciencias de la, A. et al. Effects of El Niño in Mexico during rainy and dry seasons: an extended treatment. *Atm* **30**, 221–232 (2017).
 53. Medina-Elizalde, M. et al. High resolution stalagmite climate record from the Yucatán Peninsula spanning the Maya terminal classic period. *Earth Planet. Sci. Lett.* **298**, 255–262 (2010).
 54. Medina-Elizalde, M. & Rohling, E. J. Collapse of classic maya civilization related to modest reduction in precipitation. *Science* **335**, 956–959 (2012).
 55. Milbrath, S. & Lope, C. P. Survival and revival of terminal classic traditions at postclassic Mayapan. *Lat. Am. antiq.* **20**, 581–606 (2009).
 56. Serafin, S., Lope, C. P. & Uc González, E. Bioarchaeological investigation of ancient Maya violence and warfare in inland northwest Yucatan, Mexico: Maya Violence and Warfare in northwest yucatan. *Am. J. Phys. Anthropol.* **154**, 140–151 (2014).
 57. Paris, E. H. et al. Violence, desecration, and urban collapse at the Postclassic Maya political capital of Mayapan. *J. Anthropological Archaeol.* **48**, 63–86 (2017).
 58. Smith, L. Residential and associated structures at Mayapan. in *Mayapan, Yucatan, Mexico* (eds. Pollock, H., Roys, R., Proskouriakoff, T. & Smith, L.) 165–320 (Carnegie Institution of Washington, 1962).
 59. Serafin, S. & Peraza Lope, C. Human sacrificial rites among the Maya of Mayapan: a bioarchaeological perspective. In: *New perspectives on human sacrifice and ritual body treatments in ancient Maya society* 232–250 (Springer, 2007).
 60. Adams, R. M. *Some small ceremonial structures at Mayapan*. 144–179 (1953).
 61. Stahle, D. W. et al. Major Mesoamerican droughts of the past millennium. *Geophys. Res. Lett.* **38**, n/a–n/a (2011).
 62. Craine, E. R. & Reindorp, R. C. *Codex Perez and the Book of Chilam Balam of Mani*. (University of Oklahoma Press, 1979).
 63. Masson, M. A. Resiliency and cultural reconstitution of the postclassic Mayapan confederacy and its Aftermath. in *Mesoamerican Archaeology: Theory and Practice* (eds. Hendon, J., Joyce, R. & Overholtzer, L.) (Wiley-Blackwell, 2021).
 64. Therrell, M. D., Stahle, D. W. & Soto, R. A. Aztec Drought and the “Curse of One Rabbit”. *Bull. Am. Meteor. Soc.* **85**, 1263–1272 (2004).
 65. Berdan, F. F., Masson, M. A. & Gasco, J. An International Economy. in *The Postclassic Mesoamerican World* (eds. Smith, M. & Berdan, F. F.) 96–108 (University of Utah Press, 2003).
 66. Garrison, T. G., Houston, S. & Alcover Firpi, O. Recentring the rural: Lidar and articulated landscapes among the Maya. *J. Anthropological Archaeol.* **53**, 133–146 (2019).
 67. Tankersley, K. B., Dunning, N. P., Carr, C., Lentz, D. L. & Scarborough, V. L. Zeolite water purification at Tikal, an ancient Maya city in Guatemala. *Sci. Rep.* **10**, 18021 (2020).
 68. Scarborough, V. L. & Sierra, L. G. The evolution of an ancient waterworks system at tikal. in *Tikal* (eds. Lentz, D. L., Dunning, N. P. & Scarborough, V. L.) 16–45 (Cambridge University Press, 2015). <https://doi.org/10.1017/CBO9781139227209.003>.
 69. Beach, T. et al. Ancient Maya wetland fields revealed under tropical forest canopy from laser scanning and multiproxy evidence. *Proc. Natl Acad. Sci. USA* **116**, 21469–21477 (2019).
 70. Krause, S. et al. Tropical wetland persistence through the anthropocene: multiproxy reconstruction of environmental change in a Maya agroecosystem. *Anthropocene* **34**, 100284 (2021).
 71. Kennett, D. J. & Beach, T. P. Archeological and environmental lessons for the Anthropocene from the classic Maya collapse. *Anthropocene* **4**, 88–100 (2013).
 72. Freidel, D. & Shaw, J. The lowland Maya civilization: historical consciousness and environment. in *The Way the Wind Blows: Climate, History, and Human Action* (eds. McIntosh, R., Tainter, J. & McIntosh, S. K.) 271–300 (Columbia University Press, 2000).
 73. Masson, M. A. & Freidel, D. A. An argument for classic era Maya market exchange. *J. Anthropological Archaeol.* **31**, 455–484 (2012).
 74. Wurtzel, J. B. et al. Mechanisms of southern Caribbean SST variability over the last two millennia: ATLANTIC SSTs OVER THE LAST 2000 YEARS. *Geophys. Res. Lett.* **40**, 5954–5958 (2013).
 75. Collard, M., Carleton, W. C. & Campbell, D. A. Rainfall, temperature, and classic Maya conflict: a comparison of hypotheses using Bayesian time-series analysis. *PLoS ONE* **16**, e0253043 (2021).
 76. Selby, J. & Hoffmann, C. Beyond scarcity: rethinking water, climate change and conflict in the Sudans. *Glob. Environ. Change* **29**, 360–370 (2014).
 77. Rice, P. M. Introduction to the Kowoj and Their Peten Neighbors. in *The Kowoj: Identity, Migration, and Geopolitics in Late Postclassic Petén, Guatemala* (eds. Rice, P. M. & Rice, D. S.) 3–16 (University of Colorado Press, 2009).
 78. Jones, G. D. *Maya Resistance to Spanish Rule: Time and History on a Colonial Frontier*. (University of New Mexico Press, 1990).
 79. Restall, M. *Life and death in a Maya community: the Ixil testaments of the 1760s*. (Labyrinthos, 1995).
 80. Alpuche, A. I. B., McAnany, P. A. & Dedrick, M. Yucatec Land and Labor before and after Spanish Incursions. in *The Real Business of Ancient Maya Economies* 210–223 (University Press of Florida, 2020). <https://doi.org/10.5744/florida/9780813066295.003.0012>.
 81. Restall, M. The People of the Patio: Ethnohistoric Evidence of Yucatec Maya Royal Courts. in *Royal Courts of the Maya, Vol 2, Data and Case Studies* (eds. Inomata, T. & Houston, S. D.) 335–390 (Westview Press, 2001).
 82. Hidalgo, H. G., Amador, J. A., Alfaro, E. J. & Quesada, B. Hydrological climate change projections for Central America. *J. Hydrol.* **495**, 94–112 (2013).
 83. Asmerom, Y. et al. Intertropical convergence zone variability in the Neotropics during the common era. *Sci. Adv.* **6**, eaax3644 (2020).
 84. Kennett, D. J. et al. Archaeogenomic evidence reveals prehistoric matrilineal dynasty. *Nat. Commun.* **8**, 14115 (2017).
 85. Lohse, J. C., Madsen, D. B., Culleton, B. J. & Kennett, D. J. Isotope paleoecology of episodic mid-to-late Holocene bison population expansions in the Southern Plains, U.S.A. *Quat. Sci. Rev.* **102**, 14–26 (2014).
 86. Bronk Ramsey, C. *OxCal 4.4 Manual. Electronic document*. (2020).
 87. Reimer, P. J. et al. The intCal20 Northern Hemisphere radiocarbon age calibration curve (0–55 cal kBP). *Radiocarbon* **62**, 725–757 (2020).
 88. Crema, E. R. & Bevan, A. Inference from large sets of radiocarbon dates: software and methods. *Radiocarbon* **63**, 23–39 (2021).
 89. Shennan, S. et al. Regional population collapse followed initial agriculture booms in mid-Holocene Europe. *Nat. Commun.* **4**, 2486 (2013).
 90. Hodell, D. A. et al. Climate change on the Yucatan Peninsula during the Little Ice Age. *Quat. res.* **63**, 109–121 (2005).

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Author contributions

D.J.K., M.M., S.S., S.F.M.B., and D.A.H. designed the study. M.M., C.P.L., B.W.R., E.U.G., and E.H.P. collected archeological samples. S.S. performed the osteological analysis. D.A.H., M.B., S.M., and J.H.C. collected the Mayapan speleothem and participated in other sample collections. D.J.K., B.J.C., R.J.G., J.A.H., and T.K.H. directly radiocarbonated the skeletal material and established the chronology. W.C.M. generated SPD for radiocarbon dates and conducted the generalized linear modeling. D.A.H., S.F.M.B., K.M.P., T.C.S., N.M., M.Z., Y.A., V.J.P., V.V.A., S.A.C., D.H.J., A.J.M., G.H., M.B., and J.U.L.B. generated or analyzed the climate data. D.J.K. and D.A.H. supervised the study. D.J.K., M.M., S.S., S.F.M.B., W.C.M., and D.A.H. wrote the paper with contributions from all authors.

Competing interests

The authors declare no competing interests.

Additional information

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