Report

The Role of Diet in Resilience and Vulnerability to Climate Change among Early Agricultural Communities in the Maya Lowlands

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The Terminal Classic Period (AD 750–1000) collapse of lowland Maya social, economic, and political systems has been temporally correlated with severe and extended drought in regional paleoclimate records. Ancient Maya society also experienced a protracted multicentury drought earlier during the end of the Late Preclassic Period (AD 100–300). While some large Preclassic polities declined, many more flourished through the Early Classic. Why were the effects of the Terminal Classic drought more dramatic? What allowed some earlier Maya communities to be more resilient in the face of climate change? Accelerator mass spectrometry radiocarbon dating and stable carbon and nitrogen isotope analyses of human skeletal remains from 50 individuals at the ancient Maya community of Cahal Pech from this critical time period suggest that more diverse diets may have promoted resilience in the face of changing socioecological systems at the end of the Preclassic. During the Late Classic Period (AD 600–800), isotopic data indicate that high-status individuals had a narrow and highly specialized diet, which may have created a more vulnerable socioeconomic system that ultimately disintegrated as a result of anthropogenic landscape degradation and severe drought conditions during the Terminal Classic.

The resilience and adaptability of complex human-environmental systems are critical issues facing contemporary societies worldwide, especially in the context of anthropogenic climate change. Archaeologists working in the Maya region are increasingly focused on understanding the long-term processes that promoted alternating resilience and vulnerability among societies in response to climate fluctuations in the past. Severe multicentury drought conditions, documented in paleoclimate proxy records, are recognized to have played a key role in the disintegration of ancient lowland Maya social, economic, and political systems during the Terminal Classic Period (AD 750–900/1000; Douglas et al. 2016; Hodell, Curtis, and Brenner 1995; Iannone 2014; Kennett et al. 2012), but climatic change also affected earlier Maya communities. Protracted drought resulted in the decline of large urban centers (e.g., Nakbe, El Mirador) and the depopulation of some regions at the end of the Preclassic Period (AD 100–300; Dunning et al. 2014; Ebert et al. 2017; Nooren et al. 2018). Yet the sociopolitical developments occurring after this extended Late Preclassic drought differed from those during the Terminal Classic, as more resilient political centers developed throughout the lowlands and flourished for six to seven centuries.

What factors supported the resilience and expansion of some Maya communities in the face of climate fluctuations at the end of the Preclassic? Why were the effects of the Terminal Classic Period drought more dramatic? Resilient social systems have an adaptive capacity that allows them to absorb external disturbance while still retaining essential structures and functions (Hegmon et al. 2008; Holling and Gunderson 2002). Diversity contributes to societal resilience by providing a source of options to buffer against external disturbance, including climatic variability. As systems become more complex and interconnected, they tend to become less diverse economically, socially, and politically, which creates vulnerabilities that potentially compromise their ability to adapt to long-term change and can lead to dramatic and rapid cultural transformations (Faulseit 2015; Hegmon et al. 2008). In this study, we examine the role of dietary diversity in the resilience and vulnerability of social, economic, and political systems at the Maya community of Cahal Pech, Belize, during periods of climatic stress from the Preclassic through Terminal Classic Periods (fig. 1; table 1). Cahal Pech provides a case study for understanding long-term adaptations to climatic change because of the center's continuous occupation from ~1200 BC through AD 900 (Awe 1992; Ebert 2017; Ebert et al. 2017). Archaeologists working in the southern lowlands have used stable isotope data from human remains to reconstruct past diets, testing the hypothesis that anthropogenic environmental degradation from overfarming contributed to the collapse of Classic Maya society (Somerville, Fauvelle, and Froehle 2013; Wright 2006). The relationships between societal resilience, dietary diversity, and climate, however, have not been explored closely in the Maya region.

We conducted high-precision accelerator mass spectrometry (AMS) ^{14}C dating and stable carbon and nitrogen isotope

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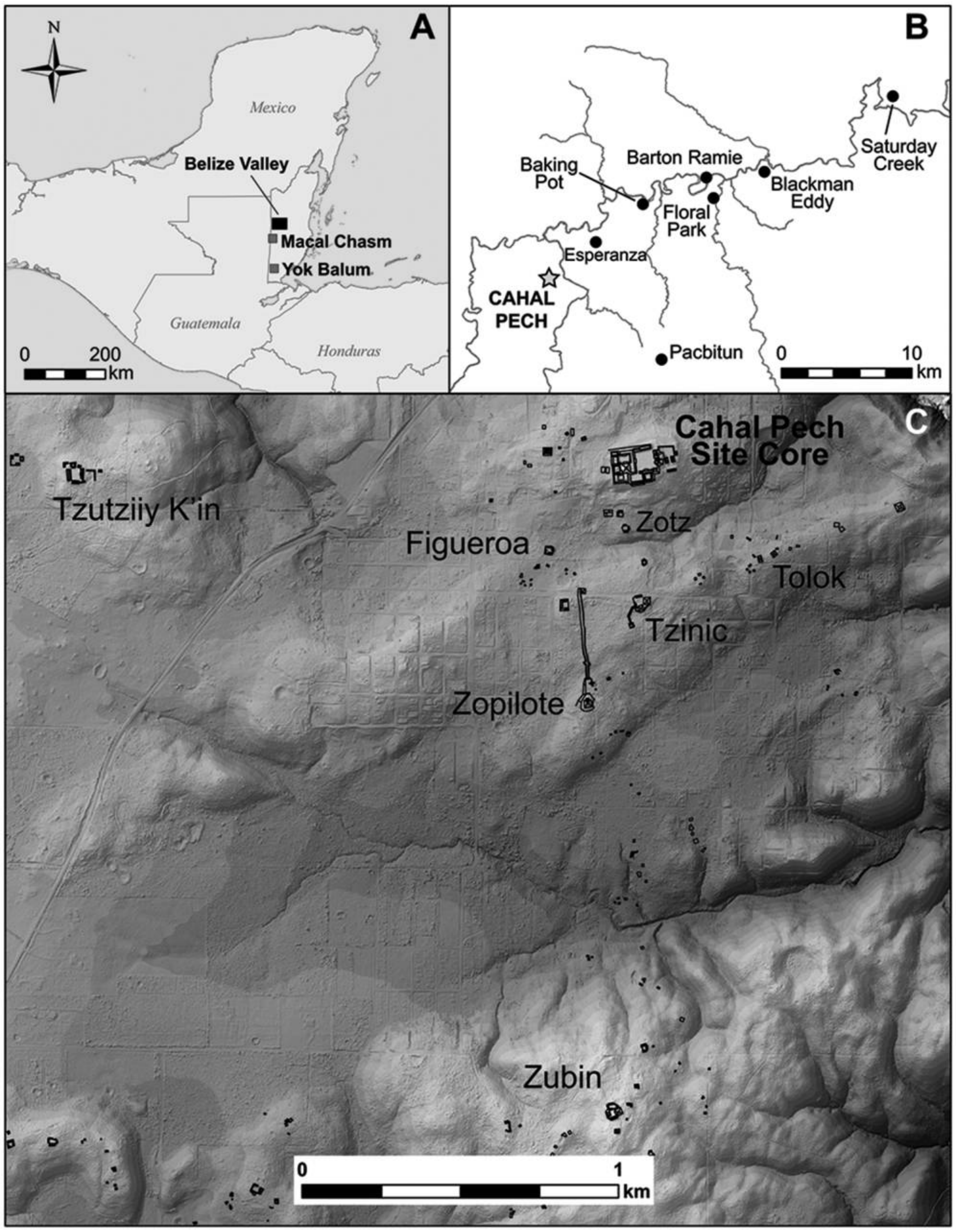

Figure 1. Belize Valley. *A*, Map of the Maya lowlands showing the location of Belize Valley and paleoclimate proxy records. *B*, Map of the Belize Valley with major sites sampled for previous stable isotope analyses, with location of Cahal Pech highlighted. *C*, Map of Cahal Pech showing location of civic-ceremonial site core in relation to peripheral residential settlement groups from where skeletal samples were collected. A color version of this figure is available online.

analyses of human skeletal remains from the civic-ceremonial site core and peripheral residential groups at Cahal Pech to address this issue. Stable isotope results indicate that Preclassic and Early Classic diet at the site was broad, including an array of locally available wild plant and animal resources that were likely used as fallback foods during times of environmental and climatic stress. By the Late Classic, the presence of monumental architecture, carved stone monuments, and elaborate elite burials identify Cahal Pech as the seat of an important regional polity governed by a dynastic lineage (Awe 2013; Awe and Zender 2016). Elite individuals also developed a highly specialized maize-based diet during this period, which was distinct from the increasingly broad diet consumed by people in surrounding households. Demand for specific foodstuffs by elite consumers likely influenced more intensive maize production and hunting locally around the community. We argue that Late and Terminal Classic population expansion and anthropogenic environmental degradation from agricultural intensification, cou-

Table 1. Chronological periods of Cahal Pech

Period	2σ-calibrated date span
Colonial	AD 1519–1821
Postclassic	AD 900–1500
Terminal Classic	AD 800–900
Late Classic	AD 600–800
Early Classic	AD 300–600
Late Preclassic	300 BC–AD 300
Middle Preclassic	900–300 BC
Early Preclassic	1200–900 BC

pled with socially conditioned food preferences, resulted in a less flexible and less resilient system. This "rigidity trap" (Hegmon et al. 2008) ultimately contributed to the failure of the Cahal Pech sociopolitical system in the face of severe drought at the end of the Terminal Classic Period. Understanding the factors that promoted resilience in the past can help mitigate the potential for similar sudden and dramatic shifts in our increasingly interconnected modern world.

Climatic Setting of the Maya Lowlands

Research on lowland Maya paleoclimate from proxy records has documented climatic fluctuations from the Preclassic through Terminal Classic Periods. We consider two speleothem paleoclimate records from Macal Chasm (Akers et al. 2016) and Yok Balum Cave (Kennett et al. 2012) in Belize to understand the climatic setting for the growth and decline of Cahal Pech and associated periods of drought and dietary change. Dry intervals in the Yok Balum record correlate closely with Colonial Period (AD 1519–1821) accounts of droughts that resulted in famine and high mortality across northern Yucatán (Hoggarth et al. 2017). Lake sediment cores from the northern and central lowlands also show corresponding long-term patterns of drought prehistorically across different paleoclimate archives (e.g., Hodell, Curtis, and Brenner 1995; Medina-Elizalde et al. 2010). These data suggest that the most severe and protracted droughts affected the entire Maya region and posed serious risks to agricultural production. Major droughts evident in the records can be correlated with AMS ^{14}C dates and stable isotope data from human remains at Cahal Pech to identify corresponding changes in dietary trends (fig. 2).

The Macal Chasm and Yok Balum speleothem records show two severe droughts at the end of the Late Preclassic (cal AD 100–300[1]), the second of which lasted more than a century (Akers et al. 2016; Kennett et al. 2012). These extreme dry conditions are contemporaneous with the depopulation of the major Preclassic centers of Nakbe and El Mirador in the neighboring Petén region of Guatemala (Dunning et al. 2014), although evidence exists for population continuity and site growth at Cahal Pech and other Belize Valley sites (Ebert 2017; Ebert et al. 2017). A relatively wet period identified in the Belize speleothem records during the Early Classic (~cal AD 400–660) promoted the centralization of a number of large polities, agricultural intensification, and population increase. Climatic instability during the eighth century culminated in two of the most severe droughts in the records between cal AD 820–900 and cal AD 1020–1100. Several studies have found correspondence between these droughts and increased warfare, the disintegration of political systems based on divine dynastic rulership, and demographic declines across the Maya lowlands (Ebert et al. 2014; Hoggarth et al. 2016; Kennett et al. 2012; Medina-Elizalde et al. 2010; Nooren et al. 2018). The effects of shifting climate regimes also influenced the adaptive capacity of Maya agricultural systems to absorb disturbance in the face of anthropogenic landscape disturbance and population expansion (Beach et al. 2015; Kennett and Beach 2013).

Archaeological Evidence for Ancient Maya Diet at Cahal Pech

The medium-sized Maya political center of Cahal Pech is located in the upper Belize Valley of western-central Belize. Archaeological investigations by the Belize Valley Archaeological Reconnaissance Project have identified domestic architecture in the site core radiocarbon dated to ~1200/1000 cal BC, providing evidence for one of the earliest farming village settlements in the Maya lowlands. Initial settlement corresponds with the appearance of the first ceramics (Cunil ceramic complex) in the Belize Valley region during the Early Preclassic Period (Awe 1992; Ebert 2017; Ebert et al. 2017; Sullivan, Awe, and Brown 2018). Specialized ceramic colanders used to produce *nixtamal* (lime-treated maize; Sullivan and Awe 2013), impressions of corn cobs on pottery from household contexts, and maize cupule fragments indicate that maize formed an important component of the diet from an early date (Lawlor et al. 1995). The Preclassic Cahal Pech community also exploited a variety of other plants from the surrounding forest and house gardens, including squash (*Curcurbita* sp.) and fruits (Wiesen and Lentz 1999). Excavations in Preclassic midden contexts have yielded a large sample ($n > 25{,}000$) of terrestrial, freshwater, and marine faunal remains, representing a diet in which maize was not the only source of protein (Powis et al. 1999; Stanchly and Awe 2015:230).

By the beginning of the Classic Period, maize had become a staple food of great social significance for the ancient Maya. The concept of life, death, and renewal as represented by the Maize God is a recurring theme in Late Preclassic and Classic Period iconography (Miller and Martin 2004:70; Taube 2005). Several royal burials from Cahal Pech reflect this ideology associated with the resurrection of the Maize God or contain jade items with Maize God imagery directly linking maize production and consumption with rulership (Awe 2013; Awe et al. 2017). Intensified agricultural production during the Classic Period, including terraces and water management systems documented by airborne lidar (light detection and ranging) analyses, supported growing residential populations and monu-

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[1] All calibrated dates listed in the article are 2σ ranges.

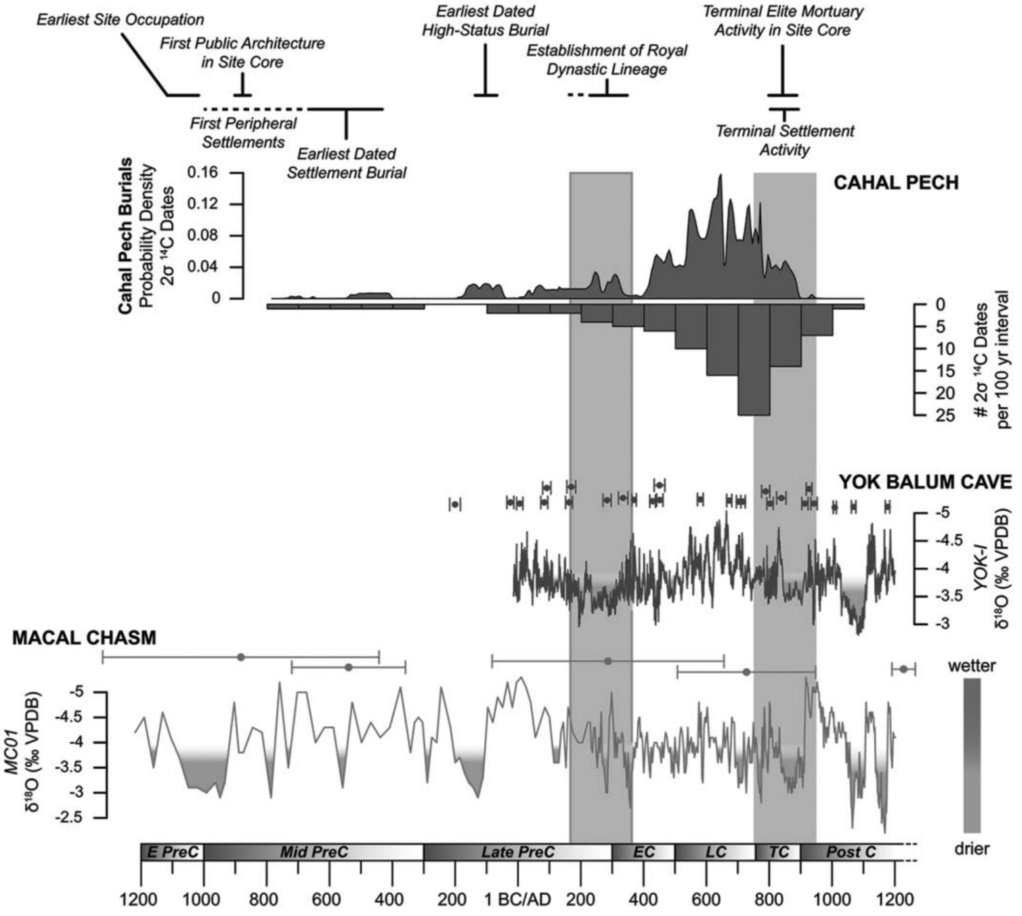

Figure 2. Summed probability distribution of Cahal Pech human burial dates shown with a histogram of 2σ calibrated ranges in 100-year bins. Directly dated historical events (2σ calibrated range) in the Cahal Pech radiocarbon sequence are indicated (*top*). The Yok Balum (YOK-I; Kennett et al. 2012) and Macal Chasm (MC01; Akers et al. 2016) speleothem records show δ^{18}O isotope data between 1200 cal BC and cal AD 1200, with major Late Preclassic and Terminal Classic droughts highlighted in gray. The U-Th and ^{14}C dates anchoring paleoclimate sequences are included for each record. A color version of this figure is available online.

mental construction programs in the Belize Valley (Ebert et al. 2016*b*).

Stable Isotope Dietary Analyses

Stable carbon (δ^{13}C) and nitrogen (δ^{15}N) isotope measurements of human bone collagen are widely used as a proxy for prehistoric human diet (Ambrose and Krigbaum 2003; DeNiro and Epstein 1978, 1981). Values for δ^{13}C are determined by the photosynthetic pathways of C_3 (trees, shrubs) and C_4 (grasses) plants. Maize was the most common C_4 plant consumed by the ancient Maya, and δ^{13}C values of bone collagen track the importance of this domesticate as a staple crop through time (White 1999). Metabolic fractionation of dietary protein by humans produces δ^{13}C values for bone collagen of $-20‰ \pm 1‰$ for a diet composed of C_3 plants and values of $-7‰ \pm 1‰$ for a C_4 plant-based diet.

Nitrogen isotope values (δ^{15}N) in human bone increase incrementally by 3‰–5‰ between trophic levels (Hedges and Reynard 2007). Several cofounding variables, however, indicate that trophic effects alone cannot account for variation in δ^{15}N values. While marine vertebrates generally have more positive δ^{15}N values relative to terrestrial vertebrates, the values associated with freshwater fish consumption are unknown (Hedges and Reynard 2007). Nitrogen isotope values in both humans and animals are also subject to shifting environmental factors. Forest loss may potentially reflect alterations in nitrogen sources to plants, although it does not necessarily have a systematic impact on δ^{15}N values (Crowley et al. 2016; Lohse et al. 2014). Higher δ^{15}N values have also been correlated with fluctuations in precipitation and increasingly arid conditions (Ambrose 1991; Crowley et al. 2016).

Maya archaeologists have suggested complex relationships between dietary diversity and social status across time and space based on δ^{13}C and δ^{15}N values of human bone collagen (Somerville, Fauvelle, and Froehle 2013; White 1999; Wright 2006). While previous isotope studies for Cahal Pech have been limited in sample size, high δ^{13}C and δ^{15}N values from Middle Preclassic burials ($n = 7$) from the site core and three settlement groups (Tolok, Cas Pek, and Zotz) have been interpreted as evidence for increased maize and marine fish consumption for high-status individuals (Powis et al. 1999; White, Longstaffe, Schwarcz 2006). More stable isotope data are available for Late Classic Period (AD 600–900) individuals from the Cahal Pech core ($n = 6$) and settlement ($n = 14$). Analyses by Piehl (2006) have indicated the consumption of a more homogenous diet composed primarily of maize-based protein throughout the Classic Period at Cahal Pech. A recent study by Green (2016) examined the origin and movement of individuals from Cahal Pech in response to changing environmental conditions based principally on carbon, oxygen, and strontium isotopes from tooth enamel, as well as a diachronic analysis of mortuary patterns. Results showed that changing climate conditions during the Late and Terminal Classic had no effect upon individual movement to or from Cahal Pech, and stability in mortuary patterns was also documented. While focused on bioarchaeological aspects of Cahal Pech mortuary data, Green's study provided six additional stable carbon and nitrogen isotope measurements of bone collagen that are incorporated into this study.

Material and Methods

A total of 42 human individuals from the Cahal Pech site core and settlement contexts were directly AMS ^{14}C dated. Stable carbon and nitrogen isotopes were also measured on the same bones to examine dietary change through time and its relationship to resilience or vulnerability in the face of drought. We also include isotope data for eight individuals from previous studies ($n = 6$, Green 2016; $n = 1$, Piehl 2006; $n = 1$, Powis et al. 1999). While the remains of these individuals were not directly dated, chronological information for their internment is based on contextual ceramic associations or associated ^{14}C dates from other materials (e.g., charcoal, faunal remains) when available. One human sample (Tolok Str. 14/15 Burial 9) was not included because δ^{15}N values were not reported for this individual (Powis et al. 1999). Additional samples from 27 humans were processed for ^{14}C dating and stable isotope analyses, but they were poorly preserved and did not meet quality control standards. Stable isotope measurement from seven different animal species (total $n = 45$ samples) excavated from contemporaneous Preclassic through Terminal Classic contexts at sites throughout the Belize River Valley provide a synchronous isotopic baseline for Belize Valley food resources (table S1; tables S1–S6 are available online). Samples were analyzed using standard procedures for bone collagen extraction and purification at the Human Paleoecology and Isotope Geochemistry Laboratory at Penn State University (see appendix, available online).

Results

High-precision AMS ^{14}C dates and δ^{13}C and δ^{15}N values for Cahal Pech burials are presented in table 2. The age and sex of each individual were determined using standard osteological methods (see Green 2016) and presented when available. Radiocarbon dates show continuous mortuary activity at Cahal Pech beginning in the Middle Preclassic, with the first directly dated burial dating between 735 and 400 cal BC. Six burials date to the Late Preclassic between 180 cal BC and cal AD 335. The majority of Cahal Pech burials date to the Classic Period ($n = 30$). A total of 11 burials date to the Early Classic, and a total of 19 burials date to the Late Classic. Five burials, including three from the site core and two from the peripheral settlement, date to the Terminal Classic between ~cal AD 800 and 850 (Awe 2013; Ebert et al. 2016*a*). One intrusive burial, located in the Cahal Pech site core (Plaza G), yielded a large calibrated date span consistent with a Colonial Period age (cal AD 1660–1950).[2]

Values for δ^{13}C and δ^{15}N for humans and seven species of fauna local to the Belize Valley are plotted in figure 3, and mean values are listed in table 3. Average δ^{13}C and δ^{15}N values for fauna provide baseline data for the local food web (table S2, available online). There is considerable overlap in human diet across all time periods from both the site core and surrounding settlement. These ranges (δ^{13}C = −14.5‰ to −7.3‰; δ^{15}N = 7.3‰ to 11.7‰) are consistent with expected variation for Maya populations consuming maize along with other terrestrial plant and meat resources (Somerville, Fauvelle, and Froehle 2013). Isotope values are also plotted by time period based on the correspondence of the calibrated AMS ^{14}C dates or relative ceramic dates when direct dates were not available (fig. 4).

Two statistical tests were used to compare isotope values for a total of 50 individuals based on their relative temporal and contextual associations (table 4). The *t*-test for independent groups (two parameters) assuming unequal variance was used to determine significant differences between the means within each group (Drennan 2009). Additionally, the nonparametric Mann-Whitney *U*-test (two parameters) for independent samples was used where applicable since not all samples were normally distributed. The null hypothesis tested whether the two samples come from the same population and therefore have similar distributions of isotopic values (Nachar 2008).

Burials were divided into two temporal categories (early and late) and according to their context in either the Cahal Pech site core or settlement to examine dietary change associated with Late Preclassic and Terminal Classic droughts identified in paleoclimate records (fig. 5). Site core burials were interred

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[2] The period between cal AD 1600 and 1950 corresponds with a plateau (less steep) on the IntCal13 radiocarbon calibration curve that produces calibrated ^{14}C date ranges up to 500 calendar years, regardless of measurement precision. Based on strontium analyses and other contextual evidence, it is likely that the Plaza G Burial dates between ~cal AD 1660 and 1805 (see Awe et al. 2017).

Table 2. Calibrated accelerator mass spectrometry ^{14}C dates and stable carbon ($\delta^{13}C$) and nitrogen ($\delta^{15}N$) isotope values from human burials at Cahal Pech

Provenience	Sex	Age	UCIAMS lab no.	^{14}C age (BP)	2σ calibrated range (BC/AD)	$\delta^{13}C$ (‰ VPDB)	$\delta^{15}N$ (‰ atm N_2)	%C	%N	C : N	Method
Site core burials:											
Cahal Pech Plz. B Op. 1o-10 Burial 1	I	A	167920	2085 ± 20	170–45 BC	−13.1	11.1	11.5	4.1	3.3	XAD
Cahal Pech Str. B1 Burial 10	M	30–50	170054	1790 ± 20	AD 135–325	−9.2	9.5	17.9	6.3	3.3	XAD
Cahal Pech Str. B1 Burial 7, Indiv. 3[a]	F?	A	X27037	1748 ± 47	AD 140–395	. . .	. . .				
Cahal Pech Str. B1 Burial 8[b]	M	30–40			AD 50–250	−8.0	10.0				
Cahal Pech Str. B2 Burial 2[b,d]	I	A			AD 200–450	−9.3	9.8				
Cahal Pech Str. B1 Burial 12[b]	M	A			AD 250–600	−8.3	9.6				
Cahal Pech Op. 4a PB-B/1	I	A	166049	1550 ± 15	AD 425–560	−10.4	7.9	41.2	14.7	3.3	UF
Cahal Pech Plz. B EU-13 Burial 1	I	OA	164842	1545 ± 15	AD 425–565	−10.0	8.2	42.3	15.1	3.3	UF
Cahal Pech Str. B1 Burial 7, Indiv. 2[a]	M	A	X27036	1516 ± 39	AD 425–620	−8.3					
Cahal Pech Str. B2 Burial B2-1	I	A	164843	1465 ± 20	AD 560–645	−8.8	9.6	46.0	16.2	3.3	UF
Cahal Pech Str. B1 Burial 7, Indiv. 1[b]	F	A	X27035	1432 ± 36	AD 545–665	−8.0	10.6				
Cahal Pech Str. B4 Lvl. 5 Burial 1	M	YA	164844	1315 ± 15	AD 560–645	−9.2	10.1	44.7	16.2	3.2	UF
Cahal Pech Str. B4-1sub	F	A	151860	1280 ± 25	AD 670–770	−7.8	9.6	46.9	16.7	3.3	UF
Cahal Pech Str. B4 Burial B4-1	F	40–50	170055	1270 ± 20	AD 680–770	−8.2	9.8	18.4	6.5	3.3	XAD
Cahal Pech Plz. B/Str. B3 Terminal deposit	M?	A	155962	1230 ± 15	AD 690–875	−13.0	10.0	27.6	9.8	3.3	XAD
Cahal Pech Str. A2 Burial 1[b,c]	I	A			AD 600–700	−8.6	8.4				
Cahal Pech Str. C2 Burial 1	I	3–5	166048	1180 ± 15	AD 775–890	−9.9	9.9	45.4	16.1	3.3	UF
Cahal Pech Str. H1 Tomb 1[b,d]	M	OA	174933	1175 ± 15	AD 770–895	−8.8	10.8				
Cahal Pech Plaza G, Unit 51	I	12–16	166050	190 ± 15	AD 1660–1950	−9.3	8.7	43.1	14.9	3.4	UF
Peripheral settlement burials:											
Zubin Str. C9-6th Burial C9-B/1	M	A	151863	2415 ± 25	735–400 BC	−11.7	8.4	42.5	15.3	3.2	UF
Tolok Str. 14/15 Burial 9, Indiv. 1[c]	I	<6			650–300 BC	−14.5	. . .			3.6	
Cas Pek Str. 1 Burial 94-2	M	35–45	167921	2095 ± 20	180–50 BC	−11.0	10.7	19.2	7.3	3.1	XAD
Tolok Str. 14/15 Burial 10	F	16–23	151861	1935 ± 25	AD 15–130	−12.6	8.5	44.5	15.9	3.3	UF
Tolok Str. 14/15 Burial 8	F	17–26	164851	1860 ± 20	AD 85–225	−11.8	7.8	44.4	15.6	3.3	UF
Tolok Str. 14/15 Burial 7[c]	I	6–8			AD 200–300	−13.0	8.4		8.3	3.6	
Zotz Str. B2 Burial 5 (Intrusive)			166058	1765 ± 15	AD 230–335	−10.6	9.2	46.7	16.0	3.4	UF
Zotz Str. A1 Burial A1-B/2			172402	1610 ± 20	AD 395–535	−10.3	7.3	15.4	14.8	3.2	XAD
Zotz Plaza Unit 7 Burial 4			166056	1590 ± 15	AD 415–540	−10.1	7.4	50.2	16.9	3.5	UF

Zotz Str. B2 Burial 2-B/4	I	A	166057	1580 ± 15	AD 420–540	−8.8	7.9	46.1	15.8	3.4	UF
Tolok Str. 14/15 Burial 3	M	25–35	170057	1525 ± 20	AD 430–600	−11.8	8.6	21.7	7.6	3.3	XAD
Tolok Str. 14/15 Burial 6	F	35+	164850	1520 ± 15	AD 430–600	−12.5	8.2	42.6	15.2	3.3	UF
Tzinic, A2 Burial, Unit 2			170060	1515 ± 20	AD 430–605	−12.3	7.4	9.7	3.3	3.4	XAD
Tolok Str. 14/15 Burial 2	F	A	164847	1515 ± 15	AD 435–605	−11.5	8.3	42.1	14.9	3.3	UF
Tolok Str. 14/15 Burial 5	F	25–40	164849	1470 ± 15	AD 560–640	−12.0	8.2	44.0	15.4	3.3	UF
Tzinic Str. 2 Burial 3			170059	1440 ± 20	AD 580–650	−11.2	9.2	13.2	4.5	3.4	XAD
Zotz Str. B2 Burial 2-B/6	I	A	164853	1415 ± 15	AD 605–655	−9.0	10.4	40.9	14.4	3.3	UF
Zubin Str. A1 Burial A1-B/1	I	A	151862	1415 ± 25	AD 595–665	−8.4	8.4	44.4	15.6	3.3	UF
Tolok Str. 14/15 Burial 4, Indiv. 1	M	25–35	164848	1415 ± 15	AD 605–655	−11.5	8.4	33.7	11.7	3.4	UF
Tolok Str. 4 Tomb 1, Indiv. 2	I	YA	170058	1415 ± 20	AD 600–660	−12.5	8.6	20.3	7.1	3.4	XAD
Tzutziiy K'in Str. 2 Burial TK-2-1	M	A	164846	1335 ± 20	AD 645–765	−10.2	10.0	41.1	14.4	3.3	XAD
Zotz Str. B2 Burial 2-B/3, Indiv. 2	I	SubA	166055	1325 ± 15	AD 655–765	−9.4	10.9	49.8	17.1	3.4	UF
Zopilote Str. 1 Burial 1[e,f]	I		169818	1320 ± 15	AD 655–765	−9.3	9.4				
Zotz Str. B2 Burial 2-B/3, Indiv. 1	M	A	166054	1310 ± 15	AD 660–765	−9.2	11.1	50.7	17.3	3.4	UF
Figueroa Str. 2 Burial 4	I		166051	1300 ± 15	AD 650–770	−11.7	9.3	42.2	15.1	3.3	UF
Tzinic Str. 2 Burial 2	I		167924	1285 ± 20	AD 665–770	−11.3	11.7	15.2	5.3	3.4	XAD
Zubin Str. A1 Burial A1-B/3, Indiv. 4	M	14–20	166059	1265 ± 20	AD 680–770	−13.3	8.4	11.9	4.0	3.5	XAD
Zubin Str. A1 Burial A1-B/3, Indiv. 3	M	A	166053	1240 ± 15	AD 685–865	−13.3	8.2	41.5	14.2	3.4	UF
Zotz Str. B2 Burial 2-B/1	M	A	164852	1235 ± 15	AD 690–870	−12.8	9.6	41.2	14.2	3.4	UF
Tzinic Str. 2 Burial 1	I		167923	1235 ± 20	AD 685–880	−11.3	11.7	7.2	2.4	3.5	XAD
Zubin Str. A1 Burial A1-B/3, Indiv. 2	F	18–25	166052	1215 ± 15	AD 725–885	−12.3	8.9	42.3	14.8	3.3	UF
Figueroa Str. 2 Burial 3b[e]	I				AD 600–900	−10.5	9.8				
Figueroa Str. 2 Burial 1			170056	1175 ± 20	AD 770–940	−10.9	9.9	15.2	5.2	3.4	XAD

Note. Samples are listed by sex (M = male, F = female, I = indeterminate). Ages are listed in years when determination was possible or by relative age range (A = adult, YA = young adult, OA = old adult) following Green (2016). Sample preparation methods for ^{14}C dated samples discussed in the appendix, available online.

[a] Radiocarbon dates on human teeth from Novotny et al. (2018).

[b] Stable isotope data from Green (2016, table 5.1).

[c] Stable isotope data from Powis et al. (1999, table 5). Dates based on ceramic association.

[d] Radiocarbon date from white-tailed deer antler interred with burial Str. H1 Tomb 1.

[e] Stable isotope data from Piehl (2006, table 9.1). Dates based on ceramic association.

[f] Radiocarbon date from charcoal inside Vessel 10 interred within Zopilote Tomb 1 (after Ebert et al. 2017, table 3).

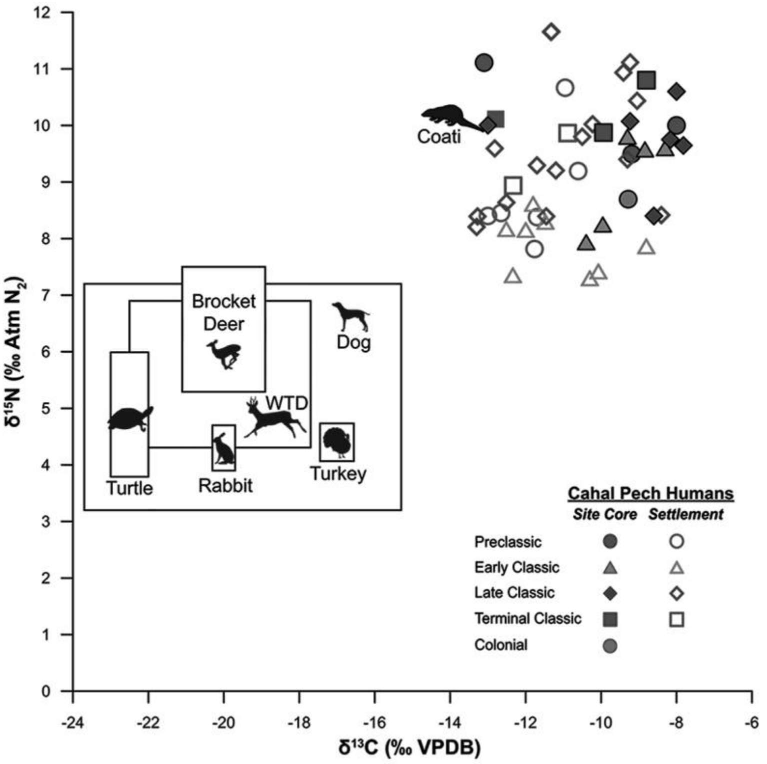

Figure 3. Bivariate plot of stable carbon (δ^{13}C) and nitrogen (δ^{15}N) isotope values for human bone collagen from Cahal Pech ($n = 45$) and faunal bone collagen ($n = 45$) from the Belize Valley. Boxes around faunal samples represent mean values with 1σ standard deviation. WTD = white-tailed deer. A color version of this figure is available online.

primarily within ceremonial contexts including tombs, crypts, or other special contexts in monumental architecture and represent the remains of high-status individuals who were likely members of the ruling elite class (Awe 2013). Settlement burials, alternatively, are located beneath house floors and represent more rural farming population at Cahal Pech. Plots comparing mean δ^{13}C and δ^{15}N values for purified human bone collagen from site core and settlement contexts through time were also created to illustrate statistical relationships between groups (fig. 6). Burials from early and late periods sampled by context were treated independently, and error ranges for 80%, 95%, and 99% confidence intervals (CIs) were calculated separately on the basis of each sample (table 3).

Comparing early and late time periods, there is a significant difference in δ^{13}C between individuals from the site core and settlement during the Preclassic and Early Classic. Values for δ^{15}N are significantly different between early and late populations at Cahal Pech ($t = -3.28$, df = 44, $P = .002$). During the early period (Preclassic and Early Classic periods), the mean δ^{13}C value for individuals interred in the settlement is −11.6‰, with a mean δ^{15}N value of 8.3‰. Site core individuals during the same period have a mean δ^{13}C of −9.6‰ and δ^{15}N

Table 3. Results of statistical analyses for temporal and contextual groups

Groups	*n*	Variables	*t*-test (*P*)	Mann-Whitney *U*-test (*P*)
Preclassic and Early Classic vs. Late and Terminal Classic	23, 26	δ^{13}C	.168	.337
	22, 26	δ^{15}N	**.001**	**.002**
Preclassic and Early Classic site core vs. settlement	8, 15	δ^{13}C	**.005**	**.011**
	8, 15	δ^{15}N	**.007**	**.016**
Late and Terminal Classic site core vs. settlement	8, 18	δ^{13}C	**.011**	**.010**
	8, 18	δ^{15}N	.294	.471
Preclassic and Early Classic site core vs. Late and Terminal Classic site core	8, 8	δ^{13}C	.300	.294
	8, 8	δ^{15}N	.190	.226
Preclassic and Early Classic settlement vs. Late and Terminal Classic settlement	15, 18	δ^{13}C	.114	.244
	14, 18	δ15N	**<.001**	**<.001**

Note. Statistically significant values ($\alpha = .05$) are in boldface.

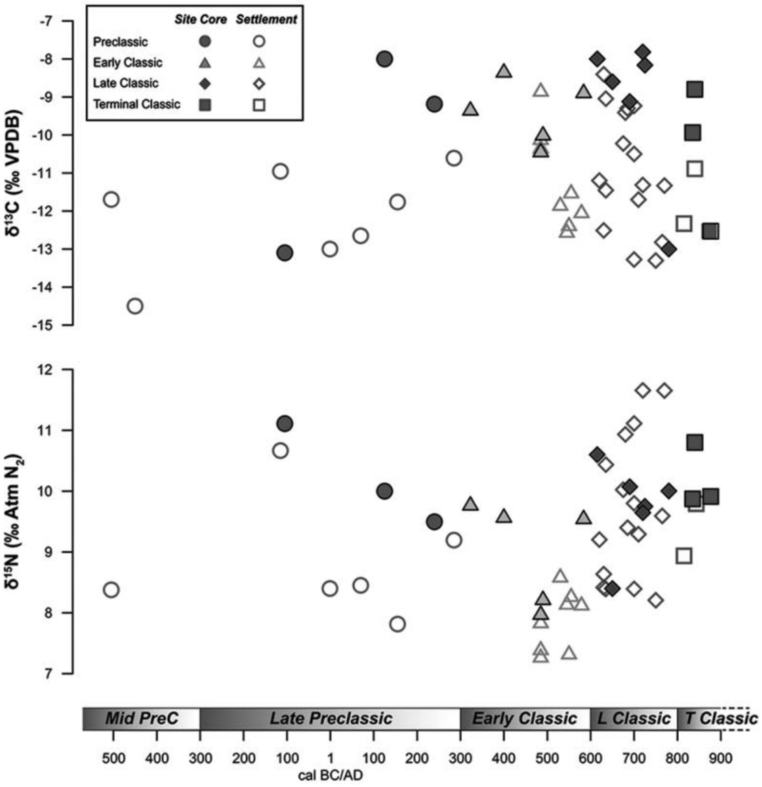

Figure 4. Stable carbon ($\delta^{13}C$) and nitrogen ($\delta^{15}N$) isotope values for all Cahal Pech burials plotted by accelerator mass spectrometry ^{14}C date (mean in 2σ probability distribution) and context. A color version of this figure is available online.

value of 9.5‰. The mean $\delta^{13}C$ and $\delta^{15}N$ values for site core burials are significantly different compared to settlement burials ($\delta^{13}C$ $t = 2.98$, df = 13, $P = .005$; $\delta^{15}N$ $t = 2.80$, df = 13, $P = .007$), suggesting higher consumption of C_4-based foods and animal protein by higher-status individuals. During the late temporal period (Late and Terminal Classic Periods), the diet of individuals from the site core became increasingly restricted and distinct compared to individuals from the surrounding settlement. The mean $\delta^{13}C$ for the site core (−9.2‰) increased by ~1.8‰ compared to the preceding time period. Site core burials also have mean $\delta^{13}C$ values significantly different at the 99% CI from settlement burials dating to the same period ($t = 5.19$, df = 21, $P < .001$). There is no significant increase in $\delta^{15}N$ values within the site core group compared to the preceding period. Within the settlement, mean $\delta^{13}C$ values increased slightly from the preceding time period. There is significant shift in $\delta^{15}N$ for this later period compared with the early period in the settlement (significantly different at the 95% CI; $t = -3.91$, df = 30, $P < .001$). While this may reflect differential consumption of animal protein among individuals from this group, it is likely that other factors influenced the later $\delta^{15}N$ values in the Cahal Pech settlement, including drought conditions. During dry periods, the $\delta^{15}N$ values of fauna would also be expected to increase. Paleoclimate records from both the northern and southern Maya lowlands show the most volatile climatic conditions, with a drying trend beginning around AD 650 that was also punctuated by shorter-term wet and dry intervals (Akers et al. 2016; Kennett et al. 2012). It

Table 4. Mean $\delta^{13}C$ and $\delta^{15}N$ values for Cahal Pech by time period and burial context

Time period/context	*n*	$\delta^{13}C$ (‰ VPDB)	SD	*n*	$\delta^{15}N$ (‰ atm N_2)	SD
All Late and Terminal Classic	26	−10.5	1.8	26	9.7	1.0
All Preclassic and Early Classic	23	−10.9	1.7	22	8.7	1.0
Site core:						
Late and Terminal Classic	8	−9.2	1.7	8	9.9	.7
Preclassic and Early Classic	8	−9.6	1.6	8	9.5	1.0
Settlement:						
Late and Terminal Classic	18	−11.0	1.5	18	9.7	1.1
Preclassic and Early Classic	15	−11.6	1.4	14	8.3	.9

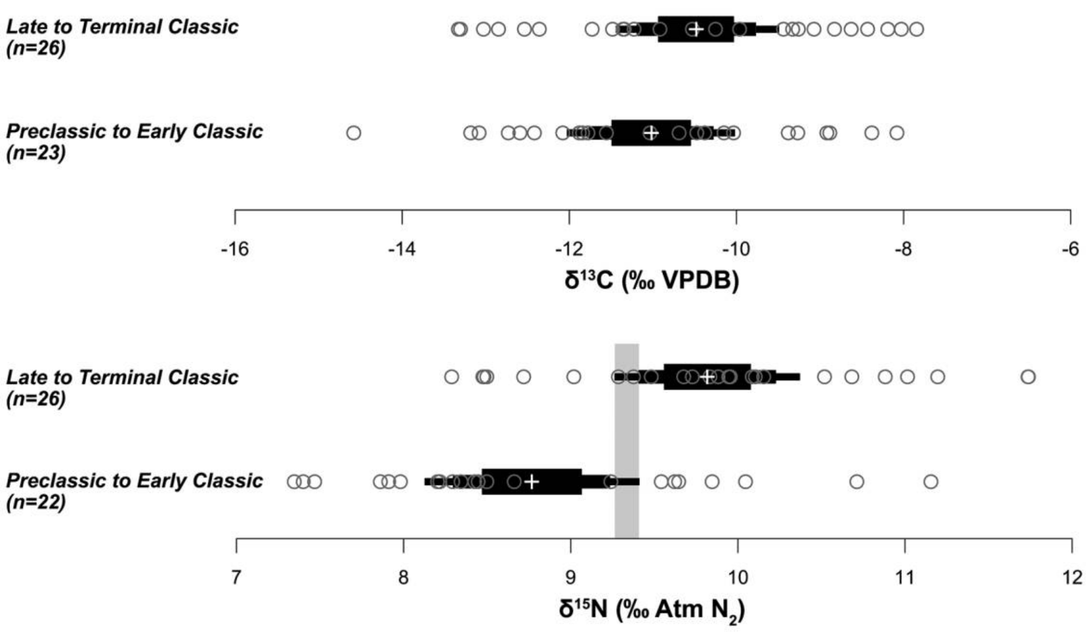

Figure 5. Mean stable carbon (δ^{13}C; *top*) and nitrogen (δ^{15}N; *bottom*) isotope values for Cahal Pech individuals plotted by early (Preclassic to Early Classic) and late (Late Classic to Terminal Classic) temporal categories. Data points are shown as circles with the means for each context indicated by a cross. The bullet graph shows the 80%, 95%, and 99% confidence intervals (CIs; thickest to thinnest bullets) around the mean. Gray line highlights that statistical differences at the 99% CI for δ^{15}N values between early and late burials.

is likely that the cumulative effect of changing climate conditions on both animals and humans affected the δ^{15}N values, obscuring clear trends toward increased animal protein in the diet of individuals living at Cahal Pech.

Discussion

We used stable isotope analyses of AMS ^{14}C-dated human burials to understand the relationships between climatic fluctuations and the dietary diversity of populations living at the ancient Maya site of Cahal Pech from the Preclassic through Terminal Classic periods. These data were also compared with regional paleoclimate proxy records to help interpret the climatic contexts of site growth and decline during two severe droughts in the Late Preclassic and Terminal Classic periods. Summed probability distributions of radiocarbon dates show that steady and uninterrupted site growth at Cahal Pech began ~1200 cal BC during the Early Preclassic. This likely represents low-level early occupation with growth from the Preclassic to the Early Classic. Isotopic data from burials dating to this interval suggest that the early inhabitants of the site had more flexible and diverse dietary practices in the context of severe drought. Directly dated burials, in addition to dates from early construction activity in peripheral settlements (Ebert 2017; Ebert et al. 2017), provide evidence for population growth across the site after cal AD 400. Within the monumental core, the construction of several large temple and palace buildings and directly dated human burials document the construction of the first tomb (Burial 7, Str. B1) associated with an elite lineage between cal AD 140 and 395 (Novotny et al. 2018).

We argue that the resilience of complex social systems at Cahal Pech from the Preclassic through Early Classic Periods was dependent in part on a broad subsistence strategy that helped to absorb shocks to maize-based food production in the context of drought. The results of stable isotope analyses of human skeletal remains from the Preclassic and Early Classic suggest that the inhabitants of Cahal Pech, from both the site core and settlement, had a broad and diverse diet. While most site core individuals from this period consumed high quantities of C_4 foods (i.e., maize), δ^{15}N values overlap with individuals interred in settlement contexts and span several trophic levels. Consumption of marine and freshwater fish, represented by faunal remains from household and site core assemblages, may account for elevated δ^{15}N values for some of these individuals (Powis et al. 1999; White, Longstaffe, Schwarcz 2006). Lower δ^{13}C values for most individuals living in more rural settlements suggest that maize was a smaller component of the diet for this period and that wild plants were also consumed widely. Paleobotanical and faunal evidence recovered from household contexts also indicate that a range of wild and domesticated plant and animal resources were procured from slash-and-burn farming, household gardens, and hunting (Awe 1992; Powis et al. 1999; Wiesen and Lentz 1999). This broad subsistence strategy persisted in both site core and settlement contexts through the severe drought at the end of the Preclassic, between cal AD 100 and 300, likely taking advantage of

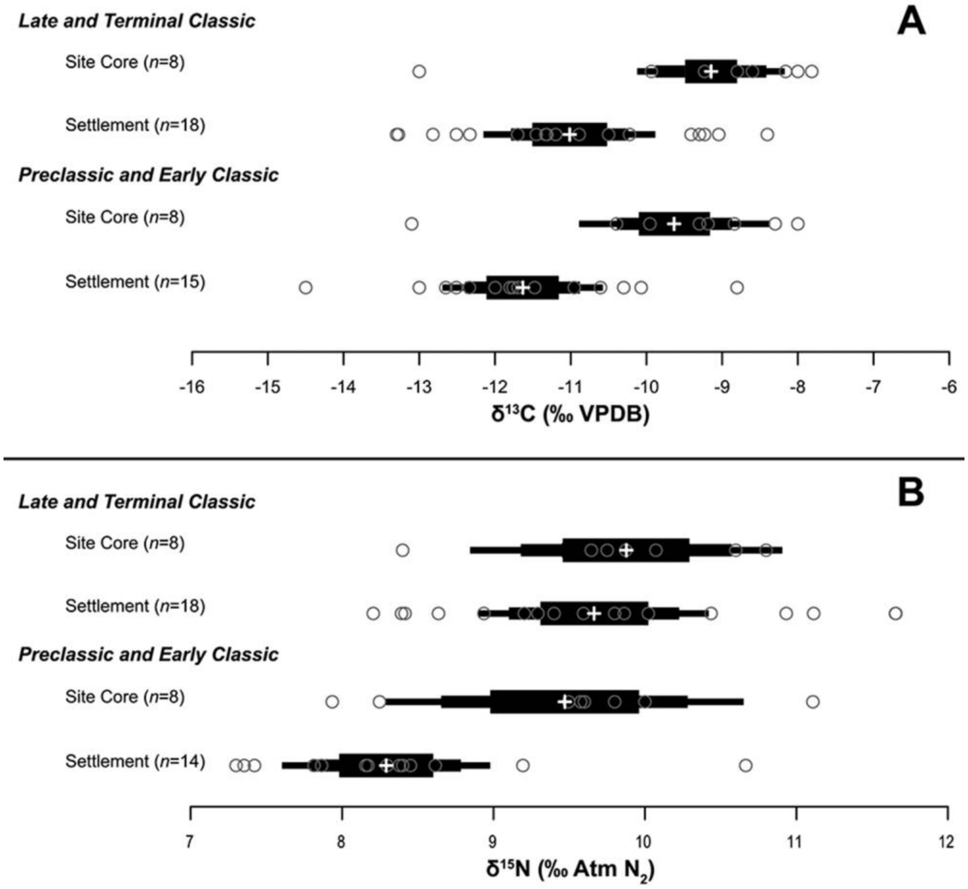

Figure 6. Mean stable carbon ($\delta^{13}C$; *A*) and nitrogen ($\delta^{15}N$; *B*) isotope values for Cahal Pech individuals plotted by early (Preclassic to Early Classic) and late (Late Classic to Terminal Classic) temporal categories and by context in the site core or settlement. Data points are shown as circles with the means for each context indicated by a cross. The bullet graph shows the 80%, 95%, and 99% confidence intervals (thickest to thinnest bullets) around the mean.

wild resources that could be exploited as fallback foods during climatic fluctuations.

A key component of growing hierarchies and societal integration for the Late Classic Maya was agricultural intensification and increasing reliance on maize as a staple crop (Kennett and Beach 2013), which made populations more vulnerable to drought conditions. Stable isotopes document statistically significant shifts in $\delta^{13}C$ and $\delta^{15}N$ values at Cahal Pech between status groups. The $\delta^{13}C$ signal for elite individuals from the site core increased significantly by the Late Classic, and Terminal Classic burials exhibit similar values. This pattern is consistent with the stable isotope data for elite diets at other large Late and Terminal Classic lowland Maya sites (e.g., Altar de Sacrificios and Dos Pilas, Wright 2006; Altun Ha, White, Longstaffe, Schwarcz 2001; Pacbitun, White et al. 1993). Many of these studies show that elites had greater access to maize, in addition to a greater diversity of foods including high proportions of animal protein and imported exotic foods (e.g., marine fish, Somerville, Fauvelle, and Froehle 2013). While Caribbean marine fish species have been found at Cahal Pech, our results show a different pattern of highly restricted $\delta^{13}C$ and $\delta^{15}N$ values for elite individuals in the Late and Terminal Classic, which correspond to a hyperspecialized maize-based diet that persisted through the final abandonment of the site. This stands in contrast to an increase in the range of $\delta^{13}C$ and $\delta^{15}N$ values of individuals from the settlement during the same time. Individuals living in more rural settings may have expanded their diets in part as a response to increasing aridity in paleoclimate records beginning after ~AD 660 (Kennett et al. 2012). Households likely developed alternative subsistence strategies, as they were also stressed by elite demands for increased maize production (Webster 1985).

Shifts in $\delta^{15}N$ values during the Late and Terminal Classic periods point to other types of accumulating sociopolitical, economic, and environmental stresses, which added to vulnerabilities at Cahal Pech. High $\delta^{15}N$ values often correlate with arid conditions, with reductions in rainfall corresponding to enrichment within a trophic level (Ambrose 1991). Landscape alterations, including agricultural developments and forest loss, also drive $\delta^{15}N$ enrichment (Lohse et al. 2014). A positive shift in δ^{15}N values, when considering all analyzed individuals at Cahal Pech, corresponds with a trend toward drier climatic conditions beginning in the Late Classic and possibly deforestation related to agricultural intensification (Turner 2018). While no spatial relationship exists between δ^{15}N values and distance from the site core, deforestation and agricultural expansion could have influenced a positive shift in δ^{15}N values for some individuals. AMS ^{14}C dating of human burials indicates an abrupt cessation of elite mortuary and political activity at the site between cal AD 775 and 890, corresponding with a multidecadal dry interval in the Macal Chasm and Yok Balum paleoclimate records. There is only limited evidence for occupation in surrounding settlements after ~cal AD 900, indicating that vulnerability to drought conditions ultimately affected the demographic decline at peripheral settlement groups in addition to the disintegration of the Cahal Pech sociopolitical system.

Conclusions

Stable isotope research in the Maya region has focused on examining the relationships between diet, social status, and ecological degradation during the Terminal Classic Period. The role of diet and the differential resilience of groups to climate change remains underexplored. AMS ^{14}C dates and stable carbon and nitrogen isotope data from 50 human burials from the Belize Valley site of Cahal Pech suggest that diet played a key role in societal resilience and vulnerability in the face of two periods of multicentury droughts in the Late Preclassic and the Terminal Classic. A mixed diet that incorporated wild and domestic resources promoted resilience to and persistence of populations through drought during the end of the Preclassic Period. Dense populations and a highly interconnected sociopolitical system developed at Cahal Pech in the Late Classic. Maize was economically and ideologically central to this system, and increased stable carbon isotope values indicate that elite individuals from the site core developed a preference for a highly specialized maize-based diet, a pattern that persisted through the Terminal Classic period. Nitrogen isotope data also document dietary change across the entire Cahal Pech population that reflects increasing aridity and/or deforestation after ~cal AD 660. Elite economic demands for increased agricultural production, increased dietary reliance on maize agriculture, and extreme dry conditions undermined and ultimately influenced the collapse of Cahal Pech. These data provide a long-term perspective on factors that affected resilience and decline of ancient lowland Maya society and contribute to our understanding of vulnerability to climate change in modern times.

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Supplemental Documentation

AMS Radiocarbon Dating and Stable Isotope Analysis Methods

A total of 72 burials from Cahal Pech were processed for AMS radiocarbon dating and stable carbon and nitrogen isotope analyses. An additional 45 samples of fauna from Cahal Pech and the nearby site of Baking Pot, were also processed for stable isotope analyses (Table S1). Cortical bone was preferentially sampled when available to maximize collagen yield. Approximately 1000 mg of dry bone from each sample were cleaned of adhering sediment with an X-acto® blade. Bone collagen was extracted and purified using the modified Longin (1971) method with ultrafiltration (Brown et al. 1988) or XAD-purification for more poorly preserved samples (Lohse et al. 2014; Stafford et al. 1998). Samples were demineralized for 24–48 hours in 0.5 N HCl at 5 °C, followed by a brief (<1 h) alkali bath in 0.1 N NaOH at room temperature to remove humates. The resulting pseudomorph was rinsed to neutrality in multiple changes of Nanopure H_2O and then gelatinized for 12 h at 60 °C in 0.01 N HCl. Ultrafilitration methods (Brown et al. 1988) for the purification of or well-preserved collagen samples. For these samples, the gelatin solution was pipetted into pre-cleaned Centriprep® 30 ultrafilters (retaining > 30 kDa molecular weight gelatin) and centrifuged 3 times for 30 min, and diluted with Nanopure H_2O and centrifuged 3 more times for 30 min to desalt the solution (ultrafilter cleaning methods are described in McClure et al. 2011: 28–29). Ultrafiltered collagen was lyophilized and weighed to determine percent yield as a first evaluation of the degree of bone collagen preservation.

XAD-purification was used for more poorly preserved samples according to procedures described by Stafford et al. (1998), with modifications described by Lohse et al. (2014). Contaminants were eliminated by breaking down bone collagen into individual amino acids by hydrolysis in 2mL 6 N HCl for 22 hours at 110 °C, releasing humic and fulvic acids into solution. Supelco ENVI-Chrom® SPE (Solid Phase Extraction; SigmaeAldrich) columns were prepped with 2 washes of methanol and rinsed with 10 mL DI H2O. With a 0.45 mm Millex Durapore filter attached, the SPE Column was equilibrated with 50 mL 6 N HCl and the washings discarded. Next, 2 mL collagen hydrolysate as HCl was pipetted onto the SPE column and driven with an additional 10 mL 6 N HCl dropwise with the syringe into a 20 mm culture tube. The hydrolyzate was finally dried into a viscous syrup by passing UHP N2 gas over the sample heated at 50 °C for ~12 hours.

A total of 20 samples failed processing preparation due to poor preservation (Table S2), and were not submitted for additional AMS ^{14}C and stable isotope analyses. Preservation tended to be biased towards burials recovered from residential contexts. These individuals were often buried within simple cysts underneath house floors. Burials from monumental contexts, especially in the site core, tended to be placed in lime plastered chambers or beneath plastered floors and were more poorly preserved. This observation may indicate that the plaster is elevating the pH within the burial matrix, resulting in alkaline soils that degrade bone collagen.

Carbon and nitrogen concentrations and stable isotope ratios were measured at the Yale Analytical and Stable Isotope Center with a Costech ECS 4010 Elemental Analyzer with Conflo III interface. Sample quality was evaluated by % crude gelatin yield, %C, %N, and C:N ratios. C:N ratios for 42 samples fell between 3.10 and 3.5, indicating good collagen preservation (DeNiro 1985; van Klinken 1999). Samples with C:N ratios outside of this range did not meet quality control standards (*n*=7; Table S3), and are therefore not considered for additional analyses in this study. We also include stable isotope data from an additional six individuals reported from previous studies in our analyses (Piehl 2006; Powis et al. 1999). We reanalyzed 14 individuals from these studies for AMS radiocarbon dating, and our stable isotope results fall within ±2 ‰ of previously reported results, which is in the expected range of variation for an individual (Table S4; DeNiro and Epstein 1978).

AMS radiocarbon samples (~2.5 mg) were combusted for 3 hr at 900°C in vacuum-sealed quartz tubes with CuO wire and Ag wire. Sample CO_2 was sent to KCCAMS (University of California, Irvine) where it was reduced to graphite at 550°C using H_2 and a Fe catalyst, with reaction water drawn off with Mg(ClO4)2 (Santos et al. 2004). Graphite samples were pressed into targets in Al boats and loaded on the target wheel for AMS analysis. ^{14}C ages were corrected for mass-dependent fractionation with measured $\delta^{13}C$ values (Stuiver and Polach 1977), and compared with samples of Pleistocene whale bone (background, >48 14C kyr BP), late Holocene bison bone (~1850 14C BP), late AD 1800s cow bone, and OX-1 oxalic acid standards for calibration.

All dates are reported as conventional ^{14}C ages corrected for fractionation, with measured $\delta^{13}C$ following Stuiver and Polach (1977). Date calibrations were produced in OxCal v.4.2 (Bronk Ramsey 2009) using the IntCal13 Northern Hemisphere atmospheric curve (Reimer et al. 2013). Given the proximity of Cahal Pech to the Belize River and the likelihood of some amount of riverine food in the ancient Maya diet, an unquantified freshwater reservoir effect (R_f) may impacts some or all of the skeletons, but are relatively minimal (Hoggarth et al (2014: 1062)

Figure S1 shows the calibrated date ranges from all Cahal Pech burials for the Preclassic through Terminal Classic Periods, with the summed probability distribution of dates plotted at the bottom. Relative ceramic phases are also indicated. The summed probability distributions show shifts in occupational activity at Cahal Pech, with rises and falls represented general positive and negative demographic trends. Calibrated distributions were plotted against a histogram showing the number of calibrated 2-σ ^{14}C dates binned in 50-year intervals (Figure 2 in text). These data show general positive and negative trends in the summed distributions with attached confidence intervals. Considered alongside stable isotope and paleoclimate proxy data, the summed distributions of burial dates also helps to identify the timing of dietary shifts, represented in stable isotope data, which correspond to climatic trends.

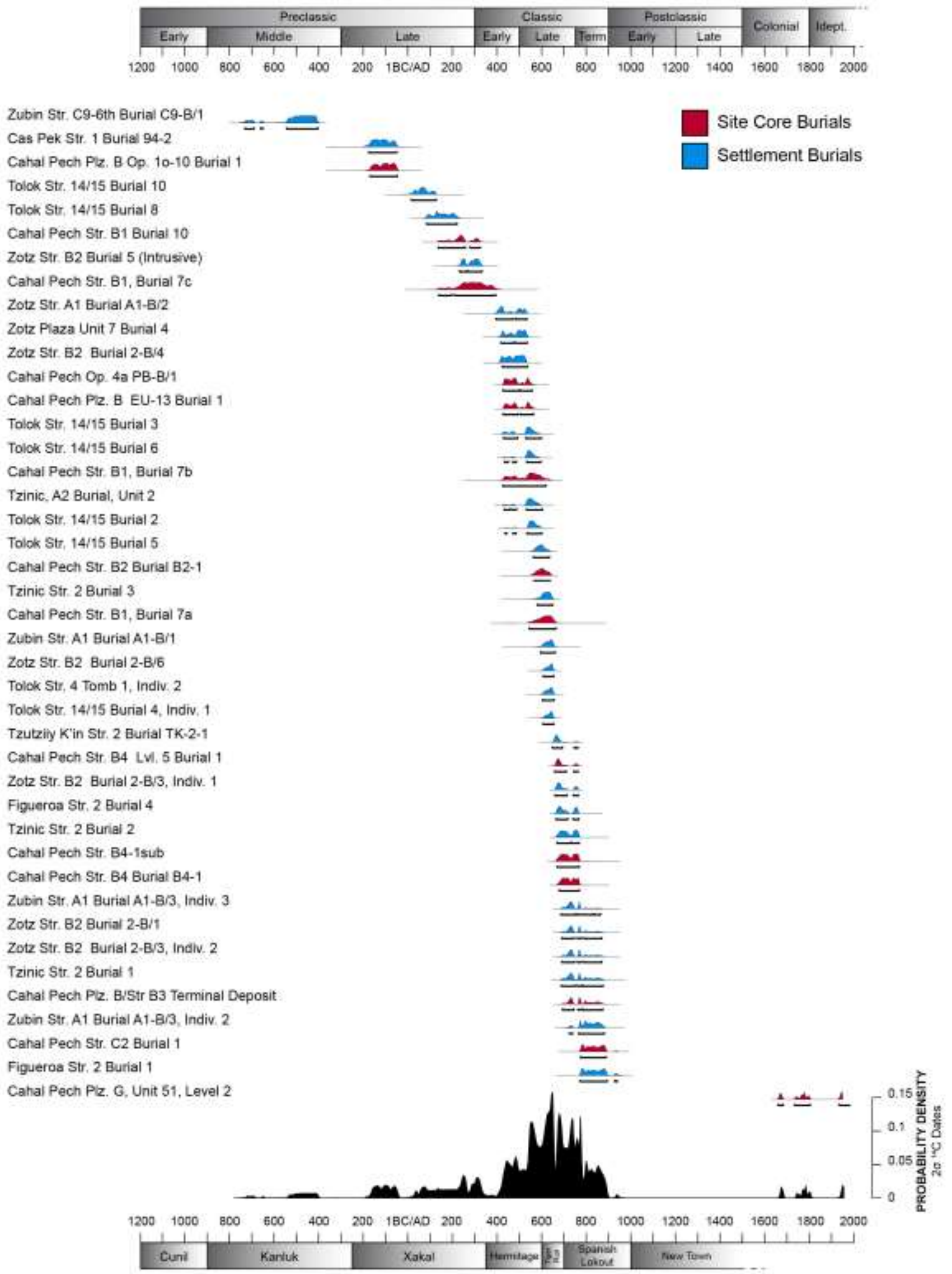

Figure S1: Calibrated 2σ dates for Cahal Pech burials, with summed probability distribution of burials plotted at the bottom. Relative chronological periods considered in this study (top) and associated ceramics for Cahal Pech (bottom) are also indicated.

Table S1. Variation in mean ($\delta^{13}C$) and nitrogen ($\delta^{15}N$) isotope values for archaeological fauna (*n*=45) from Belize Valley sites Cahal Pech and Baking Pot.

Species	**Common Name**	***n***	**$\delta^{13}C$ (‰ VPDB)**	**St. Dev.**	**$\delta^{15}N$ (‰ Atm N_2)**	**St. Dev.**
Canis familiaris	Dog	3	-19.5	4.2	5.2	2.0
Chelonia	Freshwater turtle	3	-22.5	0.5	4.9	1.1
Mazama americana	Red brocket deer	3	-20.0	1.1	6.4	1.1
Meleagridae	Turkey	1	-17.0		4.4	
Nasua narica	Coati	1	-13.5		10.1	
Odocoileus virginianus	White-tailed deer	31	-20.1	2.4	5.6	1.3
Sylvilagus sp.	Forest rabbit	3	-20.0	0.3	4.3	0.4

Table S2. Poorly preserved burials (*n*=20) from Cahal Pech that failed during AMS ^{14}C and stable isotope processing. Samples are listed by relative time period based on ceramic associations.

Provenience/Burial	**Sex**	**Age**	**Time Period**
Cahal Pech Str. B1 Burial 8	M	30-40	Late Preclassic
Cahal Pech Str. B4 Burial 1/-6	I	A	Late Preclassic
Zubin Str. A1 Burial A1-B/10	I	4-5	Late Preclassic
Zubin Str. A1 Burial A1-B/9	I	25-40	Late Preclassic/Early Classic
Cahal Pech Str. B1 Burial 11	M	40+	Early Classic
Cahal Pech Str. B1 Burial 12	M	A	Early Classic
Zotz Str. 7, Burial 7	I		Early Classic
Cahal Pech Plaza A Burial A3-1	I	8-10	Late Classic
Figueroa Str. 2 Burial 2			Late Classic
Tzinic Str. 2 Burial 4			Late Classic
Tzinic Str. 2 Burial 5			Late Classic
Tzinic Str. 2 Burial 6			Late Classic
Tzinic Str. 8 Burial 1			Late Classic
Zopilote Str. 1 Tomb 1, Indiv 2			Late Classic
Zotz Str. 2 Burial 3			Late Classic
Zotz Str. 2 Burial SE side			Late Classic
Zubin Str. A1 Burial A1-B/3, Indiv 5	M	A	Late Classic
Zubin Str. A1 Burial A1-B/4	I	I	Late Classic
Cahal Pech Str. B1 Burial 9	I	A	Terminal Classic
Cahal Pech Str. B1 Burial 13	F	40+	?

Table S3: Burials from Cahal Pech that failed C:N quality control measures (*n*=7). Samples are listed by relative time period based on ceramic associations.

Provenience	**Sex**	**Age**	**Time Period**	**δ^{15}N (‰ Atm N2)**	**δ^{13}C (‰ VPDB)**	**%N**	**%C**	**C:N**
Tzutziiy K’in Str. 2 LT3			Early Classic			0.3	1.4	5.5
Figueroa Str. 2 Burial 3a			Late Classic	7.8	-16.5	1.1	3.8	4.0
Zubin St. A1 Burial A1-B/2	I	I	Late Classic	18.7		0.6	2.5	5.1
Zubin St. A1 Burial A1-B/6	I	I	Late Classic			0.3	1.4	6.1
Cahal Pech Plaza A Burial A3-1	I	8-10	Late Classic				0.6	
Cahal Pech Plaza H Tomb 1	M	OA	Terminal Classic	12.4		1.8	5.9	3.8

Table S4. Comparison of previously reported stable carbon and nitrogen isotope results from Piehl (2005) and Powis et al. (1999) to reanalysis of samples performed for this study.

Provenience	**Previous Studies**		**This Study**	
	δ^{13}C (‰ VPDB)	**δ^{15}N (‰ Atm N2)**	**δ^{13}C (‰ VPDB)**	**δ^{15}N (‰ Atm N2)**
Zotz Str. B2 Burial 1	-12.5	9.2	-12.8	9.6
Zotz Str. B2 Burial 3	-9.0	11.2	-9.2	11.1
Zotz Str. B2 Burial 4	-11.1	7.8	-8.8	7.9
Zotz Str. B2 Burial 5	-10.2	9.6	-10.6	9.2
Zotz Str. B2 Burial 6	-11.9	9.9	-9.0	10.4
Figueroa Str. 2 Burial 4	-8.8	10.0	-11.7	9.3
Tolok Str. 14/15 Burial 2	-10.4	8.5	-11.5	8.3
Tolok Str. 14/15 Burial 3	-12.1	8.3	-11.8	8.6
Tolok Str. 14/15 Burial 4	-12.2	8.2	-11.5	8.4
Tolok Str. 14/15 Burial 8	-13.0	8.4	-11.8	7.8
Tolok Str. 14/15 Burial 10	-13.8	8.4	-12.6	8.5
Tzinic Str. 2 Burial 1	-10.1	9.4	-11.3	11.7
Tzinic Str. 2 Burial 2	-10.9	9.9	-11.3	11.7
Tzinic Str. A2 Burial 1	-13.0	7.2	-12.3	7.4

Statistical Analyses

For statistical analyses, five different groups were formed for the analyzed individuals based on the relative temporal and contextual associations (Table S4). The *t*-test for independent groups (two parameters) assuming unequal variance was used to determine significant differences between the means within each group (Ruxton 2006). Additionally, the non-parametric Mann–Whitney *U* test (two parameters) for independent samples was used where applicable due to the small sample size since not all samples were normally distributed. Significance was set at $\alpha = 0.05$ for all tests. Box plots comparing $\delta^{13}C$ and $\delta^{15}N$ values for purified human bone collagen from site core and settlement contexts through time were also created to illustrate statistical relationships between groups (Figure S2 and S3). One human sample (Tolok Str. 14/15 Burial 9) was not included because $\delta^{15}N$ values were not reported for this individual (Powis et al. 1999). Comparing early and late time periods, no significant differences are evident in $\delta^{13}C$. In contrast, $\delta^{15}N$ is significantly different between early and late populations at Cahal Pech ($t = -3.32$; df = 42; $p = .002$).

We also examined if there was an age or sex effect influencing isotope values. Enriched $\delta^{15}N$ values in sub-adults (less than 5 years old) has been shown to reflect some breast-feeding among some populations (Katzenberg and Pfeiffer 1995; Richards et al. 2002). We compared both $\delta^{13}C$ the $\delta^{15}N$ values for all individuals in the sample for which age could be determined (sub-adults $n = 5$, adults $n = 24$). There was no significant different between sub-adults and adults for either $\delta^{13}C$ ($t = -0.6$; df = 5; $p = 0.487$) or $\delta^{15}N$ ($t = -1.04$; df = 7; $p = 0.166$). Comparing stable isotope values for sex differences across all time periods (Table S6), there was not a significant difference for $\delta^{13}C$ between males ($n = 12$) and females ($n = 8$). However there was a significant difference for $\delta^{15}N$ values ($t = -1.97$; df = 18; $p = 0.032$), with males having more enriched values. However, when sex differences were evaluated by time period, there were no significant differences between male and female diets, indicating that changes in $\delta^{13}C$ and $\delta^{15}N$ values through time is likely not influenced by dietary difference between sexes.

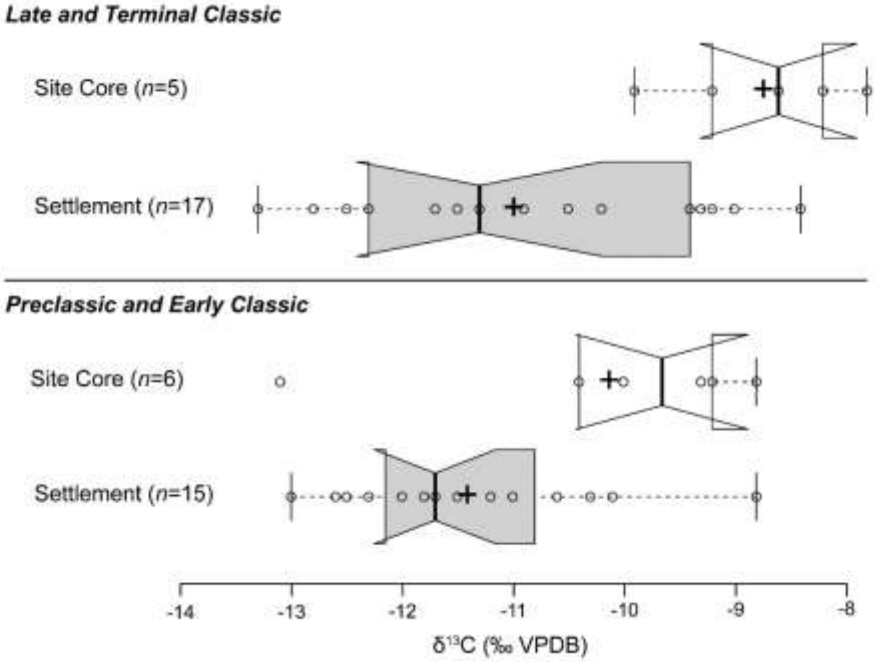

Figure S2: Box plots of stable carbon ($\delta^{13}C$) isotope values for human bone collagen from the Cahal Pech site core and settlement. Notches represent the 95% confidence interval for each median. The mean is represented by the "+" symbol.

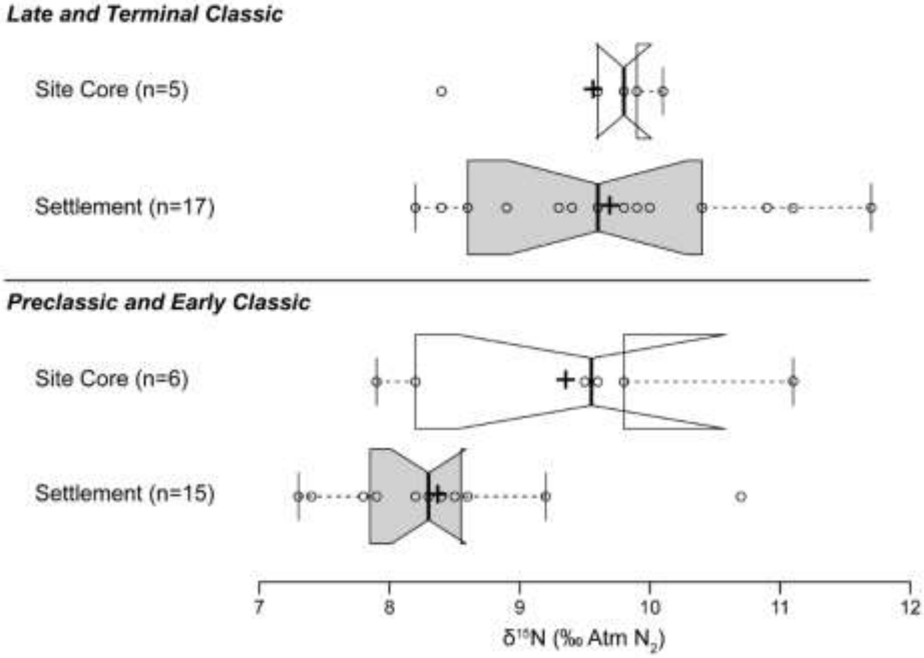

Figure S3: Box plots of stable nitrogen ($\delta^{15}N$) isotope values for human bone collagen from the Cahal Pech site core and settlement. Notches represent the 95% confidence interval for each median. The mean is represented by the "+" symbol.

Table S5. Results of statistical analyses for different groups.

Groups	***n***	**Variables**	***t*-test (*p*)**	**Mann-Whitney *U* (*p*)**
Preclassic and Early Classic vs. Late and Terminal Classic	21; 23	$\delta^{13}C$	0.174	0.358
		$\delta^{15}N$	<0.001	0.001
Preclassic and Early Classic Site Core vs. Settlement	6; 15	$\delta^{13}C$	0.050	0.080
		$\delta^{15}N$	0.046	0.067
Late and Terminal Classic Site Core vs. Settlement	5; 17	$\delta^{13}C$	<0.001	0.008
		$\delta^{15}N$	0.365	0.938
Preclassic and Early Classic Site Core vs. Late and Terminal Classic Site Core	6; 5	$\delta^{13}C$	0.054	0.067
		$\delta^{15}N$	0.372	0.412
Preclassic and Early Classic Settlement vs. Late and Terminal Classic Settlement	15; 17	$\delta^{13}C$	0.200	0.224
		$\delta^{15}N$	<0.001	0.001

Table S6. Results of statistical analyses for sex differences. Mann-Whitney *U* not performed for some groups due to insufficient sample size.

Groups	***n***	**Variables**	***t*-test (*p*)**	**Mann-Whitney *U* (*p*)**
All Time Periods Female vs. Male	8; 12	$\delta^{13}C$	0.378	0.425
		$\delta^{15}N$	0.032	0.038
Preclassic and Early Classic Female vs. Male	4; 4	$\delta^{13}C$	0.075	-
		$\delta^{15}N$	0.068	-
Late and Terminal Classic Female vs. Male	4; 8	$\delta^{13}C$	0.162	-
		$\delta^{15}N$	0.258	-

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