ANTHROPOLOGY

Late Archaic large-scale fisheries in the wetlands of the pre-Columbian Maya Lowlands

Eleanor Harrison-Buck[1]*, Samantha M. Krause[2], Marieka Brouwer Burg[3], Mark Willis[4], Angelina Perrotti[5], Katie Bailey[3]

Multiproxy data collected from the largest inland wetland in Belize, Central America, demonstrate the presence of large-scale pre-Columbian fish-trapping facilities built by Late Archaic hunter-gatherer-fishers, which continued to be used by their Maya descendants during Formative times (approximately 2000 BCE to 200 CE). This is the earliest large-scale Archaic fish-trapping facility recorded in ancient Mesoamerica. We suggest that such landscape-scale intensification may have been a response to long-term climate disturbance recorded between 2200 and 1900 BCE. Agricultural intensification after 2000 BCE has been credited for supporting the rise of pre-Columbian civilizations in Formative Mesoamerica, but we suggest that some groups relied more heavily on the mass harvesting of aquatic resources. We argue that such early intensification of aquatic food production offered a high value subsistence strategy that was instrumental in the emergence of Formative period sedentarism and the development of complexity among pre-Columbian civilizations like the Maya.

INTRODUCTION

Wetlands are among the most productive ecosystems in the world (*1*). These environments provide a valuable array of ecosystem services that are beneficial to both environmental and human health (*2*). Wetlands act as a buffer from flooding and drought, help to regulate air quality and climate change, and provide both humans and animals a valuable array of resources, such as fish, fiber, and freshwater supply (*3*, *4*). As rich repositories of biological diversity, it is not unexpected that wetlands have been actively managed and enhanced in various ways for millennia by people across the globe.

Some of the earliest wetland enhancements occurred around 6000 to 8000 years ago when Archaic hunter-gatherer-fisher groups constructed fish weirs using a range of materials, including rocks, reeds, earth, and wood (*5*–*7*). Weirs are found in a variety of environments—from estuarine tidal flats and rivers to wetlands and savanna floodplains (*8*, *9*). Weirs were designed to capture large quantities of fish but varied in form from impediments built of rocks with v-shaped chutes for trapping fish in faster-moving water to earthen channels in slower-moving water to guide the flow and movement of migrating fish during annual flooding cycles. While prehistoric fisheries have been documented in the wetlands of native North and South America, this is the first large-scale Archaic fish-trapping facility recorded in Central America.

In this study, we present multiproxy data from a landscape-scale study of the Crooked Tree Wildlife Sanctuary (CTWS)—the largest inland wetland in Belize, Central America. Here and in several other locations in the Maya Lowlands (Fig. 1), our team has identified through remote sensing (using drones and Google Earth imagery) a vast network of linear earthen channels or weirs (for close-ups of these maps, see figs. S1 to S3). These linear features closely resemble other pre-Columbian fish-trapping facilities recorded in similar tropical environments of the Bolivian Amazon as well as ethnographic examples found in Zambia, Africa (Fig. 2) (*10*–*12*). We report on excavations of three channels in the CTWS that yielded multiple radiocarbon dates, which suggest that the fisheries were initially constructed by Archaic hunter-gatherer-fishers and continued to be used by their Formative Maya descendants (approximately 2000 BCE to 200 CE), predating the Amazonian examples by a thousand years or more.

Background of the study

The CTWS is a Ramsar wetland of international importance in northern Belize. The CTWS is a biologically diverse environment that contains a wealth of food resources, including fish, Mollusca, plants, waterfowl, and other wildlife. Perhaps not coincidently, archaeological investigations in the CTWS have revealed evidence of nearly 10,000 years of continuous occupation. The Belize River East Archaeology (BREA) project has documented occupation in this area beginning in Archaic times and continuing with ancient Maya and Colonial occupation (*13*–*18*). The wildlife sanctuary is a 167-km^2 protected area that comprises a complex network of streams connecting freshwater and brackish lagoons and a vast wetland complex with a strongly seasonal flood pulse. During the rainy season, the flow in Black Creek reverses course due to flooding from the Belize River, infilling the Western and Northern Lagoons of the CTWS (*19*). These annual flooding cycles inundate wetlands and lagoons, making them attractive for schools of fish to spawn (*20*). The archaeological evidence presented here suggests that the area has been an important fishing ground for millennia, as it is today.

Pyburn (*19*) was the first to investigate the modified wetlands in the CTWS, originally documenting a total of 11 linear features in the Western Lagoon, proximate to the large ancient Maya center of Chau Hiix. The assumption was that these linear features were constructed by the ancient Maya. Pyburn (*19*) noted that these features may have been used secondarily for aquaculture but concluded that they primarily served as an "enormously productive agricultural technology" (p. 123). Similar linear anomalies have been documented in the upper Candelaria in Mexico, first identified from the air in 1968 by Siemens and Puleston (*21*). In their map of the region, they were able to distinguish these longer and wider channels that

[1]Department of Anthropology, University of New Hampshire, Durham, NH 03824, USA. [2]Department of Geography & Environmental Studies, Texas State University, San Marcos, TX 78666, USA. [3]Department of Anthropology, University of Vermont, Burlington, VT 05405, USA. [4]Department of Archaeology, Flinders University, Adelaide, South Australia, Australia. [5]Palynology & Environmental Archaeology Research Lab, Monona, WI 53716, USA.
*Corresponding author. Email: e.harrison-buck@unh.edu

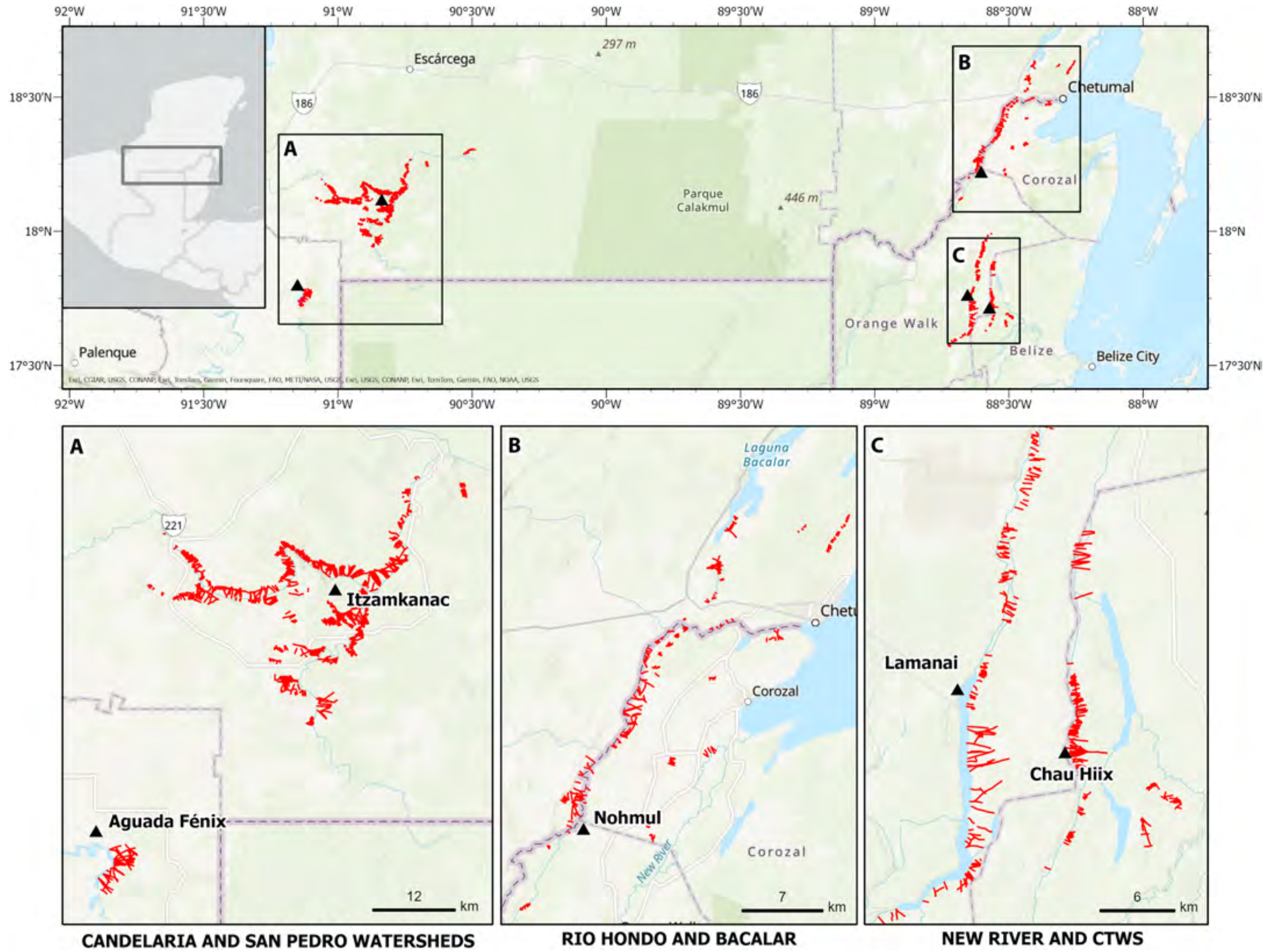

Fig. 1. Linear wetland features identified in remote sensing data as probable fish-trapping facilities from areas across the Maya Lowlands. An overview map (top) with inset maps below showing linear channels identified in (**A**) the Candelaria and neighboring San Pedro Drainage, (**B**) the Rio Hondo and Bacalar, and (**C**) the New River and Western Lagoon in the CTWS (all images courtesy of the BREA project).

crisscross the wetlands from what they classified as "complexes of ridged fields"—more often today referred to as "ditched and drained" wetland agricultural fields. Thompson (*22*) proposed that the longer, wider channels in the Candelaria may have functioned as fish refuges. However, all subsequent scholarship has interpreted them as primarily associated with ditched and drained wetland agricultural production, either as check dams or transportation canals [(*23*–*25*); for a rare exception, see Palka (*26*)].

Although weirs leave an archaeological trace, often, they are partially or fully submerged, which makes them difficult to identify on the ground. Aerial imagery has been the most effective means for identifying weirs and over the past two decades; the development of a range of more powerful remote sensing technologies has markedly improved our ability to map landscape-scale wetland features from a bird's-eye view (*27*–*32*). Below, we describe the results of our remote sensing and geospatial studies, along with the results of three test excavations of the linear channels in the CTWS, which together have transformed our understanding of these features.

RESULTS

Remote sensing and geospatial studies

Our geospatial analysis of the CTWS is derived from a combination of remote sensing techniques, including Google Earth satellite imagery and custom imagery acquired by unmanned aerial vehicles (UAVs), otherwise known as drones. The wetland features are most pronounced in the aerial imagery (and only accessible on foot) during the dry season when flood waters recede. When the lagoon is nearly dry, it resembles a marshy grassland with long linear channels crisscrossing the open area and continuing for some distance into the higher ground of the lagoon's shoreline, which is covered with low scrubby vegetation (fig. S4). Today, the earthen channels are subtle concave linear features with an elevation difference of about 20 cm in depth that is barely discernible on the ground. These artificial wetland enhancements are most visible from the air because the soils in the shallow channels retain more moisture, and thus vegetation maintains more vigor in the dry season when compared to the surrounding sedge and grass that is at a slightly higher elevation.

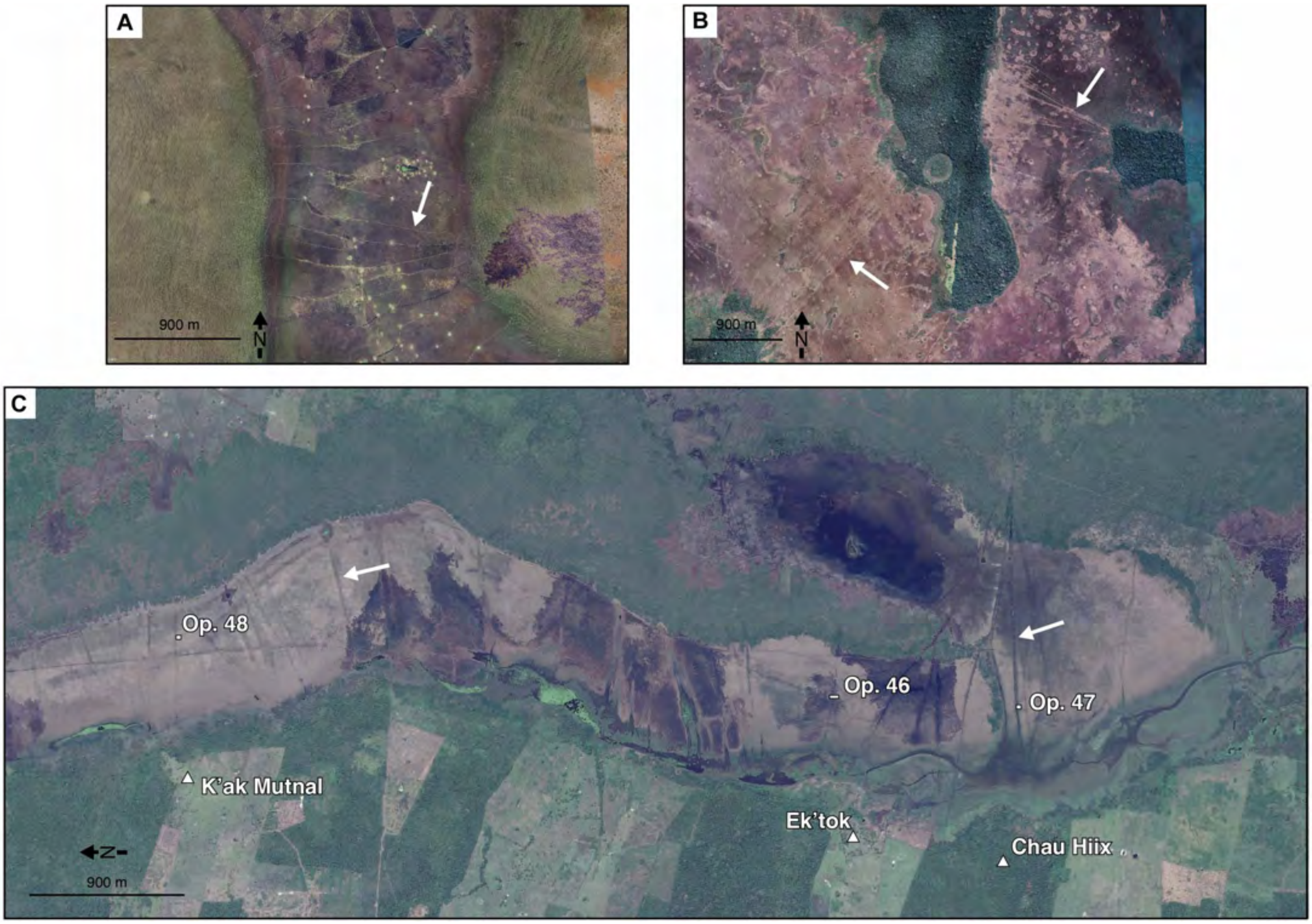

Fig. 2. Seasonal floodplain landscapes with earthen fish weirs that resemble those in the CTWS. Satellite imagery includes (**A**) a contemporary fishery in Zambia, Africa; (**B**) an ancient fishery in the Bolivian Amazon; and (**C**) the ancient fishery in the Western Lagoon, CTWS, Belize (all images courtesy of Google Earth).

To gain finer resolution imagery, our team conducted a total of 32 drone flights over the southern half of the Western Lagoon in the CTWS during the height of the dry season in the summer of 2017 (*32*). The resulting digital elevation model (DEM) was compared alongside the Google Earth satellite imagery to provide finer resolution and a more accurate map of the wetland features in the Western Lagoon (Fig. 3). In examining the full length of the lagoonal system including the Spanish Creek drainage, we identified through remote sensing a total of 167 linear features, with an average length of 0.64 km. The total area of wetland modifications in the CTWS measures roughly 41.8 km^2 or 4180 ha. A total of 107.7 km of linear features crisscrosses the 41.8-km^2 area with a linear density of ~2.6 km/km^2 (Table 1).

We compared these dimensions with similar linear anomalies that we identified through remote sensing along the New River, the Rio Hondo, and the upper Candelaria (see Fig. 1 and Table 1; for close-up maps, see figs. S1 to S3). The average length of these linear features is 0.68 km long. Across all four areas, the Candelaria has the largest total area (N = 167.2 km^2). In their original aerial survey, Siemens and Puleston (*21*) identified roughly 235 linear features—what they refer to as "canals" on their map of the upper Candelaria—which they distinguish from the neighboring complexes of ditched and drained fields. In our recent inspection of more fine-grained satellite imagery on Google Earth, we identified and mapped a total of 906 "canal" features in this area that, when combined, have a total length of 643.7 km. The average linear density of the Candelaria is the highest of those we investigated at 3.9 km/km^2, followed by CTWS at 2.6 km/km^2, Rio Hondo at 1.1 km/km^2, and New River at 0.68 km/km^2 (see Table 1).

Our geospatial analysis of these linear zigzag anomalies in the CTWS has revealed that most are paired with a series of pond features (Fig. 3 and fig. S5). Ponds or other more amorphous water bodies may also be paired with the channels in the upper Candelaria, Rio Hondo, and New River drainages, but the pattern is not as clear in the remote sensing data. Ponds are not found associated with ethnographic examples of contemporary weirs in Zambia (*12*), but they do regularly occur with the pre-Columbian fish-trapping facilities in the Bolivian Amazon (Fig. 2) (*10*). We have started to analyze the relationship between the linear features and the ponds in the CTWS. A two-tailed t test has indicated, for example, that the locations of the ponds are not statistically random (see table S1), suggesting that the ponds may have been intentionally placed (or the linear features were constructed to run proximate to existing naturally occurring ponds). In either case, the relationship between the linear channels and the ponds appears to be purposeful.

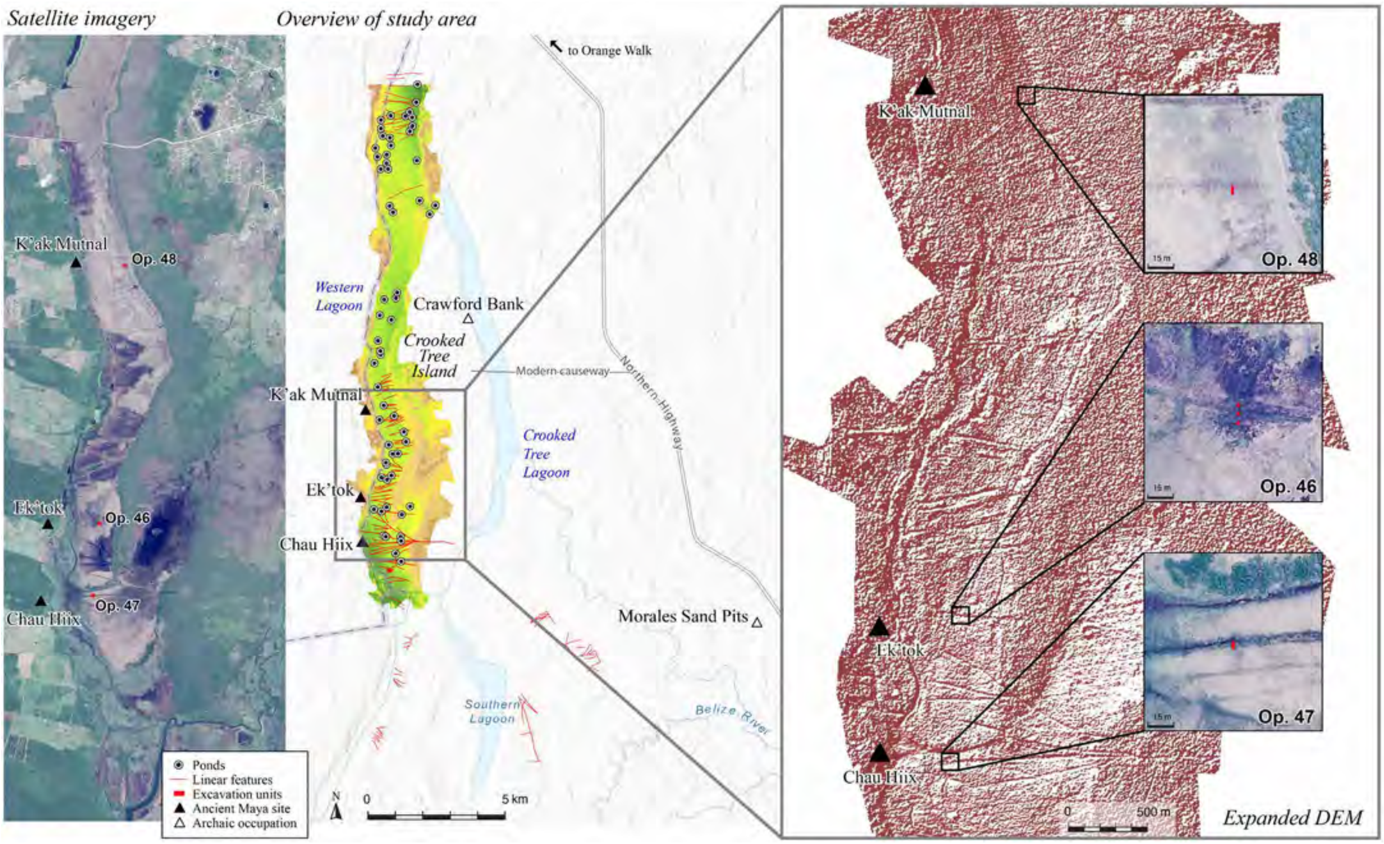

Fig. 3. Map of Western Lagoon CTWS showing linear channels and ponds and archaeological sites mentioned in the text. Satellite and DEM overview and close-up maps showing the series of linear channels paired with ponds and the locations of Operations 46, 47, and 48 (all images courtesy of the BREA project).

Table 1. Measurements of linear wetland features identified in remote sensing data from areas across the Maya Lowlands.

Wetland areas	Feature count	Total length (km)	Mean length (km)	Area (km^2)	Density (total length divided by area)
CTWS	167	107.7	0.64	41.8	2.58
New River	144	101.8	0.71	69.2	0.68
Rio Hondo	152	95.8	0.63	87.0	1.10
Candelaria	906	643.7	0.71	167.2	3.85

Scholars working in the Amazon have also identified such statistical relationships and suggest that the linear channels and ponds were an integrated system used for fish trapping and live storage (*10*). While Erickson (*11*) posited that the ponds were artificial, Blatrix and colleagues (*10*) suggest the possibility of a natural origin for the ponds and that the channels and a series of v-shaped chutes or outlets were artificially constructed. They note that these features point downstream and effectively guide the flow of receding water at the end of the flooding period. Instead of serving as fishways for traps as was the case for the Zambian fisheries, they suggest that the chutes channeled the movement of out-migrating fish, concentrating them into the ponds where they could be more easily caught (*10*). Ethnographic data also suggest that people walking the canals use nets to drive fish as well as turtles and other aquatic life into more restricted water bodies where they can be more easily caught [(*27*, *33*, *34*), pp. 34–38].

While, in the CTWS, there are no v-shaped chutes, we posit a similar function in the pairing of zigzag linear channels and pond features; rather than standard weirs with fishways for traps, the ponds served as the "traps" and the network of linear zigzag anomalies was artificially constructed to channel the flow of receding water at the end of the dry season and concentrate out-migrating fish in ponds. This made them easier to capture in the dry season once the flood waters subsided. While these features have filled in somewhat over the years, locals inform us that the ponds still concentrate fish during the dry season today. However, regulations on fishing in the CTWS restrict harvesting and locals report that large quantities of fish trapped in the low waters often are just left to die and rot in these "source ponds" at the height of the dry season (*20*).

We contend that rain and the seasonal hydrological fluctuation was a key component to the functioning of the large-scale fish-trapping facilities. In addition to remote sensing and geospatial analysis, we have used ground truthing and test excavations that involve geomorphological studies. As Stark (*35*) noted some time ago, geomorphological analyses are crucial for understanding the construction history of these earthen modifications, the hydrology of the system, and the natural postdepositional activity. Below, we describe the results of our test excavations in the CTWS.

Test excavations

Our team carried out geomorphological testing in the CTWS with three test excavations placed in the Western Lagoon—Operations 46, 47, and 48 (Fig. 3) (*36*). Seasonal inundation during the rainy season (June to December) means that the channels and ponds are only exposed for a few months of the year. Often, the wetland-lagoonal environment around Crooked Tree remains wet even during the dry season, making access and excavation extremely limited. Even in the driest of circumstances, the conditions do not permit extensive excavation like regular open-air sites.

In the summer of 2019, there was a severe drought, and our team was able to access the middle of the Western Lagoon area and open up three excavation units (henceforth referred to as Ops. 46 to 48). This exceptionally dry summer meant that the area remained dry enough to access the wetland-lagoon with sufficient time before the rains began to test three widely separated channels. These linear features were initially selected for their proximity to Chau Hiix, Ek'tok, K'ak Mutnal, and other Maya settlement known to exist on the western shoreline of the Western Lagoon (see Fig. 3). Our team was able to excavate down a meter or more in some cases without any risk of inundation but only along the very edges of the channels. Even at the peak dry period under drought conditions, when we attempted an excavation in the center of one of the artificial channels (see Op. 46 Sq. B, described below), the unit filled with water at around 100 cm below the ground surface and we were unable to reach the bottom of this artificial channel (see Fig. 4). Therefore, while all three of our excavations helped to shed light on the construction and chronology of these linear earthen cut features, we were not able to expose the lowest depth of these artificial features in the center of the channels.

Each excavation trench was oriented north-south across one of the long and wide linear earthen channels that traverse from the eastern to western margins of the Western Lagoon in the CTWS (Fig. 3).

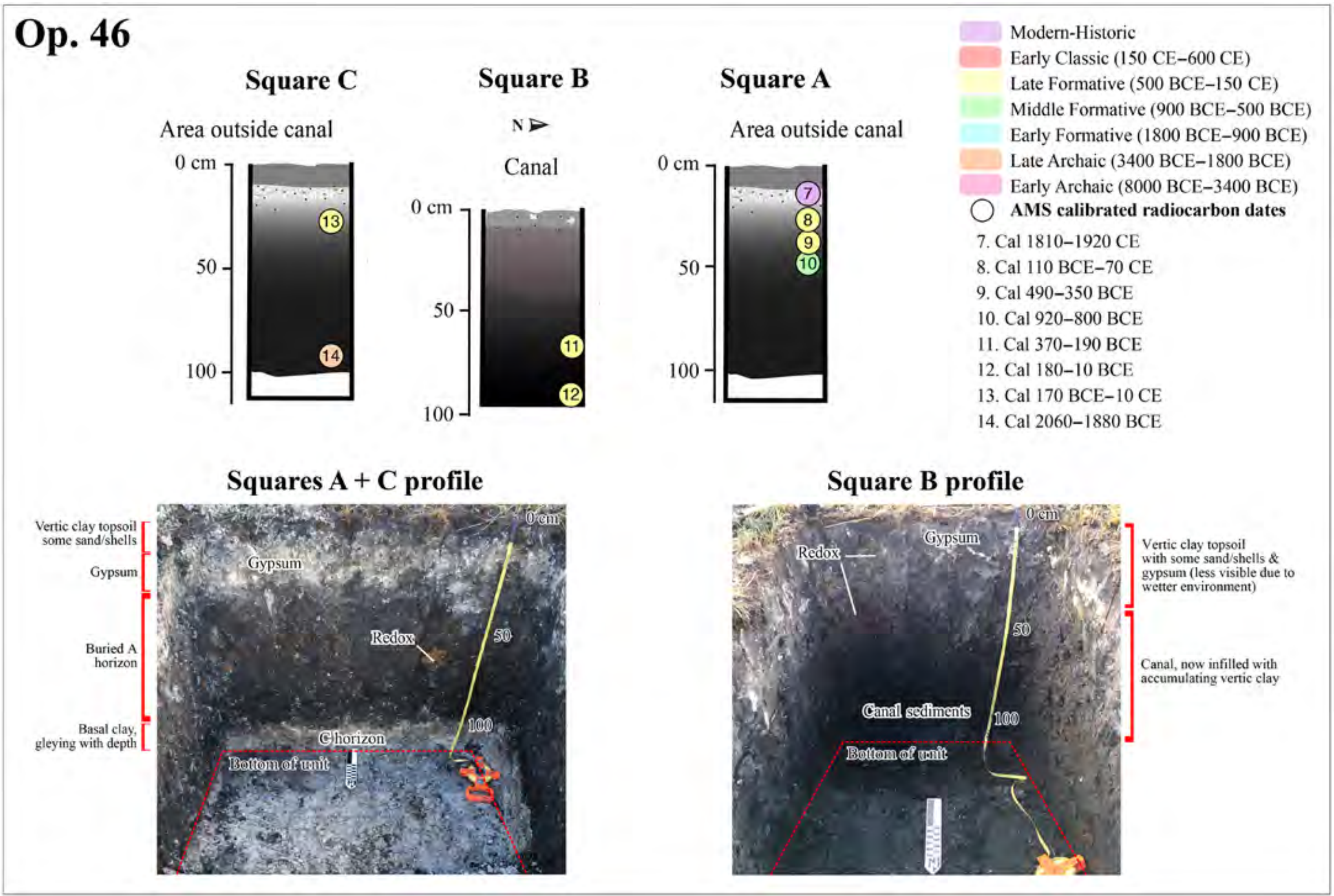

Fig. 4. Operation 46 (Sqs. A to C). Cross sections showing associated calibrated radiocarbon dates and photos of excavations with geomorphological descriptions (images courtesy of the BREA project).

Given the width of these features (15 to 20 m), the test excavations could only capture a small portion of each channel cross section. In the case of Op. 46, the unit was divided into three noncontiguous 1.5-m by 2-m squares (A, B, and C) spread out in a north-south line so as to capture the micro-high zones on either side of the channel (Sqs. A and C) and the lowest point in the center of the channel (Sq. B). As noted above, it quickly became clear that excavation in the center of these channels posed a water inundation problem. Therefore, Ops. 47 and 48 were positioned on the edges of two other channels, aimed at exposing the cut of the linear feature and gaining a better understanding of the stratigraphy of the soils from low to high zones. Ops. 47 and 48 were both laid out as 1.5-m by 6-m–long units that began on the south side of a channel in a micro-high zone and ran north into the lower portions of the linear features (see Fig. 3).

Each of the operations was sampled for sediments for further geomorphological analysis. Sediment samples were collected in 5-cm increments along the walls of excavation units using a cleaned trowel and bagged in plastic ziplock bags. Samples were subsequently exported to the US where subsamples of peat, charcoal, and organic sediment were selected for accelerator mass spectrometry (AMS) dating, geochemical studies, and pollen analysis. An overview discussion of the results of these analyses is presented below.

Geomorphological analysis

The stratigraphy in the Western Lagoon followed a distinct sequence in Ops. 46 and 48 (Figs. 4 and 5). These two operations revealed dense Vertisol soils with pockets of shell-rich layers and redoximorphic features (indicative of a seasonally wet/dry environment) that developed over an oxygen-depleted bluish (reduced) gray clay C horizon and basal sascab. The dense organic rich Vertisol is deepest in the canal portions in both Ops. 46 and Op 48. These clay-rich soils have since aggraded in more recent times and reflect the infilling of the canal features. In Op. 46 Sq. B (the lowest canal sequence), lithic debitage was recovered at 64 cm below the ground surface. In Op. 48, the original construction of the artificial channel can be seen cutting into lower basal material (see Fig. 5).

In Op. 47, the top horizon is the same organic rich Vertisol clay, but this descends into a thick, cumulic layer of decomposed peat with charcoal and shell. This organic rich clay is mixed with some peat material and marks the infilling of the canal. The bottom of this sequence is a sapric peat, indicative of intermittent wet and dry conditions. The artificial canal cut into the lower sapric peat deposit is demarcated in Fig. 6. Below the sapric peat layer in Op. 47, there is a grayish-white lacustrine deposit. Here, the peat sediments are more laminated and banded with lacustrine material, suggesting that a wet marsh environment with intermittent flows existed, which transitioned to a banded shell-rich marl/lacustrine deposit.

Additional vibracoring across the wetland-lagoon demonstrates that the sediment profile observed in Ops. 46 and 48 occurs only across the northern portion of the lagoon, while the sediment profile in Op. 47 is restricted to the southern portion of the lagoon. This layered/banded peat horizon contains abundant fibrous organic matter, likely representing an older perennially wet and shallow lagoonal environment that later transitioned to a strongly seasonally wet/dry sedgeland environment, which characterizes the wetland-lagoon today.

The higher area of the peat/buried A horizon is thicker in the southern end of Op. 47, representing a surface that formed during the Late Archaic to Early Formative transition. The lower sapric peat was cut into by the canal, which slopes down to the north and marks

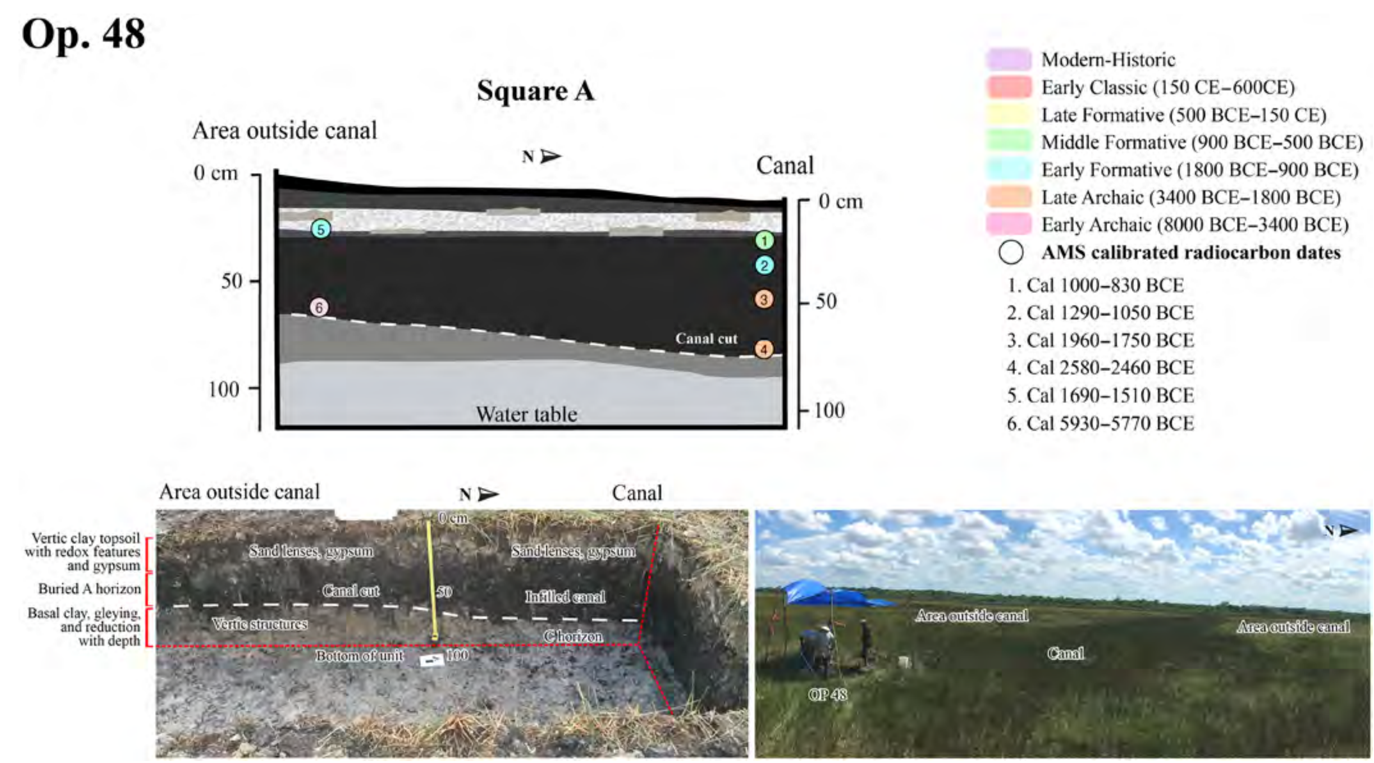

Fig. 5. Operation 48. Cross section showing associated calibrated radiocarbon dates and photos of excavations with geomorphological descriptions (images courtesy of the BREA project).

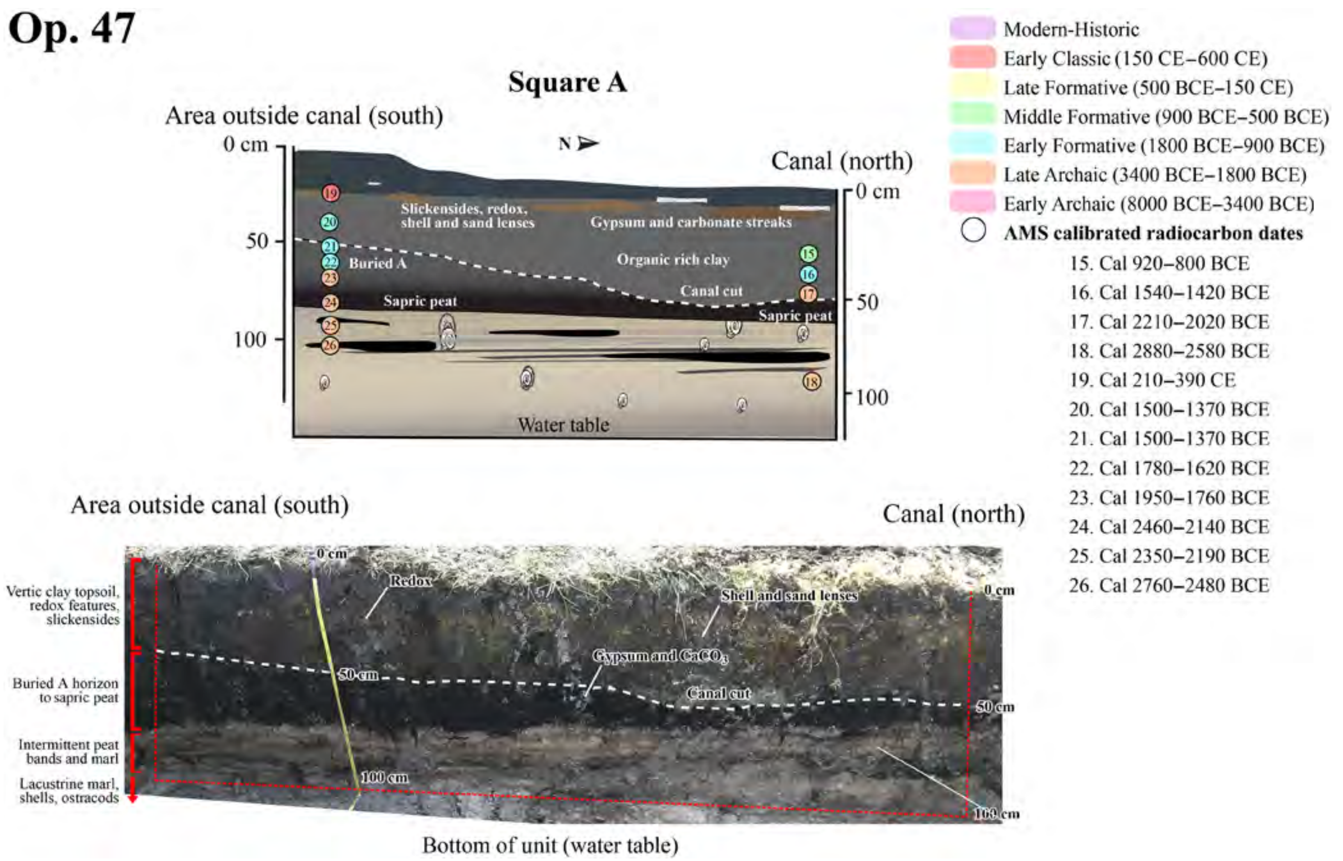

Fig. 6. Operation 47. Cross section showing associated calibrated radiocarbon dates and photo of excavation with geomorphological descriptions (images courtesy of the BREA project).

the edge of the channel with the bottom of the cut dating to the Late Archaic (see Fig. 6). Our excavations show no formalized modifications along the edges of the earthen channels, such as stone placement, rammed earth, or evidence of wooden posts, which have been found associated with some ditched and drained agricultural fields and other ancient Maya wetland enhancements [(33), p. 452]. The features discussed here are a fundamentally different kind of wetland artificial expression when compared to the "lattice-like" ditched and drained Maya wetland fields, which are well documented elsewhere [(*24*, *28*–*31*, *33*, *37*), among others]. The linear features are much shallower, wider, and longer channels and resemble what Erickson [(*11*), p. 191] describes elsewhere as a "zigzag structure" and a "particular form of artificial earthwork" found in seasonally inundated wetland savannas. The dates, discussed below, suggest that the CTWS channels were constructed following a drying event when the environment transitioned to a seasonally wet/dry sedgeland (for more on the paleoenvironment and geomorphology, see Supplementary Text).

Radiocarbon analysis

Radiocarbon dates associated with the peat lens overlying the lighter lacustrine sediment in Op. 47 suggest that a perennially wet environment existed in this area during the Late Archaic period. The data suggest that, around ~4100 to 4000 years before the present (yr B.P.), the perennially wet environment shifted to a shallow marshland, which then began to aggrade as the environment transitioned to a seasonally wet/dry environment. The hydrologic changes observed in the sediments of the Western Lagoon at the end of the Late Archaic may be linked to long-term drought conditions recorded in many different parts of the Northern Hemisphere around 4200 yr B.P. [or 2200 to 1900 cal BCE (*38*–*41*)]. Well-stratified radiocarbon dates from the excavated linear features in the Western Lagoon presented in Table 2 suggest that they were built right around this time, perhaps sometime after 2000 cal BCE, prior to the Formative Maya period. It may be that Late Archaic hunter-gatherer-fisher people intensified their fish trapping in response to this 200- to 300-year drying event (see further below). Of the 26 samples that were run for radiocarbon dating, only one sample yielded a modern historical date and came from 20 to 25 cm below the ground surface in Op. 46, the shallowest elevation of any sample tested. This sample yielded a 2-sigma calibrated date range of 1810 to 1920 CE (Sample 7 in Table 2). Only one piece of charcoal from our excavations (Sample 19 in Table 2) dated to the Maya Early Classic period. It was collected less than 40 cm below the ground surface in Op. 47 just outside of the canal feature and yielded a 2-sigma calibrated date range of 210 to 390 CE. Unexpectedly, this marks our latest prehistoric Maya date that we have found associated with the linear features thus far; all other 24 radiocarbon dates span the Late Archaic to Terminal Formative Maya period (see Figs. 4 to 6 and Table 2).

Ops. 47 and 48 both exposed the cut of the canals with associated calibrated radiocarbon dates corresponding to the Late Archaic period (Samples 3, 4, and 17). Op. 47 reached the greatest depth in

Table 2. Calibrated radiocarbon dates from Operations 46, 47, and 48. Time periods: Modern-Historic, post-1521 CE; Early Classic, 150 CE to 600 CE; Late Formative, 500 BCE to 150 CE; Middle Formative, 900 BCE to 500 BCE; Early Formative, 1800 BCE to 900 BCE; Late Archaic, 3400 BCE to 1800 BCE; Early Archaic, 8000 BCE to 3400 BCE. Depth (cmbs): centimeters below the surface.

Lab code	ICA Lab ID	Sample	Operation/Unit		Depth (cmbs)	Material	Conventional age	Calibrated BCE/CE	Time period
Operation 48 "Canal"									
FCB 28-6	14C-7187	1	48	North Wall, Canal	30–35	Organic sediment	2770 ± 30 yr B.P.	Cal 1000–830 BCE	Middle Formative
FCB 28-8	14C-8280	2	48	North Wall, Canal	40–45	Organic sediment	2970 ± 30 yr B.P.	Cal 1290–1050 BCE	Early Formative
FCB 28-11	14C-8281	3	48	North Wall, Canal	55–60	Organic sediment	3540 ± 30 yr B.P.	Cal 1960–1750 BCE	Late Archaic
FCB 33-05	20C/0248	4	48	North Wall, Canal	85	Charcoal	3990 ± 30 yr B.P.	Cal 2580–2460 BCE	Late Archaic
Operation 48 "Outside of Canal"									
FCB 31-5	14C-7186	5	48	South Wall	25–30	Peat	3330 ± 30 yr B.P.	Cal 1690–1510 BCE	Early Formative
FCB 31-14	14C-7188	6	48	South Wall	60–65	Organic sediment	6990 ± 30 yr B.P.	Cal 5930–5770 BCE (77.5%)	Early Archaic
Operation 46 Square A "Outside of Canal"									
FCB 22-3	14C-7192	7	46	Square A	20–25	Charcoal	30 ± 30 yr B.P.	Cal 1810–1920 CE (67.0%)	Modern-Historic
FCB 22-5	14C-8272	8	46	Square A	30–35	Organic sediment	2030 ± 30 yr B.P.	Cal 110 BCE - 70 CE (94.8%)	Late Formative
FCB 22-7	14C-8273	9	46	Square A	40–45	Organic sediment	2330 ± 30 yr B.P.	Cal 490–350 BCE (91.4%)	Late Formative
FCB 22-9	14C-8274	10	46	Square A	50–55	Organic sediment	2730 ± 30 yr B.P.	Cal 920–800 BCE	Middle Formative
Operation 46 Square B "Canal"									
FCB 32-02	20C/0246	11	46	Square B, Canal	75	Charcoal	2200 + 30 yr B.P.	Cal 370–190 BCE	Late Formative
FCB 23-21	14C-7193	12	46	Square B, Canal	105–110	Organic sediment	2080 ± 30 yr B.P.	Cal 180–10 BCE	Late Formative
Operation 46 Square C "Outside of Canal"									
FCB 24-7	14C-8275	13	46	Square C	35–40	Organic sediment	2070 ± 30 yr B.P.	Cal 170 BCE–10 CE	Late Formative
FCB 32-06	20C/0247	14	46	Square C	95	Charcoal	3610 ± 40 yr B.P.	Cal 2060–1880 BCE (88.7%)	Late Archaic

(*Continued*)

(*Continued*)

Lab code	ICA Lab ID	Sample	Operation/Unit		Depth (cmbs)	Material	Conventional age	Calibrated BCE/CE	Time period
Operation 47 "Canal"									
FCB 26-5	14C-8277	15	47	North Wall, Canal	30–35	Organic sediment	2720 ± 30 yr B.P.	Cal 920–800 BCE	Middle Formative
FCB 25-7	14C-8276	16	47	North Wall, Canal	40–45	Organic sediment	3220 ± 30 yr B.P.	Cal 1540–1420 BCE	Early Formative
FCB 26-9	14C-7189	17	47	North Wall, Canal	45–50	Peat	3710 ± 30 yr B.P.	Cal 2210–2020 BCE (94.2%)	Late Archaic
FCB 34-04	20C/0251	18	47	North Wall, Canal	95–100	Charcoal	4140 ± 40 yr B.P.	Cal 2880–2580 BCE	Late Archaic
Operation 47 "Outside of Canal"									
FCB 34-03	20C/0250	19	47	South Wall, Field	33–38	Charcoal	1760 ± 30 yr B.P.	Cal 210–390 CE (93.1%)	Early Classic
FCB 27-7	14C-8278	20	47	South Wall, Field	40–45	Organic sediment	3130 ± 30 yr B.P.	Cal 1500–1370 BCE (69.9%)	Early Formative
FCB 27-11	14C-8279	21	47	South Wall, Field	55–60	Organic sediment	3140 ± 30 yr B.P.	Cal 1500–1370 BCE (79.4%)	Early Formative
FCB 27-12	14C-7190	22	47	South Wall, Field	60–65	Peat	3430 ± 30 yr B.P.	Cal 1780–1620 BCE (78.4%)	Early Formative
FCB 34-01	20C/0249	23	47	South Wall, Field	68	Charcoal	3530 ± 30 yr B.P.	Cal 1950–1760 BCE	Late Archaic
FCB 34-09	20C/0253	24	47	South Wall, Field	85	Charcoal	3820 ± 40 yr B.P.	Cal 2460–2140 BCE	Late Archaic
FCB 27-21	14C-7191	25	47	South Wall, Field	92–94	Peat	3820 ± 30 yr B.P.	Cal 2350–2190 BCE (82.5%)	Late Archaic
FCB 34-05	20C/0252	26	47	South Wall, Field	100	Charcoal	4080 ± 40 yr B.P.	Cal 2760–2480 BCE (78.8%)	Late Archaic

excavation and presents the most representative sample of radiocarbon dates ($N = 10$) from the stratigraphic sequences exposed. These 10 dates were plotted with an OxCal program (*42*, *43*), which allows for the grouping and analysis of the entire span of chronological information (Fig. 7). The results of this plotting show the boundaries for the start and end dates and are presented in two groups based on where they were found—either in the canal or just outside the canal feature in the micro-high zones. In both contexts, the OxCal graphic shows that the vast majority of calibrated date ranges (both in and outside of the canal) span the Late Archaic to Early Formative, corresponding with the so-called preceramic period. The graphic illustrates a clustering of dates with most dating to before cal 1200 BCE, which is the earliest dated ceramic-using sedentary Maya occupation in this part of Mesoamerica (see discussion further below).

Geochemical analyses

Geochemical studies of the sediment samples focused on Op. 47, the most well-dated sequence, and were carried out to reconstruct environmental changes in the lagoon over time. We first examined the elemental profile of the sediment sequence as well as carbon and nitrogen (C/N) ratios. The basal lacustrine zone is rich in calcium (Ca) and manganese (Mn), but these diminish in the upper zones of the profile, while aluminum (Al), silicon (Si), and titanium (Ti) all increase, indicative of a more stable terrestrial soil (see fig. S6 for geochemical results). The ratio of C/N increases up the profile as well, which suggests a relative increase in terrestrial inputs over aquatic and wetland plants as well as algae (*44*, *45*). The results of this geochemical analysis correspond with the paleoenvironmental reconstruction described above in the geomorphological analysis of the stratigraphy.

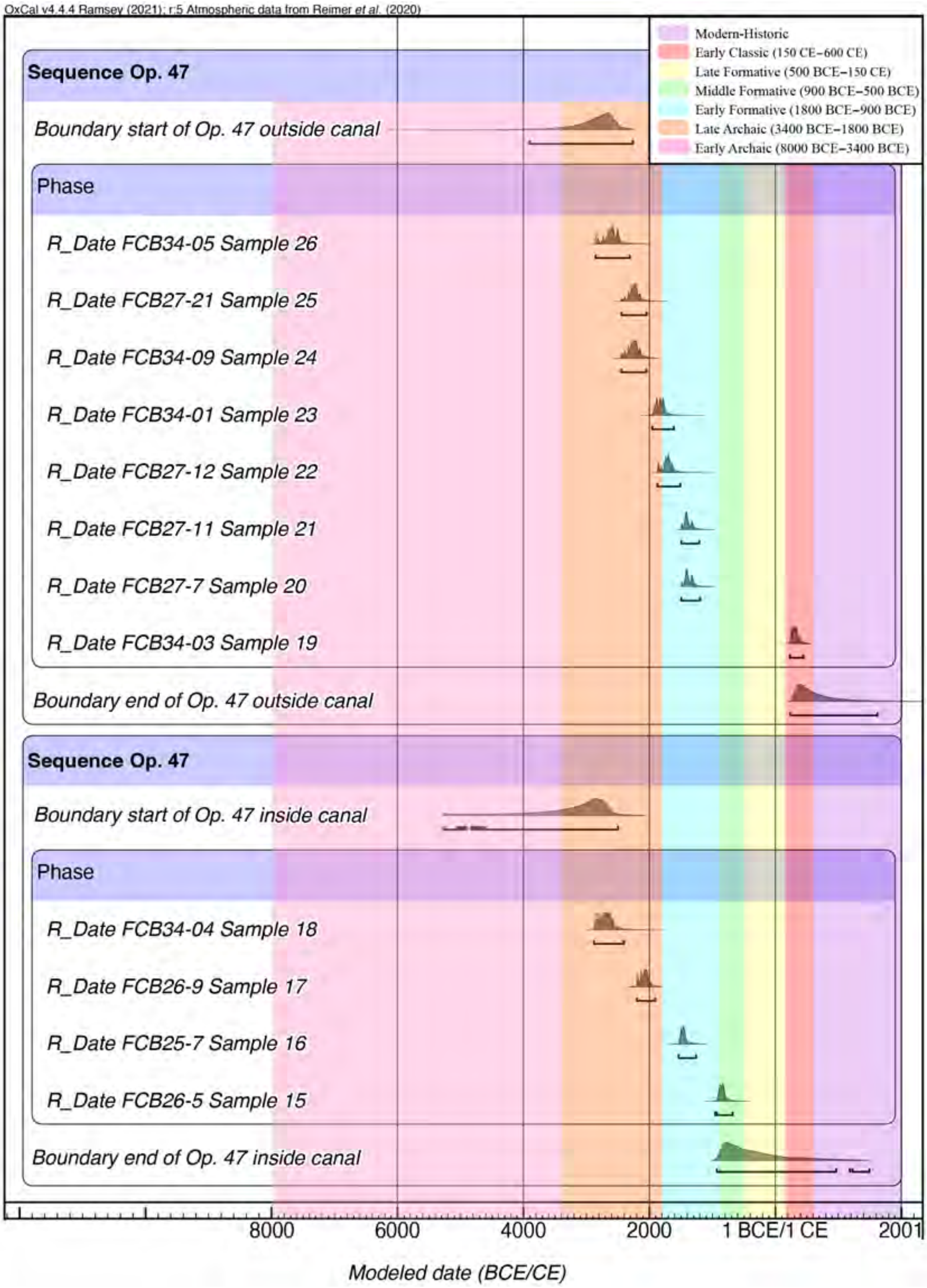

Fig. 7. OxCal for radiocarbon dates from Operation 47. Note the dates are grouped separately from outside the canal versus inside the canal (image courtesy of the BREA project).

We also examined changes in the stable isotope ratio of carbon and nitrogen in soil organic matter throughout the sediment sequence in Op. 47. Previous research suggests that shifts in the proportion of nitrogen-fixing cyanobacteria drive changes in $\delta^{15}N$ values, and the $\delta^{15}N$ of plankton increases from oligotrophic to eutrophic lakes (*44*). In Op. 47, $\delta^{15}N$ increase from the bottom to the top of the profile and suggests a shift from deeper water lacustrine conditions to shallow wetland with high primary productivity, which is generally higher in shallow water than in deeper water.

Shifts in the carbon isotopes throughout the sediment sequence has also been used with great success to determine vegetation dynamics between woody tropical C_3 species verses tropical grass C_4

species (for additional discussion, see Supplementary Text). The C_4 carbon isotope in the Maya region, when coupled with pollen data, is often indicative of maize cultivation (*46*, *47*). In the case of Op. 47, on the north (topographically lower) portion of the excavation in the artificial channel feature, the average $\delta^{13}C$ value is −30.39 per mil (‰), and on the south (topographically higher) portion of the excavation outside of the channel, the average $\delta^{13}C$ value is −29.19‰. The sediments show a strong C_3 (tropical forest) dominance throughout the profile of Op. 47 and do not indicate that C_4 grasses were present in any notable amount. Thus, no evidence of crop cultivation, specifically maize, can be demonstrated from the carbon isotope signatures. The pollen record, discussed below, reinforces these finds.

Pollen and particulate carbon analyses

Op. 47 yielded the highest pollen concentration values and the most taxonomic diversity compared with Ops. 46 and 48. Therefore, we selected 11 pollen samples from down-profile of Op. 47 on the south (topographically higher) area of the excavation outside of the channel to provide a discrete record of the pollen sequence (refer to Fig. 8). The aim was to reconstruct any changes in the paleoenvironment over time and to capture evidence of plant cultivation, allowing for speculation on the history of possible horticultural practices in this area. The lowest portion of the record represents the marl/lacustrine zone and is characterized by moderate but decreasing abundance of tree and shrub pollen from 56 to 44%. Freshwater marsh and aquatic plants including *Typha* (cattail) and *Sagittaria* (arrowhead) indicate submerged conditions. Three radiocarbon samples (Samples 18, 25, and 26 in Figs. 6 and 8 and Table 2) from this marl/lacustrine zone have an average mean date of around 2400 BCE, suggesting year-round submerged conditions in this area of Western Lagoon during this time.

By roughly 2000 cal BCE, the area appears to have transitioned to seasonal marshland. Between 100 and 25 cm below the ground surface, there are increasingly high levels of pollen from herbaceous and aquatic plants (see Fig. 8). Amaranthaceae pollen, a weedy species, is most abundant between 48 and 86%, indicating a disturbed and nearly treeless environment beginning around 100 cm below datum. A spike in this weedy genus can indicate secondary growth due to burning and forest clearing, which may have begun naturally, perhaps during the centuries-long drought between 2200 and 1900 BCE. Analysis of macrocharcoal counts shows a peak in burning between 80 and 45 cm (see Supplementary Text for further details on the diversity of particulate charcoal morphology). This spike in carbon particulates suggests that the disturbance that favored weedy species like Amaranthaceae may have involved anthropogenic burning by this time, when the landscape-scale fish-trapping facilities were in full swing. It is conceivable that some varieties of Amaranthaceae were actively being collected and perhaps even cultivated during this time (*48*). These plants grow especially well under drought conditions and in disturbed contexts, such as ditches and disturbed banks of artificial channels (*49*, *50*)—the very conditions we find in the Western Lagoon (see Supplementary Text for more on Amaranthaceae).

Controlled burning of savannas and temperate grasslands is well attested today in Belize and elsewhere (*51*). Controlled fire is used for a range of management activities, from pest control to waste material, for developing and maintaining pastureland and hunting grounds and for fertilizing soils in agricultural and agroforestry practices (*52*). Notably, scholars also suggest that burning as a fertilizing process also enhances systems of aquaculture (*26*). In the Maya area, paleoenvironmental evidence of forest burning is indicated by a sharp increase in particulate carbon (macrocharcoal) in the soils. In some areas, it is accompanied by an increase in maize pollen, which scholars interpret as evidence of more intensive land clearing for cultivation and agricultural expansion (*53*). However, a lack of maize pollen, coupled with the carbon isotope record in the CTWS, does not suggest that maize cultivation was taking place in this area. Instead, the data

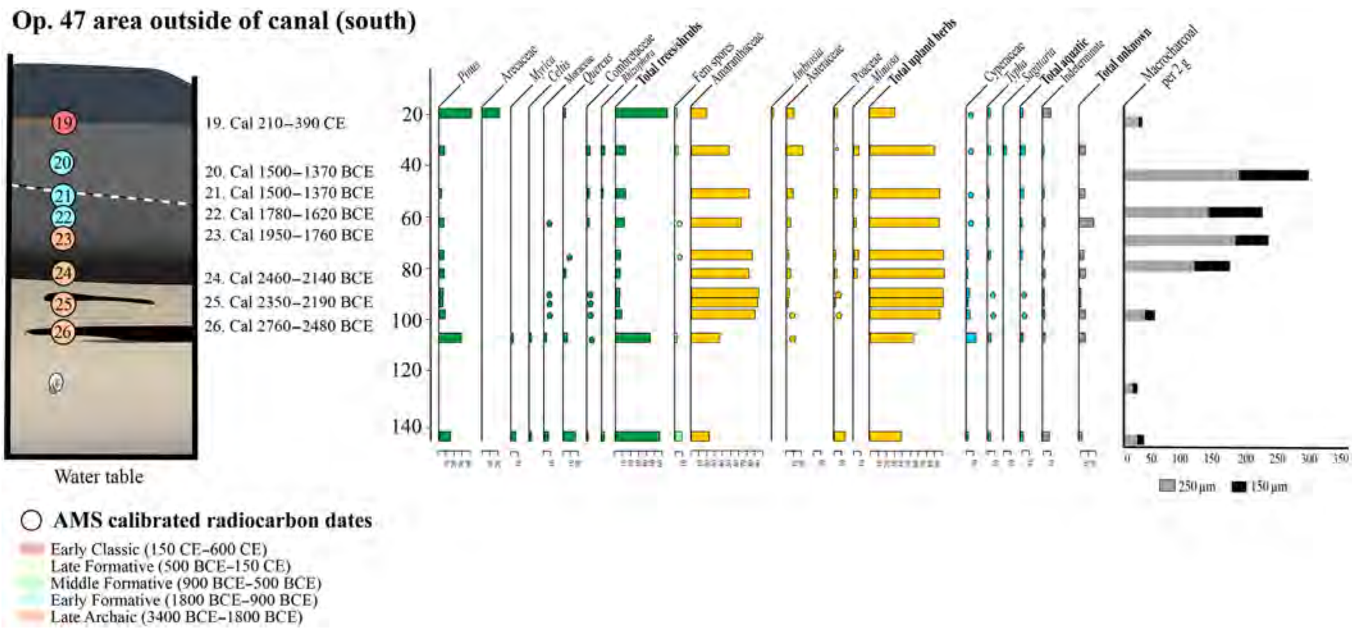

Fig. 8. Cross section of Operation 47 compared alongside the pollen record and quantities of macrocharcoal. Corresponding radiocarbon dates show the timing for the rise in Amaranthaceae and concurrent peak in macrocharcoal (images courtesy of the BREA project).

suggest that, alongside natural fires, controlled burning may have occurred in an effort to promote the growth of Amaranthaceae and its selective harvesting. Anthropogenic burning may have also increased over time for the express purpose of hunting and fishing activities, perhaps for easier access to the canals and ponds and perhaps also for the purpose of drying and smoking fish along the shoreline.

DISCUSSION

Archaic subsistence

In the CTWS, we have recorded a vast network of linear channels and pond features. Maize pollen has not been detected, and no ditched and drained agricultural fields have been securely identified in the area to date. The multiproxy data presented here suggest that Thompson's (*22*) initial suggestion based on ethnohistoric accounts was correct; these distinctive long linear zigzag channels served primarily as large-scale fish-trapping facilities. The CTWS wetland-lagoon environment provides a rich array of aquatic food resources available on a regular basis, including a uniquely abundant source of fish and was arguably one of the primary reasons for Archaic occupation in this area. Evidence from previous research undertaken in northern Belize by the Belize Archaic Archaeological Reconnaissance project (*54*–*58*) and the Colha Preceramic Project (*59*–*61*) indicates that Archaic groups targeted a range of environments in pursuit of seasonally abundant food and nonfood resources. Tool remains suggest that many occupations were focused on extracting specific resources, such as at Crawford Bank, where use-wear analysis revealed that most lithic tools were primarily used in processing wood (*62*).

The development of large-scale fish-trapping facilities involved intensive modification and investment in the landscape, perhaps prompting more semipermanent residence at the end of the Archaic. We suspect that deeply buried Archaic residential sites may exist along the western shoreline of the Western Lagoon, where dense Formative and Classic period Maya settlement have been recorded, including Chau Hiix, Ek'tok, and K'ak Mutnal (see Figs. 2 and 3). Additional testing of these areas is needed to confirm this hypothesis. However, archaeological evidence of Archaic residential base camps in the CTWS has already been preliminarily identified by our team at several locations proximate to wetland-lagoon environments, including Crawford Bank and Morales Sand Pit (see Fig. 3) (*13*). Both sites have yielded evidence of Archaic barbed points indicative of spear fishing (*63*, *64*), and the latter site has revealed the presence of stone bowls and pestles suggestive of plant processing. While evidence for maize cultivation has not yet been found in the Western Lagoon sediments, the introduction of weedy species in the pollen record and the co-occurrence of closed-form ground stone bowls and pestles may indicate that drought-resistant grains like amaranth were being harvested and processed in this area (*65*), perhaps to supplement their aquatic diet. In addition to such plant resources, it would not be unexpected to find other evidence for mixed strategies of subsistence characteristic of the Archaic "broad spectrum" diet, including a range of wetland species such as turtle, Mollusca, waterfowl as well as the hunting and gathering of other plants and animals found in the pine ridge savanna and other neighboring ecotonal environments (*13*).

Fish consumption and population estimates

Even without these supplemental foods, conservative estimates of fish yields would have far exceeded the dietary needs of the Late Archaic population when considering demographic estimates. On the basis of ethnographic comparisons of contemporary hunter-gatherer-horticulturalists, population estimates for the Late Archaic was probably very low, maybe around ~0.75 people/km, which translates to upward of roughly 17,000 people in Belize [(*13*), p. 5]. Using estimates from ethnographic data of fish weirs found across 22,500 ha of Zambia's floodplains, Huchzermeyer (*66*) estimated an annual yield of around 800,000 kg of fish or roughly 35.5 kg of fish/ha per year. In applying these numbers to the 4180 ha of ponds and fish weirs documented in the CTWS, this would place the annual yield at an estimated 148,390 kg of fish. This is a more conservative estimate when compared to Erickson's (*11*) projections where he estimated as much as 1000 kg of fish/ha for the fishponds in the Bolivian Amazon. In applying these numbers, the annual yield for the CTWS facilities would be over 4 million kg of fish! McKey and colleagues (*12*) note that Erickson's "very high figure certainly represents the concentration in dry-season refugia of fishes from a much larger (but unknown) area of rainy-season floodplain" (p. 14941). This same high figure may also apply in the CTWS to select source ponds when the highest fish concentrations are observed during the peak dry-season months of March to May (*20*). If we apply Erickson's calculation of 1000 kg/ha for just these 3 months, then an estimate of roughly 1 million kg of fish might be a more reasonable projection of the annual yield for the CTWS fish weirs.

Knowledge of drying, salting, or smoking for preservation would have been imperative for any group using weirs because fish spoil very rapidly (*67*–*69*). We have documented salt production nearby for the Maya (*70*), and we assume that Archaic hunter-gatherer-fisher groups had likewise developed a means of preserving their fish year-round. The projected consumption rates outlined here only include fish and do not account for the other supplemental foods, noted above, that were available in and around the lagoonal wetlands of Crooked Tree, such as turtle and other animal and plant resources, which would increase the overall potential food yield and projected population estimates.

Today, annual fish consumption ranges between 20 and 80 kg of fish per person per year, with the highest consumption rates taking place in coastal countries (*71*). If we use a mean of 40 kg of fish per person per year to estimate past consumption and apply the more conservative Zambian estimate for annual yield, then we can estimate that the fish weirs in the CTWS could have fed minimally 3700 people year-round. Assuming the higher yields projected by Erickson during the dry-season months, we can estimate that the fish weirs in the CTWS could have fed more than 25,000 people. This is assuming that all fish weirs were constructed and used at the same time, which remains speculative without further testing. Perhaps, an average somewhere between these two extremes (~15,000 people) might be a more realistic number.

To be clear, we are not claiming that 15,000 people were congregating at any one time in the CTWS during the Late Archaic. However, there is evidence for such population growth in the Maya area by Middle to Late Formative times (*72*). The projected annual fish yield would certainly have satisfied the needs of this growing demographic in Formative times and suggests that fisheries were more than capable of supporting year-round sedentarism and the emergence of complex society characteristic of pre-Columbian Maya civilization in this area. Of the three canals investigated in the CTWS, Op. 47 marks the largest of the channels and leads directly to the major ancient Maya center of Chau Hiix (Fig. 1). The initial establishment of this site has been dated to the Formative period, approximately 1100 BCE to 200 CE, based on the ceramic data (*19*). This chronology is in line with the earliest evidence for sedentary villages found elsewhere in Belize, which dates approximately 1200 to 1100 BCE (*53*, *73*, *74*). The earliest evidence for ditched and drained wetland agricultural fields has been dated to around 1000 BCE (*53*).

The dates from our test excavations in the CTWS suggest that the artificial channels in the Western Lagoon were present during this Middle to Late Formative period in Maya prehistory. However, radiocarbon dates recovered from the lowest levels of the canals (exposed in Ops. 47 and 48) suggest that their initial construction occurred hundreds of years earlier toward the end of the Late Archaic period, perhaps as early as 2000 BCE or shortly thereafter, well before the traditional (1200 to 1100 BCE) start date of Formative Maya sedentarism (see Figs. 5 and 6). There is no clear evidence in any of the three excavations that the later Formative Maya cleaned out or subsequently modified these channels like the canal features for ditched and drained agricultural fields found elsewhere in the Maya Lowlands (*75*, *76*). However, the presence of radiocarbon dates corresponding to the Middle to Late Formative, coupled with evidence of some eroded pottery in stratigraphically lower levels, suggests that these wetland modifications continued to be used in some capacity during this time. Further investigations are necessary to clarify this full history.

Summary

On the basis of the data presented here, we conclude that the wetland features our team has investigated in the CTWS were initially constructed by Late Archaic hunter-gatherer-fisher groups and continued to be used by the Formative Maya. They were designed to channel annual flood waters into source ponds for fish trapping. The paleoenvironmental record suggests that they were constructed after the Western Lagoon had shifted from a perennial to a seasonal marshland. This environmental shift recorded in the lagoon sediments coincides with a long-term drought documented in the paleoenvironmental record of Mesoamerica between 2200 and 1900 cal BCE and is also recorded in the climate record across a broader area of the Northern Hemisphere (*38*–*41*).

Rosenswig (*41*) argues that this three-century-long drying event encouraged a macroscale shift in food production, with Archaic forager-horticulturalist groups becoming increasingly reliant on domesticated plants, such as maize. The carbon isotopes and pollen data from the Western Lagoon excavations does not suggest maize cultivation in this location. Instead, the data suggest that hunter-gatherer-fisher groups responded by intensifying the fish trapping as their primary food source, perhaps supplemented by other aquatic food sources and drought-resistant species like amaranth that grow well in clay-rich, sandy soils characteristic of Belize's wetland-lagoon environments. Horticulture appears to have been experimented with, in a piecemeal manner, prior to full-scale farming and sedentism. While archaeological evidence from Archaic occupation elsewhere in Belize suggests heavy maize consumption by at least 4000 yr B.P. (*77*, *78*), the results of our pollen samples from Western Lagoon dating to the Late Archaic recovered no traces of maize. The most parsimonious explanation is that horticulture was added to the existing "mosaic of Archaic adaptations" (*41*) when conditions were conducive and a need was present.

Controlled fire burning not only would have encouraged the annual regrowth of amaranth and other weedy economic species but also would have fertilized the fish-trapping facilities, facilitated fish processing on the shoreline, and created open access to the fish canals and ponds. Intensified burning is signaled by increasing charcoal particulate and may suggest ongoing fire management evolved alongside the development of large-scale fish-trapping facilities. Such intensive investments in the landscape may have affected the degree of residential mobility in the Late Archaic, attracting larger parties of hunter-gatherer-fisher groups to congregate for longer periods of time around wetland-lagoons like those in the CTWS. Annual harvests and social gatherings likely encouraged recursive mobility and may have been what led to incipient forms of sedentism (*79*–*82*).

While this is the first report of large-scale Archaic fish-trapping facilities in ancient Mesoamerica, reliance on wetlands and aquatic resources is well documented in the Late Archaic and Early Formative periods (*34*, *83*–*91*). The results of this study add to a growing body of archaeological evidence reported from across Mesoamerica, including its "cradle" of early civilization in the isthmian lowlands, where findings suggest that "floodplain resources, not maize (*Zea mays*) agriculture, [were] instrumental in the emergence of Early Formative (approximately 1500 to 900 uncal BC) complexity" [(*83*), p. 397]. In the Gulf Coast and Soconūsco, archaeological evidence highlights the predominant role of nonagricultural resources in the low-lying floodplain and wetland environment even after the establishment of sedentism in the Early Formative among the Olmec and other early Mesoamerican societies (*83*, *86*, *87*). The archaeological evidence in such areas suggests that fish and other aquatic resources like turtle and mollusk procurement served as staples in the diet during the Late Archaic and Early Formative, more so than maize and other domesticates [(*83*, *86*, *87*), pp. 338–340, (*89*–*91*), but see (*78*)].

The 2200 cal BCE drying event that produced centuries of long-term drought may have been what encouraged groups to build the fish-trapping facilities in the CTWS and other parts of the Maya Lowlands, including the New River, Rio Hondo, the Candelaria, and elsewhere (see Fig. 1). Future testing in and around these loci is needed to cross-examine whether these forms of landscape-scale intensification that we argue were specifically geared for fish trapping were constructed on the heels of this long-term drought. If so, then we would expect these areas to yield evidence of Late Archaic to Formative Maya occupation similar to the CTWS. Notably, in the locations with probable fish-trapping facilities, we find evidence of monumental Maya centers with Early-Middle Formative occupation, which includes sites such as Chau Hiix, Lamanai, and Nohmul in northern Belize, and Itzamkanac and Aguada Fénix in Campeche and Tabasco, Mexico, respectively (Fig. 1) (*20*, *30*, *74*, *92*–*95*). Both the environmental and social conditions likely encouraged increasingly larger social gatherings and communal feasting in the CTWS and possibly elsewhere. The mass harvesting of fish in these wetland-lagoonal environments served as a primary food source capable of supporting sizeable populations and semipermanent residence in the Late Archaic and ultimately fully sedentary pre-Columbian Maya populations by Formative times.

MATERIALS AND METHODS

Remote sensing

For the remote sensing, we used a combination of publicly available Google Earth satellite imagery and data collected from our UAVs. We used a TuffWing fixed-wing camera-mounted drone to fly an area in the CTWS that measured ~48 km^2 (18.5 mi^2), which, for perspective, is roughly equivalent to the surface area of 80% of the city of Manhattan. In total, 12,030 images were collected and combined to create a DEM with a 15-cm resolution, meaning that, for every 15 cm of surface area across the 48 km^2, an elevation data point was generated. This resulted in more than 2.4 billion data points in the DEM that revealed subtle changes in elevation and allowed us to map the linear features and associated ponds with greater precision (see Fig. 3 and fig. S5).

To examine whether a positive correlation exists between ponds and linear features in the CTWS, we tested the distance between the ponds and random points to the weirs. To do this, we calculated the distance from 25 of the ponds to the closest linear features using the Near function in ArcMap 10.8.2. Then, we generated 25 randomly located points to represent hypothetical ponds within the Western Lagoon wetlands. The distance from these 25 random points to the linear features was also computed. Then, we ran a two-tailed t test assuming equal variance on the mean distances between the ponds and the linear features and the random points and the linear features. The results indicate that there is a statistically significant difference between these distances ($P = 0.003$), with an average pond-to-weir distance of 19.5 m and an average random point-to-weir distance of 66.5 m (see table S1).

Geomorphology and geochemistry

We sampled each excavation unit (Ops. 46, 47, and 48) in the Western Lagoon for sediments to carry out further geoarchaeological and stratigraphic analysis. Sediment samples were collected in 5-cm increments along the walls of all three excavation units in the Western Lagoon. A complete description of the three excavation units, the soil descriptions, and their stratigraphic sequences can be found in the BREA interim report (*36*). Soil sampling was collected using a cleaned trowel and bagged in a plastic ziplock bag. All soil samples were subsequently weighed and shipped to the Soils and Geoarchaeology Laboratory at the University of Texas at Austin in the Department of Geography and the Environment for bulk elemental analysis. Subsamples of sediments were air dried and homogenized. Subsamples were analyzed in triplicate using a handheld portable x-ray fluorescence (pXRF) analyzer (reported in weight %) to measure the concentrations of elements within the sediment profile. The pXRF underwent necessary calibration checks prior to and after analysis.

Radiocarbon and carbon isotope analyses

Between 2019 and 2023, both charcoal and organic sediment collected directly from the subsamples from all three excavation units (Ops. 46, 47, and 48) were submitted for radiocarbon dating. A total of 26 samples of both charcoal and organic sediment were shipped to International Chemical Analysis Inc. (ICA) in 2020, 2022, and 2023 (Table 2). Radiocarbon dating was carried out on an accelerator mass spectrometer to measure carbon-14 (^{14}C) radioisotope from the organic materials. All ^{14}C ages were calibrated using INTCAL2 and corrected for natural isotope fractionation with a reported error of 1 SD, unless otherwise noted (*43*). Conventional ages are given in years before the present (1950 AD), and the calibrated dates are given in Gregorian calendar years as CE (Common era) and BCE (Before the Common era) throughout.

Subsamples were further prepped and shipped to the W. M. Keck Paleoenvironmental and Environmental Stable Isotope Laboratory at the University of Kansas for stable carbon isotope analysis to be conducted on the organic matter fraction of the sediment. Carbonates were removed from samples with HCl and samples were then analyzed using an isotope ratio mass spectrometer. Compositions within each sample are conveyed as changes in per mil of the ratios $^{13}C/^{12}C$ in the sample against Vienna Pee Dee belemnite.

Pollen and particulate charcoal

Samples from Ops. 46 and 47 in the Western Lagoon were sent to the PEARL Laboratory for pollen extraction and analysis. Pollen processing followed standard protocols and techniques described by Riding (*96*), which is discussed in more detail in the Supplementary Text. Pollen samples were identified and counted. A 300-grain pollen count was the target for each sample but was sometimes not possible due to low pollen concentration and high levels of organic matter. At least 200 grains were counted for every sample, and identifications were made to the family level. Pollen was identified and counted using pollen atlases for nearby locations (*97–99*) as well as a digitized pollen reference collection from Texas A&M University. Pollen data was plotted using the rioja R package (*100*) and recolored using CorelDraw (dots on the bar chart indicate pollen in <1% abundance throughout the sequences). Major and minor types are included in the plant taxon description table (Fig. 8; see also Supplementary Text, fig. S7, and table S2).

To reconstruct fire activity, subsamples of 2 g were selected from down-profile in Op. 47, soaked in a sodium hexametaphosphate solution for >24 hours, and wet sieved using staked 250- and 150-μm mesh (*101–103*). The remaining material was examined in a petri dish using a Nikon stereomicroscope. Charcoal fragments were classified into broad categories of charcoal morphologies following Mustaphi and Pisaric (*103*).

Supplementary Materials

This PDF file includes:
Supplementary Text
Figs. S1 to S7
Tables S1 and S2
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Acknowledgments: We thank the Belize Institute of Archaeology for granting E.H.-B. a permit, especially J. Morris and M. Badillo for their continued support of the BREA project. Additional support was provided by the University of New Hampshire, University of Vermont, Texas State University, and the University of Texas at Austin. We thank M. Miller for assistance on the statistics presented herein. We are especially grateful to A. Runggaldier, T. Beach, and S. Luzadder-Beach of UT Austin. They introduced S. Krause to the BREA project in the summer of 2019 and generously funded travel to Belize with their Planet Texas 2050 grant. They offered crucial support in allowing us to export all sediment samples to the Soils and Geoarchaeology Laboratory at UT Austin where S.M.K. prepared them for further analysis. We also wish to thank undergraduate researcher E. Hernandez of Sewanee for their assistance on the excavations, along with the research team from the village of Crooked Tree. We are especially grateful for the support of the Crooked Tree Village Chairman, J. Gillett, and the entire Village Council who welcomed us and permitted us to map and excavate in the wetlands around their community. **Funding:** We acknowledge the generous financial support from the following: Alphawood Foundation Chicago (E.H.-B. and M.B.B.) and National Science Foundation Collaborative Research grant #2120534 (M.B.B. and E.H.-B.). **Author contributions:** E.H.-B. led the planning and administration of this research. S.M.K. led the excavations, collected and prepared all samples, and carried out the geomorphology, geochemistry, and macrocharcoal analysis. M.B.B. performed the geospatial analysis and mapping of all features in Google Earth. M.W. collected and processed all drone imagery and produced the DEM images. A.P. and K.B. analyzed all pollen data and prepared a report of their findings. E.H.-B. conceptualized this research and drafted the original manuscript. E.H.-B., S.M.K., and M.B.B. reviewed and edited subsequent drafts of the manuscript and designed the figures. All authors reviewed and provided comments on the final draft of this manuscript prior to submission. **Competing interests:** The authors declare that they have no competing interests. **Data and materials availability:** All data needed to evaluate the conclusions in the paper are present in the paper and/or the Supplementary Materials.

Submitted 29 April 2024
Accepted 23 October 2024
Published 22 November 2024
10.1126/sciadv.adq1444