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A late Holocene paleoenvironmental reconstruction from Agua Caliente, southern Belize, linked to regional climate variability and cultural change at the Maya polity of Uxbenká

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ABSTRACT

We report high-resolution macroscopic charcoal, pollen and sedimentological data for Agua Caliente, a freshwater lagoon located in southern Belize, and infer a late Holocene record of human land-use/climate interactions for the nearby prehistoric Maya center of Uxbenká. Land-use activities spanning the initial clearance of forests for agriculture through the drought-linked Maya collapse and continuing into the historic recolonization of the region are all reflected in the record. Human land alteration in association with swidden agriculture is evident early in the record during the Middle Preclassic starting ca. 2600 cal yr BP. Fire slowly tapered off during the Late and Terminal Classic, consistent with the gradual political demise and depopulation of the Uxbenká polity sometime between ca. 1150 and 950 cal yr BP, during a period of multiple droughts evident in a nearby speleothem record. Fire activity was at its lowest during the Maya Postclassic ca. 950–430 cal yr BP, but rose consistent with increasing recolonization of the region between ca. 430 cal yr BP and present. These data suggest that this environmental record provides both a proxy for 2800 years of cultural change, including colonization, growth, decline, and reorganization of regional populations, and an independent confirmation of recent paleoclimate reconstructions from the same region.

Introduction

Understanding the relationship between past climate variability, landscape change, and human land-use patterns has become an increasingly important goal of paleoecological research (Dearing et al., 2006). This is especially true in the Maya region of Mesoamerica where many researchers have argued that drought-induced reductions in agricultural productivity played a major role in the disintegration of Maya political systems at the end of the Classic Period (Hodell et al., 1995; Haug et al., 2003; Webster et al., 2007; Kennett et al., 2012). Paleoecological records from regions with large populations prior to Euro-American settlement, specifically those based on palynology, are not always useful for reconstructing past climatic variability. In many instances human influences on vegetation tend to blur or even overrule the effects of climate and make it difficult to interpret pollen records (Horn and Sanford, 1992; Hodell et al., 1995; Rosenmeier et al., 2002; Santos, 2004; Anselmetti et al., 2007). On the other hand, pollen analysis has proven useful in helping to decipher the link between past climatic variability and the way in which humans respond to changing environmental conditions (Brenner et al., 2002; Kennett et al., 2010; McNeil et al., 2010; Mueller et al., 2010). Often pollen records are most useful for illustrating the timing and direction of human landscape alteration as a result of rising/falling population numbers and changes in agricultural strategies (Rue, 1987; Goman and Byrne, 1998; Pope et al., 2001; Leyden, 2002; Neff et al., 2006; Park et al., 2010).

Perhaps even more helpful for understanding past human–environment interactions are records of fire activity, especially those from regions where natural ignitions are limited. Throughout much of the tropics humans are the primary source of fire and likely have been for many thousands of years (Billings and Schmidtke, 2002; Anchukaitis and Horn, 2005). This is especially true in tropical lowland broadleaf forests where lightning strikes are rare, evidenced by the fact that most species of trees are not adapted to fire and have likely evolved in the absence of it (Budowski, 1966; Meerman and Sabido, 2001). Historically, human ignitions are primarily the result of swidden (slash-and-burn) agriculture, which is used throughout these forests today as well as many other parts of Mesoamerica to clear tracts of land in order to plant crops such as maize, rice, beans, and cassava (Montagnini and Mendelsohn, 1997; Harvey et al., 2005). As a result, charcoal records from areas where swidden agriculture has traditionally been employed may prove more reliable than pollen records in terms of identifying the timing and nature of expanding agricultural systems, particularly when climate drying can be ruled out with independent records.

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Studies from Central and Mesoamerica that use both pollen and charcoal as an indicator of past anthropogenic activity are limited (Nevle and Bird, 2008), and only a few come from within the Maya region, including the Petén of Guatemala (Vaughan et al., 1985; Dunning et al., 1998; Johnston et al., 2001; Hillesheim et al., 2005; Correa-Metrio et al., 2012; Wahl et al., 2013), the southern Maya area of Guatemala and El Salvador (Tsukada and Deevey, 1967), Pacific coastal Guatemala and Mexico (Neff et al., 2006; Kennett et al., 2010), western El Salvador (Dull, 2007), the Yucatan peninsula of Mexico (Leyden et al., 1994; Leyden, 2002), and the Copan Valley of Honduras (Rue et al., 2002). Only two such studies have been carried out in Belize (Pohl et al., 1996; Rushton et al., 2013), although several pollen records exist from the northern and central portion of the country (Hansen, 1990; Jones, 1994; Wooller et al., 2007; Monacci et al., 2009, 2011). However, out of all of these studies only Wahl et al. (2013) examined macroscopic charcoal (as opposed to pollen-slide charcoal), which provides a continuous reconstruction of local fire activity (Whitlock and Larsen, 2001). The lack of previous paleoecological work in southern Belize is largely due to the limited number of suitable study sites (e.g., lakes); however, several freshwater lagoons do exist and were targeted for this study.

The goal of this study was to reconstruct a late Holocene record of environmental change from southern Belize using multiple incremental proxies within lacustrine sediments recovered from the Agua Caliente lagoon (Toledo District). Our specific objectives were to: 1) reconstruct the fire and vegetation history of the Agua Caliente watershed using macroscopic charcoal, pollen, and sedimentological analyses, and 2) to compare these results with local climatic and archeological records in order to determine linkages between climate variability, environmental change, and human land-use in the region. For the local climate record, we used a recently published 2000-year long speleothem record from Yok Balum Cave (Kennett et al., 2012), which is located approximately 11 km WNW of our study site. The archeological record comes from Uxbenká, which is the ancient Maya settlement geographically closest to our study site and the primary Classic Maya center in the Agua Caliente watershed (Prufer et al., 2011; Culleton, 2012). Ideally, we hope that this reconstruction can contribute to our collective understanding of human-caused landscape alteration within the vicinity of the ancient Maya center of Uxbenká.

Study area

Background

The Toledo District of southern Belize extends from the eastern branch of the Monkey River in the north to the Sarstoon River in the south, which forms the border with Guatemala, and west to Guatemala along 88°12.500′W longitude (Fig. 1). Within the district the geography varies widely. In the west, the Maya Mountains dominate and extend more than 1000 m above sea level (asl). Composed primarily of Cretaceous limestones (Keller et al., 2003), the Maya Mountains are dominated by lush submontane broadleaf forest (Meerman and Sabido, 2001). The eastern foothills of the Maya Mountains drop to approximately 500 m asl and are underlain primarily by Cretaceous limestones and the Toledo Beds, a series of interbedded Tertiary marine sediments (Keller et al., 2003). The area's vegetation is characterized by lowland broadleaf forest and shrubland (Meerman and Sabido, 2001), although much of it has been altered by agricultural practices, both ancient and modern (Culleton, 2012). A relatively flat coastal plain extends from the base of the Maya Mountain foothills east to the Atlantic Ocean. This plain is underlain by Pleistocene fluvial sediments originating from the Maya Mountains and surrounding foothills (Bateson and Hall, 1977). Lowland broadleaf forest and shrubland also dominate this region, except in a few areas where lowland pine forest and savanna exist (Meerman and Sabido, 2001). This region has recently been severely altered by more intensive forms of maize and rice

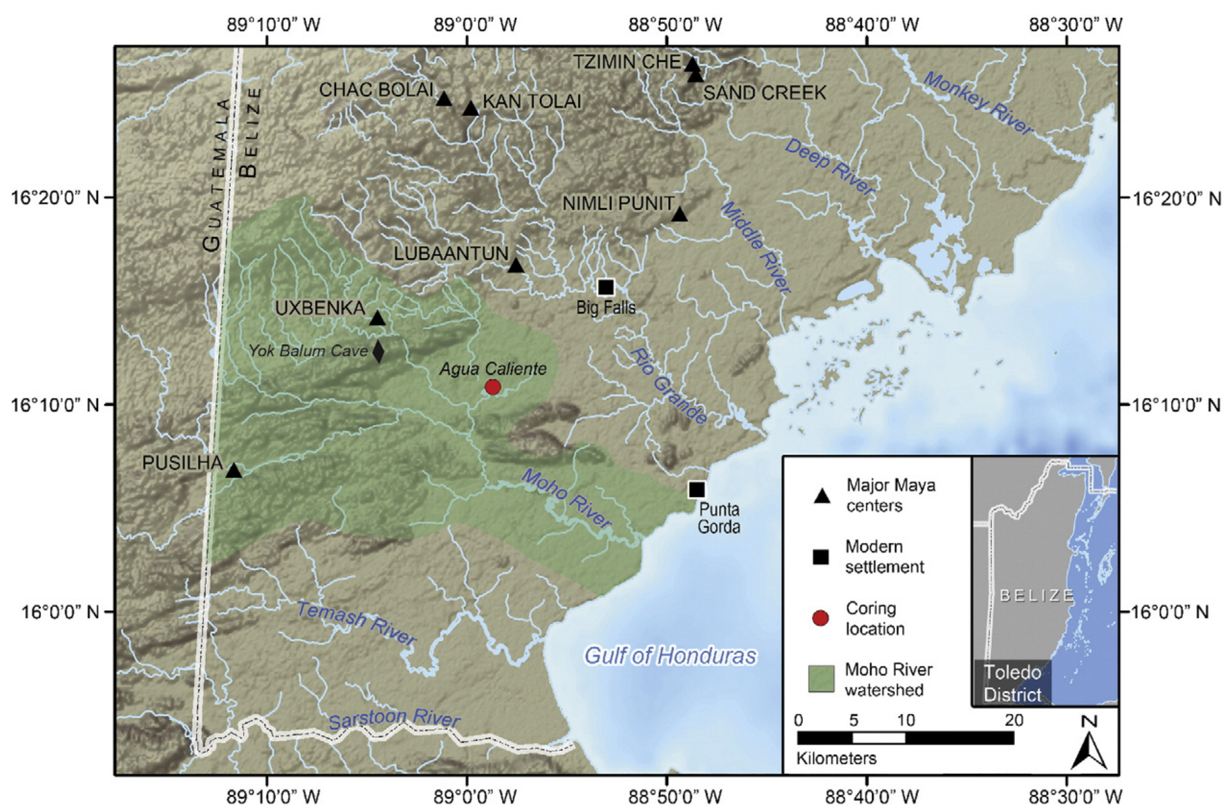


Figure 1. Map of Toledo District (southern Belize) and adjacent areas showing the coring location (16°10.698′N, 88°58.048′W; elevation ~13 m asl), Yok Balum cave location, Moho River watershed, and major Maya centers.
Figure credit: T. Harper.

agriculture (Meerman et al., 2006). Mangrove forest, dominated by the salt-tolerant taxa *Rhizophora mangle* (red mangrove), exists along much of the coast of southern Belize.

The climate of the Toledo District is typical of a subtropical coastal region. Average maximum monthly temperatures typically range from 28 to 32°C and are generally highest before and after the summer rainy season in May and September. Average minimum monthly temperatures range from 18 to 23°C and are lowest December through January (Fig. 2). Average monthly and annual precipitation amounts are high overall and rainfall distribution throughout the year generally follows the movement of the Intertropical Convergence Zone (ITCZ) (Nyberg et al., 2001; Gill et al., 2007). Precipitation is highest in July and lowest in March, with average annual precipitation totals of approximately 2900 mm, 3035 mm, and 3730 mm for the Big Falls, Blue Creek, and Punta Gorda climate stations, respectively. Interannual variability in the timing and strength of the wet season is primarily a result of the position of the ITCZ (Haug et al., 2001; Kennett et al., 2012) as modulated by the El Niño Southern Oscillation (Giannini et al., 2000; Poveda et al., 2006).

Study site

The study site is a series of freshwater lagoons that exist within the boundaries of the Agua Caliente Wildlife Sanctuary in the Toledo District of southern Belize (Fig. 3). The sanctuary comprises more than 2200 ha of lagoons, swamps, savannas, and small forested hills, located approximately 18 km NW of the town of Punta Gorda and 13 km SW of the town of Big Falls. The geology of the area is described as Eocene–Paleocene–limestone–Toledo bed formations overlain by Pleistocene alluvial deposits (Cornec, 1986). There are three main lagoons within Agua Caliente that sit within a bajo-like feature that fills seasonally with precipitation and runoff from surrounding areas (Meerman et al., 2006). Agua Caliente exists entirely within the watershed of the Moho River (~126,000 ha) and three perennial creeks drain into it: Mafredi, Agua Caliente, and Piedra creeks (Figs. 1 and 3). Agua Caliente also acts as a wet season reservoir for Blue Creek during periods of seasonally high flow when excess water cannot drain quickly enough into the Moho River (Meerman et al., 2006). These drainages encompass the entire watershed of the ancient Maya polity of Uxbenká, where human alteration of the landscape has been documented for at least 2500 years (Culleton, 2012). All water from Agua Caliente flows from the lagoons into lower Blue Creek and eventually into the Moho River, which enters the Caribbean Sea approximately 6 km south of Punta Gorda. The water level of the lagoons varies greatly from the wet to the dry season, but portions of each lagoon remain wet throughout the year.

Agua Caliente generally exists within the lowland broadleaf forest and shrubland ecosystem class (Meerman and Sabido, 2001). The vegetation communities of the Agua Caliente Wildlife Sanctuary were determined by a Rapid Ecological Assessment (Meerman et al., 2006). This study broadly describes the vegetation within the sanctuary as a mixture of tropical evergreen broad-leaved lowland forest (the majority of which is swamp forest), deciduous broad-leaved lowland shrubland (some of which is riparian), tropical lowland reed swamp, swamp grassland (with no trees or shrubs), and *Eleocharis* (sedge) marsh. Primarily surrounding the lagoon used in this study is tropical evergreen broad-leaved lowland swamp forest, deciduous broad-leaved lowland disturbed shrubland, and swamp grassland communities.

Eugenia aeruginea (Myrtaceae family) is the dominant tree species found in the tropical evergreen broad-leaved lowland swamp forest, but also common are *Lonchocarpus hondurensis* (Fabaceae), *Dalbergia glabra* (Fabaceae: Papilionoideae), *Pachira aquatica* (Bombacaceae), *Alibertia edulis* (Rubiaceae), *Bactris* spp. (Arecaceae), and *Calyptranthes chytraculia* (Myrtaceae). Abundant grasses and epiphytes also exist in this community. Typical species found in the deciduous broad-leaved lowland shrubland community include *Spondias radlkoferi* (Anacardiaceae), *Stemmadenia* (*Taebernaemontana*) *donnell-smithii* (Apocynaceae), *Thevetia ahouai* (Apocynaceae), *Dendropanax arboreus* (Araliaceae), *Attalea cohune* (Arecaceae), *Bactris mexicana* (Arecaceae), *Cecropia obtusifolia* (Cecropiaceae), *Heliconia latispatha* (Heliconiaceae), *Psidium guajava* (Myrtaceae), and *Rottboellia cochinchinensis* (Poaceae). *Neeragrostis contrerasii* (Poaceae) is the dominant species within the swamp grassland community that seasonally colonizes the edges of the lagoons when the water levels drop in February. Other common plants include *Cyperus articulatus* var. *articulates* (Cyperaceae), *Ludwigia octovalvis* (Onagraceae), *Lippia stoechadifolia* (Verbenaceae), *Solanum campechiense* (Solanaceae) and *Spigelia polystachya* (Loganiaceae) (Meerman et al., 2006).

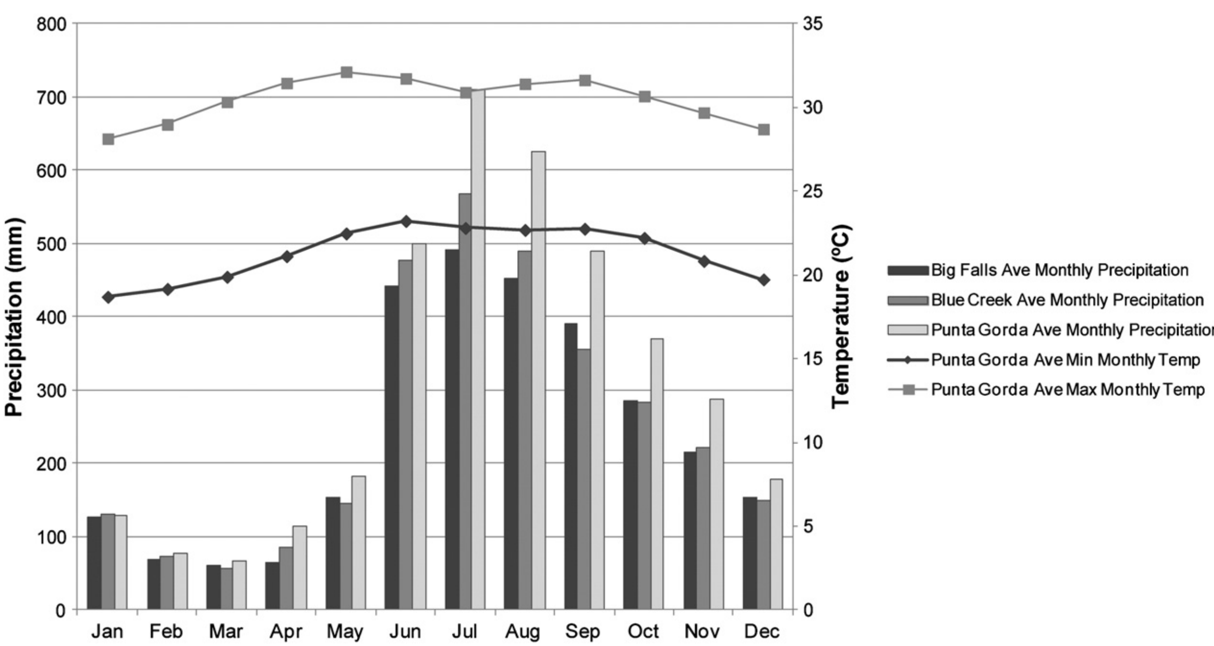


Figure 2. Average monthly temperature and precipitation values for climate stations in southern Belize: Big Falls precipitation data 1985–2005, Blue Creek precipitation data 1966–2005, Punta Gorda precipitation data 1966–2005, and Punta Gorda temperature data 1977–2005.
Data: Hydromet Belize.

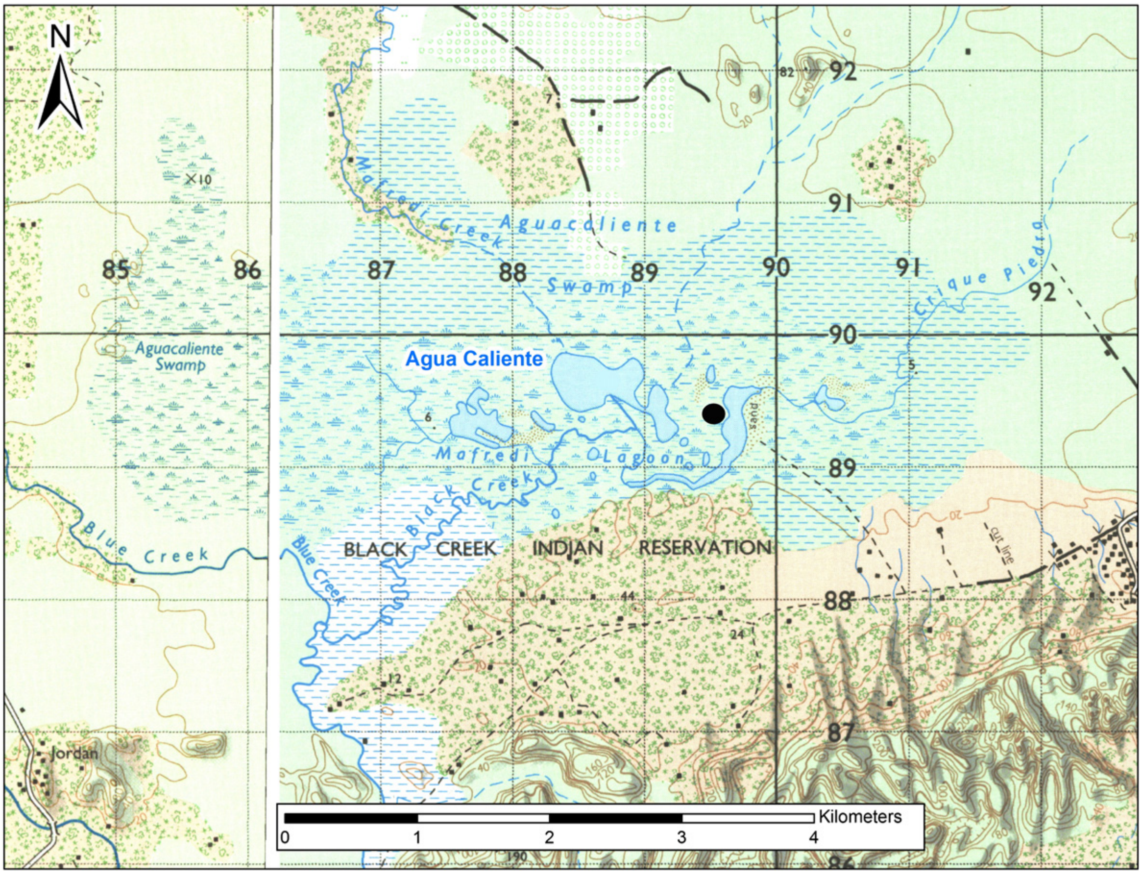


Figure 3. Topographic map of the Agua Caliente lagoons, coring location (black dot), and the creeks that drain into the study site. Figure credit: Amy Thompson.

Several villages exist near Agua Caliente, including Blue Creek, Mafredi, Dump, Laguna, and Jordan, but their populations are small. Most of the villages are either Q'eqchi' or Creole and were established sometime within the past 50 years (Meerman et al., 2006). Within the Agua Caliente drainage the villages of San Antonio and Pueblo Viejo were founded in the late 19th century. Farming hamlets likely dotted the landscape since the 16th century, including in the vicinity of the ancient Uxbenká polity. Current agricultural activities in these areas include milpa (swidden) and matahambre (mulching) agriculture, as well as some mechanized rice cultivation. There is also evidence that Agua Caliente has been used in the last 50 years for hunting and fishing, but it is likely that these activities have taken place for many centuries if not millennia. The Machaca Forest Reserve, which sits just to the east of the sanctuary, was planted with pine between 1947 and 1959. Selective logging of both the Reserve and other nearby areas has taken place within the last decade or so, but likely with little impact on Agua Caliente (Meerman et al., 2006).

Methods

In February 2007, a 1.23 m-long sediment core (AC07B) was extracted from the seasonally dry southern shoreline of the Agua Caliente lagoon at a location of 16°10.698′N latitude and 88°58.048′W longitude and an elevation of ~13 m asl (Fig. 3). The core was obtained using a hand-operated 5-cm diameter modified Livingstone piston coring device (Wright et al., 1983). The coring effort was stopped by the presence of extremely dense clay, so it is unclear if all of the available sediment was recovered. Core segments were extruded in the field, wrapped in plastic wrap and aluminum foil and packaged in split PVC lengths for safe transport to the United States. In the laboratory, the cores were sliced longitudinally and described based on lithological characteristics. Features such as color and composition were noted, as well as the presence of macrofossils (e.g., wood, charcoal). Chronological control of the sediment cores was determined using AMS ^{14}C dating of macrofossils and concentrated macroscopic charcoal (Table 1).

Magnetic susceptibility analysis was used to determine the flux of clastic material in the sediment core (Thompson and Oldfield, 1986) from such events as volcanic eruptions, surface runoff, and stream flow (Dearing and Flower, 1982). Magnetic susceptibility readings were taken at contiguous 1-cm intervals using a Sapphire Instruments magnetic susceptibility ring sensor. Loss-on-ignition analysis was used to determine the amount of organic and carbonate material in the core (Dean, 1974). Samples of 1 cm^3 were taken at 5-cm intervals and placed in crucibles and heated for 2 h at 550°C and 900°C. The weight loss after the first burning was used to determine the organic matter content, and the weight loss after the second burning was used to determine the carbonate content. To calculate the percent carbonate matter, the weight lost after the second burning was divided by the dry weight, multiplied by 1.36, and then multiplied by 100 (Heiri et al., 2001).

Macroscopic charcoal analysis was used to reconstruct the fire history of the Agua Caliente core; methods followed techniques described in Whitlock and Larsen (2001) and modified by Walsh et al. (2008). Contiguous samples of 1 cm^3 were disaggregated in a 5% solution of sodium hexametaphosphate for 1–3 days, gently washed through nested sedimentological screens of 250 and 125-μm mesh size, and placed in scored Petri dishes for counting. Charcoal particles were tallied under a binocular microscope at approximately 50× magnification. Charcoal particles were tallied separately based on their appearance (Walsh et al., 2010). All charcoal was identified by its "charcoal sheen" and the fact that it splinters into many smaller pieces when pressed upon. Herbaceous charcoal was separated from woody charcoal based on the presence of stomatal openings, and by the fact that it was flat instead of 3-D like

Table 1
Radiocarbon dates and calibrated ages for the Agua Caliente core (AC07B), Belize.

Depth (cm below surface)	Lab number (UCIAMS)	Source material	Age (^{14}C yr BP)[a]	Age (cal yr BP)[b]
13–15	60743	Concentrated charcoal	160 +/− 25	180 (0–285)
41–42	46301	Concentrated charcoal	1615 +/− 25	1530 (1416–1553)
65–67	60744	Concentrated charcoal	2565 +/− 25	2730 (2541–2753)[c]
108.5	42814	Single twig	2480 +/− 15	2580 (2471–2708)

[a] ^{14}C age determinations from the Keck Carbon Cycle Accelerator Mass Spectrometry Laboratory at the University of California, Irvine.
[b] Calendar ages determined using Calib 6.0 html (Reimer et al., 2009). Ages rounded to the nearest decade with 2σ ranges reported.
[c] Age determination not used in the creation of the AC07B age–depth model.

wood charcoal (Figs. 4A and B). Another category of charcoal was encountered in the core and tallied as lattice charcoal (Kennett et al., 2010). It is likely that this charcoal also comes from an herbaceous source given its flatness and the presence of numerous holes; however, the holes did not appear to be stomata (Fig. 4C). The presence of several large, intact pieces of this charcoal indicates that it may be a burned seed pod from the Asteraceae family. All charcoal that was not clearly identifiable as herbaceous or lattice was classified as woody. Charcoal concentration (particles/cm^3) was calculated by dividing the total count for each sample by the volume of the sample (1 cm^3). Charcoal influx (CHAR; particles/cm^2/yr) was calculated by dividing the charcoal concentration by the deposition time (yr/cm) of the samples.

Pollen analysis was used to reconstruct the vegetation history near Agua Caliente. Pollen samples of 2-cm^3 were taken at 5-cm intervals in the core and processed following standard techniques described in Faegri and Iversen (1989). Pollen residues were mounted in silicon oil and 300–500 pollen grains were counted per sample. An exotic tracer *Lycopodium* was added to each sample and tallied so that pollen accumulation rates (grains/cm^3) could be calculated. Pollen was identified to the lowest taxonomic level possible based on modern pollen collections and published reference collections (Roubik and Moreno, 1991; Willard et al., 2004), and pollen types were assigned based on modern phytogeography. Pollen types formerly categorized as Cheno-Am (Chenopodiaceae and Amaranthaceae families) were combined under the Amaranthaceae family (APG II, 2003). Extended slide scans were also completed to determine the presence of *Zea* spp. (maize or teosinte) pollen in the core. The entire cover slip of two additional slides from every pollen level was scanned at 100× resolution and only grains larger than 75 μm with a pore to long axis ratio from 5 to 9 were counted as *Zea* spp. pollen (Whitehead and Langham, 1965; Holst et al., 2007). Four pollen zones were designated based on a visual assessment of the pollen diagram.

Results

Chronology and lithology

The chronology of the AC07B core is shown in Figure 5. The age model is based on three AMS ^{14}C dates and a date of 2007 (−57 cal yr BP) for the top of the core (Table 1). Radiocarbon ages were converted to calendar years before present (cal yr BP; present = AD 1950) using the Calib 6.0 program (Reimer et al., 2009). The median age (i.e., the 50th percentile of the probability distribution function (PDF) curve) was chosen as the calibrated (calendar) age if it did not fall in a trough on the PDF curve. If the median age did fall in a trough on the PDF curve, then the value of the nearest, largest peak was chosen. The radiocarbon date from a depth of 65–67 cm caused a reversal in the chronology of the core and was not included in the development of the age–depth model. This radiocarbon date was excluded as opposed to the date from a depth of 108.5 cm because it is more likely that the concentrated woody charcoal had an in-built (pre-sample) age, as opposed to the single twig (McFadgen, 1982; Oswald et al., 2005). The age model for the core was developed using a constrained cubic smoothing spline, which suggests a basal date of 2800 cal yr BP (Fig. 5).

Sedimentation rate varies considerably throughout the AC07B core, although overall it is very low (see Fig. 5— the curve of the constrained cubic spline illustrates the trends in the sedimentation rate of the core). The rate is generally high and consistent from the base of the core to a depth of 42 cm (ca. 1540 cal yr BP), which means that the first 81 cm of the core was deposited in approximately ~1300 years. After that, the sedimentation rate slows considerably from 42 to 15 cm (ca. 1540–210 cal yr BP). Above 15 cm, the sedimentation rate again increases to a rate generally consistent with that prior to ca. 1540 cal yr BP. The median temporal resolution of the core is 23 yr/cm.

The AC07B core consists almost entirely of gray clay with orange to red mottling. Only the top 10 cm has a noticeable amount of organic material. A visible charcoal layer is present in the core at a depth of 65–67 cm, which consists almost exclusively of woody charcoal and corresponds to the highest charcoal concentration and CHAR values of the record (discussed below). Notably, a chert flake measuring approximately 27 mm in length was recovered from a depth of 108–109 cm.

Magnetic susceptibility and loss-on-ignition

Magnetic susceptibility and loss-on-ignition values for core AC07B are shown in Figure 6. Magnetic susceptibility values increase from the bottom of the core to a depth of 60 cm (ca. 2800–1910 cal yr BP). Above that, values drop more quickly at first and then more slowly until a depth of 30 cm (ca. 1000 cal yr BP). Above 30 cm values rise slightly until dropping again in the top 6 cm of the core (ca. 20 cal yr BP). Loss-on-ignition analysis shows that the organic content of the core is very low. Percent organic values remain between 5 and 10% for almost the entire length of the record, but are slightly higher within the top 12 cm of the core (ca. 130 cal yr BP–present). Carbonate values remain between 1 and 5% for the entire core (not shown).

Charcoal

Numerous studies have shown both theoretically and empirically that macroscopic charcoal is incorporated into lake and wetland sediments following fires as an indicator of local fire activity (Clark et al., 1998; Carcaillet et al., 2001). This charcoal is generally derived from fires occurring less than ~10 km away from the site (Gardner and Whitlock, 2001; Pisaric, 2002; Higuera et al., 2010). Charcoal that was not transported to Agua Caliente via air was likely transported to the wetland via the numerous streams that connect it with the adjacent upland area. The farmed lands surrounding Uxbenká sit entirely within the watershed of the streams that feed Agua Caliente and are a likely source of the charcoal in the record (Figs. 1 and 3).

Charcoal concentration and influx values (CHAR) vary greatly throughout the record (Fig. 6). For the bottom 12 cm of the core (ca. 2800–2610 cal yr BP) there is almost no charcoal present, with an average charcoal concentration of 0.58 particles/cm^3 and an average CHAR of 0.2 particles/cm^2/yr. Charcoal content then increases dramatically in the core. From a depth of 110–61 cm (ca. 2610–1910 cal yr BP), average charcoal concentration is 113.7 particles/cm^3 and the average CHAR is 22.0 particles/cm^2/yr. The largest peak in both charcoal concentration and CHAR occurs at a depth of 67–65 cm (ca. 2030–2000 cal yr BP). From a depth of 60–44 cm (ca. 1910–1570 cal yr BP), charcoal

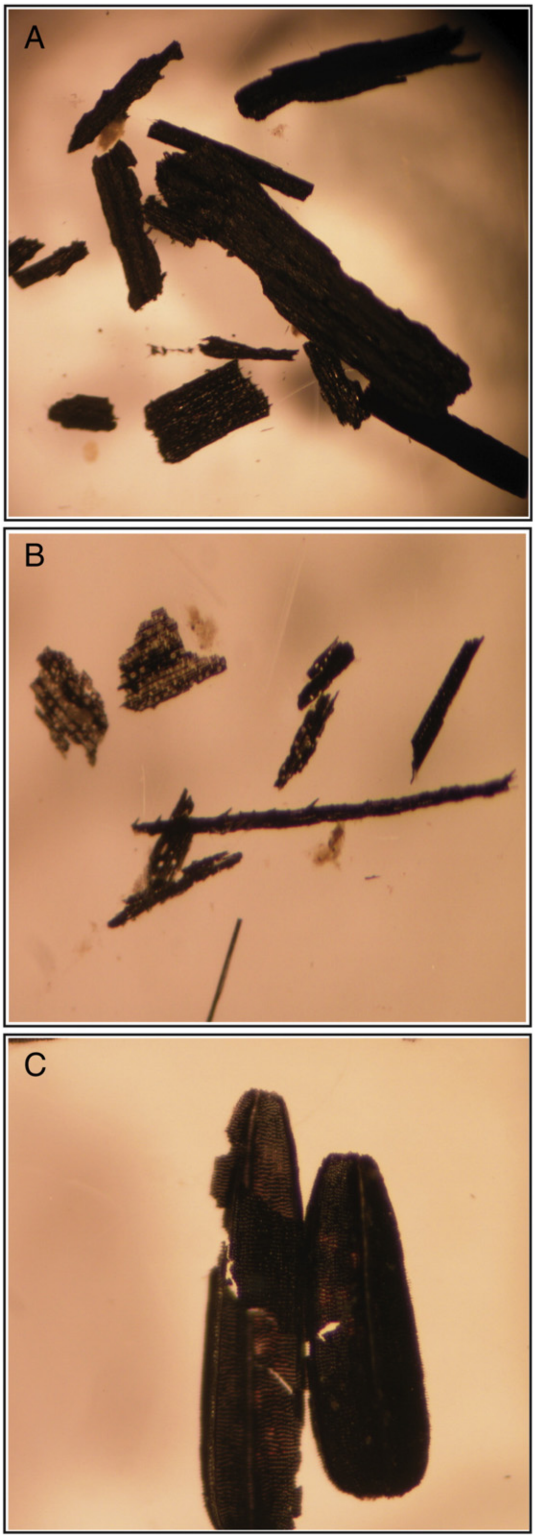


Figure 4. Photos showing the three charcoal morphotypes from the AC07B core: (A) woody charcoal, (B) herbaceous charcoal, and (C) lattice charcoal.
Photos: M. Walsh.

concentration and CHAR are markedly lower with an average of 33.3 particles/cm^3 and 0.9 particles/cm^2/yr, respectively. Following that, charcoal concentration and CHAR both increase from a depth of 43–32 cm (ca. 1570–1060 cal yr BP), with an average charcoal concentration of 76.4 particles/cm^3 and an average CHAR value of 1.8 particles/cm^2/yr. From a depth of 32–17 cm (ca. 1060–240 cal yr BP), charcoal concentration and CHAR are again lower with an average of 25.8 particles/cm^3 and 0.5 particles/cm^2/yr, respectively. Above 17 cm (ca. 240 cal yr BP–present), charcoal content again increases and remains considerably higher than the previous approximately 800 years. Charcoal concentration for this portion of the core is 58.4 particles/cm^3 and CHAR is 3.1 particles/cm^2/yr.

The ratio of charcoal morphotypes present in the record also varies dramatically. Charcoal identified as woody is found in highest abundance from a depth of 110–32 cm. This corresponds to the period of highest charcoal concentration and CHAR, ca. 2610–1060 cal yr BP. The average woody charcoal content for this period is 86.1%. Above that, the percent of lattice charcoal increases in the core. From a depth of 32 cm to the top of the core, the average lattice charcoal content is 54.9%. Notably, the percent of woody charcoal increases sharply in the top 17 cm (ca. 240 cal yr BP) of the core from its lowest point in the entire record, and eventually replaces lattice charcoal as the most abundant charcoal morphotype in the record ca. 90 cal yr BP. In general, herbaceous charcoal remains low throughout most of the core, with slightly higher percentages occurring from a depth of 110–84 cm (ca. 2610–2270 cal yr BP). The average during this interval is 6.3%.

Pollen

The pollen record from Agua Caliente indicates several important vegetation shifts during the late Holocene (Fig. 7). Zone AC07B-1 extends from the base of the core to a depth of 112 cm (ca. 2800–2630 cal yr BP) and is dominated by herbaceous and aquatic taxa. Asteraceae (sunflower) taxa occur in the greatest percentage (~72%), with lesser amounts of Poaceae (~21%) and Cyperaceae (~4%). Few trees and shrubs are present in this zone, with only small amounts of Myrtaceae (*Eugenia* and *Psidium*-type) and *Coccoloba*. Some ferns are also present.

Zone AC07B-2 extends from a depth of 112–50.5 cm (ca. 2630–1720 cal yr BP) and is also dominated by herbaceous and aquatic taxa; however, percentages of trees and shrubs increase as well. Poaceae increases dramatically in this zone; the zone average is 57%. *Pinus* and *Quercus* pollen appear for the first time at the start of this zone, as well as most other trees and shrubs. As a note, *Pinus* and *Quercus* do not grow locally (although as noted above, *Pinus* was planted near the site during the 1940–50s), therefore changes in the abundance of these pollen types likely represent shifts in forests far removed from the site (outside the watershed) (Bhattacharya et al., 2011). Percentages of Myrtaceae (*Eugenia* and *Psidium*-types) and *Coccoloba* generally increase in Zone 2. This zone records the highest percentages of aquatic taxa, including Cyperaceae, *Typha*, and *Nymphaea*, with averages of 13%, 0.5%, and 0.5%, respectively. Fern percentages were also highest in this zone with an average of 3%. *Zea* spp. pollen is present in this zone and is found in four samples at depths of 85.5 cm (ca. 2300 cal yr BP), 76.5 cm (ca. 2180 cal yr BP), 66.5 cm (ca. 2020 cal yr BP), and 55.5 cm (ca. 1830 cal yr BP). *Zea* spp. pollen is found in no other zones and no other domesticates appear in the record at any time.

Zone AC07B-3 begins at a depth of 50.5 cm and extends to 20.5 cm (ca. 1720–410 cal yr BP). High percentages of Poaceae pollen dominate the assemblage, with an average of 96% for the zone. Percentages of most trees and shrubs decrease in Zone 3, including *Pinus*, *Coccoloba*, Sapindaceae, Moraceae, and Anacardiaceae. Only Myrtaceae (*Eugenia*-type) decreases and then increases by the end of the zone. Aquatic taxa such as Cyperaceae and *Typha* also decrease at the beginning of the zone and remain generally low.

Zone AC07B-4 starts at a depth of 20.5 cm and extends to the top of the record (ca. 410 cal yr BP–present). Poaceae pollen remains dominant in Zone 4 with an average of 91%. Some trees and shrubs increase in this zone, including Myrtaceae and *Coccoloba*. Asteraceae pollen also increases slightly to a zone average of 4% as compared to 2% in Zone 3. Cyperaceae and *Typha* increase somewhat and near the

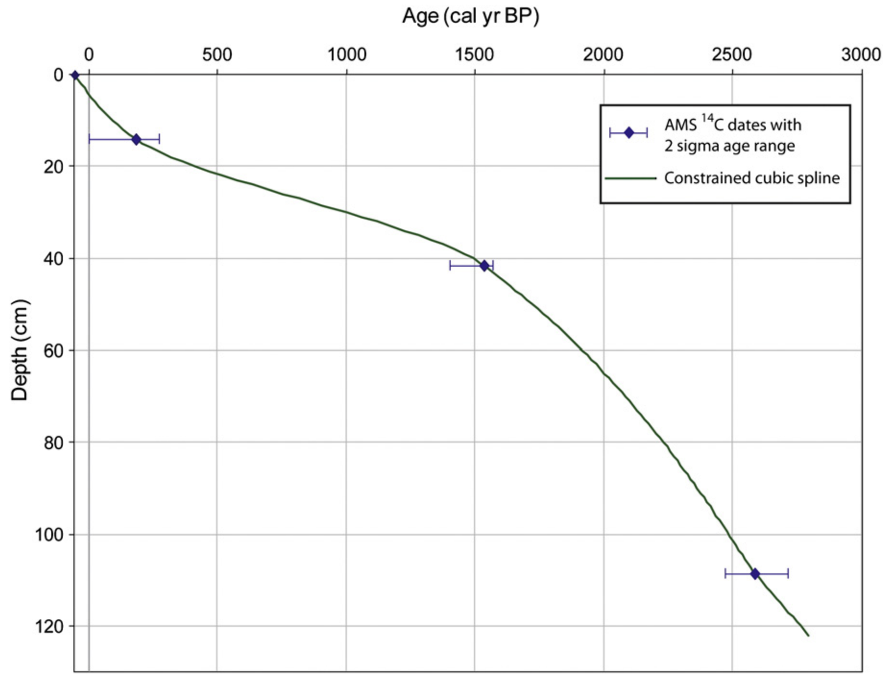


Figure 5. Depth-versus-age relations for the AC07B core based on AMS ^{14}C dates.

top of the zone; slightly higher percentages of *Coccoloba*, *Myrica*, Amaranthaceae, Mimosoideae, and ferns are recorded.

Discussion

Middle Preclassic Period (ca. 2800–2350 cal yr BP; 850–400 BC)

The very deepest deposits dating from ca. 2800 to 2610 cal yr BP (850–660 BC) indicate very little fire activity (average charcoal influx of 0.4 particles/cm^2/yr) in the Agua Caliente watershed at this time (Fig. 8). This suggests relatively low human population density in the area and/or a lack of extensive swidden agriculture. The pollen record from this interval shows that Agua Caliente was dominated by Asteraceae pollen, which are typically considered weedy species (Dull, 2004), and their presence likely indicates a highly disturbed, non-forest environment. These sediments could indicate a period before the formation of the wetland, given that they most closely resemble the pollen assemblage from a current-day fallow pasture (Bhattacharya et al., 2011). However, it is also possible that this period illustrates a reduction in forest extent as compared to earlier due to regional drying during the previous 1500 years (Mueller et al., 2009; Wahl et al., 2013). Low percentages of lowland forest pollen and the absence of *Pinus*/*Quercus* pollen seem to

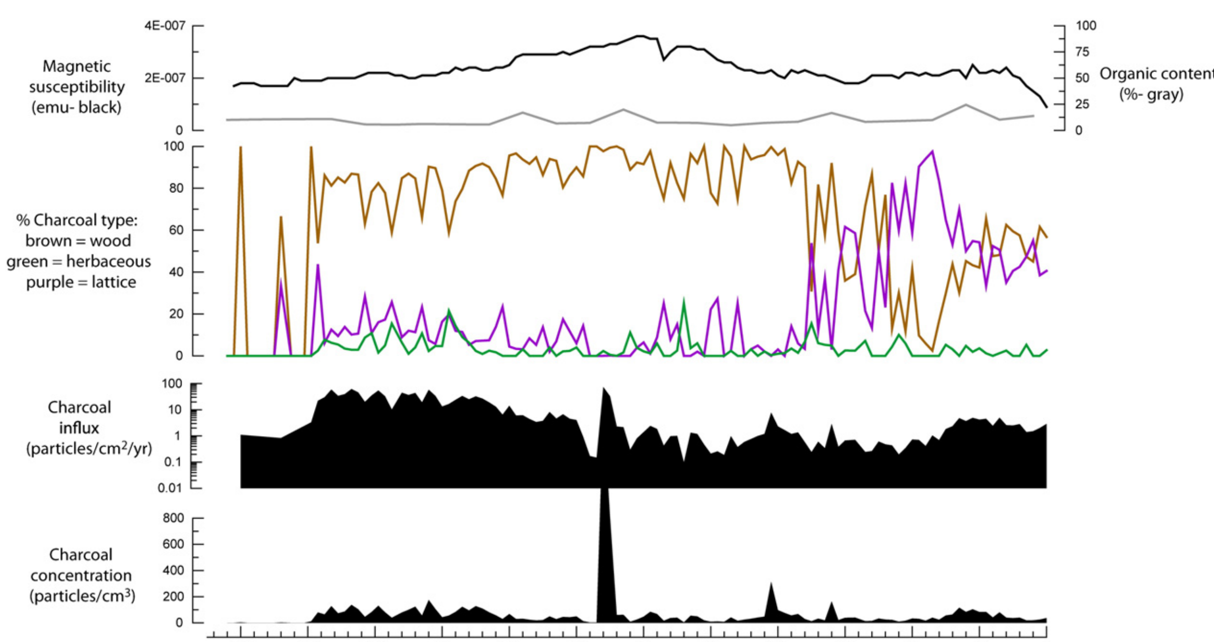


Figure 6. Magnetic susceptibility (electromagnetic units; black line), organic content (%; gray line), charcoal type (%; brown line = woody charcoal, green line = herbaceous charcoal, purple line = lattice charcoal), charcoal influx (particles/cm^2/yr; log scale), and charcoal concentration (particles/cm^3; linear scale) for AC07B plotted against core depth (cm).

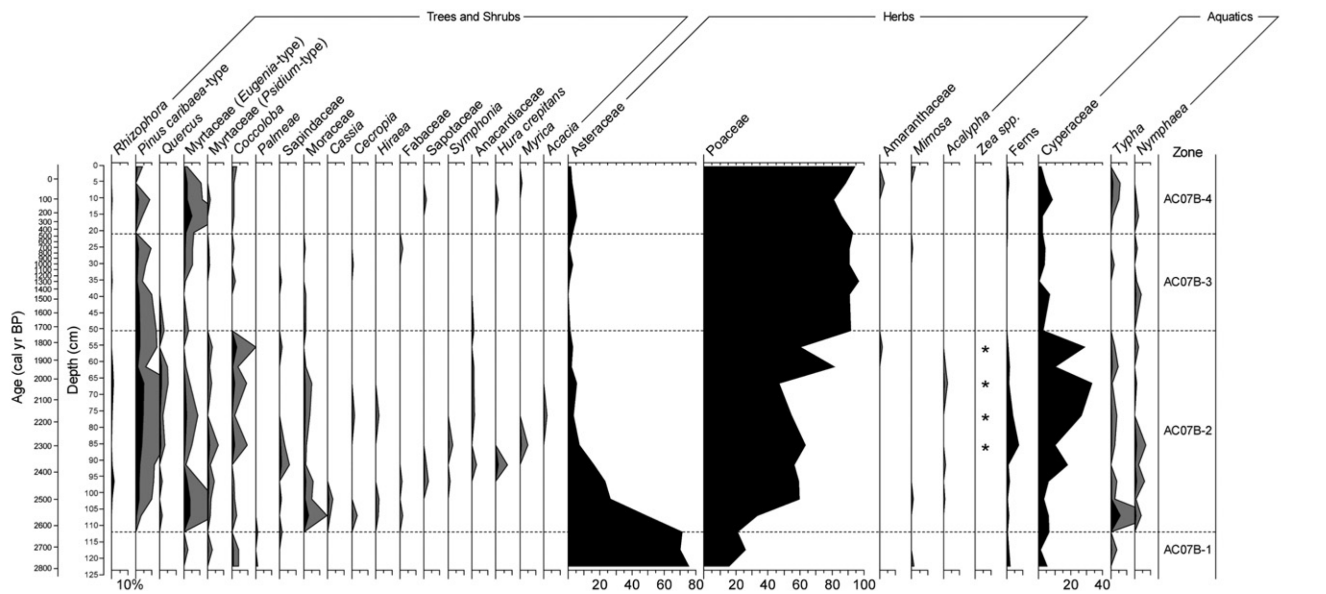


Figure 7. Percentages of selected pollen taxa and spores from core AC07B plotted against depth (cm) and age (cal yr BP). Gray curves represent a 5× exaggeration of the solid black curve. Terrestrial pollen counts were converted to percentages using the total terrestrial pollen and spores in each sample. Aquatic pollen counts were converted to percentages using the total terrestrial and aquatic pollen and spore sum. Asterisks indicate the depth at which *Zea* spp. pollen is present.

support this, but longer paleoecological records will be required to test this hypothesis further.

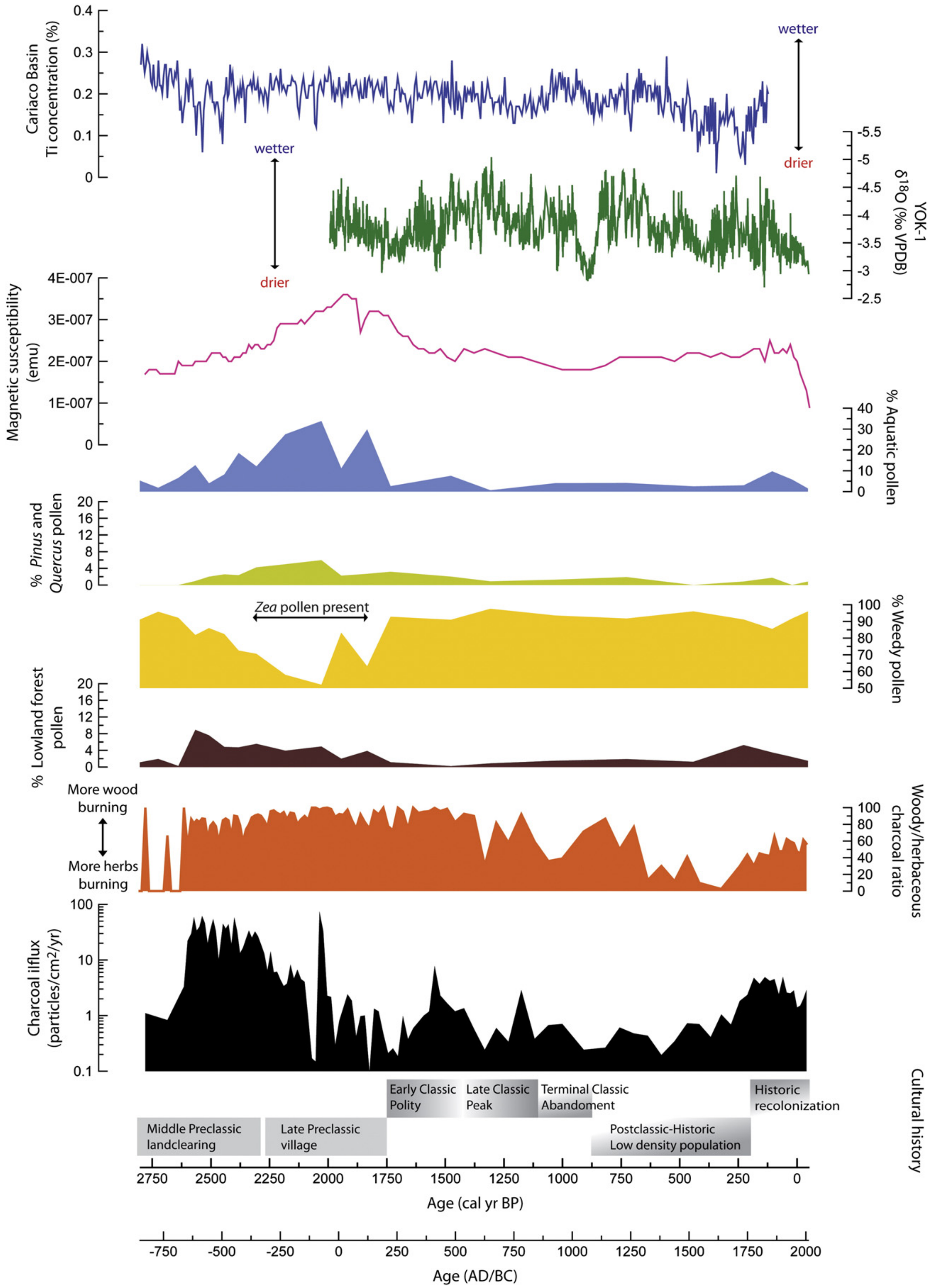
The remainder of the Middle Preclassic (ca. 2610–2350 cal yr BP; 660–400 BC) was characterized by the highest fire activity of the entire record (average charcoal influx of 35.6 particles/cm^2/yr) with high woody/herbaceous charcoal ratios indicating that mostly trees and shrubs were burned within the catchment (Fig. 8). This suggests that major human alteration in the Agua Caliente watershed, primarily the use of fire in association with land clearance for agriculture (Wilk, 1991; Piperno and Smith, 2012; Kennett and Beach, 2014), began ca. 2600 cal yr BP (650 BC). Multiple lines of evidence support this interpretation, including the Uxbenká archeological record, which puts the earliest evidence of human activity between ca. 3700 and 2600 cal yr BP (1750–650 BC; Culleton, 2012). Additional evidence of human activity within the Agua Caliente watershed comes from the consistent decline in the percent of lowland forest pollen, which had rebounded to its highest percentages at the beginning of this period, starting ca. 2500 cal yr BP (550 BC). This likely signifies forest clearance in the upper part of the basin (Leyden, 2002). Although the Cariaco Basin titanium record (Fig. 8) indicates that this was a generally dry period (Haug et al., 2001), which could have caused some reduction in the surrounding forests (Mueller et al., 2009), this seems unlikely given the current precipitation totals of the study site and the presence of many of these forest taxa in the northern Yucatan today in areas with significantly lower precipitation totals (Leyden et al., 1998). The pollen data, especially higher percentages of Poaceae, Myrtaceae, Moraceae, *Nymphaea* and *Typha*, seem to indicate the initial formation of the Agua Caliente swamp grassland and surrounding lowland swamp forest by ca. 2600 cal yr BP (Bhattacharya et al., 2011).

Moreover, evidence of widespread agricultural activity in the Agua Caliente watershed during the Middle Preclassic comes from the increasing magnetic susceptibility values (Fig. 8) and sedimentation rate (Fig. 5) of the record at this time that we argue resulted from land clearance in the upper part of the basin. This activity presumably caused a high amount of erosion on hill slopes, which led to greater sediment deposition into Agua Caliente as compared to before. This probably explains the presence of a chert flake within the record at ca. 2600 cal yr BP (700 BC), which was likely washed in from a nearby archeological site. The timing of this deforestation and erosion is later than most sites from other parts of the Maya region, which show that high amounts of erosion in association with land clearance for agriculture occurred as much as one to three millennia earlier than at Agua Caliente (Dunning et al., 1998; Leyden et al., 1998; Brenner et al., 2002; Wahl et al., 2006, 2007, 2013; Anselmetti et al., 2007; Dull, 2007; McNeil et al., 2010), including several sites in northern Belize (Jones, 1994; Pohl et al., 1996; Rushton et al., 2013). Although there is no clear "Maya clay" layer within the Agua Caliente core as there is in many other lake sediment cores from the region (Deevey et al., 1979; Dunning et al., 1998; Anselmetti et al., 2007; Mueller et al., 2009), its presence may be indistinguishable because almost the entire core is made up of clay and is very low in organic material.

Late Preclassic Period (ca. 2350–1650 cal yr BP; 400 BC–AD 300)

The Late Preclassic witnessed a drop in fire activity in the Agua Caliente watershed as compared to the previous period, but overall fire activity remained high (average charcoal influx of 8.7 particles/cm^2/yr). The high woody/herbaceous charcoal ratios indicate that frequent fires still burned mostly trees and shrubs (Fig. 8). The overall reduction in burning coincides with the highest magnetic susceptibility values of the record and a continued high sedimentation rate, that likely point toward higher erosion rates and the mobilization of even greater amounts of clastic material into the Agua Caliente lagoon. The YOK-I speleothem indicates that ca. 1850–1650 cal yr BP (AD 100–300) was an extended dry interval in southern Belize (Kennett et al., 2012), which may have contributed to the overall decline in agriculture-related burning. However, the persistence of charcoal in the record, albeit at lower levels than before, along with a decline in the percentage of lowland forest pollen shows that forest clearance associated with agriculture continued within the watershed.

This interpretation is supported by the regional archeological record, which suggests that sedentary communities developed slowly in the vicinity of Agua Caliente during the Late Preclassic (Prufer et al., 2011). Uxbenká is the oldest known center within the region dating to at least 1900 cal yr BP (50 BC). It expanded in size after this time and became an important regional political center until it went into decline


Cariaco Basin
Ti concentration (%)
wetter
drier
wetter
drier
YOK-1
δ18O (‰ VPDB)
Magnetic susceptibility
(emu)
% Aquatic pollen
% Pinus and Quercus pollen
Zea pollen present
% Weedy pollen
% Lowland forest pollen
More wood burning
More herbs burning
Woody/herbaceous charcoal ratio
Charcoal iflflux
(particles/cm2/yr)
Cultural history
Early Classic Polity
Late Classic Peak
Terminal Classic Abandonment
Historic recolonization
Middle Preclassic landclearing
Late Preclassic village
Postclassic-Historic Low density population
Age (cal yr BP)
Age (AD/BC)

by ca. 1200 cal yr BP (AD 750) (Prufer et al., 2011; Culleton et al., 2012). The initial permanent settlement date at Uxbenká is generally synchronous with the largest spike in charcoal influx of the entire record, which occurred ca. 2030–2000 cal yr BP (80–50 BC), and could indicate large-scale clearance of permanent, albeit shifting agricultural fields, illustrated by the continued decline of lowland forest taxa percentages.

Many of these agricultural fields were likely located in close proximity to Uxbenká; however, the presence of *Zea* spp. pollen in the Agua Caliente record from ca. 2300 to 1830 cal yr BP (350 BC–AD 120) could also indicate use of the wetland for local agricultural production. This hypothesis is supported by several lines of evidence. First, *Zea* spp. pollen grains are only present in the Agua Caliente record during the Late Preclassic. Maize pollen grains are large and do not disperse over long distances (Raynor et al., 1972) and are possibly only incorporated into sediment records when maize is planted on the shore of a lake (Islebe et al., 1996; Clement and Horn, 2001). This leads us to believe that maize was planted locally at this time in order for the pollen to appear in this part of the Agua Caliente record. Second, the presence of *Zea* spp. grains in the record during the Late Preclassic is coincident with the highest Cyperaceae percentages, possibly indicating a drop in water levels at Agua Caliente and the colonization of the lagoon's edges by emergent sedges (Wahl et al., 2006). This would have provided the opportunity for maize to be planted on formerly submerged land. Third, studies from northern Belize show that the Maya used wetlands for agriculture during similar time periods (Jones, 1991; Pohl et al., 1996), so it seems likely that comparable strategies would have existed in southern Belize, although as of yet there is no evidence of ditching or channel straightening as seen at Cobweb Swamp (Jacob, 1995). It is also possible that locales near Agua Caliente may have been farmed during the dry season when upland soils lack moisture for reliable cultivation, particularly during drier periods, a common modern practice of recessional agriculture in southern Belize that may have ancient correlates (Wilk, 1985). The subsequent increase in the percent of weedy species (primarily Poaceae) at Agua Caliente ca. 1800 cal yr BP (AD 150) likely reflects the establishment of the modern swamp grassland around the lagoon as water levels rose at the end of the Late Preclassic (Bhattacharya et al., 2011) and possibly the abandonment of agriculture along the shores of the lagoon.

It is unclear why fire activity decreased within the Agua Caliente watershed during the Late Preclassic as compared to the Middle Preclassic, but this trend is similar to that of Cob Swamp in northern Belize, which also shows decreased fire activity after initially high charcoal concentrations during a phase of land clearance in the Middle Preclassic (Pohl et al., 1996; Leyden, 2002). Additionally, Wahl et al. (2013) show extremely low charcoal deposition rates at Laguna Yaloch in the Petén of Guatemala during the Preclassic and hypothesize that this could have been the result of more intensive agricultural techniques, such as raised/ditched fields and terraces. There is no evidence of terracing or other soil conservation measures near Uxbenká (Culleton, 2012), or anywhere else in southern Belize, so this seems an unlikely explanation for the decline in burning. It could be that less rainfall in the region transported and deposited less charcoal in the Agua Caliente record during this period; however, the unchanging sedimentation rate and the high magnetic susceptibility values also make this explanation unlikely. Therefore, a climatically-induced shift in agricultural intensity or strategy seems most plausible to explain the decline in burning.

Early Classic to Terminal Classic Period (ca. 1650–950 cal yr BP; AD 300–1000)

Fire activity initially increased in the Agua Caliente watershed during the Early Classic (average charcoal influx of 1.8 particles/cm^2/yr) and remained relatively high, albeit at lower levels than the Middle and Late Preclassic, until the start of the Late Classic ca. 1350 cal yr BP (AD 600) (Fig. 8). This increase in burning may have been associated with increased agricultural production resulting from higher rainfall ca. 1500–1300 cal yr BP (AD 450–650; Kennett et al., 2012), and is generally similar to fire activity at other sites in the Maya region (Rue et al., 2002; Dull, 2007; Wahl et al., 2013). Percentages of lowland forest pollen were at their lowest during this period, likely indicating the period of greatest land clearance for agriculture within the Agua Caliente watershed. However, the lack of *Zea* spp. pollen in the record at this time suggests that agricultural activity may have been primarily located away from the area immediately surrounding Agua Caliente, likely focused in the Toledo Uplands near Uxbenká. This interpretation is supported by the Uxbenká archeological record, which indicates that the period from 1500 to 1300 cal yr BP was the time of peak regional populations with at least 10 political capitals and up to 100 smaller communities within a 40 km radius of Agua Caliente (Prufer et al., 2011). It also corresponds with the intensified use of plasters in building at both Uxbenká civic-ceremonial center and large outlying settlement groups. The production of plaster would have been a fuel-intensive activity for burning limestone (Turner and Sabloff, 2012).

Fire activity decreased at Agua Caliente during the Late Classic (ca. 1350–1150 cal yr BP; AD 600–800) and remained generally low during the Terminal Classic (ca. 1150–950 cal yr BP; AD 800–1000), with average charcoal influx values of 1.0 particles/cm^2/yr and 0.6 particles/cm^2/yr, respectively. This decline may have resulted from a general decrease in burning related to persistent and intensive agricultural activity in the area, and is consistent with decreased charcoal influx at other sites within the Maya region (Neff et al., 2006; Dull, 2007; Rushton et al., 2013; Wahl et al., 2013) as well as the biomass burning trend from Central and Mesoamerica as a whole (Power et al., 2013). Pollen percentages from Agua Caliente during this period indicate little change on the landscape with relatively stable percentages of weedy, aquatic, and lowland forest taxa. However, more variable fuel sources near the end of the period (i.e., more herbs burning and less wood burning) may indicate a shift in agricultural strategies as the region struggled with more frequent drought and less predictable rainfall (Kennett and Beach, 2014).

The charcoal record from Agua Caliente does not indicate a clear “collapse” in agricultural activity during the Terminal Classic Period associated with the disintegration of the Uxbenká polity. Burning slowly declined and is consistent with the decentralization and a gradual reduction in regional populations. The sample resolution in this part of the record is relatively coarse so we are hesitant to over-interpret the timing of the observed drop. However, the fire-history reconstruction and the magnetic susceptibility curve (Fig. 8) seem to suggest that human use of fire and subsequent erosion in the watershed became less common sometime between ca. 1150 and 950 cal yr BP (AD 800–1000), during an interval of repeated droughts followed by an extended period of drought ca. 950–850 cal yr BP (AD 1000–1100; Kennett et al., 2012). The Uxbenká archeological record also suggests that by 1200 cal yr BP (AD 750) the region was in decline as political centers were abandoned and population contracted due to

Figure 8. Cultural history for Uxbenká (gray panels), charcoal influx (log scale; black curve), woody/herbaceous charcoal ratio (herbaceous charcoal includes both herbaceous and lattice-type charcoal morphotypes; orange curve), percent lowland forest pollen (includes Myrtaceae, Moraceae, *Mimosa*, Malpighiaceae, *Acalypha*, *Borreria*, Anacardiaceae, *Cassia*, *Cecropia*, *Coccoloba*, *Hura*, Sapotaceae, and Sapindaceae; brown curve), percent weedy pollen (includes Poaceae, Asteraceae, Amaranthaceae; yellow curve), percent *Pinus* and *Quercus* pollen (light green curve), percent aquatic taxa (includes Cyperaceae, *Typha*, *Nymphaea*; light blue curve), and magnetic susceptibility (pink line) from the AC07B core. Also plotted are the YOK-I $\delta^{18}O$ speleothem record (green line; Kennett et al., 2012) and the Cariaco Basin titanium concentration (dark blue line; Haug et al., 2001).

emigration or other factors (Prufer et al., 2011). The timing of the decline of the Uxbenká polity as suggested by the charcoal curve fits well within the established timeline for the decline of other Classic Maya polities between 1200 and 950 cal yr BP (AD 750–1000; Kennett and Beach, 2014).

Postclassic and Colonization Period (ca. 950–150 cal yr BP; AD 1000–1800)

Fire activity was lowest in the Agua Caliente watershed during the Postclassic (950–430 cal yr BP; AD 1000–1520), with an average charcoal influx of only 0.4 particles/cm^2/yr, but fire was never entirely absent (Fig. 8). This low level of burning is consistent with other sites across the Maya region (Rue et al., 2002; Neff et al., 2006; Dull, 2007; Rushton et al., 2013; Wahl et al., 2013), but is contradictory to the general trend of biomass burning in Central and Mesoamerica as a whole (Power et al., 2013). However, many of the sites analyzed by Power et al. (2013) were from outside the Maya region and did not experience the same degree of population expansion and collapse before and after ca. 1100 cal yr BP (AD 850). Many of these outside sites saw a later decrease in biomass burning, starting ca. 500 cal yr BP (AD 1450), likely as a result of decreased temperature and precipitation associated with the Little Ice Age (Power et al., 2013). At Agua Caliente, the pollen record indicates little change in the vegetation during the Postclassic except for a marginal increase in Myrtaceae (*Eugenia*-type). Fires that did burn alternated fuel sources, from more woody material burning during the Early Postclassic (ca. 950–650 cal yr BP; AD 1000–1300) to more herbaceous material burning during the Late Postclassic (ca. 650–431 cal yr BP; AD 1300–1519).

An increase in fire activity in the Agua Caliente watershed was coincident with gradual recolonization of the region by Maya slash-and-burn farmers after the collapse and Spanish as well as British colonization of southern Belize after ca. 430 cal yr BP (AD 1520) (Graham et al., 1989). Ethnohistorians have documented several Maya farming communities in the region (Jones, 1989) as well as land clearing for cacao (chocolate) tree groves by 310 cal yr BP (AD 1640) (Thompson, 1972). This is supported by archeological data from Uxbenká (Kalosky et al., 2012) indicating that low-density populations persisted near Agua Caliente until ca. 300 cal yr BP (AD 1650) when the Spanish forcibly removed many local residents to Guatemala as part of the colonial enterprise (Prufer, 2002), leaving only a scattering of agricultural households or communities. This increase in burning is also marked by an increase in woody/herbaceous charcoal ratios, indicating that once again more trees and shrubs were burned than herbaceous plants, although at lower levels than earlier in the record. As well, the relatively greater abundance of Asteraceae and Amaranthaceae pollen, which are weedy taxa (Rosenmeier et al., 2002; Dull, 2004), is indicative of renewed disturbance within the watershed.

The rise in burning that seemingly accompanied European colonization of the Agua Caliente watershed is unique when compared to other charcoal records from the Maya region (Neff et al., 2006; Dull, 2007; Rushton et al., 2013; Wahl et al., 2013), although most available records are not of high enough resolution or are missing sediment from the last ~500 years, so it is difficult to say whether Agua Caliente is truly the only site that shows an increase during this period. Several sites from outside the Maya region show an increase in burning during the last ~500 years (AD 1450) (Piperno, 1994; Goman and Byrne, 1998; Kennedy et al., 2006); however, Nevle and Bird (2008) conclude that the overall trend for tropical Central and South America is a marked reduction in biomass burning due to disease-induced population reduction resulting from European contact.

Historic Recolonization Period (ca. 150–57 cal yr BP; AD 1800–2007)

The last two centuries witnessed human recolonization of the Agua Caliente watershed beginning in the AD 1800 s when the first modern agricultural communities were founded by Maya immigrants from Guatemala combined with residual inhabitants (Thompson, 1972; Jones, 1989). By AD 2007 these had grown to include 35 Q'eqchi' and Mopan speaking subsistence farming villages within 30 km of Agua Caliente. Fire activity was high during the past few centuries with an average charcoal influx of 3.1 particles/cm^2/yr, and is comparable to the levels of burning experienced during the Early Classic Period. This likely reflects increased population pressure and a return of extensive swidden agriculture, which is practiced today within the watershed (Wilk, 1985; Culleton, 2012), along with increasing mechanized farming and land clearance for industrial monoculture citrus farming. Woody/herbaceous charcoal ratios also remained high during this time and indicate that charcoal was derived primarily from burned trees and shrubs (Fig. 8). However, it is also likely that charcoal entering the record in the last several decades has come from the burning of agricultural fields (primarily for rice cultivation) along the margins of the Agua Caliente Reserve, although the low concentration of herbaceous charcoal in the top portion of the core indicates that this has had little impact on the most recent fire history.

Conclusions

The paleoecological reconstruction presented here is only the second high-resolution macroscopic charcoal record from the Maya lowlands and shows clear evidence for uninterrupted burning within the Agua Caliente watershed during the past ca. 2600 years (650 BC–AD 2007). Given the general lack of lightning ignitions in this area, this suggests that fire was continuously employed by Maya populations during this interval to modify the landscape, primarily for land clearance in association with swidden agriculture. Periods of higher fire activity are closely associated with a Middle Preclassic land clearance phase (ca. 2610–2350 cal yr BP; 790–400 BC), the Early Classic peak in Maya populations at Uxbenká (ca. 1650–1350 cal yr BP; AD 300–600), the slow recovery of Maya populations and early Spanish and British colonization (ca. 431–150 cal yr BP; AD 1591–1800), and the period of most recent migrations of Q'eqchi' and Mopan speaking Maya from Guatemala (ca. 150 cal yr BP to present; AD 1800 to present) to the Agua Caliente watershed. The interval of lowest fire activity is coincident with the Postclassic Period (ca. 950–430 cal yr BP; AD 1000–1520), a time when regional populations declined in the wake of the Classic Maya collapse (Prufer, 2002; Braswell and Prufer, 2009).

The paleoecological data from Agua Caliente therefore provide a proxy for the regional intensity of agricultural activity and, by extension, a crude measure of population in the Agua Caliente watershed through time. Based on this observation we argue that agricultural intensity and the number of people living in the Agua Caliente watershed were mediated, in part, by changes in precipitation evident in the nearby YOK-I speleothem record (Kennett et al., 2012). Burning decreased in the Late Preclassic, ca. 2350–1650 cal yr BP (400 BC–AD 300) during a multi-decadal dry interval that reduced agricultural production and may have stimulated a brief interval of regional population decline that coincided with the lower concentration of populations near Uxbenká (Prufer et al., 2011). Extended periods of greater than normal precipitation during the Early Classic (ca. 1650–1350 cal yr BP; AD 300–600) fostered more widespread cultivation, population growth and increased burning within the Agua Caliente watershed. Declining agricultural activity between ca. 1150 and 950 cal yr BP (AD 800–1000) was synchronous with a general drying trend and a series of multi-decadal droughts that culminated in the most extended and severe dry interval between 950 and 850 cal yr BP (AD 1000–1100). This coincided with the disintegration of the Uxbenká polity and associated regional population decline evident in both archeological and paleoecological records. These data show a linkage between climate drying/drought and decreased agricultural activity/potential only assumed in previous studies (e.g., Hodell et al., 1995; Haug et al., 2003; Kennett et al., 2012).

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