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A B S T R A C T

Analyses of an ~6 m sediment core from Lago Paixban in Peten, Guatemala, document the complex evolution of a perennial wetland over the last 10,300 years. The basal sediment is comprised of alluvial/colluvial fill deposited in the early Holocene. The absence of pollen and gastropods in the basal sediments suggests intermittently dry conditions until ~9000 cal yr. BP (henceforth BP) when the basin began to hold water perennially. Lowland tropical forest taxa dominated the local vegetation at this time. A distinct band of carbonate dating to ~8200 BP suggests regionally dry conditions, possibly associated with the 8.2 ka event. Wetter conditions during the Holocene Thermal Maximum are indicated by evidence of a raised water level and an open water lake. The timing of this interval coincides with strengthening of the Central American Monsoon. An abrupt change at 5500 BP involved the development of a sawgrass marsh and onset of peat deposition. The lowest recorded water levels date to 5500–4500 BP. Pollen, isotope, geochemical, and sedimentological data indicate that the coring site was near the edge of the marsh during this period. A rise in the water table after 4500 BP persisted until around 3500 BP. Clay marl deposition from 3500 to 210 BP corresponds to the period of Maya settlement. An increase in δ^{13}C, the presence of *Zea* pollen, and a reduction in the percentage of forest taxa pollen indicate agricultural activity at this time. In contrast to several nearby paleoenvironmental studies, proxy evidence from Lago Paixban indicates human presence through the Classic/Postclassic period transition (~1000 BP) and persisting until the arrival of Europeans. Cessation of human activity around 210 BP resulted in local afforestation and the re-establishment of the current sawgrass marsh at Lago Paixban.

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1. Introduction

The thesis that drought may have played a role in the widespread abandonment of the southern Maya lowlands during the Terminal Classic Period (A.D. 800–1000) has been proposed by several authors (Gill, 2000; Haug et al., 2003; Hodell et al., 1995, 2001). This in turn has led to an expanded effort to understand climate dynamics in eastern lowland Mesoamerica. Studies from the Yucatan Peninsula and circum-Caribbean show significant Holocene climate variability (Curtis et al., 1996; Haug et al., 2001, 2003; Hodell et al., 1991, 1995, 2001, 2005; Kennett et al., 2012; Lane et al., 2009, 2014; Nyberg et al., 2001; Wahl et al., 2014), yet very few climate reconstructions come from the southern Maya lowlands where the abandonment occurred. Moreover, Holocene length paleoclimate records are relatively scarce in the Maya region, and this limits our ability to place high frequency variability in the context of longer-term climate change.

Paleoenvironmental studies have also provided evidence of early migration and settlement, land-use, and demographic shifts associated with local and regional abandonments. For example, previous paleoecological work in lowland Mesoamerica shows that the arrival of agriculture often pre-dates archaeological evidence of permanent settlement (Beach et al., 2009; Pohl et al., 1996; Pope et al., 2001; Sluyter and Dominguez, 2006; Wahl et al., 2007a). Many of these records also show ecological responses to changing land use associated with population declines. Data from well-dated sediment cores have proven useful in constraining the timing of these shifts, clarifying, for example, if and when areas were abandoned during the Terminal Classic Period (Islebe et al., 1996; Mueller et al., 2010; Wahl et al., 2007a, 2007b).

Sedimentary cores from lakes and marshes provide an opportunity to explore these themes, though disentangling the relative importance of human activity and climate change in proxy signals has proven

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difficult in areas with substantial prehistoric populations. Increased spatial and temporal resolution is needed to define more precisely the role of climate change and human impacts in Mesoamerican prehistory.

Here we present the results of a paleoecological study in the Mirador area of northern Peten, Guatemala. The objectives of the study were twofold: to increase our understanding of Holocene climate dynamics, and to assess local environmental change caused by prehistoric land use. In order to address these objectives, we analyzed a 6-m sediment core retrieved from Lago Paixban, a large perennial wetland in northern Peten, Guatemala (Fig. 1). Analyses included pollen, carbon isotope ratios, magnetic susceptibility, loss on ignition, physical properties, and accelerator mass spectrometry (AMS) radiocarbon. The sedimentary sequence spans the last 10,300 years.

2. Regional setting

Lago Paixban is a relatively large (~1.25 km^2) perennial wetland occupying a topographic low within a *bajo* system in the far northern Peten, Guatemala (17°48′56″N, 90°07′15″W; Fig. 1). It lies on the border with Campeche, Mexico, and is located near the western edge of the Mirador–Calakmul Basin system (Hansen, 2012a). Topographers Claudio Urrutia and Miles Rock first described the marsh as a water source in 1882 (maps and notes on file with Foundation for Anthropological Research & Environmental Studies (FARES), supplied by Rolando Urrutia). The marsh is currently dominated by sawgrass (*Cladium jamaicense*) and, as such, is characterized locally as a *cival* (the local term for sawgrass). Other common aquatic taxa include water lily (*Nymphaea ampla*), cat-tail (*Typha domingensis*), and spikerush (*Eleocharis interstincta*). Areas of shallow open water (1–2 m) exist within the marsh, forming rectilinear patterns among the sawgrass. Although not observed directly at Lago Paixban, other *civales* fluctuate seasonally as a result of changes in height of the local water table. Overall, this environment is very similar to ridge and slough marshes of the Florida Everglades in both geomorphology and species composition. As such, Lago Paixban offers a rare analog to study long-term ecological responses to climate change and human impacts in sawgrass marshes.

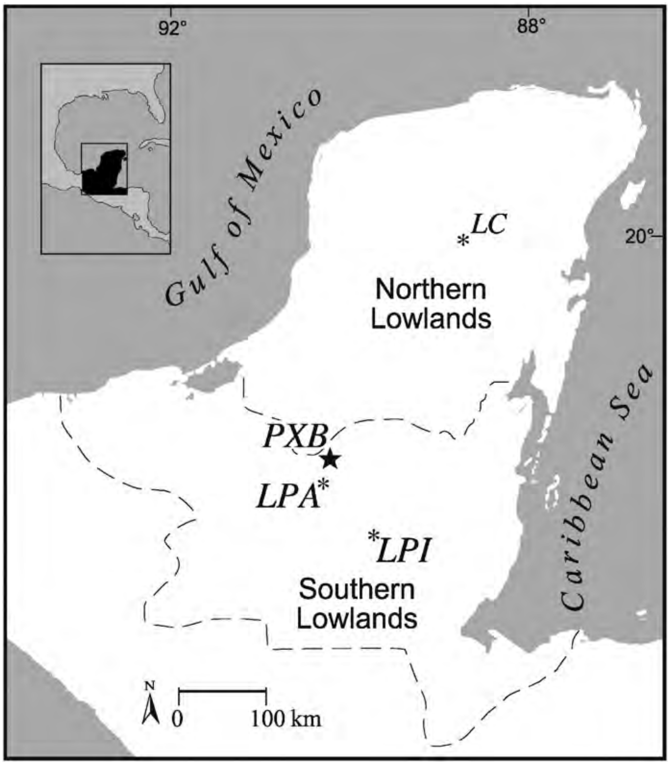

Fig. 1. Map of Yucatan Peninsula, showing the location of Lago Paixban (PXB) and other sites mentioned in the text (LPA, Lago Puerto Arturo; LC, Lake Chichancanab; LPI, Lago Peten Itza).

The nearest weather station, which contains 24 years of data, is around 100 km to the south of Lago Paixban in Flores, Peten. Average annual precipitation is ~1840 cm; average maximum and minimum temperatures are 32.4 and 20.6 °C respectively (http://www.insivumeh.gob.gt). The regional climate is strongly seasonal, with ~75% of annual rainfall occurring during the wet season from May to October and the remainder during the dry season from November to April. This seasonality reflects the latitudinal migration of the North Atlantic High and the Intertropical Convergence Zone (ITCZ). Interannual variability is primarily controlled by a combination of the North Atlantic Oscillation and ENSO (Czaja et al., 2002; Giannini et al., 2000).

Lago Paixban is located relatively close (tens of kilometers) to many large prehistoric urban centers, including El Mirador, Nakbe, and Xulnal. Archaeological research shows early cultural growth in this area, marked by the establishment of one of Mesoamerica's first nation-states, an early dynastic empire, and monumental architecture in the Preclassic period (Clark and Hansen, 2001; Hansen, 1998, 2001, 2012b; Hansen and Guenter, 2005). These early developments have led scholars to characterize the region as the "cradle" of Maya civilization.

3. Methods

In 2003 we recovered a 5.94 m sediment core from Lago Paixban with a modified Livingstone piston corer (Wright et al., 1984) in 0.80 m of water. A replicate core, offset by 40 cm, was taken to ensure complete recovery of the sedimentary sequence. However, thick clay horizons prevented full recovery in some sections, resulting in small discontinuities. The open water area at Lago Paixban is surrounded by wide zone of sawgrass marsh. Core collection and recovery required construction of a pier supporting a wooden walkway extending ~60 m out to open water.

Ten samples were submitted for AMS radiocarbon age determination. Emergent aquatic plant fragments, wood, seeds, and insect fragments were selected in order to avoid hardwater error (Deevey et al., 1954). The radiocarbon sample taken from 550 cm was comprised of a small amount of unidentifiable plant material. δ^{13}C was not measured on 8 samples due to small sample size, in which case a value of −25‰ was used during the calibration process. Radiocarbon years were calibrated to calendar years using Calib 7.0 (Stuiver and Reimer, 1993) and the IntCal13 dataset (Reimer et al., 2013). The age-depth curve was modeled using clam.R 2.2 (Blaauw, 2010). The dates were fitted with 10,000 iterations of a smooth spline (spar = 0.3) and constrained to 95% probability for the calibrated ages. A weighted average was used to assign ages at 1 cm intervals based on the age probability density curve, again using a 95% confidence interval, for each depth from all iterations of the model.

Whole core magnetic susceptibility was measured in 1-cm increments using a Bartington MS2C Sensor. Due to the extremely low magnetic values, each core was measured twice and the results averaged together. Cores were then split longitudinally and imaged using a GEOTEK Multi-Sensor Core Logger (MSCL). Bulk density, water content, organic and carbonate content were calculated using loss on ignition (LOI) techniques (Dean, 1974) (Fig. 3).

Isotopic composition of C was measured on sedimentary organic matter (SOM) using a VG Optima Mass Spectrometer. Samples were pretreated with a 2 N solution of HCl to remove inorganic carbon (Meyers and Teranes, 2001). C and N abundances in sedimentary organic matter were measured using a Fisons EA1500 Elemental Analyzer on all samples analyzed for isotopic composition. Atomic C:N ratios can be useful in differentiating terrestrial and aquatic sources to sedimentary carbon (Meyers and Lallier-Vergès, 1999). Results of C content from

Table 1
AMS radiocarbon dates from Lago Paixban.

Lab no.	Depth (cm)	Material submitted	δ^{13}C	Radiocarbon age ^{14}C yr. BP	Age range 2σ (cal yr. BP)	Median age (cal yr. BP)	Calendar year (AD/BC)
WW8017	35[a]	Macro-plant material	−24.54	Modern	n.a.	n.a.	n.a.
CAMS-105056	41[a]	Wood fragment	−25	Modern	n.a.	n.a.	n.a.
WW8016	47	Macro-plant material	−26.74	90 ± 30	22–265	110	AD 1840
Beta-289139	65	Macro-plant material	−25.60	640 ± 40	551–668	600	AD 1350
CAMS-155024	87	microscopic charcoal	−25	770 ± 180	457–1074	735	AD 1215
CAMS-105057	146	Wood fragment	−25	3385 ± 30	3568–3696	3630	1680 BC
CAMS-131370	160	Seed	−25	3900 ± 60	4153–4514	4330	2380 BC
CAMS-105058	242	Wood/insect fragments	−25	4430 ± 45	4869–5281	5030	3080 BC
CAMS-131676	253	Seed	−25	4755 ± 30	5332–5586	5520	3570 BC
CAMS-111476	356	Wood fragment	−25	6110 ± 160	6572–7414	6990	5040 BC
CAMS-105059	430	Wood/insect fragments	−25	7190 ± 60	7880–8164	8010	6060 BC
CAMS-111477	550	Macro-plant material	−25	8700 ± 60	9542–9833	9660	7710 BC

[a] Indicates samples not used in age model.

the elemental analyzer were used as a control to compare against results determined with LOI.

Pollen was extracted using standard processing techniques (Faegri and Iverson, 1989) and sample residue was mounted in silicon oil. Pollen grains and fern spores were identified to the lowest possible taxonomic level using the UC Berkeley Museum of Paleontology's collection of over 10,000 reference pollen samples, reference material collected in the field, and published pollen keys (Colinvaux et al., 1999; Hansen, 1990; Horn, 1986; Palacios-Chávez et al., 1991; Roubik and Moreno, 1991; Willard et al., 2004). *Cladium* was separated from other Cyperaceae pollen based on its size and the presence of an elongated tip (Faegri and Iverson, 1989). Forty-one samples were analyzed, with a minimum of 350 grains and spores counted for each, except for three (60, 74, and 164, which had totals of 202, 203, and 229 respectively). Slide labels were covered during counting to increase objectivity. Sixty-four pollen types were identified during the enumeration process. In order to determine the presence of *Zea* pollen, slides were scanned at 100× until *Zea* was encountered or three full slides had been scanned from a sample. *Zea* pollen was differentiated from other large Poaceae pollen grains based on size and long axis/pore ratio (Whitehead and Langham, 1965). Long axis measurements ranged from 60 to 91.5 μm ($\bar{x} = 69.7$ μm) and long axis/pore ratios ranged from 4.50 to 7.60 ($\bar{x} = 5.9$). It is unlikely that these grains represent wild *Zea* (teosinte), as the study area is well outside its known range (Doebley, 1990).

4. Results

The AMS radiocarbon age determinations show the core spans the period from ~10,300 to present (Table 1; Fig. 2). For the purpose of discussion, the pollen diagram has been subjectively divided into 6 zones

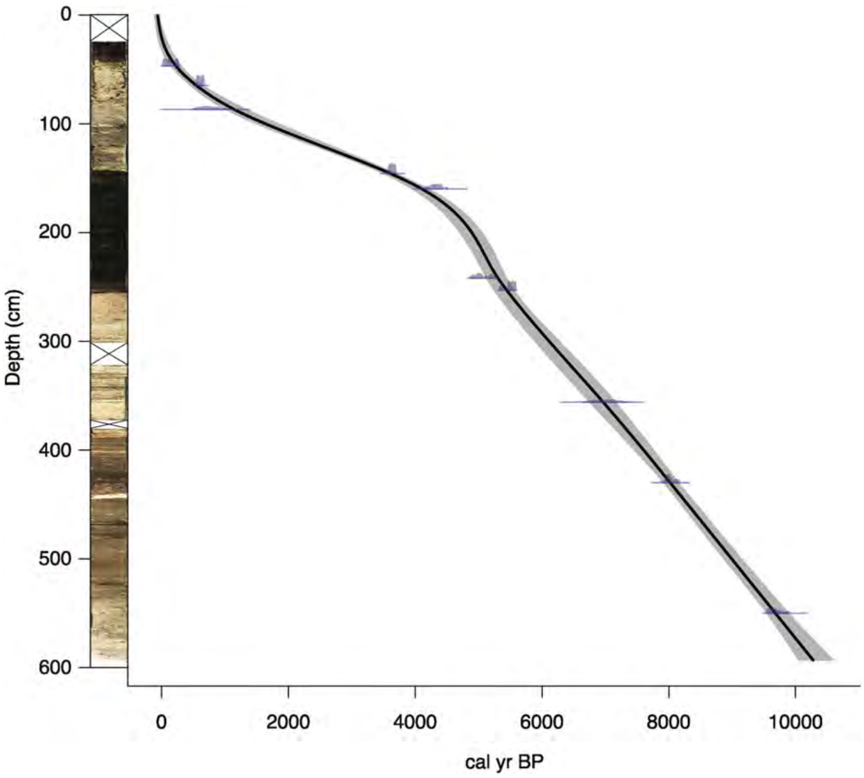

Fig. 2. Digital image of core stratigraphy shown with age-depth model for Lago Paixban. Missing core sections are indicated with a black X. Shading represents 95% confidence interval.

based on visible changes in the core stratigraphy and coeval shifts in proxy data (Fig. 3). Pollen types are plotted as % terrestrial pollen and spores, except for local marsh taxa which are plotted as % total pollen and spores (Figs. 4 and 5).

4.1. Zone 6 (5.94–5.36 m; 10,300–9490 BP)

Zone 6 includes the basal sediment and is comprised of homogenous, heavy inorganic clays with gravel sized peds. Magnetic susceptibility, bulk density and non-carbonate inorganic (alumino-silicate) values are at their highest at the base of the core and drop dramatically through the zone. The decline in magnetic susceptibility and density correspond to a rise in organic content up-core through zone 6 from 8% to 19%. Values of $\delta^{13}C_{SOM}$ average −27.18‰ in the basal sediment. No pollen or spores are preserved in the lower section of zone 6; scarce degraded pollen grains were present at 5.65 m.

4.2. Zone 5 (5.36–4.05 m; 9490–7675 BP)

The lower boundary of zone 5 corresponds to a change from heavy inorganic clay in zone 6 to less dense, more organic homogenous clay. The presence of abundant, well-preserved pollen begins at 5.08 m around 9100 BP, though very scarce degraded pollen grains were found in samples below this horizon. The pollen array in zone 5 is dominated by the Urticales group. Melastomataceae/Combretaceae (M–C) pollen is essentially absent (save for one grain at 4.97 m) until 4.43 m, above which it steadily increases in abundance. Cyperaceae pollen is consistently present at 5–10%. *Nymphaea* pollen is relatively abundant at the basal pollen level at ~10% after which it decreases to relatively low, yet persistent, values for the rest of zone 5. The homogenous clay of zone 5 is interrupted by a distinct band of $CaCO_3$ from 4.45–4.43 m. The $\delta^{13}C$ values become less negative in zone 5, with the least negative $\delta^{13}C_{SOM}$ values (−17.41‰) for the entire core at 4.48 m (8270 BP). C:N of organic carbon show a shift toward increased values in zone 5. Urticales pollen decreases and extra-local/savanna pollen types are found in low abundances throughout zone 5. Pollen from more rare arboreal taxa types is found in its greatest abundance in this zone (Fig. 5).

4.3. Zone 4 (4.05–2.54 m; 7675–5460 BP)

The transition to zone 4 is marked by a clear lithological change from inorganic clay to a bedded calcium carbonate marl unit. The calcium carbonate includes organic rich horizons and abundant gastropod shells. Unfortunately, a 9 cm gap from 3.71–3.79 m makes it difficult to date precisely the rise in $CaCO_3$ above 3.71 m. We set the zone boundary at 4.04 m where the initial increase in $CaCO_3$ and consistent bedding first occur. At 3.70 m the sediment is composed of ~50% $CaCO_3$, and remains so through the remainder of zone 4. The sediment is comprised of shell hash, with no visible banding from around 2.80 to 2.50. Magnetic susceptibility values and non-carbonate inorganic content exhibit a steady decline through zone 4, while bulk density is higher throughout the zone than above or below it. The physical characteristics of the sediment in zone 4 are generally similar to Holocene sections of lake sediment from shallow to medium water depth reported from various lakes in Peten (Curtis et al., 1998; Hillesheim et al., 2005; Mueller et al., 2009; Wahl et al., 2006).

The pollen percentages are relatively stable through this zone. Poaceae and M–C pollen both increase, and the Urticales group is the dominant type. Aquatic pollen percentages are relatively low. Pollen from rare arboreal taxa decreases in abundance, but remains consistently present in zone 4. $\delta^{13}C_{SOM}$ decreases from the relatively heavy values of zone 5 at 3.55 m. The C:N ratio shows little variability, averaging ~20 for the entire zone.

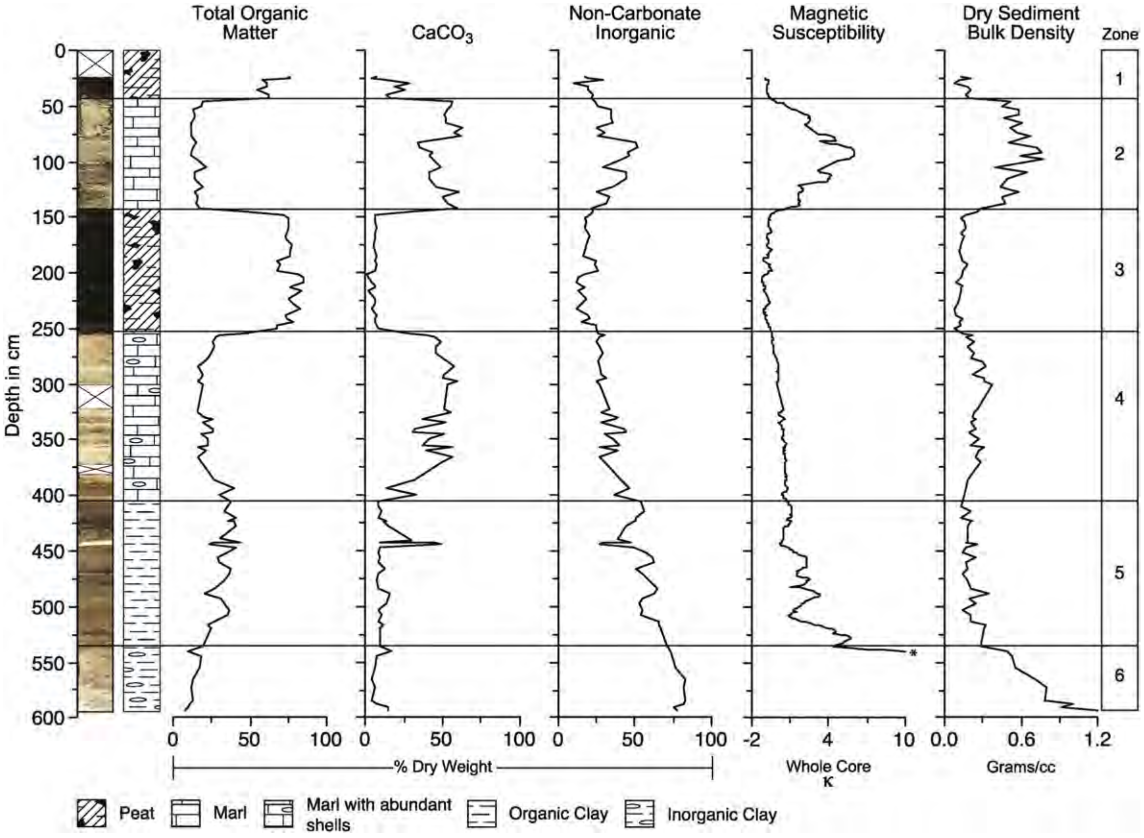

Fig. 3. Digital image of core stratigraphy and schematic lithology shown with total organic matter, $CaCO_3$, non-carbonate inorganic, magnetic susceptibility and dry sediment bulk density. The core has been divided into five zones based on distinct stratigraphic and compositional changes. *Magnetic susceptibility values rise to a value of 22.35 at the base of the core.

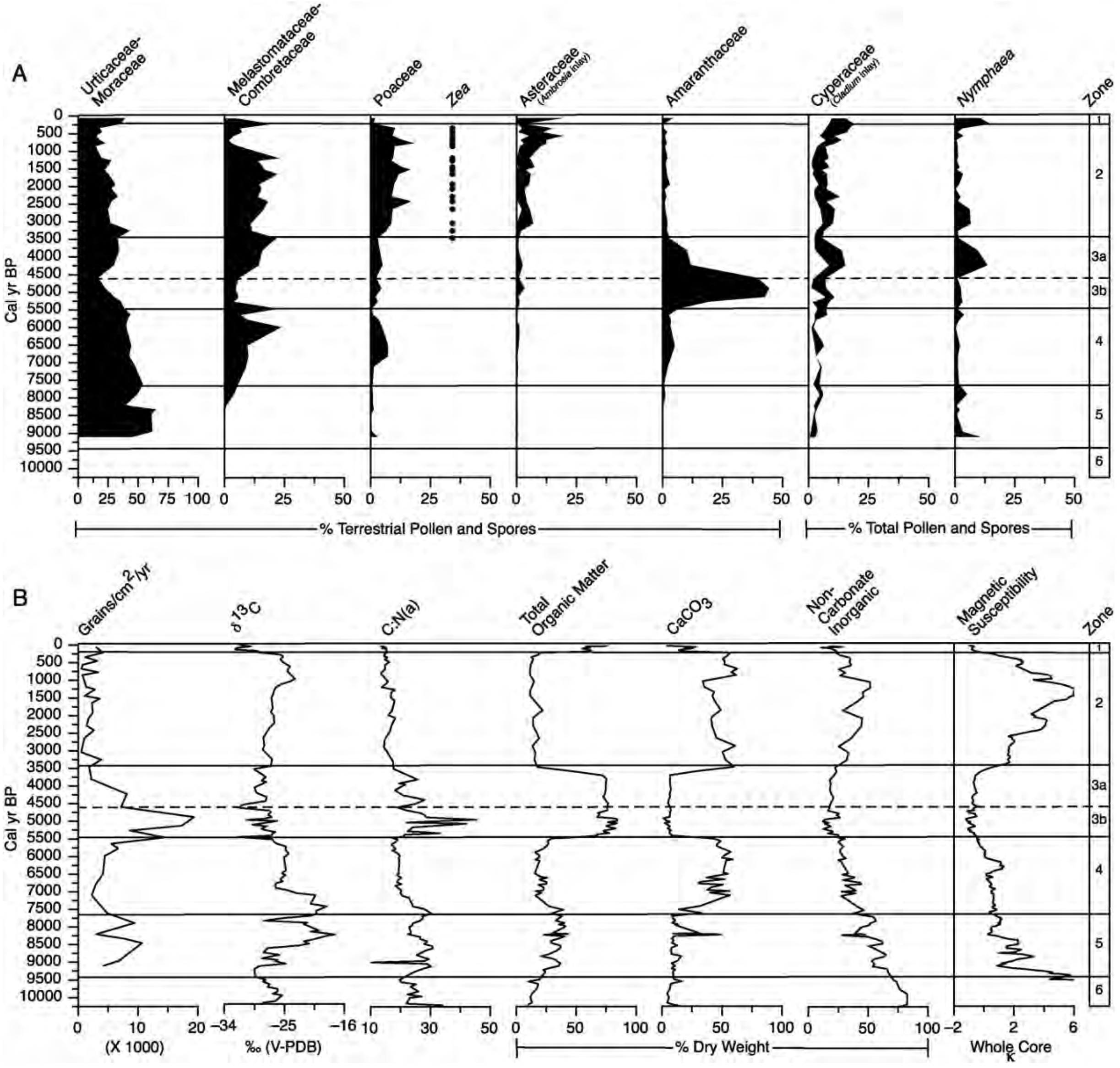

Fig. 4. A: Diagram showing percent abundances of selected pollen types. Circles indicate *Zea* pollen found during low power scans. Note x-axis scale changes in pollen data. B: Pollen influx, $\delta^{13}C_{SOM}$, elemental, compositional, and magnetic susceptibility results plotted against time.

4.4. Zone 3 (2.54–1.41 m; 5460–3420 BP)

Zone 3 is composed of an ~1-m thick peat unit. The transition between zones 3 and 4 is abrupt, marked by a dark organic-rich band. The high organic content of zone 3 sediment is evident in the LOI data, where total organic matter increases by more than 27% in just 6 cm. The average TOM content increases from 23.1% in zone 4 to 72.4% in zone 3. The zone 4/3 boundary is bracketed by two radiocarbon determinations taken 11 cm apart. Results show a sedimentation rate of 0.22 mm/year between the two sample points, which is more than 60% lower than that of the rest of the core. Thus, the distinct stratigraphic change may represent an unconformity, albeit a short-lived one.

Values for bulk density, non-carbonate inorganic, $CaCO_3$, and magnetic susceptibility are all relatively low in zone 3. A clay layer between 1.99 and 1.90 m is also reflected in the LOI data. Pollen concentrations are consistently higher through zone 3 than anywhere else in the core. $\delta^{13}C_{SOM}$ values remain relatively light throughout the zone, showing little variability.

We have divided zone 3 into sub-zones "a" and "b" based on changes in the pollen frequencies and peat composition. Zone 3b (2.54–1.80; 5460–4590 BP) consists of a fine-grained sapric peat with a distinct absence of macrofossils. Amaranthaceae pollen begins to increase at the base of zone 3 and reaches a peak value of 40% in the upper portion of the zone 3b (Fig. 4). The peak is pronounced from 2.24 to 1.80 m (5130–4590 BP), and coincides with the clay layer mentioned above. C:N and Amaranthaceae percentages diverge from otherwise complacent signals, which rise significantly to the highest values of the record. Pollen concentrations also reach their highest values coincident with high Amaranthaceae pollen. Urticales pollen makes an initial decline beginning around 5200 BP and M–C pollen shows an overall decrease across zone 3b.

Zone 3a (1.80–1.41; 4590–3420 BP) is composed of a coarser, hemic/sapric peat, with slightly higher clay content than zone 3b. The boundary between zones 3b and 3a is also marked a shift in local herbaceous taxa. *Nymphaea* and Cyperaceae percentages rise abruptly to 15% and 13% respectively, while the Amaranthaceae percentages dramatically decrease. Arboreal pollen percentages also change; Urticales percentages decrease around 13% compared to zones 3b and 4, and M–C pollen increases 7% over zone 3b abundances. Peaks of *Cecropia* and Mimosoideae pollen bracket the transition between zones 3a and 3b.

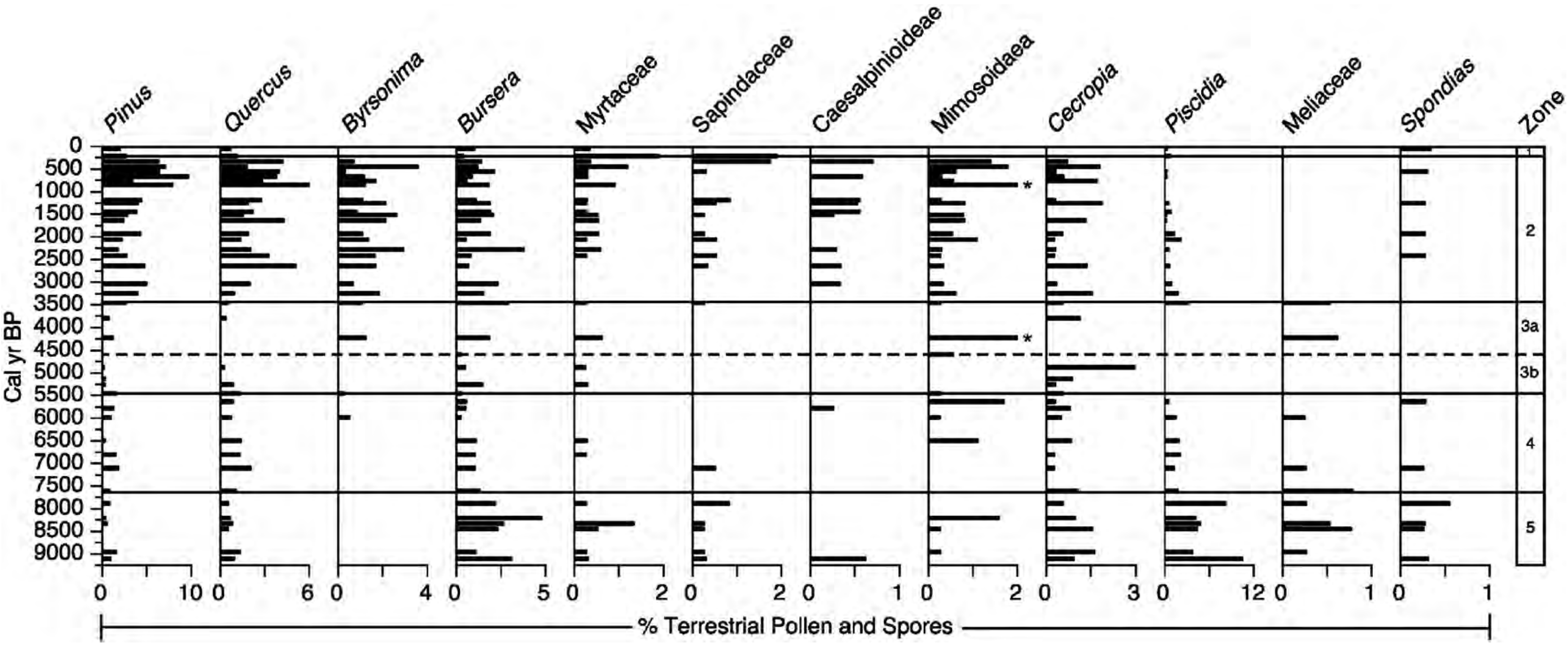

Fig. 5. Pollen percentage diagram of extra-local and rare/less common forest pollen types from the Lago Paixban sediment core. Note x-axis scale changes. *Mimosoideae percentages reach 14 and 15 on these two levels.

C:N ratios decrease in zone 3a relative to 3b, returning to values similar to those seen in zone 4.

4.5. Zone 2 (1.41–0.46 m; 3420–210 BP)

The peat that comprises zone 3 ends abruptly, marking the transition to zone 2. Organic matter decreases from 47% to 17% over 3 cm, while $CaCO_3$ and clay content increase dramatically. Zone 2 is a distinct horizon that consists of clay marl. The marl of zone 2 differs significantly from that of zone 4 in that there is no banding and there are gravel-sized peds. Magnetic susceptibility values increase to the highest levels since the lower part of zone 5, when the basin began filling in. Peaks in non-carbonate inorganic (clay) content, magnetic susceptibility, and bulk density covary in zone 2.

The Urticales type pollen percentages decrease throughout zone 2. Urticales begins a steady decline starting around 3250 BP that persists through the end of the zone. M–C pollen percentages also decline and remain low from ~1190–340 BP. *Zea* pollen is present in, and limited to, zone 2 and was not encountered above 54 cm (340 BP). Zone 2 shows a clear increase in extra-local pollen and some rare arboreal types (*Bursera*, Myrtaceae, Caesalpinioideae, and, to a lesser degree, Sapindaceae). Other forest taxa (*Piscidia*, Meliaceae, and *Spondias*) decrease or disappear altogether. *Nymphaea* pollen percentages are relatively low through zone 2. Cyperaceae pollen begins to increase in abundance near the top of the zone. Carbon isotope ratios are less negative in zone 2 than zones 1 and 3, and C:N ratios have an average value of 15.76.

4.6. Zone 1 (0.46–0.23 m; 210 BP–present)

Zone 1, the uppermost section of the core, is a fibric peat that is similar (though coarser) in composition than the peat of zone 3. The boundary between zones 1 and 2 is as abrupt as the previous two zone boundaries; total organic matter content increases from 18 to 62% across 3 cm. $CaCO_3$, non-carbonate inorganic, magnetic susceptibility, and bulk density values all decrease in concert with the increase in organic matter. Pollen percentages continue to indicate an increase in forest cover. Urticales pollen increases while Poaceae drops to <2%. M–C decreases in abundance from the upper levels of zone 2, and Asteraceae pollen rises to ~14% at 30 cm. Extra-local and rare forest pollen types decrease to near zero values. C:N ratios remain relatively low and $\delta^{13}C_{SOM}$ values are the lightest of the dataset.

5. Discussion

The interpolated basal date of the Lago Paixban core is 10,300 BP. The lake's genesis likely resulted from a broader regional increase in effective moisture. Seismic reflection data from Lake Peten-Itza indicate rapid deepening between 11,100 and 10,200 BP as a result increased precipitation following the Younger-Dryas (Anselmetti et al., 2006). However, available moisture appears to have fluctuated significantly through this period with a more stable moist climate beginning around 10,350 BP (Hillesheim et al., 2005). Based on higher than modern forest taxa pollen percentages at Lakes Quexil and Salpeten, Leyden (1984) concludes that effective moisture was relatively high in the early Holocene.

The lack of microfossil preservation in the early Holocene suggests that Lago Paixban was an ephemeral lake from ~10,300–9200 BP, after which it deepened and became a permanent lake. The inorganic clay in zone 6 and the base of zone 5 is commonly found in early Holocene sediment lining depositional basins in the region (e.g., Lago Puerto Arturo, Wahl et al., 2006; Lake Peten Itza, Curtis et al., 1998; Lake Salpeten, Leyden, 1987; Lake Quexil, Vaughan et al., 1985). Lago Paixban began to hold water permanently around 9200 BP, as evidenced by the onset of well-preserved microfossils. The pollen percentages in zone 5 indicate that lowland tropical forest was established by this time. Pollen data from Lago Peten-Itza shows the presence of mesic forest taxa at 11,250 BP (Hillesheim et al., 2005); other Peten lakes also show tropical forests becoming established in the early Holocene (Curtis et al., 1998; Leyden, 1984, 2002). Many smaller lake basins on the Yucatan peninsula were dry or ephemeral in the early Holocene (Hodell et al., 1995; Leyden et al., 1998; Wahl et al., 2006). While this suggests an overall moisture deficit, pollen data from many sites, including Lago Paixban, show that lowland forests were established prior to perennially wet conditions in nascent lake basins, and that forest taxa were well established by 10,000 BP (Hodell et al., 2008; Leyden, 1984).

A distinct carbonate layer in Lago Paixban was deposited at ~8200 BP (4.44 cm) over a period of <100 years. This coincides with the 8.2 ka climate anomaly characterized by abrupt climate shifts around the North Atlantic (Alley and Ágústsdóttir, 2005). The trigger for the 8.2 ka climate anomaly is attributed to the catastrophic draining of glacial lakes Agassiz and Ojibway into the North Atlantic (Barber et al., 1999). In Greenland, the period from 8250 to 8110 BP was marked by decreased snow accumulation and lower winter temperatures, as shown by $\delta^{18}O$ values from the GISP2 ice core (Alley et al., 1997). Although evidence for the 8.2 ka event is primarily from high-latitude sites in and around the North Atlantic, there is some evidence for a low-latitude response. Gray scale values from the Cariaco Basin show increased trade wind intensity and a possible southward excursion of the ITCZ for a brief period centered around 8200 BP (Hughen et al., 1996). Increased $\delta^{18}O$ values from 8300 to 8000 BP recorded in stalagmite carbonate in Costa Rica have been interpreted to represent relatively dry conditions in Central America (Lachniet et al., 2004). In the Maya lowlands, Hillesheim et al. (2005) note a section of increased density in core material from Lake Peten-Itza around 8.2 ka BP, which they interpret as indicating a period of drier climate associated with the event.

The Lago Paixban carbonate layer may provide additional evidence that the Yucatan was drier ~8200 BP. During this time, forest taxa pollen percentages decrease and pollen is degraded and less concentrated than the rest of zone 5. The heaviest $\delta^{13}C$ values of the entire core (−17.41‰) date to 8270 BP, just prior to the deposition of the carbonate band (Fig. 3). Carbon isotope values from lacustrine sediment organic matter are often interpreted to represent input from local vegetation, with heavier values representing C_4 tropical grasses and other weedy taxa which are usually, but not necessarily, associated with agricultural activity (Lane et al., 2004, 2008; Wright et al., 2009). The Lago Paixban pollen diagram shows little change in grass pollen abundance at this time, though an increase in C_4 grasses would not necessarily be associated with a change in grass abundance. Heavier $\delta^{13}C$ values may, in part, be related to increased productivity associated with shallower water, which can lead to decreased pCO_2 and increased incorporation of carbon from HCO_3^- by aquatic organisms (Meyers and Lallier-Vergès, 1999).

A decrease in lake levels during the 8.2 ka event could have led to deposition of the carbonate band in the Lago Paixban core, either as a result of evaporative and/or biogenic precipitation of DIC. Lake desiccation may have resulted from decreased summer precipitation coupled with cooler/dryer winters driven by the cold fresh water lens in the North Atlantic. Increases in the cross equatorial sea surface temperature gradient amplify the North Atlantic High, leading to increased trade wind activity, increased upwelling off the coast of West Africa, cooler SSTs, and, ultimately, inhibited convective uplift over the western Atlantic and Caribbean. Although annual temperatures appear to have decreased slightly in the North Atlantic region (~1°°C; Alley and Ágústsdóttir, 2005) during the 8.2 ka event, they would have remained high enough to evaporate water from what would have been a broad, shallow lake in the Lago Paixban basin.

The evidence from zones 4 and 5 of the Lago Paixban core indicates the presence of an open water lake at the coring site during the early to mid-Holocene. The finely banded carbonate/organic deposits that characterize most of these zones are indicative of relatively deep

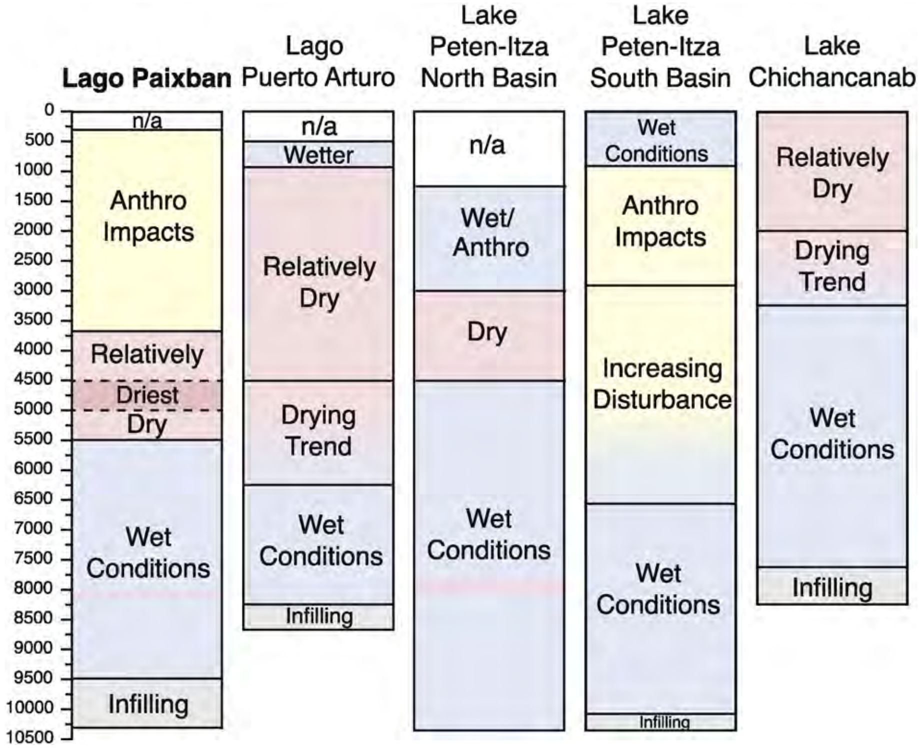

Fig. 6. Summary of interpretations from Lago Paixban shown with Holocene climate studies from the Yucatan Peninsula. Climate reconstructions from Lago Puerto Arturo are from Wahl et al., 2014, Lake Peten-Itza North Basin from Hillesheim et al., 2005 and Mueller et al., 2009, Lake Peten-Itza South Basin from Curtis et al., 1998, and Lake Chichancanab from Hodell et al., 1995.

water, similar to those found at Lake Coba during the same period (Leyden et al., 1998). Indirect evidence comes from reduced emergent aquatic pollen. In the modern environment, Cyperaceae species in the region typically grow in littoral, seasonally flooded zones. *Nymphaea* pollen undoubtedly represents *N. ampla*, which is limited to relatively shallow water (Lundell, 1937). The aquatic pollen spectra appear to indicate the coring site was not near the littoral zone. Decreased terrigenous input relative to zone 6 also suggests the presence of deeper water during this zone.

The data in zones 4 and 5 offer evidence that some low-lying depressions (*bajos*) may have been occupied by perennial lake systems during the mid-Holocene. This bears on early hypotheses that *bajo* systems of Peten once contained shallow lakes (Cooke, 1931; Ricketson and Ricketson, 1937), as well as more recent arguments that modern perennial herbaceous wetlands are remnants of more widespread wetlands or shallow lakes (Dunning et al., 2002; Hansen, 2012a; Hansen et al., 2002). It is difficult to speculate on the extent of open water in Lago Paixban during the early to mid-Holocene. Given the low relief of the surrounding terrain, only 3–4 m of standing water persisting through the dry season would have created a large shallow lake. A distinct ~4 m high escarpment along the southern edge of Lago Paixban appears to be a stranded shoreline, although time did not permit detailed mapping of the feature. A quantitative assessment of the amount of water required to inundate the *bajos* to produce a perennial lake is not possible at this point since there are currently no topographic maps or high resolution DEM data of the area.

Zones 4 and 5 correspond to the Holocene Thermal Maximum (HTM), a period of increased humidity in the circum-Caribbean region (Haug et al., 2001; Hodell et al., 1991; Dull, 2004; Lane and Horn, 2013). Lachniet et al. (2004) suggest a well-developed monsoonal circulation pattern was established around 7600 BP. Data from Lago Paixban and other lake sites on the Yucatan Peninsula imply maximum depth during the HTM (Fig. 6; Hillesheim et al., 2005; Hodell et al., 1995; Wahl et al., 2014). Increased humidity at this time likely resulted from a more northern position of the ITCZ during boreal summer coupled with attendant changes in North Atlantic pressure systems and SSTs.

The increase in Melastomataceae–Combretaceae (M–C) pollen in zone 4 can be interpreted to represent an expansion of riparian/*bajo* forest species (e.g., *Bucida buceras*, *Miconia ambigua*) (Bhattacharya et al., 2011; Lundell, 1937; Wiseman, 1978) and suggests increased humidity. A similar increase of M–C pollen, starting around 8000 BP is recorded at nearby Lago Puerto Arturo (Wahl et al., 2006). The Urticales pollen type, a multi-family group including members of the Moraceae and Urticaceae families that represent lowland forest taxa, was encountered at high levels (~50%) throughout zone 4, similar to early to mid-Holocene values from other Peten study sites (Islebe et al., 1996; Leyden, 2002; Mueller et al., 2009; Wahl et al., 2006). The initial rise in Poaceae and, to a lesser degree, Amaranthaceae pollen, at ~7000 BP likely represents the presence of weedy taxa in the littoral zone around the lake. Carbonate/organic rich banding through this zone suggests broad changes of water level, which, coupled with seasonal fluctuations, provide an environment favorable to weedy annual plant species. Weedy taxa growing in the littoral zone created by fluctuations of water level are readily observable in Peten today.

Multiple lines of evidence suggest the coring site was near the edge of a sawgrass marsh during zone 3. The overall higher pollen concentrations are likely driven by increased deposition of palynomorphs from plants in close proximity to the coring site. The presence of sapric peat indicates decomposition of coarse organics resulting from fluctuating water level and relatively frequent sub-aerial exposure. Modern pollen data from the littoral zone of sawgrass marshes in the Florida Everglades show similar pollen signatures with high percentages of Chenopodiaceae–Amaranthaceae pollen, likely representing *Amaranthus* spp. (Willard et al., 2001, 2004). An increase in C:N, indicating more terrestrial carbon input, from ~5100–4700 BP is coincident with the Amaranthaceae pollen peak and also suggests a near shore location at this time. Thus, zone 3b appears to represent a period when the core site was near the marsh edge in shallow fluctuating water with a short hydroperiod.

Zone 3a shows what appears to be a transition to somewhat deeper water. The hemic peat and wetland pollen abundances are comparable to modern, suggesting a similar environment from ~4500–3500 BP. Changes in M–C pollen abundances across zone 3 may support these interpretations, with lower percentages in zone 3b reflecting drier conditions and the subsequent rise in zone 3a reflecting moister conditions. This interpretation is complicated, however, by the nearly opposite trend of M–C pollen at nearby Lago Puerto Arturo during the same period (Wahl et al., 2006), raising the possibility that pollen abundances from this group represent more local and/or anthropogenic processes.

At present, it is unclear whether the transition to lower water levels in zone 3 was caused by a change in climate, hydroseral succession, or human activity. Climate change was likely important because the timing of this transition correlates with widespread evidence of changes in global atmospheric circulation (Thompson et al., 2006). Marine cores taken off the coast of West Africa show a sharp increase in terrigenous input at ~5500 BP marking the end of the early Holocene humid period (Adkins et al., 2006; deMenocal et al., 2000a, 2000b). Africa and the eastern Atlantic are the areas where cyclonic systems (easterly waves) that carry precipitation to the Yucatan Peninsula initially develop. The boundary conditions resulting in a drier climate near West Africa would have been conveyed downstream, as increased upwelling and cooler SSTs in the Tropical North Atlantic are associated with diminished precipitation in the Maya lowlands.

Regional records of Yucatan climate provide mixed signals for the period from 5500 to 4500 BP (Fig. 6). Increased carbonate deposition at Lago Peten-Itza suggests drier conditions setting in around 4500 BP (Mueller et al., 2009). While this is later than the onset of peat formation at Lago Paixban, it coincides with pollen, geochemical, and stratigraphic evidence for the very dry conditions recorded at Lago Paixban around 4750 BP. Stable isotope evidence from nearby Lago Puerto Arturo shows a transition from a humid mid-Holocene to drier conditions in the late Holocene between ~6250 and 4500 BP (Wahl et al., 2014). Records from the northern Yucatan on the whole show climatic stability through this period (Hodell et al., 1995; Leyden et al., 1996). Variability in timing and magnitude of changes may reflect the sensitivity of each site to climatic forcing. Changing conditions between 5500 and 4500 BP can be attributed to a southward migration of the ITCZ as a result of orbitally forced decreases in northern hemisphere summer insolation. Evidence of this process has been found in several paleoclimate reconstructions from the circum-Caribbean region (Haug et al., 2001; Hodell et al., 1991; Poore et al., 2003).

There is a possibility that human activity may have contributed to the changes evident in zone 3 of the Lago Paixban core. The earliest date for maize agriculture in the Maya lowlands is ~5340 BP at Cob Swamp in Belize (Pohl et al., 1996), corresponding to the zone 4/3 transition at Lago Paixban. At nearby Lago Puerto Arturo the earliest *Zea* pollen dates to ~4600 BP (Wahl et al., 2007a). Macroscopic charcoal evidence from Lagos Paixban and Puerto Arturo suggests an increase in anthropogenic burning between 5000 and 4500 BP (Anderson and Wahl, 2016). Further evidence of human activity in northern Peten at this time comes from recent ^{14}C dates from postholes carved in bedrock below packed earth floors in two separate locations at Nakbe, which show a consistent, pre-ceramic occupation between 4520 and 4330 BP (Hansen and Suyuc-Ley, 2014). Thus, the arrival of maize agriculturalists in the southern Maya lowlands appears to have been contemporaneous with clear shifts in the Lago Paixban proxy data. Although Lago Puerto Arturo is the only site in Peten that shows the occurrence of *Zea* pollen coinciding with mid-Holocene forest decreases, *Zea* pollen does not travel far from its parent plant which may account for the fact that it is rarely encountered in pollen studies (Raynor et al., 1972). This possibility is further diminished in pollen studies from large lakes with coring sites that are far offshore.

The Lago Paixban data appear to offer evidence of climatic drying from ~5500 to 4500 BP that ties in with records from the tropical north Atlantic showing large climatic shifts during this period. However, evidence is mounting for agricultural activity at this early date as well, and the question as to the primary cause of mid-Holocene forest decline in the Maya lowlands remains unanswered. Further work in small to mid-sized lakes in the region is needed to address this question.

Zone 2 in the Lago Paixban record coincides with the period of prehistoric Maya settlement in the Maya lowlands, from initial settlement in the late Archaic and Early Preclassic periods through abandonment at the end of the Postclassic period. *Zea* pollen throughout this zone indicates nearby agricultural activity. The rise in Poaceae and Asteraceae pollen likely represent a rise of weedy plants associated with ecological disturbance and local agriculture. The decrease in Urticales and M–C pollen around 3250 BP, followed by attenuated abundances through zone 2, likely reflect forest clearance.

Marked increases in magnetic susceptibility values and clay input throughout zone 2, indicating accelerated erosion of upland soil, is further evidence of human disturbance. The combination of decreased forest taxa pollen, increased erosion, and evidence of agriculture during the period of prehistoric settlement is a pattern of late Holocene environmental change that has been found at numerous sites across the southern Maya lowlands (Anselmetti et al., 2007; Beach et al., 2008, 2009; Islebe et al., 1996; Leyden, 2002; Wahl et al., 2007a). As such, it is becoming clear that this pattern is an ecological signature of prehistoric anthropogenic activity in the region.

Several Peten pollen records show either an initial or accelerated decline in forest taxa around 3500–3000 BP (Anselmetti et al., 2007; Dunning et al., 1998; Jones, 1991; Leyden, 2002; Leyden et al., 1998; Wahl et al., 2006). Maize pollen is present well before this date, showing up sporadically across lowland Mesoamerica between 7100 and 4500 BP (Beach et al., 2009; Pohl et al., 1996; Pope et al., 2001; Rue, 1987; Wahl et al., 2006), with many sites showing environmental change associated with the first appearance of *Zea* pollen. The implication is that early agriculturalists were causing vegetation change from 5000 to 4000 BP, although, as discussed above, it is difficult to separate human activity from climate forcing. However, paleoenvironmental records tend to align in showing increased ecological disturbance coupled with agricultural activity between 3500 and 3000 BP. A marker of this period is the more common presence of *Zea* pollen. Although there is evidence for drier conditions in the circum-Caribbean between 3500 and 3000 BP (Haug et al., 2001; Hodell et al., 1991; Wahl et al., 2014) the temporal covariance of *Zea* pollen, reduced forest cover, and increased erosion points to human activity as the primary driver of environmental change in the Maya lowlands at this time.

These findings are relevant to an ongoing archaeological debate about whether the Maya lowlands experienced a relatively long, isolated cultural development or whether they were settled relatively rapidly by agriculturalists coming in from elsewhere (Demarest and Foias, 1993; Hansen, 2005; Lohse, 2010). The pollen evidence presented here, and elsewhere, suggests that agricultural communities existed in the southern Maya lowlands for millennia prior to the earliest archaeological evidence of settlement in the region. This evidence, however, is not sufficient to resolve the question of whether or not groups from elsewhere in Mesoamerica migrated to the Maya lowlands between 3500 and 3000 BP, contributing to the dramatic, relatively time-synchronous environmental change.

The changes in sediment composition and pollen spectra suggest that human activity had a dramatic impact on the Lago Paixban basin during the period of prehispanic settlement. Increased clay input appears to have caused hydrological changes in the watershed. Increase silt and clay in runoff can result in the burial of peat by mineral deposits. Clay deposition decreases sediment permeability and can seal a basin, leading to a perched water table and the formation of a clay-rich carbonate marl. This process has been shown to occur in direct association with deforestation in Southeast Asian peat swamps (Andriesse, 1988). Recent work in Peten and Belizean swamps suggests a similar process led to silting in of wetlands during the period of Maya settlement (Beach et al., 2008; Dunning et al., 2002; Hansen et al., 2002). The aggradation of clay marl in zone 2 likely resulted from a combination of colluvial and pedogenic processes.

The relatively high percentages of *Pinus* (pine), *Quercus* (oak), and *Byrsonima* (nance) pollen in zone 2 of the Lago Paixban are difficult to interpret (Fig. 5). The species represented by these pollen types (*Pinus caribaea*, *Quercus oleoides*, and *Byrsonima crassifolia*) are associated with modern savannas in the Belize and southern Peten. Although there are currently no savannas or populations of pine or oak in northern Peten, the authors have encountered a relatively large stand of nance in Bajo Carrizal around 6 km south of El Mirador. Pollen from these taxa travels long distances, typically increasing in abundance in distal depositional settings when the filtering capability of lowland forest canopy is removed, and this process may be an explanation for the increased pollen percentages observed. Alternatively, opening of the forest during the period of prehispanic Maya settlement, particularly with the use of fire, may have promoted “savannization” in northern Peten. Given the likely economic importance of these taxa (pine and oak provide firewood and nance fruit is edible) increased abundances may also stem from prehispanic forest management practices. Interpretation of the pollen percentages for Myrtaceae and Sapindaceae families in zone 2 is difficult for similar reasons; taxa in these families are associated with both lowland forest and savanna/pine–oak forest (Domínguez-Vásquez and Islebe, 2008) and they also contain species that are economically useful. Thus, while increased pollen abundances of several taxa at this time could reflect taphonomic processes associated with regional vegetation change, elevated pollen percentages may also indicate expansion of savanna as a result of forest opening and/or resource management by the Maya.

The persistence, and apparent escalation of, ecological disturbance in the Postclassic period is notable because it provides the first evidence of human activity and environmental impacts in the Postclassic from this region. Low forest taxa pollen percentages and the presence of *Zea* pollen clearly indicate nearby settlement and agriculture. Paleoecological evidence of small Postclassic populations settling near bodies of water has been found elsewhere in the southern Maya lowlands (Brenner et al., 1990; Johnston et al., 2001), possibly refugee groups remaining in the lowlands after the region was largely abandoned. Early European accounts from the area around Lago Paixban indicate several scattered settlements (e.g. San Felipe, Batcab, Paxban, Chuntuqui), including some with populations reaching 350 people (Avendano y Loyola, 1987; Scholes and Roys, 1968; Villagutierre Soto-Mayor, 1983).

The transition to zone 1 in the Lago Paixban core marks a depopulation of the area and cessation of human impacts. Following the last appearance of *Zea* pollen around ~340 BP, weedy taxa pollen decreases sharply. The timing of this event coincides with the beginning of Spanish conquest in the southern Maya lowlands (Jones, 1998) and likely reflects demographic shifts associated with European contact. Archaeological work near Lago Paixban is needed to corroborate the local settlement history indicated in this study.

The remarkably rapid reforestation of the southern Maya lowlands following population decline, after millennia of anthropogenic pressures, has been noted elsewhere in Peten (Brenner et al., 1990; Mueller et al., 2010; Wahl et al., 2006, 2013). Although species composition was undoubtedly affected during the period of prehistoric disturbance, the fast recovery and modern diversity indicate a level of resiliency not commonly attributed to tropical ecosystems. Within the Lago Paixban basin, the rise in Cyperaceae and *Nymphaea* pollen, coupled with the deposition of fibric peat, suggest a sawgrass marsh was established shortly after the area was abandoned. Studies in the Everglades show that sawgrass marshes are quick to recover once external pressures have ceased (Bernhardt et al., 2004) and the results from this study support those findings.

6. Conclusions

The sediment cores from Lago Paixban, a large wetland in northern Guatemala, reveal a depositional sequence that provides a paleoenvironmental record extending to the early Holocene. Fossil pollen indicates that closed canopy tropical forests were established prior to the perennially wet conditions in the wetland. Sedimentological and physical property data suggest the presence of an open-water lake at the site during the Holocene Thermal Maximum. A gradual decrease in water levels led to the onset of peat accumulation at the coring site around 5500 BP, culminating in a low water table and short hydroperiod around 4750 BP. The timing of this transition from lake to marsh is coeval with evidence from the circum-Caribbean and tropical North Atlantic that indicates the onset of a drier climate following the Holocene Thermal Maximum.

Evidence for human activity and nearby maize agriculture first appears around 3300 BP. This is concordant with previous paleoecological results from the Mirador–Calakmul Basin region and elsewhere in the southern Maya lowlands that show a rapid expansion of agriculturalists and widespread use of *Zea* between 3500 and 3000 BP. The period of prehispanic Maya settlement near Lago Paixban is marked by increased terrigenous input, ecological disturbance, and the intermittent presence of *Zea* pollen. The Lago Paixban data suggest extensive, but localized, occupation dating from the late Archaic to the Proto-Historic/Historic periods.

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