



Paleoecology of mangroves along the Sibun River, Belize

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ABSTRACT

This study examines a sediment core (SR-63) from a mangrove ecosystem along the Sibun River in Belize, which is subject to both changes in sea-level and in the characteristics of the river's drainage basin. Radiocarbon dates from the core show a decreased sedimentation rate from ~6 ka to 1 cal ka BP and a marked change in lithology from primarily mangrove peat to fluvial-derived material at ~2.5 cal ka BP. Changes in the sedimentation rates observed in mangrove ecosystems offshore have previously been attributed to changes in relative sea-level and the rate of sea-level rise. Pollen analyses show a decreased abundance of *Rhizophora* (red mangrove) pollen and an increased abundance of *Avicennia* (black mangrove) pollen and non-mangrove pollen coeval with the decreased sedimentation rates. Elemental ratios ($[N:C]_a$) and stable isotope analyses ($\delta^{15}N$ and $\delta^{13}C$) show that changes in the composition of the organic material are also coeval with the change in lithology. The decrease in sedimentation rate at the site of core SR-63 and at offshore sites supports the idea that regional changes in hydrology occurred during the Holocene in Belize, influencing both mainland and offshore mangrove ecosystems.

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Introduction

Mangrove ecosystem research has shown the importance of this dynamic habitat as a food supply for biological production (e.g. Lalli and Parsons, 1993) and as a protective barrier against erosion during storm or flood events (e.g. Danielsen et al., 2005; Kathiresan and Rajendran, 2005). Mangroves are highly adaptive plants tolerant of extreme environmental conditions such as high salinity, anoxia, and constant water inundation (Vannucci, 2001). This adaptability has allowed mangroves to withstand environmental change throughout the Holocene (Monacci et al., 2009). Mangrove ecosystems present along coastlines are subject to changes in the marine environment (e.g. sea-level change and salinity) and climatic changes (e.g. changes in precipitation) (Alongi, 2002). Studies throughout Central and South America have shown that sea-level has risen throughout the Holocene (e.g. Fairbanks, 1989; Angulo and Lessa, 1997; Gischler, 2003). Published sea-level curves incorporate data from mangrove peat and Elkhorn Coral (e.g. Lighty et al., 1978; Toscano and Macintyre, 2003). Analyses of paleoecological changes in mangrove ecosystems with respect to Holocene sea-level changes have been conducted on the offshore, low-lying mangrove islands of Twin Cays (Wooller et al.,

2004, 2007) Turneffe Atoll (Wooller et al., 2009), and Spanish Lookout Cay (Monacci et al., 2009). Previous paleoenvironmental studies on the mainland have largely focused on lacustrine environments (e.g. Jacob and Hallmark, 1996). Like some of the paleoecological records from offshore, some mainland paleolimnological studies in Central America have also indicated the influence of changes in sea-level, especially when lakes are connected to an aquifer (e.g. Curtis et al., 1998; Hodell et al., 2007). For example, lacustrine deposition only began at Lake Peten-Itza in Peten, Guatemala after 8000 calibrated years before present (cal yr BP), which Curtis et al. (1998) assumed was related to rising sea-level in the early Holocene. Likewise, Hodell et al. (2007) also observed that the groundwater at Punta Laguna in Quintana Roo, Mexico is controlled by both precipitation and sea-level. These paleoenvironmental studies also subsequently related Holocene environmental changes to observed changes in local Maya culture (e.g. Leyden, 1987; Hodell et al., 1995; Curtis et al., 1996; Wahl et al., 2006).

The primary goal of this research is to determine whether environmental change, such as the effects of changes in sea-level seen in offshore mangrove ecosystems (Wooller et al., 2004, 2007, 2009; Monacci et al., 2009), can be related to changes in the mainland mangrove ecosystem along the banks of the Sibun River (SR), Belize. We also aim to determine whether changes in the mangrove paleoecology and fluvial dynamics of the SR correspond to broad climatic changes recorded in upland lake environments. To achieve

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this, we analyzed multiple proxies of past environmental conditions preserved in a sediment core taken from a riverine mangrove habitat in Belize. Radiocarbon measurements are used to determine the timing of observed changes in the core and to correlate these changes with other research. Dry bulk density (DBD), magnetic susceptibility (MS), and loss on ignition analyses of the sediments are used to examine changes in the stratigraphic characteristics of mangrove peat and sediments. Pollen analyses of the core are used to illustrate vegetation dynamics. Finally, atomic nitrogen:carbon ($[N:C]_a$) ratios of the sediments are combined with stable isotope analyses ($\delta^{15}N$ and $\delta^{13}C$) to determine the likely source of deposited organic matter at the study site.

Study site

This study took place along the SR in central Belize (Figure 1), which is located in the transition zone from the tropics to subtropics and experiences a dry season from February to May (Meerman and Sabido, 2001). Mean annual rainfall in Belmopan (Figure 1) is ~2000 mm and the region experiences flooding in the rainy season between July and December (Piaskowski et al., 2006). A mid-summer drought often occurs in mid-July to early August. Northern Belize is located on the tectonically stable Yucatán platform and is underlain by Tertiary limestone, while the mountainous, southern region is composed of Paleozoic sediments and Cretaceous limestone (Gischler and Hudson, 1998). The Maya Mountains (960 m asl) serve as the headwaters for the SR that flows northeast from the Sibun Gorge through a riparian forest, karst limestone belt, coastal marsh, and mangroves to terminate in the Caribbean Sea (Achee et al., 2006). The SR drains an area of 970 km², with discharge ranging from 35 to 65 m³ s⁻¹ (BERDS, 2007).

The location of our coring site (SR-63) along the SR, (17° 25' 13.9"N, 88° 16' 19.7"W, Figure 1), is approximately 4 km inland of the mouth of the river and 20 m from the river edge. The SR watershed has several

vegetation types: tropical evergreen seasonal mixed needle forest (e.g. *Pinus* sp.), broadleaf forest (e.g. *Quercus* sp.), mangroves (e.g. *Rhizophora mangle*), and agricultural (e.g. Poaceae, *Citrus* sp.) (Meerman and Sabido, 2001). The canopy height at the coring site is approximately 30 m and is primarily composed of *Rhizophora mangle* L. (red mangrove) with interspersed *Avicennia germinans* (L.) Stearn. (black mangrove), *Laguncularia racemosa* (L.) C.F. Gaertn. (white mangrove), and *Arcaea* sp. (palm). Given this species composition this vegetation type could be described as a transition zone on actual land, in contrast to a solid *R. mangle* forest that can typify habitats closer to the water's edge. No pine savannah or broadleaf forest (including Oak) was present in the observable vicinity. At the time core SR-63 was taken in December 2005, Belize City (~10 km north) had a flood tide and the SR had a salinity of 0.5‰; though, SR-63 is periodically exposed to more saline water, especially during storm events. Coastal Belize typically experiences a semidiurnal micro-tide (15–30 cm) (Kjerfve et al., 1982).

Methods

Sampling

An Eijkelkamp Russian peat corer was used to obtain an 8.5 m long core (SR-63) that is composed of mangrove peat and fluvial sediments. Core sections were wrapped in plastic, and kept in coolers at the Spanish Bay Conservation and Research Center on Spanish Lookout Cay. The sections were then transferred to the Water and Environmental Research Center at the University of Alaska Fairbanks (UAF), where they are archived at ~4°C. During coring, layers with lesser or greater resistance and visual color transitions were noted in the lithology (Figure 2).

Core chronology

Accelerator mass spectrometry (AMS) radiocarbon measurements (¹⁴C) were made on wood pieces taken from various core depths (Table 1), macroscopic *R. mangle* roots, and bulk peat at the National Ocean Sciences Accelerator Mass Spectrometry Facility (NOSAMS) at Woods Hole Oceanographic Institute (WHOI). All ¹⁴C yr BP dates were calibrated using CALIB 5.02 according to Reimer et al. (2004) and rounded to the nearest decade (Table 1). The sedimentation rate increases to 0.56 cm yr⁻¹ between ~1 cal ka BP and the present. Unfortunately, no wood pieces or subfossil leaves were found in the area of low sedimentation (~6 to 1 cal ka BP) in core SR-63. The two radiocarbon dates reported from this area were analyzed using macroscopic roots (Table 1), which are less than optimal for dating compared with leaf fragments (Wooller et al., 2007). However, any error in dates associated with roots would have resulted in relatively young ages, as roots from living trees grow down into peat. This scenario would produce a significant decrease in the sedimentation; however, such errors would bring the change in the lithology of the core at ~2.5 cal ka BP closer in age to the subsequent change in sedimentation rates.

Sediment characteristics

Several geological and stratigraphic analyses were performed on bulk peat samples from core SR-63. A 2 cm³ sample was taken every 10 cm throughout SR-63. MS (SI) was measured on the sample using a Bartington MS2 sensor. DBD (g cm⁻³) was determined by weighing the sample, freeze drying, and reweighing the sample. Sequential LOI measurements were conducted following standard procedures (e.g. Dean, 1974; Heiri et al., 2001) to estimate organic carbon content (LOI, %), carbonate content (CaCO₃, %), and remaining material (Residue, %).

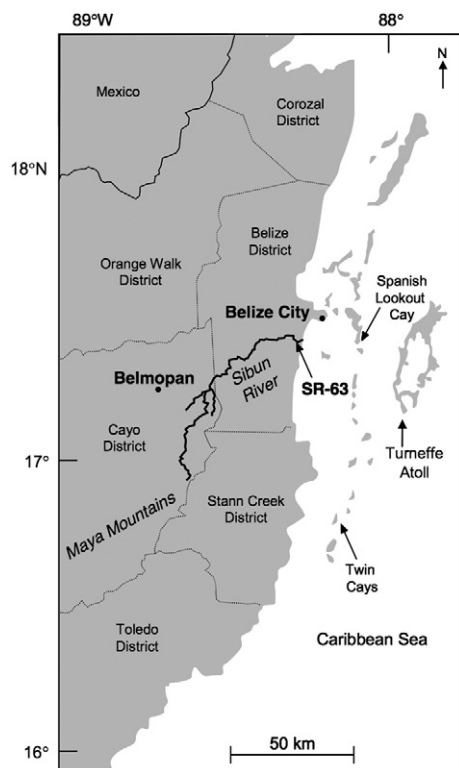


Figure 1. Map of Belize, Central America showing core site SR-63 along the Sibun River.

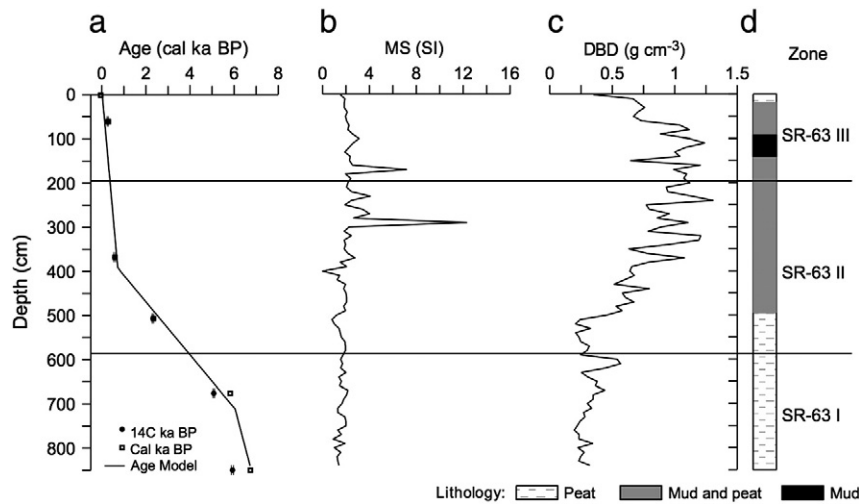


Figure 2. a) Radiocarbon ages (^{14}C yr BP), calibrated ages (cal yr BP), and age model (using Eqs. (1)–(3)). Error bars were calculated by NOSAMS at WHOI. b) Magnetic susceptibility (MS, SI units). c) Dry bulk density (DBD, g cm^{-3}). d) Lithology based on notes taken in the field during coring.

Pollen analysis

All pollen preparation and analytical procedures were performed in the Paleontology Laboratory in the Department of Geology and Geophysics at UAF. At least every 20 cm down core, a 1 cm^3 sample was prepared using the Faegri and Iversen (1989) standard method. One tablet of exotic *Lycopodium* spores ($18,583 \pm 762$ spores tablet $^{-1}$) was added prior to processing in order to calculate pollen concentrations (grains cm^{-3}) and accumulation rate (grains $\text{cm}^{-2}\text{ yr}^{-1}$). Samples were mounted in glycerin gelatin medium; a minimum of 300 pollen grains were identified for each pollen sample, with a few exceptions that were counted to ≥ 100 due to low pollen concentrations. Pollen grains were identified using published pollen morphological descriptions (e.g. Palacios-Chavez et al., 1991). Family designations are stated when greater taxonomic resolution could not be achieved. Pollen data are reported as percentages of the total pollen sum, which excludes fern and fungal spores and foraminifera. Pollen diagrams were created and zoned using TILIA (Grimm, 2004).

Elemental and stable isotope analysis: %N, %C, $\delta^{15}\text{N}$, $\delta^{13}\text{C}$

Bulk peat subsamples, at $\sim 10\text{ cm}$ intervals, were freeze-dried, ground, and acidified with 2N HCl to remove carbonate in preparation for elemental and stable isotopic analyses of organic material (OM). Stable isotope analyses were performed at the Alaska Stable Isotope Facility (ASIF) at UAF and reported in standard delta (δ) notation in units of permil (‰). The elemental compositions (%C and %N, wt.%) and stable isotope ratios ($\delta^{15}\text{N}$ and $\delta^{13}\text{C}$, ‰) were measured using a Costech Instruments Elemental Analyzer (EA) coupled with a ConFlo III and a Thermo Electron Delta V Plus Isotope Ratio Mass Spectrometer (IRMS). $\delta^{15}\text{N}$ is reported relative to atmospheric nitrogen (atm) and $\delta^{13}\text{C}$ is reported relative to Vienna Pee Dee Belemnite (VPDB). Peptone was

used as a reference standard to determine analytical precision: 0.9% (wt.%N), 2.8% (wt.%C), 0.5‰ ($\delta^{15}\text{N}$), and 0.3‰ ($\delta^{13}\text{C}$).

Results

All data from core SR-63 are presented within the context of three pollen zones: zone SR-63 I (585–850 cm), zone SR-63 II (195–585 cm), and zone SR-63 III (0–195 cm).

These zones were established through a Constrained Incremental Sum of Squares (CONISS) analysis performed in TILIA using the pollen data.

Chronology

Table 1 presents the radiocarbon data (^{14}C yr BP) and their corresponding calibrated dates and ranges. Ages for all depths of SR-63 and sedimentation rates were interpolated using three linear equations. The bottom section of the core (710–850 cm) was fitted with a linear equation through the lower 2 dates:

$$\text{Depth}_{\text{cm}} = 0.56\text{Age}_{\text{cal yr BP}} - 10.94, R^2 = 0.84, n = 3 \quad (1)$$

yielding a sedimentation rate of 0.19 cm yr^{-1} . The calibrated dates shown in Figure 2a were extrapolated to estimate a basal date of $\sim 6.7\text{ cal ka BP}$ for SR-63.

The middle section of the core (400–700 cm) was fitted with a linear regression through the 3 dates between 360 and 680 cm, which resulted in the following equation:

$$\text{Depth}_{\text{cm}} = 0.06\text{Age}_{\text{cal yr BP}} + 349.00, R^2 = 0.98, n = 3 \quad (2)$$

yielding a sedimentation rate of 0.06 cm yr^{-1} .

The top section of the core (0–390 cm) was fitted with a linear equation assuming an age of -55 cal yr BP (Reimer et al., 2004) for depth 0–1 cm, and using the two underlying radiocarbon dates, yielding a linear equation:

$$\text{Depth}_{\text{cm}} = 0.19\text{Age}_{\text{cal yr BP}} - 437.34, R^2 = 1, n = 2 \quad (3)$$

and resulting in a sedimentation rate of 0.56 cm yr^{-1} . We chose to use three linear fits as seen in Monacci et al. (2009) rather than five linear fits as seen in Wooller et al. (2009) due to the general trend in decreased sedimentation between depths 400 and 700 cm.

Table 1

List of AMS radiocarbon dates and calibrated dates using Calib 5.02 (Reimer et al., 2004).

Depth (cm)	Type	^{14}C age (yr BP)	Cal age (cal yr BP)	Cal range (cal yr BP)	NOSAMS number
60–61	wood	265	290	159–422	OS-55,507
366–369	wood	580	590	542–635	OS-55,441
506–507	roots	2320	2340	2332–2352	OS-55,442
675–676	roots	5070	5820	5752–5894	OS-55,451
849–850	bulk peat	5920	6730	6676–6786	OS-54,384

Sediment characteristics

The lithology of core SR-63 is divided into two main parts. The bottom of the core (850–500 cm) is primarily composed of mangrove peat with some minor fluviually deposited sediment, while the top of the core (500–15 cm) is primarily fluvial sediment with interspersed peat (Figure 2d). There is a gray, mud/clay deposit from 150 to 100 cm with little visual evidence of peat. The uppermost 15 cm is composed of peat and leaf material.

Throughout SR-63, MS ranges from 0.0 to 12.3 SI Units (Figure 2b). Zone SR-63 I has relatively constant MS values throughout, with an average of 1.6 ± 0.3 . MS values remain <2.5 in zone SR-63 II until reaching a peak value of 12.3 at 290 cm. Above this peak, MS values vary between 2.0 and 4.0 until another significant peak of 7.2 is observed at 170 cm in zone SR-63 III. MS values are less than 2.5 for the remainder of the core.

DBD ranges from 0.20 to 1.31 g cm^{-3} (Figure 2c). An average value of $0.31 \pm 0.10 \text{ g cm}^{-3}$ in zone SR-63 I is greater than the DBD observed in mangrove peat with little to no allochthonous material ($<0.15 \text{ g cm}^{-3}$; Monacci et al., 2009), but zone SR-63 I is nevertheless the least dense. Throughout zone SR-63 II, DBD values steadily increase from a basal value of 0.3 g cm^{-3} to a maximum value of 1.31 g cm^{-3} . DBD generally decreases from 1.07 g cm^{-3} at 190 cm to 0.35 g cm^{-3} at the top of zone SR-63 III.

The LOI sequence from core SR-63 (Figure 3) correlates with changes in the lithology. LOI ranges from 6 to 67% with values less than 20% in the fluvial sediments (500–15 cm). A similar trend is observed in CaCO_3 and residue. CaCO_3 ranges from 2 to 15%, with values less than 10% in the fluvial section. Percent residue, remaining material at the end of the LOI sequence, ranges from 19 to 91% with the fluvial sediment showing greater than 70% of the fraction as neither organic material nor calcium carbonate. There are differences at the pollen zone boundaries, in addition to the marked lithological difference between the top and bottom of SR-63. Peaks are observed in LOI, CaCO_3 , and residue in zone SR-63 I at ~750 cm until the transition into zone SR-63 II. Another comparable peak is observed from ~560 cm, in SR-63 II, to immediately below the transition from peat-dominated to sediment-dominated layers at 500 cm.

Pollen analysis

Figure 4 illustrates pollen summaries and Figure 5 illustrates percentages of common genera. Pollen concentrations range from ~2000 to 30,000 grains cm^{-3} and pollen accumulation rates range from ~9000 to 190,000 grains $\text{cm}^{-2} \text{ yr}^{-1}$.

SR-63 I: 850–585 cm

Pollen zone SR-63 I is dominated by mangroves (70%, Figure 4). *R. mangle* is the primary species, with a mean of 50%. *A. germinans* is the only other mangrove species present in the core; no pollen from *L. racemosa* or *Conocarpus erectus* L. (buttonwood) is observed despite their prominence in Belize (Murray et al., 2003). *A. germinans* is least abundant in zone SR-63 I, accounting for less than 20% of the pollen sum, until a peak of $>30\%$ is reached between 660 and 630 cm. Pollen from other shrubs and trees (non-mangrove) are rare in SR-63 I, with a mean of 20% throughout the zone. *Myrsine* does not appear to be a significant genus at this site. It is seen throughout the core, but it never accounts for more than 2% of the pollen sum. Other than mangroves, *Pinus* and *Quercus* are the dominant plant types in SR-63 I, with means of 5% and 11%, respectively. Members of the Aracaceae family are present throughout the core in low levels $\leq 3\%$. In general, herbs and grasses are consistently present throughout the core, averaging 8%. The highest presence of herbs and grasses (15%) is observed in SR-63 I. This peak is attributed to high amounts of Amaranthaceae/Chenopodiaceae (up to 10%) and Poaceae (up to 11%). Foraminifera are only present in zone SR-63 I. They comprise 4% of the pollen sum at depth 840 cm. Ferns averaged 3% throughout the core and are most abundant (7%) at depth 780 cm. Fungal spores are present in most of the core, averaging 16%. Due to low pollen concentrations (<4000 grains cm^{-3}) and pollen accumulation rates ($<15,000$ grains $\text{cm}^{-2} \text{ yr}^{-1}$) until 735 cm, only 100 grains slide⁻¹ were counted from samples at the base of the core.

SR-63 II: 585–195 cm

Pollen zone SR-63 II has the lowest sum of mangroves with an average of 53% including the overall minimum value for the core of 27% at 480 cm. *R. mangle* percentages decrease significantly at the beginning of SR-63 II to 6% at 480 cm, but average 20% throughout the zone. Pollen from *A. germinans* increases and averages 33% in SR-63 II, with a significant peak from 390 to 330 cm. As expected given the decrease in mangrove pollen, the percentage of pollen from other shrubs and trees increases to an average of 39%, with the maximum value of the core observed at 480 cm. This peak is primarily due to the increase in *Pinus* pollen in this zone, which averaged 26%. *Quercus* percentages remain approximately constant and average 9% throughout SR-63 II. *Podocarpus* makes a small contribution (average 1%) to the pollen assemblage in this zone, but it is not found in intervals with high percentages of *A. germinans*. Herbs and grasses remain the same as for zone SR-63 I (8%), although greater inputs of Asteraceae (average 2%, e.g. *Matricaria*) are recorded, with maximum values of 5%

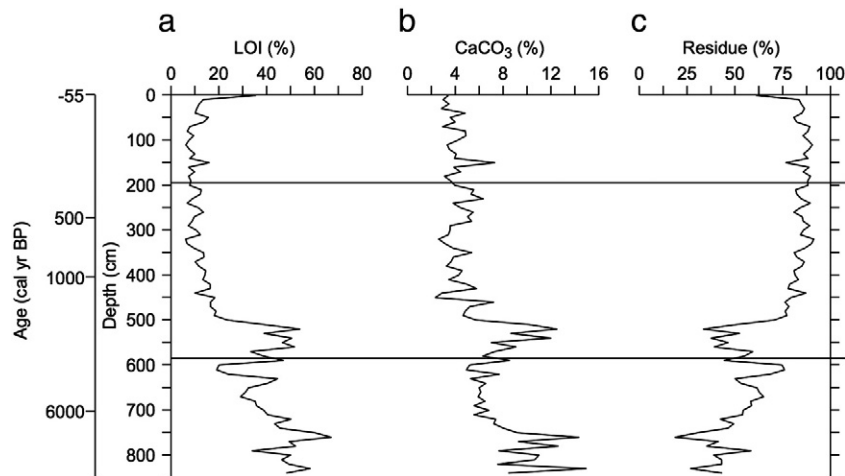


Figure 3. Plot of loss on ignition sequence: a) Loss on ignition (LOI, %). b) Calcium carbonate (CaCO_3 , %). c) Remaining material (Residue, %).

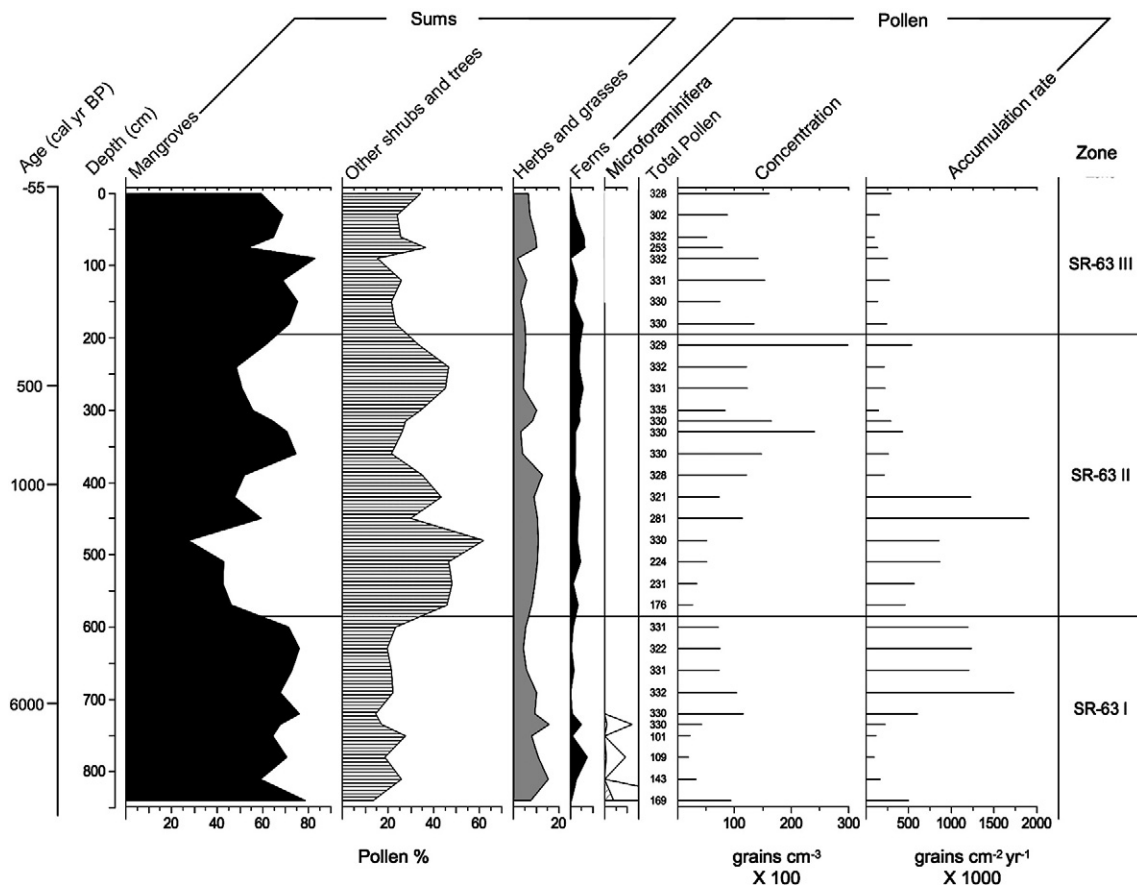


Figure 4. Summary pollen diagram showing vegetation groups, pollen concentration, pollen accumulation rate, and zones. Foraminifera percentages are illustrated with a double line: the hollow line is exaggerated by a factor of 10. Notches on the x axis represent 5% increments.

at 420 and 315 cm throughout SR-63 II. Fungal spores are prominent at 510 cm, 15% of the pollen sum. Pollen concentrations are low, 3000 grains cm^{-3} , at the base of SR-63 II and generally increase to the maximum value observed in the core, 30,000 grains cm^{-3} at 210 cm. Pollen accumulation rates also increase from the base of SR-63 II to a maximum value of 190,000 grains $\text{cm}^{-2} \text{yr}^{-1}$ at 450 cm and then decrease for the remainder of the core.

SR-63 III: 195–0 cm

The amounts of pollen from mangroves increase into pollen zone SR-63 III, while they return to an average of 68%, similar to SR-63 I. Pollen from *R. mangle* increases to an average of 27%, with a significant decrease (6%) at 120 cm and a peak zonal value of 55% at the top of the core. *A. germinans* pollen increases from 180 to 90 cm, where the maximum percentage of 73% is observed, but then decreases to 4% at the top of the core. Other shrubs and trees decrease to 26%, with a low value at 90 cm corresponding to peak abundance of *A. germinans*. *Pinus* and *Quercus* pollen both decrease to averages of 14% and 5%, respectively. *Podocarpus* averages 2%, with a maximum value of 4%. A maximum value of *Arecaceae* (3%) is recorded at 75 cm. Herbs and grasses increase to 10% between 90 and 75 cm, and then decrease to 7% to the top of the core. Pollen concentrations average 11,000 grains cm^{-3} in SR-63 III and pollen accumulation rates are the lowest in the core with an average of 19,000 grains $\text{cm}^{-2} \text{yr}^{-1}$.

Stable isotope analysis: $\delta^{15}\text{N}$ and $\delta^{13}\text{C}$

Stable isotope data and elemental ratios downcore are presented in Figure 6. $\delta^{15}\text{N}$ ranges from -2.7 to 3.0% and generally correlates

with the lithology with lower values in peat. Zone SR-63 I has the lowest $\delta^{15}\text{N}$ values with an increase of nearly 3‰ from the base of the core to the top of the zone at 590 cm. The values continue to increase to 2.9‰ in zone SR-63 II and then slightly decrease from 500 to 200 cm. In SR-63 III, the $\delta^{15}\text{N}$ values are relatively constant ($1.8 \pm 0.8\%$).

$\delta^{13}\text{C}$ ranges from -29.4 to -25.7% throughout the entire core, but averages $-27.1 \pm 0.3\%$ from 850 to 500 cm. More variation in $\delta^{13}\text{C}$ values are seen after the lithological change to greater fluvial sediment contributions at 500 cm in zone SR-63 II. There is a slight decrease in $\delta^{13}\text{C}$ to -28.3% until 340 cm, followed by an increase to -26.4% at 270 cm. The transition from zone SR-63 II into zone SR-63 III has the lowest $\delta^{13}\text{C}$ values (-29.4%) in the whole core, but then values increase nearly 4‰ to the highest $\delta^{13}\text{C}$ at 40 cm before decreasing again to -28.7% at the top of the core.

Atomic elemental ratios of nitrogen to carbon are shown in Figures 6 and 7. Following the suggestion of Goñi et al. (2003), we chose to express $[\text{N}:\text{C}]_a$ rather than $[\text{C}:\text{N}]_a$ due to the low nitrogen composition of these samples. $[\text{N}:\text{C}]_a$ values range from 0.01 to 0.09 mol:mol; however, values greater than 0.02 mol:mol were not observed in SR-63 I. At 400 cm in SR-63 II, $[\text{N}:\text{C}]_a$ values begin to increase until the top of the core. Two peaks are recorded, 0.07 mol:mol at 230 cm and 0.09 mol:mol at 140 cm. Figure 7 shows $[\text{N}:\text{C}]_a$ versus $\delta^{13}\text{C}$ values of core samples relative to possible sources of organic matter (OM). This approach has previously been used in other tropical, fluvial environments (e.g. Hedges et al., 1986; Goñi et al., 2006). Values from horizons below 500 cm depth are tightly clustered. The OM in these samples is most likely derived from C_3 vascular plants, primarily mangroves given the lithology. Intervals at depths above 500 cm in SR-63 II are more variable, but appear to

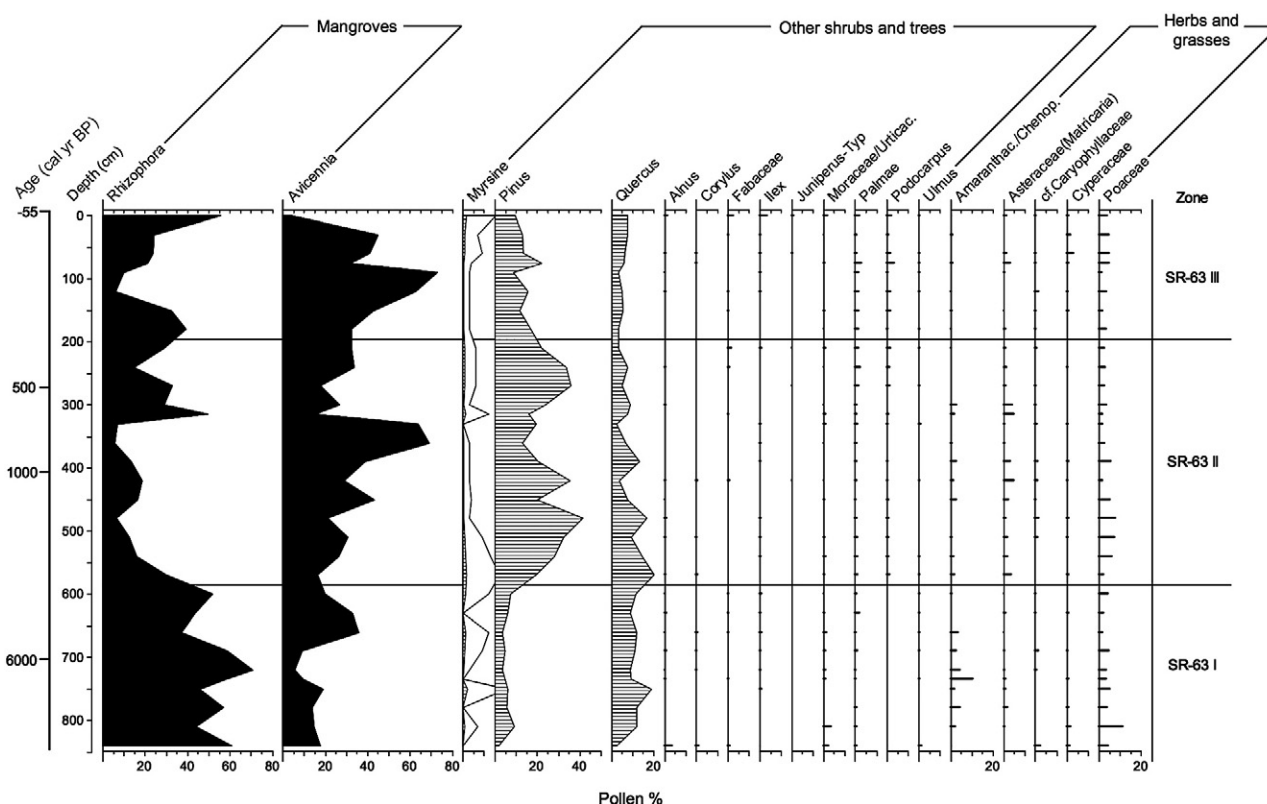


Figure 5. Percentage pollen diagram showing the most frequent pollen taxa. Myrsine percentages are illustrated with a double line: the hollow line is exaggerated by a factor of 10. Notches on the x axis represent 5% increments.

record a dominant C₃ source. SR-63 III shows the greatest variability in [N:C]_a and δ¹³C sources and may contain a greater portion of soil or algal OM.

Interpretation and discussion

Zone SR-63 I: 6780 to 3930 cal yr BP

Our primary goal was to determine whether environmental change, such as the effects of changes in sea-level seen in offshore mangrove ecosystems (Wooller et al., 2004, 2007, 2009; Monacci et al., 2009), can be related to changes in a mainland mangrove ecosystem, along the banks of the Sibun River (SR), Belize. The site of core SR-63 had a well-established mangrove ecosystem present during the mid-Holocene, which is evident from the peat that

comprised the basal section (850 to 500 cm) of the core and the high percentages of mangrove pollen in this interval. This was expected, because sea-level inundated other near coastal mainland sites at ~7 cal ka BP (e.g. Jacob and Hallmark, 1996), providing the slightly marine or brackish habitat needed to maintain typical mangrove ecosystems. By 7 cal ka BP, mangrove stands had been established for ~1 ka yr on mangrove islands offshore Belize, including Twin Cays (Wooller et al., 2004, 2007), Turneffe Atoll (Wooller et al., 2009) and Spanish Lookout Cay (Monacci et al., 2009). Likewise, lakes in Guatemala connected to an aquifer began to fill after 8 cal ka BP as a result of a rising sea-level (Curtis et al., 1998). Foraminifera present at the beginning of zone SR-63 I, also record the influence of marine water during this time.

The first decrease in the rate of sea-level rise from published sea-level curves began at about 7.7 cal ka BP (Toscano and Macintyre,

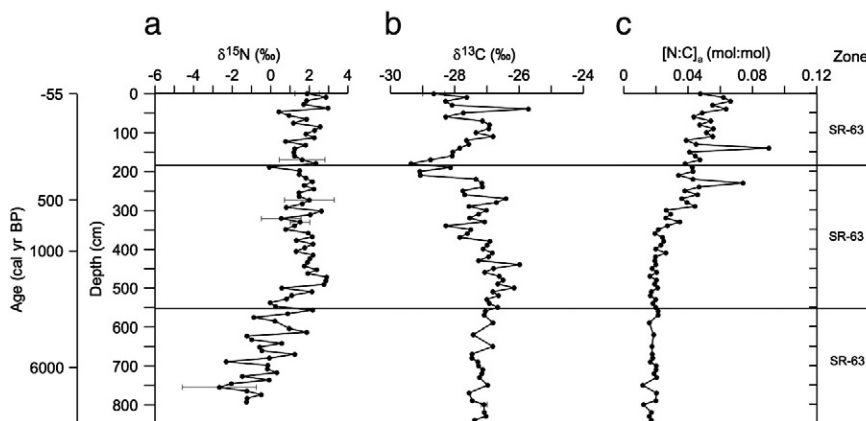


Figure 6. Plot of organic matter data: a) δ¹⁵N (‰) vs. air. b) δ¹³C (‰) vs. VPDB. c) [N:C]_a (mol:mol). Error bars show standard deviations of triplicate analyses.

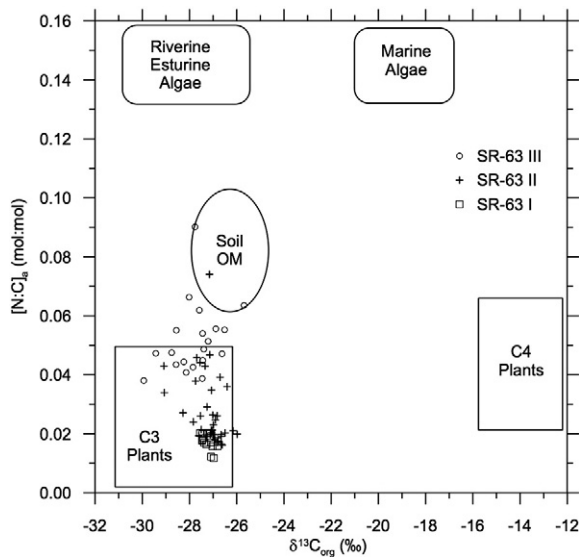


Figure 7. Plot of $[N:C]_a$ (mol:mol) vs. $\delta^{13}C$ (‰) where symbols indicate the zone. The ranges drawn have been previously published from comparable environments (e.g. Hedges et al., 1986; Goñi et al., 2006).

2003), which is too old to account for the observed change in sedimentation rates recorded from core SR-63. A dominant feature in zone SR-63 I is the decrease in sedimentation rates (Figure 2) from 0.19 cm yr^{-1} to 0.06 cm yr^{-1} at $\sim 6 \text{ cal ka BP}$. Sedimentation rates also decreased on Spanish Lookout Cay at $\sim 6 \text{ cal ka BP}$ (Monacci et al., 2009). Blanchon (2005) suggested that a smooth sea-level curve for the Caribbean during the Holocene is inappropriate and that a “stepped curve” is more realistic. Based on this interpretation, a decrease in the rate of sea-level rise could be followed by a latter increase in the rate of sea-level rise. Our data are consistent with a stepped decline in sea-level rise at $\sim 6 \text{ cal ka BP}$.

Discussions of the Caribbean sea-level curve reconstruction for the Holocene stress the need for caution when interpreting radiocarbon dates from mangrove peat. The problem of autocompaction of peat has been raised by multiple authors (e.g. Woodroffe, 1988; Bird et al., 2004; Gischler, 2006). However, the DBD data from zone SR-63 I do not indicate autocompaction, because there is no increase with depth and time (Bird et al., 2004). The LOI sequence from zone SR-63 I shows a significant change just before the decrease in sedimentation at $\sim 6 \text{ cal ka BP}$. The material at the bottom of zone SR-63 I ($\sim 850\text{--}750 \text{ cm}$) has a greater biogenic content (organic material and calcium carbonate) than lithogenic content (residual material, non-carbonate/inorganic). There are no corresponding features seen in the elemental or stable isotope ratios to explain a source change in the organic material at this time. DBD and MS data during this change in accumulation rate are also relatively uniform. However, there is relatively high abundance of fern spores observed at site SR-63 prior to the change in accumulation rate ($>6 \text{ cal ka BP}$), which can be an indication of a transitional or disrupted site (Traverse, 1988).

The carbonate content at the bottom of zone SR-63 I is similar to the percentages seen at core site BT-79 on Spanish Lookout Cay (Monacci et al., 2009), but values from the top of the zone ($\sim 750\text{--}600 \text{ cm}$) are significantly lower. If it is assumed that no significant changes in precipitation or discharge rates of the river occurred at this time, then perhaps a decrease in the rate of rise of sea-level altered both the sedimentation rate and the composition of the deposited materials, according to the LOI sequence, with no obvious changes in the lithology. Foraminifera are present in zone SR-63 I prior to $\sim 6 \text{ cal ka BP}$, but are not observed after this time. If the carbonate primarily indicates the presence of these organisms, this line of evidence could support decreased intrusion of saline water. This could

also account for a change in the productivity of the mangrove stand at that time and the subsequent decrease in peat accumulation rates. A scenario involving decreased seawater inundation of this site was not sufficient to affect the composition of vegetation types, as mangrove species represent $>60\%$ of the pollen with no marked changes in the percentages of pollen from other shrubs and trees (freshwater species).

Zone SR-63 II: 3930 to 370 cal yr BP

The lower boundary of zone SR-63 II is marked by a significant change in pollen types. Overall, there is a decrease in mangrove pollen and an increase of other shrubs or trees, which are assumed to be less salt tolerant than the mangroves. There is a marked decrease in *R. mangle* percentages and an increase in *A. germinans*. Relative to offshore mangrove ecosystems (Wooler et al., 2004, 2007, 2009; Monacci et al., 2009) and those along the Amazon River (Behling and da Costa, 2001), the percentages ($>20\%$) of *A. germinans* pollen observed in core SR-63 are very high. *A. germinans* is a low pollen producer (Behling et al., 2001), thus a prolific black mangrove stand must have been in the immediate vicinity of site SR-63 to produce such high percentages (Vedel et al., 2006). *Avicennia* are typically not dominant in the same mainland vegetation zone as *Rhizophora* and are usually found more inland (Murray et al., 2003), in more saline conditions. The general increase in *A. germinans* pollen from $\sim 6 \text{ ka}$ to 600 cal yr BP correlates with a decrease in sedimentation rate. Assuming there was a decrease in the rate of sea-level rise during this period; the SR-63 site would have experienced decreased inundation and may have become more saline through increased evapotranspiration. The hydraulic properties of *A. germinans* include higher water use efficiency, providing an advantage in areas with higher salinities (Sobrado, 2000). This and other physiological differences between *A. germinans* and *R. mangle* can also prohibit *A. germinans* from being an effective competitor in areas with lower salinities (Sobrado, 2000). It is therefore assumed that the high abundance of *A. germinans* indicates high salinity and evaporation. However, it is possible that the increase in salinity could be attributed to a decrease in the rate of sea-level rise, and a change in the dynamics of the SR or its drainage basin, or both. Alternatively, *R. mangle* had built up sediment (by trapping detritus in prop roots in the water). Compared to earlier times, the rate of sea-level rise was reduced, allowing land to form that was colonized by *A. germinans*. There was subsequently accretion of *R. mangle* into the water. This corresponds as well to an increase in oak and pine in the area, with a generally “improving” landscape and the formation of a pine savannah (Bhattacharya et al., 2011). This improved landscape also is the time of the ancient Maya settlement in Belize (800 BC to AD 300) and the Classic period civilization (AD 300–900).

A transition from the basal peat-dominated lithology (850–500 cm) to the overlying mud-dominated lithology (500–0 cm) occurs in zone SR-63 II. This change from predominantly peat material to predominantly fluvial material occurs at $\sim 2.5 \text{ cal ka BP}$ (Figure 2). Several proxies reflect this transition: the LOI sequence becomes virtually uniform for the remainder of the core, there is an overall increase in DBD to the top of the zone, indicating the increase in material with higher density and possibly resulting in compaction, and there are changes in the elemental and isotopic composition of the organic material. $\delta^{15}N$ becomes higher and fairly uniform for the remainder of the core, there is a slight decrease in $\delta^{13}C$ toward the top of the zone, and there is a slight increase in $[N:C]_a$ at the lithological boundary. These characteristics contrast with data from peat cores taken from offshore environments, which have fairly uniform stratigraphic and geochemical characteristics (e.g. Monacci et al., 2009). For example, $\delta^{13}C$ analyses on bulk peat from a 7.5 m continuous mangrove peat core, have shown minimal variation, $-27.1 \pm 0.5\%$ (Monacci et al., 2009). Therefore, the majority of the

material being deposited at the top of core SR-63 is presumed to be allochthonous, indicative of a regional, rather than local, signal.

Our secondary aim was to determine whether changes in the mangrove paleoecology and fluvial dynamics of the SR correspond to broad climatic changes recorded in upland lake environments. The muddy sediments in zone SR-63 II are comparable with the “Maya clay” that has been observed in several limnological studies (e.g. Leyden, 1987; Jacob and Hallmark, 1996). Maya clay has been recognized as a thick, clay-rich stratigraphic unit that has been found in the Peten Lake District of Guatemala (e.g. Binford et al., 1987), and can also be identified through analysis of MS and pollen. Fine materials with high MS and disturbed pollen taxa were produced by human-induced erosion and deforestation at ~2.8 cal ka BP (Curtis et al., 1998). Swidden agriculture, a slash and burn technique used by Maya (e.g. Hodell et al., 2007), may have increased erosion and deforestation. An increase in erosion related to anthropogenic influences coeval with an increase in agricultural pollen (e.g. maize or *Zea mays*) has been observed at sites in Venezuela (e.g. Leyden, 1987). Some agricultural plants used by the Maya (e.g. maize) are C₄, which have distinct $\delta^{13}\text{C}$ signatures from mangroves or other C₃ plants (e.g. Polk et al., 2007). The change in the lithology at ~2.5 cal ka BP at the SR-63 site suggests that similar anthropogenic mechanisms could have been responsible. Despite the similarity in lithological characteristics, no significant change in the percentages of herb and grass pollen types is recorded at our SR-63 site (Figure 4). The data do not suggest a shift in the $\delta^{13}\text{C}$ of the organic material (Figure 7) toward values more typical of C₄ plants. A shift in $\delta^{13}\text{C}$ toward C₄ plants has been recognized at other Maya sites (Polk et al., 2007), and is thought to reflect Maya agriculture (e.g. maize).

Although human-induced erosion may have been responsible for the increased lithogenic material and allochthonous organic matter at ~2.5 cal ka BP in core SR-63, it is important to consider other possible environmental changes. For instance, past fluctuations in the position of the Intertropical Convergence Zone (ITCZ) may have resulted in an increase in precipitation and erosion at the site (Haug et al., 2001; Hodell et al., 2007). Haug et al. (2001) described how the ITCZ dynamically links changes in biogenic and terrigenous sediments with precipitation in the Cariaco Basin off Venezuela and effects of variation in the ITCZ can be seen throughout the Caribbean region. Increased precipitation occurs in the Maya Mountains when the ITCZ is in the northern position and decreased precipitation when the ITCZ is in the southern position (Haug et al., 2001; Polk et al., 2007). Research on cave sediments in the Vaca Plateau region, near the headwaters of the SR, has shown evidence of changes in precipitation and more frequent intervals of aridity during the past ~2.6 cal ka BP (Polk et al., 2007). We find that the period from the start of pollen zone SR-63 II at ~3.9 cal ka BP to the marked change in the lithology at ~2.5 cal ka BP most likely represents a period of higher salinities at the site, most likely induced by higher evaporation and/or a decreased input of freshwater at the site (i.e. decreased precipitation). We note that these findings are consistent with the evidence of climate drying during the period from 4.5 cal ka BP to 3 cal ka BP in the northern lowlands of Guatemala (Mueller et al., 2009).

Zone SR-63 III: 370 cal yr BP to present

Sedimentation rates during zone SR-63 III are implied to be constant by our age model, and the composition of the deposited material is fairly uniform as evident from the LOI sequence (Figure 3). It is possible that the muddy portion of the core's lithology in this zone represents deposition from a flooding event, perhaps even associated with a hurricane during the historic period. The DBD shows an overall decrease from the beginning of the zone to the top of the core, where values are similar to those in mangrove peat of zone SR-63 I. This indicates that site SR-63 transitioned back to a mangrove-dominated environment, or flood events were less frequent, which are consistent with the habitat present at the site today. Pollen analyses support this

interpretation, as mangrove pollen percentages increase during zone SR-63 III. Even though *A. germinans* pollen is still abundant in this zone, *R. mangle* increases significantly. As a result, the pollen from other shrubs and trees, most notably *Pinus*, decreases. This could be caused by a greater inundation of seawater at this site during the last 370 yr.

Conclusions

Previous studies have shown the response of aquatic ecosystems such as coral reefs, mangroves, and lacustrine habitats to Holocene climate change in the greater Caribbean region (e.g. Woodroffe, 1988; Hodell et al., 2001; Gischler, 2003). Interpretations of factors driving these changes include orbital forcing (e.g. Leyden et al., 1994), sea-level change (e.g. Fairbanks, 1989), variations in precipitation (e.g. Higuera-Gundy et al., 1999), anthropogenic influences (Hodell et al., 2007), often in combination. In order to better understand the driving mechanisms and responses, a greater number of sites need to be examined. Core SR-63, from a mangrove ecosystem on the banks of the SR, showed a decrease in sedimentation from ~6 ka to 1 cal ka BP. A similar decrease is observed in a core of continuous mangrove peat from Spanish Lookout Cay, 15 km offshore (Monacci et al., 2009). Changes in the sedimentation rates observed in mangrove ecosystems offshore have previously been attributed to changes in relative sea-level and the rate of sea-level rise (Wooller et al., 2007). A coeval decrease in sedimentation rate at the site of SR-63 on the mainland supports the idea that regional changes in sea-level occurred at this time and had wide ranging effects on these mainland mangrove ecosystems. The period from 3.9 cal ka BP to 2.5 cal ka BP in our core represents a period of increased salinity at the site, most likely induced by increased evaporation and decreased freshwater input (e.g. decreased precipitation). Notably this period corresponds with the timing of a period of drying climate in the lowlands of northern Guatemala.

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