Lake Sediment-Based Reconstructions of Late-Holocene Lowland Environments of Dominican Republic and Barbuda, Northern Caribbean

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Abstract (Academic)

Questions remain regarding the impacts of late-Holocene human activities and environmental change on landscapes of the Caribbean islands. This dissertation examined the long-term environmental history of two sites in the northern Caribbean primarily through the analysis of proxy data sources contained in sediment cores. At Laguna Alejandro, a coastal lagoon in the southwestern Dominican Republic, we interpreted, from sediment lithology and stable oxygen isotope data, at least ten storm events over the past 1,000 years, producing the first long record of storm activity from the island. During the Little Ice Age (1400−1800 CE), we interpreted an increased frequency of hurricane landfalls at the study site with longer ecosystem recovery times and decreased fire activity versus during earlier, more moist periods of the late-Holocene. At Freshwater Pond, an inland pond on Barbuda, we interpreted vegetation disturbance from presence of disturbance pollen taxa and biomass burning near the pond from abundance of macroscopic (>125 µm) charcoal from sediments representing ~150 BCE–1250 CE, with consistency of burning and human history on the island informed by the archaeological record suggesting fire activity was primarily due to Pre-Columbian inhabitants. Microscopic charcoal analysis indicated that extra-local burning, primarily island-wide, continued until ~1610 CE then declined, possibly reflecting a change in land-use practices by Europeans who entered the region in 1492 CE and established a permanent settlement on the island in the 1660s. My study on modern pollen from surface soils and sediments, the first from lowland seasonally-dry vegetation of the Greater Antilles, informed our ideas on vegetation-pollen representation in different plant communities, including tropical dry forest, thorn forest, mangrove, mudflat, and lagoon. My modern pollen results also aided in the interpretation of stratigraphic pollen in the study of nearby L. Alejandro's sediments and revealed changes in floristic composition at the study site through time. Pollen of maize (*Zea mays*) and *Prosopis juliflora* in sediments representing ~1760 CE document human subsistence agriculture and disturbance to tropical dry forest in the watershed.

Lake Sediment-Based Reconstructions of Late-Holocene Lowland Environments of Dominican Republic and Barbuda, Northern Caribbean

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Abstract (General Audience)

Past (or paleo-) environments of the Caribbean islands are understudied. This dissertation examined the long-term environmental history of two sites in the northern Caribbean primarily through proxy data sources contained in lake sediment cores, namely pollen and spores, charcoal particles, and sediment physical and chemical characteristics. Analysis of multiple proxies allowed the reconstruction of watershed vegetation and fire history, wetland development, and possible human impacts on the environment. At Laguna Alejandro, a coastal lagoon in the Dominican Republic (DR), we interpreted at least ten tropical storm events over the past 1,000 years, producing the first long record of hurricanes for the island. During the Little Ice Age (LIA, 1400−1800 CE), we interpreted an increased frequency of hurricane landfalls at the study site and longer ecosystem recovery times and decreased fire activity versus during earlier, more moist periods, possibly linked to more arid conditions and associated declines in biomass. At Freshwater Pond, an inland pond on Barbuda, we interpreted vegetation disturbance from presence of pollen of disturbance taxa and biomass burning near the pond from abundance of large charcoal fragments in sediments representing ~150 BCE–1250 CE. The consistency of burning and human history on the island, informed by the archaeological record, suggests fire activity was largely controlled by Pre-Columbian inhabitants. Smaller charcoal fragments suggest island-wide burning continued until ~1610 CE then declined, possibly reflecting a change in land-use practices by Europeans who entered the region in 1492 CE and established a permanent settlement on the island in the 1660s as well as declines in biomass tied to LIA. The analysis of pollen and spores collected from surface soils and sediments (modern pollen) in lowland seasonally-dry vegetation types in the Dominican Republic, revealed how different vegetation types (tropical dry forest, thorn forest, mangrove, mudflat, and lagoon) were represented in the pollen rain, including identifying pollen provenance and over- and under-represented taxa. The study also aided in the interpretation of sediment core pollen from Laguna Alejandro, documenting changes in the composition of the vegetation through time and revealing subsistence agricultural activities and disturbance to tropical dry forest.

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Attribution

All the manuscripts in this dissertation, i.e., chapters 2, 3, and 4 have co-authors. Contribution of all co-authors is described below:

Allison R. Le Blanc, MS: I collected and analyzed data for chapters 2, 3, and 4, including field collection and laboratory processing of samples, data analysis and interpretation. I authored the first drafts of all three manuscripts. I am also co-principal investigator of a National Science Foundation (NSF) grant with Lisa Kennedy (BCS- 1302757) entitled: *Modern Pollen Spectra from Coasts and Lowlands of the Dominican Republic and Their Application to the Interpretation of Sedimentary Pollen Records* that funded and led to the development of the chapter 4 manuscript.

Lisa M. Kennedy, PhD: Professor, Department of Geography at Virginia Tech. She is a co-principal investigator (co-PI) of the National Science Foundation grant (BCS- 1302757) with LeBlanc. She is also co-PI of NSF grant (BCS-0964138) with Kam-biu Liu entitled: *Collaborative Research: Long-Term Dynamics of Caribbean Maritime Forest Ecosystems in the Context of Major Disturbance Events: The Role of Hurricanes and Fires* that funded and led to the development of the chapter 2 manuscript. Lisa Kennedy also developed a Research Development Initiatives Grant, awarded to Allison Bain (PI, grant no. 820-2010-0189) via the Social Science and Humanities Research Council of Canada (SSHRC) that funded and led to development of the chapter 3 manuscript. Kennedy also participated in field work for chapters 2, 3, and 4 and reviewed all three manuscripts.

Kam-biu Liu, PhD: Professor, Department of Oceanography and Coastal Sciences, Louisiana State University. He is a co-principal investigator of the National Science Foundation grant (BCS-0964138) with Lisa Kennedy that funded research and led to development of the chapter 2 manuscript. He also participated in the field collection of data towards chapters 2 and 4 and analyzed data and reviewed the chapter 2 manuscript.

Chad S. Lane, PhD: Professor, Department of Geography and Geology, University of North Carolina Wilmington. He contributed data (stable isotope) and reviewed the chapter 2 manuscript.

Michael Burn, PhD: Professor, Department of Geography and Geology, The University of the West Indies. Burn developed a Research Development Initiatives Grant, awarded to Allison Bain (PI, grant no. 820-2010-0189) via SSHRC that funded and led to development of the chapter 3 manuscript. He participated in the field collection of data that led to the chapter 3 manuscript, in addition to contributing data (radiocarbon dates, age-depth model, stable isotopes, faunal counts) and analyzing the data and reviewing the chapter 3 manuscript.

Allison Bain, PhD: Professor, Department of History, Laval University. Along with Kennedy and Burn, developed a Research Development Initiatives Grant, awarded to Bain (PI, grant no. 820-2010-0189) via the SSHRC that funded and led to development of the chapter 3 manuscript. She participated in the field collection of data that led to the chapter 3 manuscript, in addition to contributing data (radiocarbon dates and archaeobotanical remains from excavations) and analyzing the data and reviewing the chapter 3 manuscript.

Sophia Perdikaris, PhD: Professor in the Department of Anthropology and Archaeology at Brooklyn College, and director of the Barbuda Research Center, Antigua and Barbuda. Perdikaris has contributed to Barbuda's environmental and archaeological record as co-PI of NSF grant entitled: *REU: Islands of Change* (grant no. PLR-0851727), with her research leading to the development of the chapter 3 manuscript. She also contributed data (radiocarbon dates from archaeological excavations) and interpretation of the archaeological record of the island to the chapter 3 manuscript.

Chapter 1: Introduction

Research context and significance

Interpretations of sedimentary records from tropical America and the Caribbean agree that the mid- to late-Holocene was a time of climate variability and environmental change (Burn et al., 2016; Fensterer et al., 2013; Fritz et al., 2011; Peros et al., 2007; Haug et al., 2001; Higuera-Gundy et al., 1999; Hodell et al., 1991). While Hispaniola remains the most studied Caribbean island (Caffrey et al, 2015; Lane et al., 2011; Lane et al., 2009; Medley et al., 2007; Greer and Swart, 2006; Kennedy et al., 2006; Higuera-Gundy et al., 1999; Hodell et al., 1991; Brenner and Binford, 1988), many of the paleorecords from the islands are from inland locations (Medley et al., 2007; Greer and Swart, 2006) at mid- and high-elevations (Lane et al., 2014; 2011; 2009; Kennedy et al., 2006), unlike lowland and coastal areas of the same island. Only sedimentary pollen records from Lake Miragoâne, Haiti (Higuera-Gundy et al., 1999), and Laguna Saladilla, Dominican Republic (Caffrey et al., 2015) represent the vegetation history of the island. Further, the L. Saladilla record, from the northern coast, is dominated by pollen of mangroves, herbs and grasses, and aquatics, leaving the Miragoâne record as the singular record documenting lowland tropical dry and humid forest history for the island. The arid and semi-arid southwestern region of Hispaniola experiences high floral endemism (Cano-Ortiz et al., 2015; García-Fuentes et al., 2015) and possesses tracts of mature tropical dry forest, a high conservation priority as these forests have largely been converted to thorn forest and savanna from human activities (Sánchez-Azofeifa and Portillo-Quintero, 2011; Roth, 1999) Thus, lowland sites, especially with tropical dry forests, of the islands represent a key area of study.

The fire history and long-term impacts of hurricanes on ecosystems, particularly floristic composition, of the Caribbean islands are also largely undocumented. Fire histories from the islands have been from sites with pines in the local or regional vicinity (Caffrey et al. 2015; Kennedy et al., 2006; Horn et al., 2000; Higuera-Gundy et al., 1999; Kjellmark, 1996; Burney et al., 1994). The long-term fire history of sites with dry tropical forest remains a knowledge gap in the paleoecology of the Caribbean (Murphy and Lugo, 1995; 1986). Studies combining paleotempestology, the study of prehistoric tropical cyclones, with analysis of stratigraphic pollen, spores, and charcoal, have interpreted increases in major fires and delayed forest recovery post-hurricane, from study sites within pine-oak-hickory forests of the Gulf coast of the United States (Liu et al., 2008) and in moist swamp forests of Nicaragua (Urquhart, 2009). Recently, Peros et al. (2015) documented hurricane, vegetation, and fire history from a coastal mangrove lagoon in Cuba (Peros et al. 2015). Additional paleorecords from region are needed to establish long-term records of hurricane activity in the region, climate, and hurricane-vegetation-disturbance dynamics, including patterns of fire activity.

While experiencing significant changes in climate and environment, the Holocene also saw the peopling of the Caribbean islands. Archaeological evidence indicates the earliest documented settlements of the Caribbean occurred when fisher-gatherer-foragers first moved out of the Orinoco river delta (northern South America) into Trinidad ~6000 BCE (8,000 yr BP). In the western Caribbean, the first migrants, also fisher-gatherer-foragers, moved out of Central America in the western Greater Antilles ~6,000 years ago. The Lesser Antilles, particularly the northern islands, were initially colonized almost a millennium later (5,000 years ago) though the provenance of the original inhabitants remains uncertain (Rousseau et al., 2017; Wilson, 2007; Newsom and Wing, 2004). Most archaeological investigations agree that the Pre-Columbian settlers of the Lesser Antilles relied extensively on marine and terrestrial resources though much is still unknow regarding the impacts of these first inhabitants on the environments they encountered (Siegel et al., 2015; Wilson, 2007; Newsom and Wing, 2004). The island of Barbuda in the northern Lesser Antilles has a long human prehistory, with seasonal to permanent occupation of the island from the Archaic (~4000–2000 BCE) through post-Colonial periods (Bain et al., 2017; Rousseau et al., 2017). The island is an ideal study site for examining late-Holocene vegetation and fire history of arid to semi-arid lowland environments of the Caribbean islands considering the recent archaeological (Bain et al., 2017; Rousseau et al., 2017) and paleoclimatic (Burn et al., 2016) investigations.

Methods from paleoenvironmental reconstruction can fill these knowledge gaps through the analysis of micro-(e.g. pollen, spores, charcoal >10 µm) and macro-(e.g. mollusks, charcoal > 125 µm) scopic proxies contained in lake sediments. Analysis of stratigraphic pollen and spores from sediment cores is one of the most widely adopted techniques of reconstructing regional vegetation and climate histories (Lowe and Walker, 1997). The analysis of macroscopic (>125 µm) and microscopic (>10 µm) sedimentary charcoal can provide long-term local or regional fire histories, respectively (Whitlock and Anderson, 2003; Whitlock and Larsen, 2001). Paleoenvironmental datasets can also document initial human colonization of island environments by the concurrence of sedimentary pollen and spores of ethnobotanically significant (i.e. food, medicine) and disturbance taxa with dramatic and sustained increases in larger charcoal particles documenting increased fire activity (<150 µm; Siegel et al., 2015). Human impacts on vegetation, including forest clearance and agriculture, have also been interpreted from decreases in pollen spectra representing forest taxa and coincident increases in grasses, Asteraceae, and Amaranthaceae, along with increases in fire activity (Bhattacharya et al., 2011; Higuera-Gundy et al., 1999; Kjellmark, 1996).

While reconstructions of past vegetation, climate, and environment have been successfully derived from Neotropical sedimentary records (e.g. Caffrey et al., 2015; Lane et al., 2014; Higuera-Gundy et al., 1999) lack of modern pollen records, and thus limited knowledge of pollen-vegetation relationships, restricts the interpretation of tropical sedimentary pollen. In comparison to temperate sites, relatively few modern pollen records exist for vegetation communities of tropical America and the Caribbean. Several modern pollen studies have been conducted in Central America (Figueroa-Rangel et al., 2016; Bhattacharya et al., 2011; Correa-Metrio et al., 2011; Ortuño et al., 2011; Bush and Rivera, 2001; Bush, 2000; Rodgers and Horn, 1996; Islebe and Hooghiemstra, 1995; Jacobs, 1982; and references therein) and South America (Guimarães et al., 2017; Burn et al., 2010; Gosling et al., 2009; Urrego et al., 2010, 2009; Kuentz et al., 2007; Weng et al., 2004; Markgraf et al., 2002; and references therein). However, there remains a deficiency of studies from the Greater Antilles islands, with only a single published study from the Cordillera Central, Dominican Republic (Kennedy et al., 2005), an area dominated by pine (*Pinus occidentalis*) forests and grasslands, unlike lowland sites on the same island. Not only do modern pollen data reflect present-day vegetation communities (Gosling et al., 2009; Rodgers and Horn, 1996; Liu and Lam, 1985; Webb, 1974), but modern pollen data can also be applied to the interpretation of pollen from sediment cores obtained within similar pollen source area. Using associations or assemblages of pollen taxa has led to the successful separation of tropical vegetation types in pollen spectra in several studies in tropical South and Central America (Gosling et al., 2009; Bush, 2000; Rodgers and Horn, 1996). The deficiency of modern pollen studies from this region limits the interpretation of sedimentary pollen and paleoenvironmental reconstructions from the region.

Through modern pollen analysis, this dissertation will contribute to the paleoecology of the Caribbean through increased knowledge of vegetation-pollen relationships of coastal and lowland vegetation of the Greater Antilles, including floristic composition and knowledge of pollen taxa over- and under-representation. Through multiproxy analysis of sediment cores from Laguna Alejandro, a hypersaline coastal lagoon in the southwestern Dominican Republic, and Freshwater Pond, an inland freshwater pond in southwestern Barbuda, this research will contribute to several gaps in the literature, including questions on vegetation response to late-Holocene climate variability, long-term patterns of fire in tropical dry forest, and the long-term history of human-environment interactions around both of these study sites. This dissertation will represent the first modern pollen study from lowlands of the Greater Antilles, one of few sedimentary pollen records from a lowland coastal site in Hispaniola, and the only sedimentary pollen and charcoal analysis from Barbuda.

Dissertation Chapters

This dissertation consists of an already published manuscript (chapter 2) and two additional chapters in preparation for submission to peer-reviewed academic journals. This dissertation examined the storm, vegetation, and environmental history from a coastal lowland site in the Dominican Republic (chapter 2) and an inland site from Barbuda in the Lesser Antilles (chapter 3), and modern pollen analysis of surface soils and sediments of the Dominican Republic and its application to the interpretation of stratigraphic (sediment core) pollen spectra (chapter 4).

Through radiocarbon dates, analysis of sediment lithology and biological (pollen and spores, charcoal particles, ostracods, mollusks) and geochemical (stable isotopes) proxies from

Laguna Alejandro (chapter 2), a coastal lagoon in the arid southwestern Dominican Republic, and Freshwater Pond (chapter 3), an inland fresh water pond in arid Barbuda, this dissertation contributed to the late-Holocene paleoecology of the northeastern Caribbean. My research also contributed to several gaps in the literature, including the vegetation history of the sites, tropical lowland vegetation responses to late-Holocene climate variability, patterns of fire in these vegetation communities, and possible human-environment interactions at the study sites. At L. Alejandro, my research provided the first long-term record of storm activity for the island.

Modern pollen collected from surface soils and sediments from tropical dry forest, thorn forest, mangrove, mudflat, and lagoon samples from the southwestern Dominican Republic were analyzed for chapter 4 of this dissertation. Ordination analysis of modern and sedimentary pollen, from nearby Laguna Alejandro, revealed the taxonomic similarity/dissimilarity of samples by vegetation type and pollen provenance, aiding in the reconstruction of vegetation and environmental history of my study site. This research also revealed taxonomic diversity of the vegetation in the pollen record as well as over- and under-represented pollen taxa in comparison to importance of the taxa on the landscape. While preliminary, my modern pollen analysis will aid in the interpretation of other sedimentary pollen records obtained within similar pollen source areas and thus strengthen our understanding of Caribbean vegetation dynamics across long time scales.

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Chapter 2

Linking hurricane landfalls, precipitation variability, fires, and vegetation response over the past millennium from analysis of coastal lagoon sediments, southwestern Dominican Republic

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Abstract

We reconstructed the late-Holocene environmental history of a coastal lagoon in semi-arid southwestern Hispaniola through multiproxy analysis of a sediment core, including pollen, macroscopic and microscopic charcoal, loss-on-ignition analysis (LOI), stable isotope analysis, bulk density, and magnetic susceptibility. Four chronological accelerator mass spectrometry (AMS) radiocarbon dates indicated that our core represents the past 1000 years. We interpreted ten hurricanes events over the past millennium from high-resolution geological proxies, LOI data, and ostracod valve stable oxygen isotope data, thus producing the first long record of hurricanes from the Dominican Republic (DR). Geological proxies indicated a high-energy event abruptly changed the ecosystem state of our core site from a shallow mangrove wetland to a lacustrine environment ~330 cal yr BP. We interpret the driver of that event to be the landfall of a strong hurricane that initiated lowland flooding, mangrove mortality, and subsequent peat collapse at the core site. Pollen data indicated that during the relatively moist Medieval Warm Period (MWP), hurricanes led to temporary declines in tropical dry forest taxa that recovered within several decades following disturbance. By comparison, during the relatively arid Little Ice Age (LIA), when precipitation was highly variable in the circum-Caribbean, closely spaced hurricanes seemed to delay forest recovery. Sedimentary charcoal concentrations revealed increased fire activity after inferred hurricane landfalls in the MWP, providing evidence of a link between enhanced biomass and fuel availability during moister periods and burning in recently disturbed dry forests and scrub of our semi-arid study region. Our interpretations of increased aridity and precipitation variability, indicated by alternating thin layers of microbial mats with evaporite layers, along with more frequent hurricanes from ~330 cal yr BP to present, generally

agree with other sedimentary records from the circum-Caribbean, and may be linked to a more southerly position of the Intertropical Convergence Zone during the LIA.

Introduction

Hurricanes are complex disturbance events that threaten life and property and may be forcing mechanisms for vegetation change and other disturbance types, including fires and mass movements (Lugo and Waide 1983; Tanner et al. 1991; Liu et al. 2008; Urquhart 2009). The short-term (<10 years) ecological impacts of hurricanes on tropical vegetation in the Caribbean region are well documented (Van Bloem et al. 2007; Imbert and Portecop 2008; Metcalfe et al. 2008), but whether hurricanes have lasting impacts on vegetation composition is still in question. Studies from the Caribbean have suggested that while hurricanes can have long-lasting effects on basic forest structure and function, their impacts on species richness are not lasting and actually reinforce the pre-disturbance species composition of vegetation (Tanner et al. 1991; Van Bloem et al. 2007). That conception, however, is based on short-term (typically one to a few years) ecological studies; examination of longer-term hurricane impacts on vegetation using pollen analysis are needed to fully understand hurricane-vegetation dynamics (Tanner et al. 1991).

Two rare studies of long-term ecological responses to hurricane strikes, Liu et al. (2008) and Urquhart (2009), identified hurricane landfalls and vegetation responses using proxy data sources in the sediments of Little Lake, Alabama and Laguna Negra, Nicaragua, respectively. Both studies had similar findings in that forest pollen taxa declined, while pollen of disturbance taxa increased in sediments deposited after paleo-hurricanes. Liu et al. (2008) examined coastal pine-oak-hickory forests of the southern U.S., while Urquhart (2009) looked at a tropical moist swamp forest. Our literature search indicates that such studies have yet to be replicated in other tropical and subtropical vegetation types.

The question of whether hurricanes are linked to fires in tropical forests also deserves attention. Myers and van Lear (1998) hypothesized that hurricanes would increase fuel loads, thereby raising the risks of post-hurricane fires in the subtropical maritime pine-oak-hickory forests of the southeastern United States. The sediment record from Little Lake, Alabama (Liu et al. 2008) revealed spikes in microscopic (pollen slide) charcoal after hurricanes, suggesting that major fires followed late-Holocene hurricane landfalls. Pollen data from the same sediments indicated that while the pine-dominated communities surrounding Little Lake eventually recovered post-hurricane, forest recovery was impeded by increased fire activity in the years and decades following major paleo-hurricane strikes (Liu et al. 2008). Urquhart (2009) found a similar relationship between increased sedimentary charcoal content and an interpreted hurricane overwash event (3,340±50 yr BP) in moist swamp forests of eastern Nicaragua. At Laguna Negra, major fires following the paleo-hurricane strike prevented regeneration of moist swamp forests for 500 years (Urquhart 2009). Apart from Liu et al. (2008) and Urquhart (2009), the relationship between hurricane incidence and fire activity has not been extensively studied, particularly within seasonally dry tropical ecosystems of the Caribbean where fire regimes are poorly understood. The prevailing paradigm suggests that fires in tropical dry forests of the Caribbean are largely tied to human activities (rather than natural ignitions) and that frequent fires may convert these forests to savanna (Middleton et al. 1997; Vieira and Scariot 2006; Sánchez-Azofeifa and Portillo-Quintero 2011).

In this study, we combined methods from paleoecology and paleotempestology (the study of prehistoric tropical cyclones) to document late-Holocene hurricanes and ecosystem response through analysis of coastal lagoon sediments from semi-arid southwestern Dominican Republic. Reconstructions of prehistoric hurricanes have largely focused on the study of clastic overwash deposits in coastal lakes and wetlands via storm surges during hurricanes. Contemporary hurricanes and associated overwash deposits have provided modern analogs of depositional dynamics related to storm surge and wave action during major (categories 3, 4, and 5) events (Liu and Fearn 2000; Donnelly et al. 2001; Liu et al. 2008; Liu 2013). When hurricane deposits are identified in lake sediment records, then local changes in vegetation composition before and after hurricanes can be documented through analyses of sedimentary pollen and spores in strata below and above interpreted hurricane events (Liu et al. 2008). Using a similar methodology, the effects of hurricanes on regional and local fire regimes can be documented through analysis of sedimentary micro- and macroscopic charcoal, respectively (Patterson et al. 1987; Whitlock and Larson 2001; Liu et al. 2008; Urquhart 2009).

Study area

The Dominican Republic (DR, Fig. 1, centroid 18.9˚ N, 70.4˚ W) occupies the eastern two-thirds of Hispaniola in the Caribbean Sea. The distribution of rainfall in the DR is bimodal, with two rainy (late-spring and mid-fall) and dry seasons (mid-summer and winter). The Cordillera Central trend diagonally across the island, blocking onshore flow of humid ocean air masses (northeastern trade winds) and creating a strong rainshadow effect, and aridity, in southwestern DR (Bolay 1997).

Our study area (18.313097˚ N, 71.030802˚W; ~1m asl; Fig. 1) includes the ~30 ha hypersaline (>80 ppt) Laguna Alejandro at the eastern edge of the Enriquillo Valley, a paleo-sea channel in southern DR that became isolated from the Caribbean Sea ~4,000 years ago (Greer and Swart 2006). Alejandro is situated at the base of alluvial fans emanating from Sierra Martín

García (SMG, ~1329 m asl, Mann et al. 1995). The semi-arid lowlands around Alejandro receive 400–700 mm precipitation annually, while higher elevations of SMG may receive 800–1200 mm. Average monthly temperatures range from 25–28˚C (Izzo et al. 2010). We have observed maximum water depths of ~4 m at Alejandro during dry-season visits but satellite imagery indicates that the lake's surface area expands into the surrounding mudflats during the wet-season and during tropical storms.

A 75–100 m wide coastal barrier of low relief (2–4 m asl) separates the lake from Neiba Bay. The barrier consists of a cobble beach that rises steeply to a clast supported ridge, likely deposited by hurricane storm surges as the barrier is well above the observed high tide. Additionally, historical records indicate that at least 21 hurricanes and tropical storms have passed over the study area since 1851 (Knapp et al. 2010) while no credible tsunamis have been reported for the area (O'Loughlin and Lander JF 2004; Bakun et al. 2012) Overwash deposits consisting of large fragments of fossilized coral extend inland from the ridge fining to steep-sided deposits of sand- and pebble-sized clasts that terminate abruptly on the barrier while additional overwash fans terminate in the lake.

The lowlands around Alejandro, including the coastal barrier and lower portions of the alluvial fans, are vegetated by a mosaic of xeric to sub-xeric coastal scrub, scattered deciduous broadleaf trees typical of Caribbean dry forests (*Bursera simaruba* (L.) Sarg., *Calophyllum calabra* L., *Coccoloba uvifera* (L.) L., *Guaiacum officinale* L., *G. sanctum* L., Fabaceae spp.), and palms. Mangrove species (*Avicennia germinans* (L.) L., *Laguncularia racemose* (L.) Gaertn. f.), and *Rhizophora mangle* (L.) occupy some of the lake and coastal margins. Vegetation on the alluvial fans and lower slopes of SMG transitions from tropical deciduous broadleaf to mixed deciduous and evergreen broadleaf forests at ~500 m elevation. Two ephemeral streams flow from the mountain during high precipitation periods and enter the lagoon at its northeastern edge.

Archaeological sites are relatively rare on the island, but a site "El Curro," (1450 BC, 3400 yr BP), is located ~6 km west of Alejandro near the mouth of the Enriquillo Valley (Ortega and Guerrero 1981). Present human influences on the lake include a saltpan operation on the eastern side and a recently constructed canal on the western edge for release of water to the sea.

Materials and methods

In February 2008, we collected two overlapping sediment cores (ALEJ08) using a Colinvaux-Vohnout piston corer from ~260 cm of water. The profile reached 160.5 cm below the sediment-water interface where we encountered an impenetrable gravel layer. The core site was ~35 m from the barrier shoreline (Fig. 1). We capped the tubes and returned them to Virginia Tech where they were stored at 6 °C prior to analysis. The cores were split at Lamont-Doherty Earth Observatory and run through a GEOTEK core logger that spectrally photographed and analyzed the cores at 1-cm resolution for density (g cm^{-3}) and magnetic susceptibility (SI).

X-radiographs provided detailed stratigraphy, such as the presence of worm tubes and gastropod shells. Gastropod shells were picked from eight 2- cm^3 samples removed along the length of the core where shells were sufficiently concentrated (0–50 cm contained no shells) and identified by Robert Hershler of the Smithsonian. Dating plant macrofossils and charcoal fragments from four stratigraphic levels via the Accelerator Mass Spectrometry Laboratory at the University of Arizona and University of Georgia Center for Applied Isotope Studies provided chronological control (Table 1). Sample ages were calibrated using the Bayesian age-depth modeling program Bacon (Blaauw and Christen 2011) and Intcal13 dataset (Stuiver and Reimer 1993; Reimer et al. 2009). We conducted loss-on-ignition analysis (LOI) at 1-cm intervals to determine sediment fractions of water, organic matter, and carbonates (Dean 1974).

Samples for stable isotope analysis were removed at continuous 0.5 to 1 cm intervals from all but the upper 15 cm of the core, which lacked adequate shell abundance (Hildebrandt 2013). Adult *Cyprideis* sp. ostracod valves were isolated, cleaned, and homogenized. The resulting 0.2 mg carbonate powder samples were analyzed for oxygen ($\delta^{18}O$) isotope composition using a Thermo Gasbench II/III interfaced with a Thermo Delta V Plus stable isotope mass spectrometer at the University of North Carolina Wilmington Center for Marine Science. Results were temperature corrected to 25 °C and are reported in standard δ-per mil notation relative to the Vienna-Pee Dee belemnite (V-PDB) marine-carbonate standard. Precision of the Gasbench system was ±0.15‰ for $\delta^{18}O$ using multiple internal and international standards, including NBS-19 and LSVEC (Hildebrandt 2013).

We identified hurricane events in the core using LOI, sediment lithology, bulk density, magnetic susceptibility, and stable oxygen isotope analysis (Liu and Fearn 2000; Liu et al. 2008; Lawrence et al. 2008). We looked for discrete depths of material exhibiting concurrent increases in mineral content, bulk density, and magnetic susceptibility that coincided with clastic layers. Bulk density increases are indicative of increases in grain size and can identify high-energy deposition, while positive excursions in magnetic susceptibility values indicate deposition of allochthonous material (Oldfield et al. 1983). We also looked for significantly negative (1^{st} and 2^{nd} standard deviations of 5-pt running mean) $\delta^{18}O$ anomalies from ostracod valves associated with large influxes of ^{18}O-depleted meteoric waters typical of tropical cyclones (Lawrence et al. 2008). In the Alejandro sediment profile, hurricane overwash deposits consisted of medium to coarse sand and/or pebble deposits with abrupt contacts that coincided with positive excursions of magnetic susceptibility (Liu and Fearn 2000; Donnelly et al. 2001, 2004; Donnelly 2005). In two cases, discrete layers of non-marine gastropod shells and/or plant macrofossils that coincided with significantly negative $\delta^{18}O$ anomalies, were interpreted as hurricanes that did not leave clast-dominated overwash deposits.

We processed 28 1-cm^3 sediment samples to isolate pollen, spores, and microcharcoal using standard techniques (Faegri and Iverson 1989). Sampling focused on positions of notable stratigraphic changes and interpreted hurricane-generated layers in order to document past vegetation and environmental changes. High mineral content, coarse grain size, and close spacing of inferred hurricane deposits excluded the top of the core (0–20 cm) from pollen analysis. Prior to processing, we added one *Lycopodium* spore tablet (containing 18,584 ± 371 spores) to each sample to allow calculation of pollen concentrations (Stockmarr 1971). We made slides of pollen residue and identified and counted a minimum of 200 pollen grains and spores per slide at 400x magnification. Identifications were aided by pollen/spore reference slides and published references (Roubik and Moreno 1991; Colinvaux et al. 1999). Low pollen concentrations in mineral-rich samples and poor pollen preservation at some depths limited the pollen analysis to 11 levels with sufficient pollen concentrations and preservation.

Pollen taxa of cosmopolitan families and those comprising less than 3% of individual samples (except rare types of known ecological importance) were excluded from the pollen diagram. Indeterminate pollen grains were tallied and classified as either damaged or obscured. We grouped pollen/spore types (excluding monolete and trilete spores, and indeterminate pollen) into ecologically derived categories (Bolay 1997; Smith et al. 2004): 1. Upland, 2. Lowland forest (including lowland tropical dry forest taxa), and 3. Scrub and herbaceous (including taxa of shrubs, herbs, sedges, and grasses) in the pollen diagram.

Microcharcoal fragments (>10–125 µm) were tallied for each of the 28 levels processed, including slides rejected for pollen analysis. We compared abundance of microcharcoal in the pre- and post-hurricane samples to examine the relationship between regional fires and hurricanes. We analyzed sediment samples from the same 28 intervals for macroscopic charcoal (>125 µm) to examine local fire history (Whitlock and Larson 2001). We wet-sieved 2-cm^3 sediment subsamples using 125 µm screens and picked the charcoal from the sieves under low magnification using a stereozoom microscope.

Results

Chronology and core description

Four ordered AMS radiocarbon dates provided chronological control of the sediment profile (Table 1) and indicated that the core represents the past ~1000 years (ESM1). We delineated two zones in the core based on stratigraphy and LOI (Fig. 2): Zone 1 encompasses ~330 cal yr BP to present (43–0 cm) and Zone 2 ~960 to 330 cal yr BP (160.5–43 cm). Zone 2 contained reddish silty peat (likely *Rhizophora*) with soft laminations, numerous plant macrofossils, serpulid worm tubes, and gastropod shells from two species (*Heleobops clytus* and *Pyrogophorus coronatus bermudezi*) of the largely freshwater Cochliopidae family (Strong et al. 2008). A thin layer of gastropod shells at 149–148.5 cm was overlain by a 6.5 cm peat layer from 148.5–142 cm. Another gastropod shell lamina is located at 115 cm, overtopping a thin (1 mm) layer of plant macrofossils, likely leaves. We excluded the 65–49 cm core section from pollen analysis due to evidence of bioturbation of the softly laminated silty peat by vertical worm tube and mangrove root (now decomposed) growth. We sampled the unaffected intervals of the section for other proxy analyses. Sediments of Zone 1 (43–0 cm) consist of ~23 cm of microbial mats finely laminated with layers of evaporite minerals, clay, silt, and sand overlain by 20 cm of coarse sand, salt crystals, and pebble-sized clasts (Fig. 2).

Carbonate content was highest throughout Zone 2 (particularly 160–79 cm) comprising ~50% of the sediment with a gradual decline upward to the transition to Zone 1. Gradually increasing silicate contents from the bottom to the top of the core were reflected by increasing sediment density values (Fig. 2). Silicates increased to ~90% of the sediment mass in Zone 1, except for a few synchronous peaks at 41, 33, and 22 cm in the water, carbonate, and organic components. Magnetic susceptibility values were relatively stable and low in Zone 2 with increasing variability towards the top of the core. In Zone 1, peaks in magnetic susceptibility values corresponded with increases in silicate fractions and deposits of coarse sand and pebbles (Fig. 2).

Identification of hurricane deposited sediments

We interpreted eight hurricane events in the core between ~910–170 cal yr BP (Fig. 2) based on sediment lithology and geochemistry. The oldest interpreted hurricane (~910 cal yr BP) deposit consists of a gastropod shell lamina ~0.5 cm thick overlain by 6.5 cm of mangrove peat from 148.5–142 cm. Stable oxygen isotope results (Hildebrandt 2013) revealed a significant negative $\delta^{18}O$ excursion at this depth interval as well, interpreted as large influxes of hurricane-derived meteoric waters (Fig. 2; Lawrence et al. 2008). Another negative $\delta^{18}O$ excursion occurred in sediments from 127 cm (~800 cal yr BP), along with a distinctive layer of organics (probably leaf fragments), possibly deposited by a weaker storm that did not generate overwash of shells or sand. Another Cochliopidae shell lamina at 115.0 cm (~730 cal yr BP), also associated with a significantly negative excursion in the $\delta^{18}O$ record (Hildebrandt 2013), overlaid a thin (1 mm) layer of plant macrofossils, again mainly leaf fragments. Stable oxygen isotope analysis reveals evidence for additional hurricanes at 80 and 75 cm (~530 and 500 cal yr BP) though no overwash, shell, or plant macrofossil deposits were found at these depths. Zone 1 contained a high number of closely spaced hurricane overwash events, with clast layers from 43–36 cm (~330 cal yr BP), 33–28 cm (~260 cal yr BP), 26 cm (~210 cal yr BP), 24–22 cm (~200 cal yr BP), and 20 cm (~170 cal yr BP). Poor ostracod valve preservation precluded examination of the stable oxygen isotope record for clastic layers found above 65 cm.

Pollen and charcoal stratigraphy

Pollen concentrations varied substantially (8,930–172,874 grains cm^{-3}) across samples, with the highest found in the more organic Zone 2 sediments. Pollen preservation also varied among samples, with indeterminate pollen grains accounting for 18–38% of the pollen sum. Samples contained pollen representing 43 families (ESM2), with dominant taxa including Urticaceae/Moraceae (excluding *Cecropia*), Fabaceae (subfamily Mimosoideae), and Cyperaceae (sedges). Other important taxa represented included *Pinus*, Poaceae, Araceae, Melastomataceae, Piperaceae, *Celtis, Bursera*, and Arecaceae (palms) (Fig. 3). Most pollen grains represented lowland dry forest (Fabaceae), scrub (Urticaceae/Moracaceae), and sedges.

Pollen grains of Urticaceae/Moraceae and Mimosoideae, present at all sampled depths, accounted for ~4–50% percent of the sample pollen sums. In general, pollen representative of lowland tropical dry forest was more abundant in Zone 2, while Zone 1 is dominated by scrub and herb pollen taxa. Pollen of upland and montane moist forest taxa (including Ericaceae, *Myrica*, *Weinmannia*, and *Pinus*; Bolay 1997; García et al. 2007) were relatively rare in the Alejandro record, with greater representation in Zone 2, particularly from 118–83 cm (~750 to 540 cal yr BP).

Microcharcoal fragments were present in all 28 levels varying from ~1,500–119,000 fragments cm^{-3}. Concentrations were generally higher in the older sediment samples, particularly from ~920–780 cal yr BP. A major peak in microcharcoal concentration at 137 cm (~850 cal yr BP) occurred in the sample just above the earliest inferred hurricane deposit (~910 cal yr BP). We found macroscopic charcoal in six (67.5, 83, 112, 118, 127, and 136 cm) of the 28 levels examined, all in Zone 2 (Fig. 3), including in sediments at or above four inferred hurricanes (~910, ~800, ~730, and ~500 cal yr BP).

Discussion

Lake history

We interpret the basal sediments of the Alejandro core, composed mainly of silty mangrove peat and containing sedge pollen, abundant plant macrofossils, Cochliopidae gastropod shells, and *Cyprideis* ostracod carapaces (Fig. 2), as evidence that the core site was part of a shallow, fresh- to brackish-mangrove wetland by ~960 cal yr BP. Wetland conditions persisted until ~330 cal yr

BP, when deposition of a coarse sand layer representative of a high energy event initiated an abrupt environmental shift to lacustrine conditions. We interpreted the sand layer as an overwash deposit by a major hurricane that produced strong winds, storm surge, and lowland flooding in coastal areas that can cause massive mangrove mortality (Sherman et al. 2001; Cahoon et al. 2003; Smith et al. 2009) and probably led to subsequent peat collapse at our core site. Mangroves at Alejandro may be especially sensitive to damage from hurricane winds and flooding owing to the lake's windward location for Caribbean storm tracks and its hydrogeomorphic position as a coastal body of water at the base of Sierra Martín García (Fig. 1). Clays overtopping the sand layer, along with the change to clastic sedimentation from ~330 cal yr BP to present (Fig. 2), further support our interpretation of a major ecosystem shift from a shallow wetland to lacustrine conditions.

The mangrove peat in the lower section of our core suggests a core-site elevation near sea level from ~960 to 330 cal yr BP, but we obtained the core under ~2.6 m of water. The abrupt boundary between peat and clastic sediments may indicate a rapid lowering of the lake bottom after the ~330 cal yr BP hurricane. Today, mangrove forests fringing Alejandro are small in spatial extent and located mainly on the landward shores of the lake, though the interpreted *Rhizophora* peat in our lower core documented the history of mangroves at our presently inundated core site near the coastal shoreline of the present lake.

Peat collapse, documented in experimental plots and interpreted from sediment cores, has been linked to hurricane landfalls, sea-level rise, and tectonic subsidence (Cahoon et al. 2003; van Asselen et al. 2011; McCloskey and Liu 2013b). McCloskey and Liu (2013b) suggested seismic activity or a hurricane as possible causes of peat collapse interpreted from abrupt shift from mangrove peat to carbonate deposition representative of deeper water levels in sediment cores from Turneffe Atoll, Belize. At Bay Islands, Honduras, the passage of Hurricane Mitch in 1998 led to mass mangrove mortality followed by decomposition of the dead root material and sediment compaction (Cahoon et al. 2003). Reduced sediment elevation caused by peat collapse can have negative impacts on mangrove recruitment, which is primarily controlled by sediment elevation relative to tide height. Cahoon et al. (2003) suggested that peat collapse at Bay Islands (~11 mm yr^{-1} when measured 18 and 33 months post-hurricane) would continue for years due to reduced recruitment and poor root production from surviving mangroves. At Alejandro, we have evidence of relatively frequent hurricane landfalls from ~330 cal yr BP to present that may have allowed continued peat subsidence that slowed or prevented mangrove recovery, perhaps exacerbated by the deposition of ~43 cm of siliciclastic materials during this time period.

Peat compaction may also be linked to coastal flooding due to eustatic sea level rise (van Asselen et al. 2011), but the literature does not support this explanation for our site. We found no records of Holocene sea-level rise specifically for southern Hispaniola, but Holocene sea-level reconstructions from Jamaica (Digerfeldt and Hendry 1987) and the circum-Caribbean/western Atlantic (Toscano et al. 2003) indicated sea levels only ~30 cm lower than present when Alejandro sediments recorded a change from wetland to lacustrine conditions ~330 cal yr BP. The Alejandro core documents an abrupt change in hydrological conditions at that time, though sea level rise had slowed to ~0.9 mm yr^{-1} by 2,000 years ago (Toscano et al. 2003), ruling out sea level rise as the driver of hydrological change and leaving tectonic activity or tropical storms as plausible explanations.

While subsidence linked to tectonic activity could be a possible explanation for hydrological change at Alejandro, we find that our sedimentary proxies point directly at a hurricane event. Western Hispaniola is a tectonically active region, with the strike-slip

Enriquillo-Plantain Garden Fault running west-east through Haiti to the Enriquillo Valley, north of Alejandro. A 500-year record of seismic activity for western Hispaniola documented five earthquakes between 1701–1860 CE, though all postdate the interpreted change from wetland to lake conditions at Alejandro (~1620 CE). The epicenter of the of the 1701 earthquake, dating closest to the hydrological change at Alejandro, was located in Port-au-Prince (as well as three later earthquakes), ~140 km west of our study site. Historical records indicate that the 1701 event was not felt east of the Enriquillo Valley and therefore not likely to have impacted Alejandro (Bakun et al. 2012).

If our interpolated date of ~330 cal yr BP (~1620 CE) is actually more recent, then the 18th century earthquakes could be considered as a mechanism for the dramatic environmental changes at Alejandro. However, we interpret the presence of a sand overwash layer overtopping mangrove peat to be strong evidence that a hurricane was responsible for the major hydrological change and subsequent ecosystem shift at our core site. In 1680, a major hurricane devastated Santo Domingo and surrounding areas of southern Hispaniola (Schwartz 2016) and may be the event documented by our core. Geological studies of Hispaniola indicate that Sierra Martín García has remained tectonically stable since the last interglacial while the Barahona coastline (Fig. 1) has been uplifting 2.3 mm yr^{-1} in recent times (tidal gauges; Emery and Aubrey, 1991) and at a slower rate of <1 mm yr^{-1} over the past ~125K years (terraces; Mann et al. 1995). Thus, we do not expect that tectonic subsidence has impacted relative sea level at our site during the period of study.

After the ~330 cal yr BP event and to the present, Alejandro shifted to clastic sedimentation, low aquatic primary productivity, and high salinity based on lithological evidence, the lack of floral and faunal micro- and macro-fossils in this core section (Fig. 2), and present hypersalinity of the lake. The uppermost sediments representing ~200 cal yr BP to present were composed of coarse clastic sediments indicative of frequent high energy disturbance events that we think represent relatively frequent hurricane overwash deposits (Fig. 2), in agreement with historical records that document abundant hurricane activity in the Caribbean over the past two centuries (Knapp et al. 2010), as well as the presence of old overwash fans that terminate in the southern end of the lagoon and more recent fans that terminate on the coastal barrier (personal observation).

Following a period of high lake levels ~330 cal yr BP, Alejandro experienced aridity and low lake levels for almost a century, with the onset of extremely dry conditions by ~220 cal yr BP, as evidenced by finely laminated evaporites within a matrix of clastic sediments. Thin (< 5 mm) evaporite lamina alternate with thin (< 5 mm) microbial mat layers during a period of more frequent hurricane activity (Fig. 2). We interpret these microbial mats as representing brief freshening events related to hurricane events followed by the formation of evaporite deposits during rapid returns to drought conditions, an interpretation supported by the findings of Paerl et al. (2003) who documented microbial mats growth following Hurricane Floyd (1999) temporarily freshened hypersaline Salt Pond, San Salvador Island (Bahamas).

Hurricane landfalls, fire, and vegetation response

The earliest hurricane recorded in Alejandro occurred ~910 cal yr BP and is represented by a 0.5 cm layer of gastropod shells (whole and angular fragments) within a matrix of mangrove peat. While sand and coral fragments were absent from the shell deposit, we interpret the simultaneous massive freshwater (meteoric) influx, indicated by the stable isotope record (Fig. 2), as evidence that the layer represents a short-term change in water level and chemistry caused by high precipitation during a hurricane that did not produce an overwash deposit at the core site. A single sediment core would not capture all hurricanes that have struck the study site (Liu and Fearn 2000; Liu 2013). Storm strength and site characteristics, such as coastal geomorphology and barrier height, which often changes over time, can affect both the spatial variability of overwash deposits within backbarrier environments and a core site's sensitivity to overwash events over time. Our goal was to reconstruct a broader environmental history from one sediment profile rather than document a more complete hurricane history using multiple cores.

Heavy precipitation associated with the ~910 cal yr BP event would have temporarily freshened the site and expanded flood waters into low lying areas bordering the lake, providing conditions for Cochliopidae gastropods to thrive until flood waters receded and salinity increased through evaporation, causing a gastropod population collapse. Sudden, episodic increases in lake sediment ostracod assemblages and shells of *Pyrgophorus parvulus*, a freshwater gastropod of the same genus observed at Alejandro, were similarly interpreted as expansion and freshening of Freshwater Pond, Barbuda, linked to increases in precipitation (Burn et al. 2016).

After the ~910 cal yr BP event, the pollen record indicated a decline in tropical forest (Mimosoideae spp.), and expansion of disturbance and wetland vegetation around the lake (*Cecropia*, *Celtis*, and Cyperaceae). Slight increases in pollen of relatively rare humid and montane taxa (Piperacae, *Pinus*, Ericaceae (a heliophyte), and *Myrica*), may indicate increased canopy gaps in the humid forests at higher elevations of Sierra Martín García, possibly related to the ~910 cal yr BP hurricane. Fires occurred in lowland forests around Alejandro following the storm, as indicated by the presence of macroscopic charcoal. Microcharcoal concentrations peak ~850 cal yr BP and indicate an increase in regional fire activity, perhaps tied to the ~910 cal yr

BP event. Hurricane winds can prune or topple trees and would have increased fire fuel loads around Alejandro and in the broader region affected by the storm. Inundation by flood waters can also kill vegetation and contribute to fuel loads in coastal and low-lying areas. Increased insolation on forest floors after wind-generated canopy disturbance would then accelerate drying of the dead biomass increasing the probability of fires. Ignitions were likely associated with lightning (Myers and van Lear 1998).

Small charcoal fragments (<125 µm) can be lofted into the atmosphere during intense crown fires, so a portion of our microcharcoal may originate from "background" fires in pine or mixed-pine forests far from Alejandro (Patterson et al. 1987; Whitlock and Larson 2001). However, the macroscopic charcoal in sediments representing ~850 cal yr BP provides a record of local fires in forest/scrub fringing Alejandro and corroborates the interpretation of increased fires in the area. Post-hurricane fires may have prevented tropical dry forests in the pollenshed from recovering, as indicated by continued lower percentages of Fabaceae pollen relative to Urticaceae/Moraceae pollen almost a century after the hurricane (133 cm).

Post-hurricane fires and delayed forest recovery at Alejandro is consistent with findings from sedimentary studies of hurricane-fire interaction in two very different ecosystem types: mainland Caribbean swamp forests of Nicaragua (Urquhart 2009), and subtropical coastal pine-oak-hickory forests in the southeastern United States (Liu et al. 2008). Urquhart (2009) and Liu et al. (2008) also interpreted increased fire activity and delayed vegetation recovery related to hurricane landfalls from their sedimentary pollen and charcoal records. Possible increases in local fire activity during periods of frequent hurricane activity were also interpreted from macroscopic charcoal in sediments from a coastal lagoon in southeastern Cuba, though hurricane landfalls did not always lead to corresponding peaks in macroscopic charcoal (Peros et al. 2015).

Accounts of lightning-ignited fires are rare in tropical dry forests of the Neotropics, though the importance of lightning as an ignition source in tropical dry forests outside of the region has been recognized (Middleton et al. 1997). While infrequent on historical time scales, our data indicate that fires have occurred in tropical dry forests of southwestern Hispaniola and may be linked to hurricane landfalls.

The oxygen isotope record indicated another hurricane at ~800 cal yr BP (127 cm), though a storm-generated sand deposit was absent from that interval of our core. Intense precipitation associated with a hurricane may have washed organic detritus from the barrier (vegetated by mostly deciduous woody plants) into the core site, explaining the unusual 1 mm-thick layer of leaf fragments deposited in that interval. The oxygen isotope record may be a more sensitive proxy for detecting hurricanes that impacted the site but did not leave a clastic overwash deposit. Our charcoal record indicates local burning around the time of, and in the decades following, this storm. Lowland tropical dry and upland forests seemed to recover within ~50 years, as indicated by Fabaceae pollen dominance and the presence of rare upland pollen types (*Weinmannia*, *Myrsine*; Fig. 3). Changes after another inferred hurricane at ~730 cal yr BP (115 cm) followed the same pattern as the ~910 and 800 yr BP events with local fires followed by tropical dry forest decline coincident with increases in scrub, herbaceous, and disturbance taxa. Again we interpreted tropical dry forest recovery by ~50 years later as indicated by the highest pollen concentrations found in the entirety of the Alejandro sedimentary record (Fig. 3).

Significant negative $\delta^{18}O$ excursions indicated that two additional hurricanes impacted the site ~530 and 500 cal yr BP, though corresponding layers of clasts or plant macrofossils indicative of landfalls were absent (Fig. 2). The absence of geological evidence of hurricanes in our core is not surprising given the many factors that can affect whether and where overwash deposits are located (Liu 2013). Low pollen concentrations in sediments representing ~540 to ~350 cal yr BP prohibited reconstruction of vegetation changes during that period. Macrocharcoal deposited in sediments dating to ~460 cal yr BP indicated local burning around the lake, perhaps linked to one or both inferred tropical storms.

The Alejandro sedimentary record documents at least five interpreted clastic overwash deposits in the most recent ~350 years (Zone 1, Fig. 2), including a ~330 cal yr BP hurricane, which drove the shift from wetland to lake. We were unable to validate the interpreted hurricanes in Zone 1 with the oxygen isotope record due to the absence of ostracod carapaces. The pollen record, limited to two stratigraphic levels, documented lowland forest decline and the presence of disturbance taxa (Fig. 3) after the interpreted ~330 yr BP hurricane. Microcharcoal, indicative of regional fires, was present in our uppermost sediments and may be associated with hurricane disturbance of forests. We found no sedimentary evidence of local fires (macroscopic charcoal) in Zone 1 (Fig. 3). Relatively frequent hurricanes occurring during Zone 1 may have prevented sufficient accumulation of fuels to support fires. In southeastern Cuba, multiple inferred hurricane landfalls ~500–250 cal yr BP did not always lead to increases in local fire activity (Peros et al. 2015). Together, the Cuba record (Peros et al. 2015) and our findings provide evidence of multiple controls of fire activity in lowland environments of the Caribbean.

Links between tropical storms, fires, and climatic variability

Variability in fire frequency interpreted from sedimentary charcoal in the Alejandro core may have multiple causes including hurricane landfalls, shifts in climate or vegetation states, and possibly human activities. At Alejandro, hurricane landfalls alone cannot explain our fire record.

Macrocharcoal indicative of local fire is found after inferred hurricanes at ~910, 800, 730, and 500 cal yr BP indicating a likely causal effect. In contrast, relatively frequent inferred hurricane landfalls from ~330 cal yr BP to present coincided with the absence of macroscopic charcoal, possibly representing a decline in local fire or changing taphonomic processes associated with the shift from wetland to lake. For example, mangroves or wetland vegetation may have burned during the wetland phase of the lake's history, providing large charcoal directly to the sediments. The change to a lacustrine state and associated local mangrove decline may have reduced the chances for macroscopic charcoal introduction. Microcharcoal was most abundant from ~1000 to 700 years ago, with overall decreased, though variable, concentrations after ~700 years ago to present. The only major peak (~850 cal yr BP) after an inferred hurricane ~910 yr BP may reflect abundant fires after a very intense hurricane landfall, supported by the longer vegetation recovery time of ~100 years after that hurricane versus <50 years after other inferred events.

Some Caribbean lake sediments have shown increases in charcoal abundance associated with human activities (Higuera-Gundy et al. 1999; Caffrey and Horn 2015) though we found no such increases in our core. The El Curro archaeological site ~6 km from Alejandro dates to ~3400 yr BP although the interpretation of the site is debated. The investigators found *Zea mays* pollen grains in shallow (10–20 cm) soil excavations that may represent consumption or "intrusive elements" mixed downward through cultivation by later agricultural peoples (Ortega and Guerrero 1981; Lane et al. 2008). We found no pollen evidence of cultivated species, such as *Zea mays* in our sediments though it was being grown in mountains of the DR by 890 yr BP (Lane et al. 2008). Whether El Curro was occupied during the time period represented by our core is also unclear. Given the distance from Alejandro to El Curro and its description as preagricultural (Ortega and Guerrero 1981), we would not necessarily expect pollen from cultivated crops nor macroscopic charcoal associated with indigenous human activities to contribute to the Alejandro record.

In terms of possible climatic influence on fire, our analysis of the stable oxygen isotope record from Alejandro, which displayed overall negative $\delta^{18}O$ values indicative of decreased evaporation, corroborates studies that point to evidence of moister conditions in the Caribbean during the Medieval Warm Period (MWP, AD 950–1250, 1000–700 yr BP, Fig. 4). Haug et al. (2001) interpreted variable, but high, precipitation conditions from analysis of sediments from the Cariaco Basin, off the north coast of Venezuela. In the northern Caribbean, at Clear Pond and Storr's Lake, San Salvador Island, Bahamas, a change from arid to moist conditions at ~700 yr BP was reflected by stratigraphic changes in lake cores (Park 2012). Oxygen isotope data from Laguna Felipe, DR, ~60 km northeast of Alejandro, revealed relatively wet conditions during the MWP (Lane et al. 2011) as do data from Lake Miragoâne, Haiti (Hodell et al. 1991).

Increased regional fire activity, reflected by the Alejandro microcharcoal record, coincides with the MWP and may indicate that climate is another driver of Caribbean fire activity. More abundant lightning and fuels (biomass) associated with relatively moist periods could provide more frequent natural ignitions (Higuera–Gundy et al. 1999). A comparative analysis of sedimentary charcoal from Laguna Saladilla (DR), Laguna Tortuguero (Puerto Rico, Burney and Burney 1994), and Lake Miragoâne (Higuera-Gundy et al. 1999) by Caffrey and Horn (2015) documented low microcharcoal in the early Holocene and increases in all three lakes during the mid- to late-Holocene that were interpreted as evidence of climatic influences on fire activity in the Caribbean, though the role of human activity cannot be excluded. On Hispaniola, at Saladilla and Miragoâne, large charcoal increases post-European contact were associated with increasing human ignitions (Caffey and Horn 2015). Conversely, at Alejandro microcharcoal was more abundant during the MWP and only slightly increased during the last ~200 years, with this recent increase in regional fire activity possibly influenced by frequent hurricane landfalls (Fig. 2).

Sedimentary records from the circum-Caribbean have provided evidence of the onset of relatively arid conditions ~550 cal yr BP, coincident with the onset of the Little Ice Age (LIA, 15th –19th centuries, ~550–150 yr BP) and cooler sea surface temperatures (SSTs) in the North Atlantic and Caribbean (Hodell et al. 2005; Lane et al. 2011; Fensterer et al. 2012). At Las Lagunas, ~60 km northeast of Alejandro, ~650 to 300 cal yr BP was marked by increasing aridity, punctuated by extreme droughts at ~380 and 300 cal yr BP, as interpreted from oxygen isotope analyses (Lane et al. 2011). Ostracod and gastropod oxygen isotope ratios from sediments of a sinkhole pond on the Yucatan Peninsula (Hodell et al. 2005) and titanium and iron x-ray fluorescence data from sediments of the Cariaco Basin (Haug et al. 2001) also point to lower precipitation during this period. Analysis of sediments from Freshwater Pond, Barbuda (Burn et al. 2016) and a Cuban stalagmite (Fensterer et al. 2012) suggests that the region was not uniformly dry during the LIA but rather experienced greater precipitation variability by location and on multi- and sub-decadal timescales versus during the MWP. Our interpretation of brief freshening events and rapid returns to drought conditions ~220 cal yr BP (~1730 AD), in addition to the high number of hurricane overwash events in our core from ~330 cal yr BP (~1620 AD) to present also support high precipitation variability during the LIA, responsible in part to more frequent hurricane and tropical storm activity.

On multidecadal to millennial timescales, climatic variability (SSTs and precipitation) in the Caribbean is influenced by the movement of the Intertropical Convergence Zone (ITCZ), while El Niño-Southern Oscillation is linked to both precipitation variability and hurricane activity in the Atlantic on subdecadal timescales (Fensterer et al. 2012; Peros et al. 2015; Burn et al. 2016). A more southerly position of the ITCZ during the LIA, possibly tied to weaker thermohaline circulation (Fensterer et al. 2012), provides a mechanism for increased hurricane frequency (and associated precipitation variability) documented in our core (Figs. 2, 4) and in other sedimentary records in the circum-Caribbean (Liu et al. 2000; Haug et al. 2001; Fensterer et al. 2012; McCloskey and Liu 2012; McCloskey and Liu 2013a). When the ITCZ occupies a more southerly position, the Bermuda High, a semi-permanent high pressure air mass over the Atlantic subtropics, is also pushed southward and hurricane tracks are steered through the Caribbean and Gulf of Mexico versus the North Atlantic along the eastern seaboard of the United States (Liu et al. 2000; Park 2012; Peros et al. 2015).

In general agreement with other paleo-records from the region, the $\delta^{18}O$ record from Alejandro indicates a shift to increased evaporation and salinity, suggestive of more arid conditions at the site, beginning ~540 cal yr BP (Fig. 4). Stable oxygen isotope data are unavailable for ~450 cal yr BP to present, due to a lack of ostracod carapaces, but the $\delta^{18}O$ data display a consistent trend towards more positive values upward in the core from 85 cm, indicating a progressive increase in evaporation, coincident with the onset of the LIA (Fig. 4).

Conclusions

This multi-proxy analysis of a sediment core provides a 1000-year record of inferred hurricane activity and climatic shifts, and their links with fire and vegetation patterns, in seasonally-dry forests of southwestern Dominican Republic. We interpreted eight hurricanes from geological evidence and loss on ignition data, with two additional events interpreted from the stable oxygen isotope record, a new proxy data source for identification of tropical storms (Lawrence et al. 2008). The increased number of hurricanes during the last ~300 years matches well with several other sedimentary and historical records from the circum-Caribbean that documented enhanced tropical storm activity, probably linked to a more southerly position of the ITCZ during the LIA (Fensterer et al. 2012; McCloskey and Liu 2012; Peros et al. 2015).

Regional and local fire activity around Alejandro appeared to be linked to hurricane events and precipitation shifts. During the moister MWP, high microcharcoal concentrations in the Alejandro record reflected increased regional fire activity. Macrocharcoal presence within hurricane overwash deposits and in samples just above deposits provided evidence that local fires were associated with increased fuel availability after tropical storm events. Frequent droughts during the LIA, in conjunction with more frequent hurricane landfalls at Alejandro, may have limited forest recovery and accumulation of woody biomass, explaining the lack of local fires. Our findings of increased fire activity following hurricane events are similar to paleoenvironmental studies from the region: a coastal mangrove lagoon in Cuba (Peros et al. 2015), a swamp forest on the Caribbean mainland (Urquhart 2009), and a subtropical coastal lake on the Gulf coast of the United States (Liu et al. 2008).

Alejandro's pollen record suggested that during the relatively moist conditions of the MWP, hurricane landfalls and subsequent fires led to tropical dry forest decline at the expense of expanding scrub and disturbance taxa. Forest recovery followed within several decades. By contrast, during LIA, the pollen record revealed delayed recovery of Caribbean dry forests after multiple relatively closely spaced hurricanes. Frequent droughts may have exacerbated the effects of multiple hurricane strikes.

A hurricane landfall ~330 cal yr BP initiated a major change in state at our core site from shallow mangrove wetland to lacustrine conditions. The ~330 cal yr BP event initiated lowland flooding and peat collapse at the core site, drowning mangroves and permanently altering the core site and perhaps the surrounding environment. Our study adds to the body of literature documenting patterns of Caribbean tropical storm activity, drought, fire, and ecological responses to these interwoven disturbances which vary on both spatial and temporal scales. Reconstructions of long-term environmental changes are still relatively rare in the insular Caribbean and additional studies from lowland and coastal environments of the Caribbean are especially needed to reveal local and regional variations in late-Holocene hurricane activity, climate, and hurricane-vegetation-fire dynamics.

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Figure Captions

Figure 1. A. The Dominican Republic (DR, dark gray) occupies the eastern two-thirds of the island of Hispaniola. B. The study area (box) in the semi-arid southwestern DR lies in the rainshadow of the Cordillera Central. C. Location of sediment core ALEJ08 within Laguna Alejandro.

Figure 2. Chronology, lithology, loss-on-ignition, core logger (magnetic susceptibility and bulk density), and significant negative $\delta^{18}O$ excursions from stable isotope analysis of ostracod valves results for the Alejandro core. Hurricane events are indicated by gray bars.

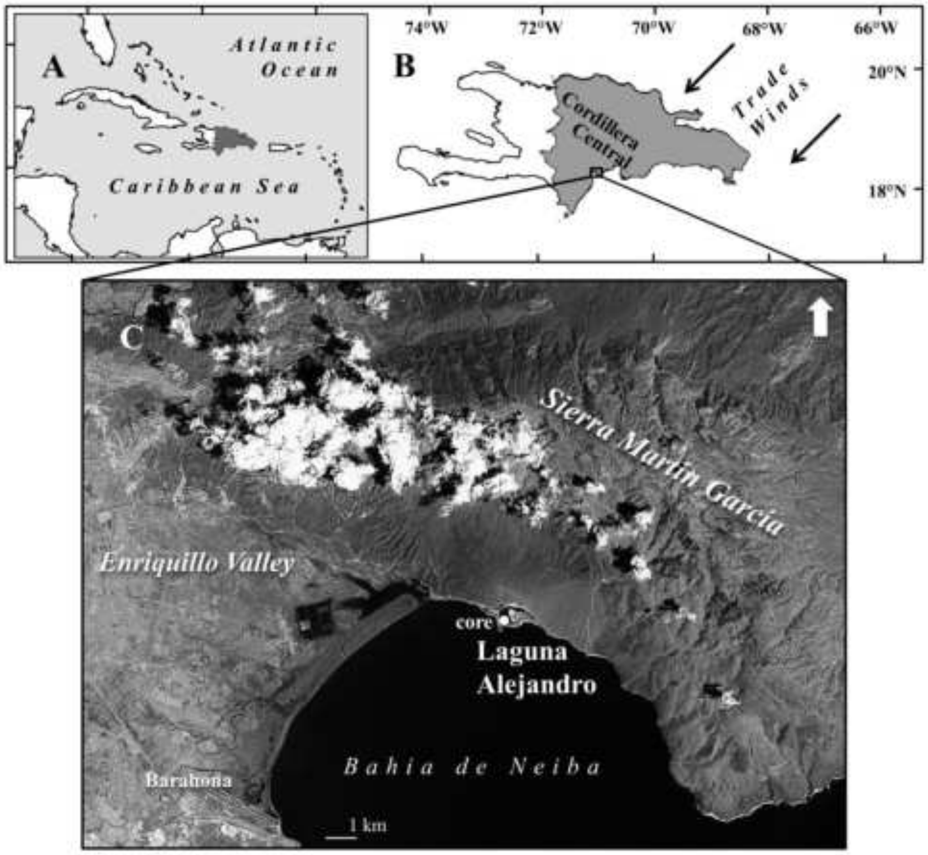
Figure 3. Core (ALEJ08) chronology, pollen and spore percentages, microscopic (>10 µm) charcoal concentration, macroscopic charcoal (>125 µm) presence, and pollen concentrations. Ages are the weighted means of the 2-sigma calibrated radiocarbon ages (cal yr BP). Black dots represent presence of rare pollen types and asterisks note presence of macroscopic charcoal. Hurricane events are indicated by gray bars. Note that the Urticaceae/Moraceae group excludes *Cecropia*.

Figure 4. Stable oxygen isotope composition of *Cyprideis* sp. ostracod valves in the Alejandro sediment core. To control for long-term variations in the $\delta^{18}O$ record, negative excursions were identified by difference from the five-point running mean value that we label $\Delta^{18}O$. Poor ostracod valve preservation prevented analysis of the stable oxygen isotope record in samples above 65 cm. Error bars represent 1σ.

Table 1. Radiocarbon date (Accelerator Mass Spectrometry) results for sediment core ALEJ08.

Lab no.[a]	Depth (cm)	Material	Uncalibrated ^{14}C age (^{14}C yr BP)	2-σ calibrated range (cal yr BP)	Weighted mean (cal yr BP)
X15115A	46.5	Plant fragments	336± 50	496–304	350
ALEJ08D	83.5	Charcoal	510±30	554–505	543
X15116	127.5	Leaf fragments	927±45	927–757	803
X15117A	159.0	Plant fragments	1,027±55	1,058–892	955

[a] Letters before lab numbers denote samples processed at the University of Georgia Center for Applied Isotope Studies (X) or the Accelerator Mass Spectrometry Laboratory at the University of Arizona.



Atlantic Ocean
A
Caribbean Sea
74°W
72°W
70°W
68°W
66°W
B
20°N
18°N
Cordillera Central
Trade Winds
C
Sierra Martin Garcia
Enriquillo Valley
core
Laguna Alejandro
Bahia de Neiba
Barahona
1 km

Figure 1

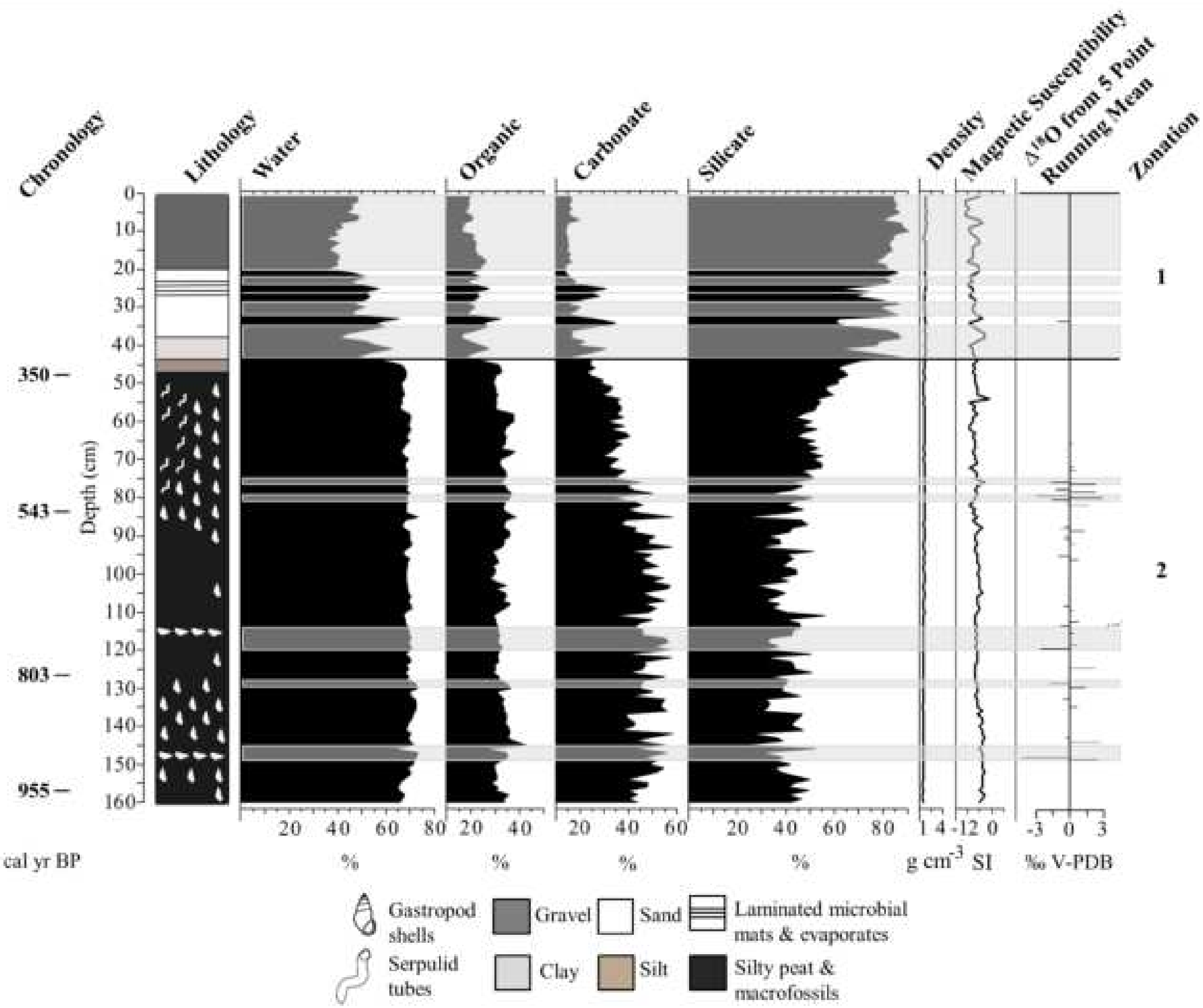
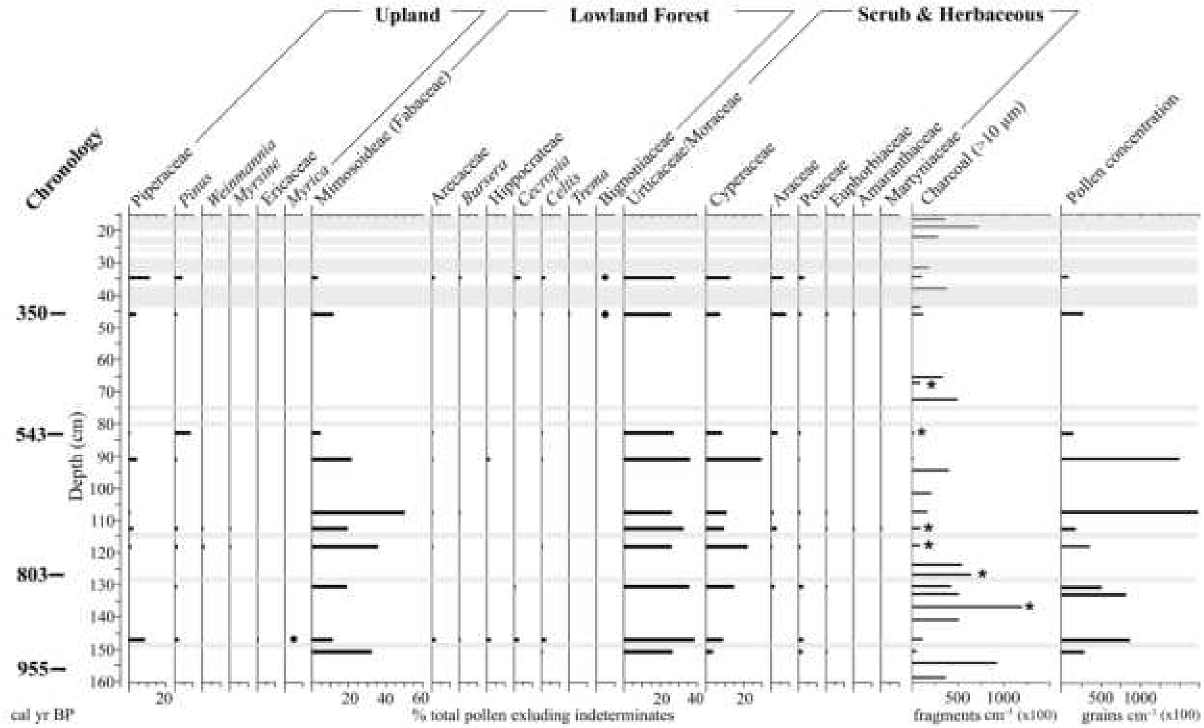

Chronology
Lithology
Water
Organic
Carbonate
Silicate
Density
Magnetic Susceptibility
Δ18O from 5 Point Running Mean
Zonation
Depth (cm)
350
543
803
955
cal yr BP
%
g cm-3
SI
‰ V-PDB
1
2
Gastropod shells
Serpulid tubes
Gravel
Clay
Sand
Silt
Laminated microbial mats & evaporates
Silty peat & macrofossils

Figure 2



Upland
Lowland Forest
Scrub & Herbaceous
Chronology
Piperaceae
Pinus
Weinmannia
Myrsine
Ericaceae
Myrica
Mimosoideae (Fabaceae)
Arecaceae
Bursera
Hippocrateae
Cecropia
Celtis
Trema
Bignoniaceae
Urticaceae/Moraceae
Cyperaceae
Araceae
Poaceae
Euphorbiaceae
Amaranthaceae
Martyniaceae
Charcoal (>10 μm)
Pollen concentration
350
543
803
955
Depth (cm)
cal yr BP
% total pollen exluding indeterminates
fragments cm⁻³ (x100)
grains cm⁻³ (x100)

Figure 3

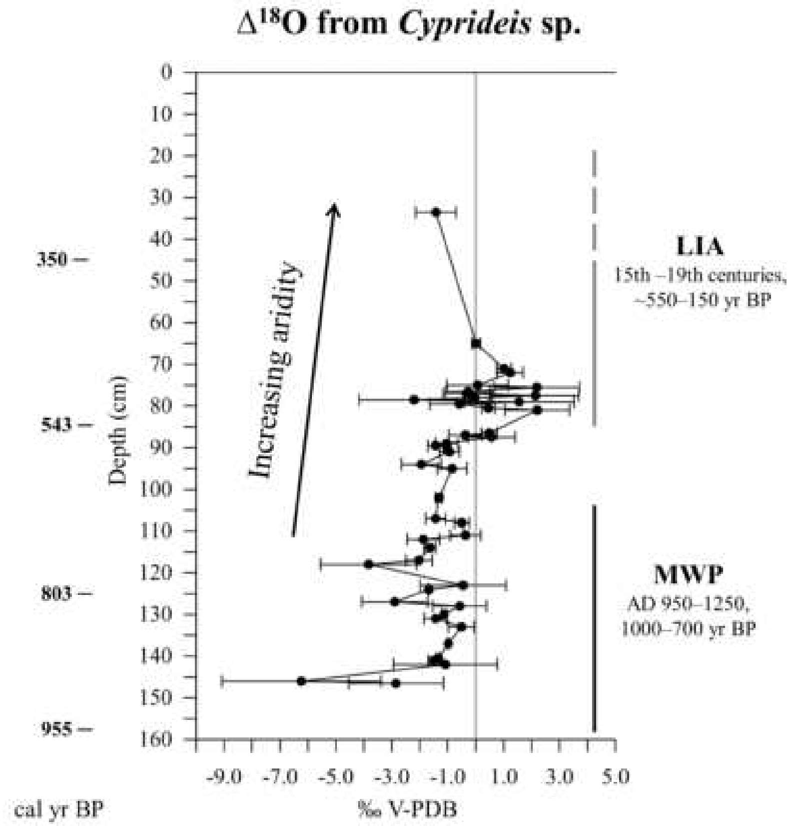
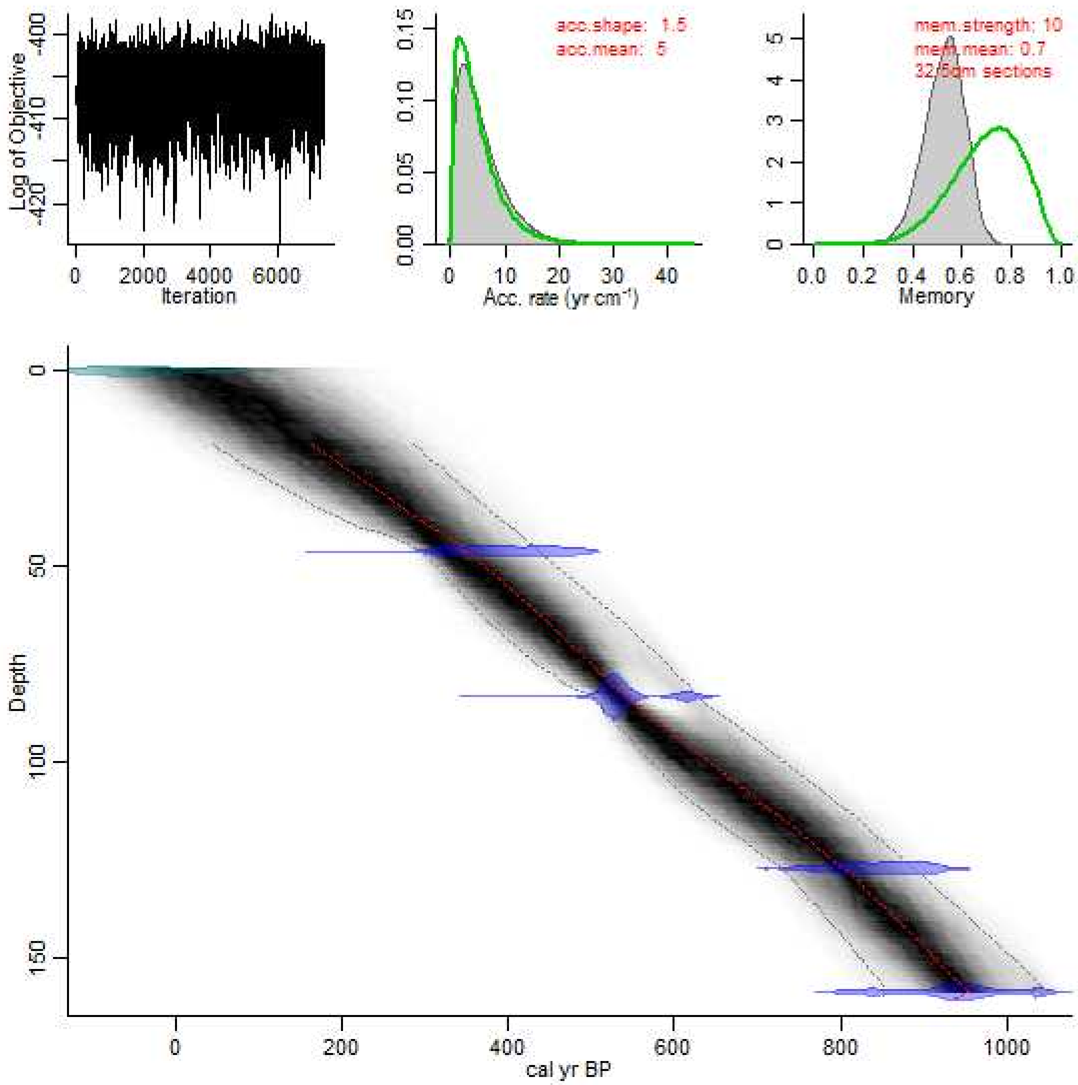

Δ18O from Cyprideis sp.
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
160
Depth (cm)
350 —
543 —
803 —
955 —
cal yr BP
Increasing aridity
-9.0 -7.0 -5.0 -3.0 -1.0 1.0 3.0 5.0
‰ V-PDB
LIA
15th –19th centuries,
~550–150 yr BP
MWP
AD 950–1250,
1000–700 yr BP

Figure 4

ESM1. Age-depth model for the Alejandro core created using Bayesian age modeling software Bacon (Blaauw and Christen, 2011). (Top Left) Log of objective shows no systematic structure across neighboring iterations, suggesting a good model run. (Top Middle) and (Top Right) show prior initial guesses (green) and posterior (gray) distributions for accumulation rate (i.e., sedimentation rate) and memory (how the accumulation rate is thought to have changed over time), respectively. (Bottom) shows calibrated dates (blue), with the mean age model (red) and 95% confidence interval of dates for a given depth (dashed lines) (6). Grayscale intensity indicates likelihood of an age for a given depth, with darker values indicating more likely calendar ages.



ESM2. Ecological groups represented by pollen taxa in the Alejandro record. Note that cosmopolitan and generalist taxa, as well as some other rare types, were not included in Figure 3, but are listed in this table.

Upland	Lowland forest	Scrub and herbaceous	Cosmopolitan and generalist taxa
Piperaceae	Mimosoideae (Fabaceae)	Urticaceae (non-*Cecropia*)/Moraceae	Acanthaceae
Pinus	Caesalpiniodeae (Fabaceae)	Cyperaceae	Amarylidaceae
Weinmannia	Arecaceae	Araceae	Annonaceae
Myrsine	*Bursera*	Poaceae	Apocynaceae
Ericaceae	Hippocrateae	Euphorbiaceae	Boraginaceae
Myrica	*Cecropia*	Amaranthaceae	Commelinaceae
	Celtis	Martyniaceae	Dioscoreaceae
	Trema	Asteraceae	Gesneriaceae
	Bignoniaceae	Scrophulariaceae	Loranthaceae
	Bromeliaceae		Lythraceae
	Lauraceae		Malpighiaceae
	Meliaceae		Malvaceae
	Myrtaceae		Monimiaceae
			Onagraceae
			Rubiaceae
			Sapindaceae
			Solanaceae

Chapter 3

Pre-Columbian anthropogenic burning and environmental change over the past two millennia from sediments of Freshwater Pond, Barbuda, Lesser Antilles

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Key Words: fire history, charcoal, pollen analysis, Caribbean, Little Ice Age, archaeology

Abstract

Questions remain regarding impacts of late-Holocene human activities and climate change to ecosystems of the Caribbean islands. Multiproxy analyses of a sediment core from Freshwater Pond combined with archaeological investigations documented more than 2,000 years of environmental and human history of Barbuda. This research represents a new entry to the sparse inland paleoenvironmental records from the Lesser Antilles that have largely focused on sediment cores documenting Holocene sea level rise and coastal wetland development. Sedimentary pollen and spores from Freshwater Pond reflect local vegetation history and indicated that the present pond was a shallow mangrove wetland until a lacustrine environment formed ~1450 CE, in response to increased precipitation in the northeastern Caribbean at the onset of the Little Ice Age (~1400–1850 CE). Abundant large charcoal particles (>125 μm) from sediments representing at least ~150 BCE (2100 cal. yr BP) to ~1250 CE suggests burning near the core site by indigenous people, a finding supported by the archaeological record. Pollen of *Cecropia* and *Piper* are likely linked to disturbance of and canopy gaps in vegetation growing near the core site over the past three millennia. Microscopic charcoal analysis indicated that extra-local burning continued until ~1610 CE, then declined, possibly reflecting a transition from indigenous human activities to land-use practices by Europeans who entered the region in 1492 CE and established a permanent settlement on the island in the 1660s. The sedimentary charcoal and pollen record of Freshwater Pond documents a long history of human disturbance that fits with recent archaeological findings and corroborates the evidence of Little Ice Age precipitation variability on Barbuda and in the region from previous analyses of gastropod abundance and stable isotopes performed on the same sediment core.

Introduction

Interpretations of sedimentary records from tropical America and the Caribbean agree that the mid- to late-Holocene was a time of climate variability and environmental change, but a review of these studies suggests that the timing and direction of changes were not consistent across the region. Pollen, microscopic charcoal, and stable oxygen isotope analyses from sediments of Lake Miragoâne, Haiti documented warm and moist climate conditions in the northern Caribbean by the mid-Holocene that persisted until ~1250 BCE (3200 ^{14}C yr BP; Higuera-Gundy et al., 1999; Hodell et al., 1991). In the Cariaco Basin, Venezuela, moist conditions during the early to mid-Holocene preceded drier conditions from ~3450 BCE (5400 cal. yr BP) to present, with increased precipitation variability interpreted for ~1850–850 BCE (3800–2800 cal. yr BP; Haug et al., 2001). By contrast, Fritz et al. (2011) interpreted decreased precipitation from sediments of crater lakes, Grand Etang and Antoine on the island of Grenada, southeastern Caribbean, lasting from the early-Holocene until ~3500 BCE (5500 cal. yr BP), after which lake level history indicated a long-term trend of increased moisture, especially from ~1250 BCE (3200 cal. yr BP) to present.

Both the Miragoâne (Hodell et al., 1991) and Cariaco Basin (Haug et al., 2001) studies interpreted variable but generally moist conditions for the Medieval Warm Period (MWP, 950–1250 CE, 1000–700 cal. yr BP). Stable oxygen isotopes from land snail shells also indicated wetter conditions during the MWP in the northeastern Caribbean at Guadeloupe (Beets et al., 2006) as do stratigraphic changes in lake cores from Clear Pond and Storr's Lake, San Salvador Island, Bahamas (Park, 2012). Several sedimentary (Grape Tree Pond, Jamaica, Burn and Palmer, 2014; Cariaco Basin, Venezuela, Haug et al., 2001; Laguna de Felipe, Dominican Republic, Lane et al., 2011) and archaeological studies (Anse à la Gourde, Guadeloupe, Beets et al., 2006) have interpreted increased aridity and drought events during the Little Ice Age (LIA, 1400–1850 CE, 550–100 cal. yr BP). Recent paleoclimatic studies in the northern Caribbean have challenged the conception of a uniformly drier Caribbean during the LIA, arguing for greater precipitation variability in some Caribbean locations on multi- and sub-decadal scales: high-resolution analyses of a stalagmite (Cuba, Fensterer et al., 2012), stable isotope analyses of sediment cores (Jamaica, Burn and Palmer, 2014; Barbuda, Burn et al., 2016), stable isotope and pollen analysis of a sediment core (Dominican Republic, LeBlanc et al., 2017). While a few paleoclimatology records represent the northern and western areas of the Caribbean region, the Lesser Antilles (eastern Caribbean) remain understudied, in part due to the dearth of appropriate study sites. Paleoenvironmental studies examining links between human activities, fires and other disturbances, and vegetation change over long time scales remain relatively rare from lowland and coastal sites in the insular Caribbean and are particularly rare in the Lesser Antilles region.

Peoples first moved out of the Orinoco river delta (northern South America) into Trinidad ~6000 BCE (8000 yr BP), though the first Archaic Age peoples did not move into the northern Lesser Antilles until ~3,000 years later, either from the Greater Antilles or South America or both, with several migrations following (Newsom and Wing, 2004; Rousseau et al., 2017; Wilson, 2007). While much is left to discover about the human history of the islands, including the timing of the colonization of the southern Lesser Antilles, archaeological investigations agree on the extensive use of marine and terrestrial resources by indigenous peoples. In the Lesser Antilles, coral reef, near shore, and coastal environments provided sources of protein, while lowland forest and mangroves provided plant-based foods, medicine, fuel, and wood for construction (Newsom and Wing, 2004; Wilson, 2007). Sparse paleoenvironmental records from coastal Lesser Antilles documented Holocene eustatic sea level rise and mangrove wetland development (Jessen et al., 2008; Ramcharan and McAndrews, 2006; Urrego et al., 2009; 2010), but few studies have tackled reconstruction of the environmental history of lowland tropical seasonal ecosystems.

Recently, Siegel et al. (2015) documented human colonization of the southern Lesser Antilles using multiproxy analysis of a suite of radiocarbon dated lake and wetland sediment cores from Trinidad, Grenada, Martinique, and Guadeloupe. Initial human colonization and impacts on terrestrial environments of the southern Lesser Antilles were interpreted for a period several millennia earlier than determined by the archaeological record, mainly by the concurrence of sedimentary pollen and spores of ethnobotanically significant and disturbance taxa with dramatic and sustained increases in charcoal particles (<150 μm). The work by Siegel et al. (2015) demonstrates that paleoenvironmental datasets can document initial human excursions into the islands despite low population densities and ephemeral material cultures of these fisher-gatherer-forager peoples. Sites dating to the early- to mid-Holocene may be largely absent from the archaeology of the Caribbean, especially the Lesser Antilles, because these Lithic Age peoples likely occupied coastal regions that were inundated or eroded by post-glacial sea level rise (Rousseau et al., 2017; Siegel et al., 2015).

Recent interpretations of spatially variable precipitation in the Caribbean during the late-Holocene and in recent centuries (Burn et al., 2016; Fensterer et al., 2012; Fritz et al., 2011) reveals the need for additional paleoenvironmental reconstructions from the Lesser Antilles to document climate change and human- and ecosystem-response. While the number of archaeological investigations in the Caribbean has increased in recent decades, there is still much to be learned of pre-Colonial human-environment interactions (Newsom and Wing, 2004; Wilson, 2007). Paleoecological studies involving analysis of biological and geochemical proxies from lake sediments in addition to the growing archaeological record from the region can elucidate the human and environmental histories of the islands.

The island of Barbuda in the northern Lesser Antilles provides an ideal study site to examine late-Holocene environmental and human history. Freshwater Pond (also referred to as Bull Hole, Watters et al., 1992), a hydrologically-closed inland pond, provided a >2,000-year sedimentary record of wetland development. A high-resolution analysis of stable isotopes and fauna (ostracods and gastropods) in sediment samples from the pond yielded a 500-year record of precipitation variability related to El Niño Southern Oscillation and Atlantic Multidecadal Oscillation (Burn et al., 2016). Ongoing archaeological work on Archaic, Ceramic, and Colonial Age (Table 1) sites across the island have provided insights into human arrival on the island, indigenous resource use and impacts on the environment, and colonization and land-use by Europeans. Our objective was to reconstruct the mid-late Holocene vegetation and fire history of Barbuda from pollen, spores, and charcoal preserved in the sediments of Freshwater Pond in the context of recent paleoclimatic (Burn et al., 2016) and archaeological findings (Bain et al., 2017; Rousseau et al., 2017).

Methods

Study area

Barbuda (Figure 1) is a small (~160 sq. km) low-lying limestone island located on the northeastern edge of the Lesser Antilles island arc, which separates the Caribbean Sea from the Atlantic Ocean (Brasier and Donahue, 1985). The island comprises Holocene and Pleistocene beach ridges and limestones, covered mostly by sands and thin, alkaline clays. The Highlands, a plateau (~45 m elevation) of older Pliocene limestone deposits (Brasier, 1975) constitutes the island's highest topography, and along with its western slopes, occupies a large portion of the east-central island. Codrington Lagoon dominates the northwestern third of island, which is characterized by a relatively flat coastal plain dotted with fresh- to saline-water ponds and lagoons and large wetland areas.

Located at the margin of the tropics (~17.5°N), Barbuda's climate is tropical seasonal (Aw in the Koeppen-Geiger system, Kottek et al., 2006). Rainfall patterns are influenced by year-round trade winds and shifting position of the Intertropical Convergence Zone. Barbuda is one of the driest Caribbean islands (Jackson, 2001), owing both to its flat topography and influence of the Bermuda High semi-permanent high-pressure system. Annual precipitation averaged 882 mm, summer temperature 29°C, and winter temperature 24°C between 1965 and 2000 (Jackson, 2001). Ten years during the same period were designated as "meteorological" droughts (Jackson, 2001). About half of Barbuda's rainfall occurs during the wet season (August to November) dropping to only ~20% during the January to April dry season (Jackson, 2001). Tropical storms and cyclones can contribute substantially to annual precipitation totals, creating considerable interannual variability in rainfall amounts. Between 1842 and 2016, 49 tropical storms and cyclones traveled within 100 km of Barbuda's center (NOAA, 2017). Twenty-four were named hurricanes Category 1–4, with Irma the first Category 5 hurricane in the historical record, devastating the island in September 2017.

Barbuda's vegetation is predominately secondary growth resulting from land use activities, particularly unrestricted grazing by cattle, goats, and other livestock after European colonization (post-1492 CE), combined with a long history of charcoal production and timber removal, and wind disturbance from repeated tropical storms. The dry, thinly soiled, lowlands are covered by an evergreen woodland (sometimes referred to as xeric- or cactus-scrub) of low canopy height (3–10 m), with densely-packed gnarled trees and shrubs, often spiny, with hard evergreen leaves of markedly reduced size, a common xerophytic adaptation. Succulents such as the cacti, *Pilosocereus royenii* (tree-form) and *Opuntia* spp., and *Agave karroto* occur in the woodland undergrowth and on cliffs and rocky exposures in the Highlands. The moister Highlands support closed-canopy, 2-storied forest with occasional emergents, such as *Bursera simaruba*, *Tabebuia heterophylla, and Ficus citrifolia,* along with other canopy species such as, *Bucida buceras, Pisonia subcordata, Canella winterana*, *Capparis* spp. (Lindsay and Horwith, 1997). Associations of taller trees, including the palm *Coccothrinax barbadensis*, *Sideroxylon* spp., *Coccoloba uvifera, Byrsonima lucida, Zanthoxylum flavum,* and several Myrtaceae species, are confined to the solution holes of the Highlands and dune depressions with permanent access to water (Lindsay and Horwith, 1997).

Coastal and wetland areas are dominated by mangrove species, including red (*Rhizophora mangle*), white (*Laguncularia racemose*), black (*Avicennia germinans*) and button mangroves (*Conocarpus erectus*) (Francis et al., 1994; Harris, 1963). Certain rarer tree species such as dogwood (*Lonchocarpus latifolius*), sweetwood (*Dipholis salicifolia*), satinwood (*Fagara flava*), lignum-vitae (*Guaiacum offincinale*), and fan palm (*Coccothrinax bardadensis*) are found on the island. These species are absent from nearby Antigua and interpreted as reflecting the more intensive land use, particularly the wide-spread establishment of plantation agriculture, on Antigua during the Colonial period (Harris, 1963).

Barbuda has a long human prehistory, with seasonal to permanent occupation of the island from the Archaic (~2000 BCE) through post-Colonial periods (Table 1). While earlier Archaic Age impacts on the Barbudan environment likely focused mainly of marine resource extraction and foraging for wild plants (Rousseau et al., 2017), the ceramic-producing culture groups practiced shifting (slash and burn) agriculture, resulting in the clearing of vegetation and burning of the residual biomass (Bain et al., 2017). Carbonized remains of tropical seasonal forest and coastal taxa, such as lignum-vitae (*Guaiacum officinale*.), cedar (*Tabebuia* spp.), and mangrove species (*Avicennia germinans*, *Conocarpus erectus*, *Laguncularia racemosa*), have been identified in archaeological sites on the island (Bain et al., 2017) confirming that these species have long been exploited for charcoal production, firewood, and construction materials by indigenous peoples (Francis et al., 1994; Harris, 1963).

Between 600–1200 CE (1350–750 yr BP), Ceramic Age cultures throughout the Caribbean were characterized by increased population growth and social and political complexity, resulting in the Taíno polities who inhabited the Greater Antilles at the time of European colonization (Newsom and Wing, 2004; Wilson, 2007). After ~1300 CE (650 yr BP), many of the Leeward Islands appear to have either been abandoned or very sparsely populated by indigenous inhabitants (Wilson, 2007). While various European powers were in the region beginning in 1493, colonies were not established in the Leeward Islands until the 1620s. Rather, the Spanish introduced livestock to the islands, and while the Spanish expanded westward, Barbuda was used as a source of livestock (horses, cattle, sheep, and goats), water, and timber until the English permanently occupied the island starting in 1666 (Bain et al., 2017; Harris, 1963). Unlike its sister island of Antigua, plantation agriculture was attempted but never established on Barbuda due to its infertile soils and low precipitation, and most inhabitants and cultivated lands were limited to the vicinity of Codrington village (Figure 1; Harris, 1963; Watters, 1980b). Much of the archaeological heritage on Barbuda has been relatively well preserved due to low modern populations (~1,600) concentrated in the only village on the island (Rousseau et al., 2017). Small-scale shifting cultivation and unrestricted livestock browsing are still practiced (Potter and Sluyter, 2010), along with timber removal and charcoal production (Harris, 1963; Watters, 1980a).

The study site, Freshwater Pond (17.600754°N, 61.793873°E; 6m asl; Figure 1) is a permanent inland fresh-brackish water lake in southwestern Barbuda. The pond is hydrologically closed, with water levels tied to precipitation and groundwater flow. Field work during the dry season and examination of Google Earth and Landsat imagery indicate that the lake's spatial extent increases during wet periods and has not desiccated in recent decades. Vegetation bordering the pond at coring included red, white, and button mangroves, sedges, and grasses. In the drier slightly higher elevations east of the pond and surrounding wetlands, vegetation transitions abruptly to evergreen woodland.

Field methods and materials

In January 2010, we retrieved sediment core FP2 (0–84 cm) from ~1 m of water using a Colinvaux-Vohnout drop-hammer modified piston corer (Colinvaux et al., 1999) pushing until the sediment could no longer be penetrated, possibly reaching bedrock. The core was extruded in the field into 1-cm slices and stored at 4°C at the University of the West Indies, where core stratigraphy, texture, and Munsell colors were described. Sediments were also analyzed for faunal analysis (gastropods and ostracods) and stable oxygen ($\delta^{18}O$) and carbon ($\delta^{13}C$) isotopes, described fully by Burn et al. (2016). Sub-samples from the core slices were placed in sample jars and shipped to Virginia Tech and stored at 6°C prior to additional analyses of pollen and spores, and charcoal.

Chronological control for the profile was provided by Accelerator Mass Spectrometry (AMS) radiocarbon dating of plant macrofossils from four depths in the profile (Table 2) at National Ocean Sciences Accelerator Mass Spectrometry Facility (NOMAS) at Woods Hole

Oceanographic Institution and the Scottish Universities Environmental Research Centre (SUERC) at the University of Glasgow. Calibrated sample ages were determined by the OxCal 4.1 software package (Ramsey, 2001) using the Intcal09 dataset (Reimer et al., 2011) and modeled in Clam 2.1 (Blaauw, 2010). The Clam 2.1 age-depth modeling program determined best estimates of calendar ages on a per cm depth resolution for the FP2 core until a depth of 65 cm, the maximum depth for which we had chronological control.

To reconstruct changes in sediment organic and inorganic carbon content, we conducted loss-on-ignition analysis (LOI, Heiri et al., 2001) at 1-cm intervals to determine the fractions of water, organic matter, and carbonates in each level. Samples were dried overnight at 100°C to determine water content, then combusted at 550°C for two hours to determine organic matter loss, and at 1000°C for one hour determine the carbonate fraction. We processed 14 sample depths throughout the sediment profile based upon LOI results and changes in stratigraphy. We used a modified pollen preparation technique (10% hydrochloric acid for the removal of carbonates, 10% potassium hydroxide to break up organics and for the removal of humic acids, 10% sodium hexametaphosphate to disperse clays, 49% hydrofluoric acid for the removal of silicates, acetolysis solution, safranin stain; Faegri and Iverson, 1989; Traverse, 2007). Prior to processing, we added a known concentration of *Lycopodium* spores (one tablet containing 18,584 ± 371 spores) to each sample to allow calculation of pollen and microscopic charcoal concentrations (Stockmarr, 1971). We made slides of sporopollenin residue and scanned them for pollen and spore preservation. When slides contained sufficient pollen and spores, we counted a minimum of 200 pollen grains and spores per slide at 400x magnification using a Leica compound light microscope. We tallied indeterminate grains and classified them as either damaged or obscured by other material in the slides.

Identification of pollen and spores was aided by pollen/spore reference slides, published references (Colinvaux et al., 1999; Hooghiemstra, 1984; Roubik and Moreno, 1991; Snyder et al., 2007; Willard et al., 2004), and online pollen databases with photographs and descriptions (Bush and Weng, 2006; Davis, 2001; Rowe, 2006; Snyder et al., 2007). We graphed and analyzed pollen/spore data using the pollen plotting software TILIA v. 2.0.41, (Grimm, 1990). To aid in interpretation of the pollen spectra, we grouped pollen types and spores (excluding indeterminate pollen) into forest and shrub or wetland and herbaceous vegetation categories based upon ecology of the taxa (Francis et al., 1994; Harris, 1963; Smith et al., 2004).

We quantified microscopic (>10–125 µm) charcoal in pollen slides to reconstruct extra-local and regional fire history (Patterson et al., 1987; Whitlock and Anderson, 2003; Whitlock and Larson, 2001). For those slides rejected for pollen analysis due to poor preservation, microcharcoal fragments and control spores were counted until a total of 200 control spores and charcoal particles were tallied (Finsinger and Tinner, 2005). To reconstruct local fire history, we isolated macroscopic charcoal (>125 µm; Whitlock and Anderson, 2003; Whitlock and Larson, 2001) from 1-cm intervals. We soaked 1 cm^3 samples of sediment in 5% sodium hexametaphosphate to disperse clays (Whitlock and Anderson, 2003; Whitlock and Larson, 2001) and gently sieved samples through 125 µm screens. All charcoal particles were identified and tallied in gridded petri dishes under low magnification using a Leica stereozoom. Depth levels 34–35, 49–50, and 53–54 cm did not contain sufficient sediment (due to use in earlier analyses) for macroscopic charcoal analysis but presence of fragments >125 µm were noted from pollen slide scans for these depths. Our microscopic (particles x $10^3/cm^3$) and macroscopic (particles/cm^3) charcoal concentrations were graphed in TILIA v. 2.0.41 (Grimm, 1990).

Results

Core chronology and description

The basal radiocarbon date at 65 cm indicates that sediments began collecting at the core site by at least 2,000 cal. yr BP. Dates for sediments deposited below 65 cm are extrapolated assuming a sedimentation rate of 1 cm per 100 years as estimated by the age-depth model (Figure 2) for sediments deposited between 49–64 cm. From 84 (core bottom) to 50 cm, the sediment is composed of greenish-gray clays overtopped by 50 cm of authigenic marl rich in carbonate micro- and macrofossils including fresh- to brackish-water ostracods, gastropods, and charophyte oospores. From 84–72 cm, the greenish-gray clay contains mangrove detritus and limestone gravels. The clays from 72–50 cm contain iron-rich red mottles while a sharp transition denotes the transition from basal clays to marl at 50 cm. This transition is also reflected in the loss-on-ignition derived carbonate fraction, which sharply increases from an average of 8% (84–50 cm) to 27% (50–0 cm) of the sediment makeup. Organic content also increases upcore, from ~5% to ~21% (Figure 2).

Microscopic charcoal and pollen stratigraphy

All 14 sample depths processed for pollen analysis contained microscopic charcoal particles (Figure 3). Microcharcoal concentrations ranged from a minimum of 4,762 particles/cm^3 deposited at 11–12 cm to a maximum of 249,557 particles/cm^3 deposited at 58–59 cm. Microcharcoal particles were moderately abundant from the bottom of the core to at least 64–65 cm (mean of 47,187 particles/cm^3), after which concentrations increased dramatically and remained high until 41–42 cm (mean of 153,386 particles/cm^3). Above 41 cm, concentrations decreased and remained low (average of 13,777 particles/cm^3) for the rest of the core.

Sediment samples contained pollen from 38 families and spores of Pteridophytes and spike moss (*Selaginella*). Pollen and spores were sufficiently preserved for analysis in nine levels between 0 and 50 cm (Figure 3). Pollen and spores were not preserved in the basal sediments (82–84 cm) and poorly preserved until the stratigraphic change from greenish-gray clay to authigenic marl at 50 cm. Low concentrations of pollen of mangroves (*Conocarpus erectus, Laguncularia racemose*, and *Rhizophora mangle*), ferns, sedges, and Fabaceae in sediments deposited 70–71 cm provide evidence of the establishment of a shallow mangrove wetland and surrounding vegetation by extrapolated 750 BCE (2700 yr BP). Damaged (oxidized, crumpled and torn pollen grains) indeterminate pollen grains and spores remained high in sediments deposited above 50 cm, accounting for 34 to a maximum of 60% (at 49–50 cm) of sporopollenin on slides, calculated as a ratio of indeterminate pollen grains to combined indeterminate and identifiable pollen and spore count.

The pollen and spore record was heavily represented by taxa of ferns and herbaceous vegetation, including Araceae, Cyperaceae, and Poaceae. Other important pollen types included white (*Laguncularia racemosa*) and red mangroves (*Rhizophora mangle*), and the terrestrial mangrove, buttonwood (*Conocarpus erectus*). Moraceae, *Piper*, and Fabaceae-*Mimosoideae* pollen largely represented forest and shrub vegetation. Pollen of *Cecropia*, a pioneer genus common in canopy gaps, disturbed areas, and understory of lowland tropical forests (Smith et al., 2004), was present in all depth levels processed for pollen analysis. Pollen of *Piper*, mostly found in canopy gaps of moist habitats (Smith et al., 2004), contributed substantially to some depth levels.

Macroscopic charcoal

Macroscopic charcoal concentrations (Figure 3) varied greatly by sediment depth, with a maximum concentration of 905 particles/cm^3 deposited at 66–67 cm. The basal sediments (84 cm) to 52 cm contained the highest amounts of macroscopic charcoal (average 415 particles/cm^3), after which larger charcoal concentrations decrease but remain moderately abundant (maximum 30 particles/cm^3) for sediments 51–37 cm. Macroscopic charcoal becomes rare in the upper sediments of our core, with single pieces deposited at 35–36, 28–29, and 11–12 cm. A change in macrocharcoal morphology also occurred at 51 cm, with charcoal deposited between 52 cm and the end of the core exhibiting various morphotypes including longer and thicker pieces with and without branches, segmented, latticed polygons, and blocky/rectangular with no structure, following Enache and Cumming (2006; 2007) and Mustaphi and Pisaric (2014). Above 52 cm, all charcoal is of one morphotype: shorter blocky/rectangular pieces with no branches. Charred mangrove plant macrofossils were also observed for sediments below 51 cm.

Discussion

Mid- to late-Holocene fire history of Barbuda and the region from microscopic charcoal

The presence of microscopic charcoal throughout the Freshwater Pond sediment core representing the last extrapolated ~4,000 years reveals a long history of biomass burning on Barbuda and possibly nearby islands. Microscopic charcoal particles (>10 µm diameter) may be lofted high into the atmosphere during fires and are typically interpreted to represent fires within 20–100 km of core sites (Conedera et al., 2009; MacDonald et al., 1991; Tinner et al., 1998). While the northern coast of Antigua, Barbuda's nearest neighbor, lies ~48 km from our core site, regional wind patterns (northeasterly) in addition to Barbuda's location at the outer edge of the northern Lesser Antilles (Figure 1) decreases the contribution of small charcoal particles from fires on surrounding islands to sediments of Freshwater Pond. Thus, we interpret the microcharcoal content of our sediment core to have been largely produced from fire activity on Barbuda. The active volcano Montserrat is about 108 km distant and in theory could have contributed charcoal associated with eruptions, but it is directly southwest, thus the northeast trade winds (if stable) would prevent such deposits on Barbuda. We found no tephra layers in the sediment core.

In lowland ecosystems of the Caribbean islands, natural fire regimes are poorly understood (Murphy and Lugo, 1986; 1995; Sánchez-Azofeifa and Portillo-Quintero, 2011) and long fire histories are rare, especially for the Lesser Antilles. Increases in lake sediment charcoal and associated increases in pollen representative of disturbance or cultivated taxa have been interpreted as evidence of human biomass burning in several Caribbean paleoecological studies (Burney and Burney, 1994; Kjellmark, 1996; Siegel et al., 2015) while others have proposed climate as the primary driver of biomass burning in lowland Neotropical ecosystems (Caffrey and Horn, 2015; Power et al., 2012). A comparative analysis by Caffrey and Horn (2015) of sedimentary charcoal from Laguna Saladilla (Dominican Republic), and reanalysis of records from Laguna Tortuguero (Puerto Rico, Burney and Burney, 1994), and Lake Miragoâne (Higuera-Gundy et al., 1999) documented relatively low microcharcoal influx in the early Holocene, with increases in microcharcoal in all three lakes during the mid- to late-Holocene (Miragoâne: ~4050–1250 BCE; Tortuguero: ~3250–1550 BCE; Saladilla: ~550 BCE) attributed primarily to increasing winter insolation but acknowledged that human activity also had a role. At the two sites in Hispaniola, charcoal increases post-European contact were attributed to increasing human ignitions (Caffey and Horn, 2015). In seasonally dry forests of the Maya lowlands, the fire regime shifted from infrequent, natural (interpreted as climate-driven) early-Holocene fires to more-frequent, anthropogenic fire during the mid-Holocene with the arrival of sedentary agriculturalists, highlighting the potential for drivers of fire activity to change over time (Anderson and Wahl, 2016).

Large-scale studies examining soil and sedimentary charcoal influx from a range of elevations in both island and continental locations have shown decreases in charcoal influx after ~1450 CE (500 yr BP) concomitant with the onset of the Little Ice Age (LIA, ~1400–1850 CE; Dull et al., 2010; Nevle et al., 2011; Power et al., 2012). While several proxy records from the circum-Caribbean have provided evidence of relatively arid conditions during the LIA (Fensterer et al., 2012; Hodell et al., 2005; Lane et al., 2011), other, high temporal-resolution isotopic studies, including an earlier analysis of our Freshwater Pond sediment core (Burn et al., 2016), a Cuban stalagmite (Fensterer et al., 2012), and a Jamaican sediment core (Burn and Palmer, 2014) have proposed that the region was not uniformly dry during the LIA, but rather experienced greater spatial and temporal (sub- and multi-decadal) variability of precipitation. With documented increased precipitation variability in some areas of the Caribbean, climate seems to be an incomplete explanation for uniform decreased biomass burning in the Neotropics from 1500 to 1700 CE (Dull et al., 2010; Nevle et al., 2011; Power et al., 2012).

In contrast to the climate-driven hypothesis for reduced biomass burning during the LIA, some researchers have invoked a population collapse hypothesis, in which the documented pandemics that spread throughout the Americas at European contact caused rapid population collapses of indigenous peoples thereby significantly reducing human ignitions in tropical forest biomes (Dull et al., 2010; Nevle et al., 2011). Reforestation following the indigenous population collapse may have transformed the region from a carbon source to a carbon sink, explaining the decrease in atmospheric CO_2 during the LIA (Dull et al., 2010; Nevle et al., 2011). Under the population collapse hypothesis, decreased anthropogenic burning and increased carbon sequestration were significant forcing mechanisms of the LIA (Dull et al., 2010). Additional paleoecological and archaeological analyses from understudied regions, such as the Lesser Antilles, may reveal late-Holocene climatic change, human activities, and ecosystem responses. The Caribbean islands are represented by a handful of studies in the Greater Antilles while the Lesser Antilles are poorly represented. Recently, Siegel et al. (2015) documented Holocene biomass burning from sedimentary charcoal from lakes in Trinidad, Grenada, Martinique, and Gaudeloupe. While plentiful charcoal particles in their uppermost sediments date to the late-Holocene, a lack of high-resolution chronologies does not allow for the interpretation of the potential impacts of the LIA on vegetation, fire, or human histories of the islands.

In our Freshwater Pond record, microcharcoal abundance, reflecting extra-local (island) burning remained relatively moderate and stable from ~2050 (extrapolated) to ~150 BCE (4000–2100 yr BP), a period of relatively arid conditions in the subtropical northern and western Caribbean (Haug et al., 2001; Higuera-Gundy et al., 1999, Hodell et al., 1991). Microcharcoal peaked ~540 CE (1410 yr BP) at Freshwater Pond and remained relatively high for ~1,000 years until ~1610 CE (Figure 3) compared with the large-scale analyses (Dull et al., 2010; Nevle et al., 2011) that documented significant decreases in microscopic charcoal influx by ~1500 CE in tropical America and ~1400 CE in the non-Americas. The substantial increase in biomass burning at ~540 CE occurs after the first known permanent settlement on Barbuda dating to ~100 BCE (2050 yr BP, Seaview site, Bain et al., 2017). That period is coincident with the beginning of the Ceramic culture period in the Caribbean, noted for slash and burn agriculture and large settlements (Wilson, 2007). This period of relatively frequent burning on the island of Barbuda may document the migration of Ceramic Age agriculturalists from northern South America through the Lesser Antilles, between 3,000 and 2,000 years ago (Wilson, 2007).

Analyses of archaeological sites on Barbuda dating to the Ceramic culture periods supports our interpretation that the Freshwater Pond microcharcoal record primarily documents burning by indigenous peoples on the island. Our high charcoal period (~540–1610 CE) coincides with the occupation of the Seaview (100 BCE–650 CE, 2050–1300 yr BP), Indian Town Trail (1130 CE, 820 yr BP), and Sufferers (550–900 CE, 1400–1050 yr BP) archaeological sites (Figure 1; Bain et al. 2017). Macrocharcoal (>4 mm) remains from those archaeological sites provide evidence of indigenous use of woody species for timber, fuel, and fruit (Bain et al., 2017), and further, evidence of anthropogenic disturbance to Barbuda's terrestrial ecosystems. High amounts of microscopic charcoal in the FP2 core following the European colonization of the region (post-1492 CE) may reflect burning associated with small-scale cultivation and other uses of fire on Barbuda (Harris, 1963; Watts, 1987).

The decline in microscopic charcoal after ~1610 may reflect changes from indigenous to European land use and activities that produced less or no charcoal signatures. The reduced charcoal/fire period by ~1650 CE coincides both with the latter half of the LIA and the date of permanent settlement by the English (~1660 CE; Bain et al., 2017; Harris, 1963). Preceding that decline, relatively abundant microcharcoal was deposited ~1610 CE, following the most severe drought of recent centuries (~1600 CE; Burn et al. 2016). Freshwater gastropod (*Pyrgophorus parvulus*) abundance data and the stable oxygen isotope record from our core identified three additional periods of extended aridity in the last few centuries (Burn et al., 2016), but we found no corresponding increase in microcharcoal (Figure 3).

While we might expect sedimentary records of fire activity to vary with changes in precipitation and the subsequent availability of fuels (Anderson and Wahl, 2016; Marlon et al., 2013), the charcoal record from Freshwater Pond, representing the last ~500 years, did not co-vary with interpreted droughts during the Colonial and Post-Colonial periods (Burn et al., 2016), suggesting primarily human-driven fire regimes on Barbuda throughout the period of known human habitation. Our interpretation is corroborated by the increasingly well-documented archaeological record of human activities on the island of Barbuda and throughout the Lesser Antilles (Bain et al., 2017; Rousseau et al., 2017). Our findings agree with those of Dull et al. (2010) and Nevle et al. (2011) who proposed that reductions in biomass burning in tropical America at the time of European contact are primarily tied to reductions in human ignitions, linked to dramatic reductions in indigenous populations on the continents.

A broader explanation of the microscopic charcoal decline over the past 400 years recognizes the potential influence of climatic fluctuations on a landscape already strongly influenced by several millennia of human activities. Barbuda, an island of low relief with thin and infertile soils, high temperatures and evaporation rates, and consistent warm winds, is highly vulnerable to droughts (Jackson, 2001). Barbuda's past four centuries, encompassing European occupation, have experienced highly variable precipitation including extended droughts (Burn et al., 2016). At the same time, Europeans practiced only subsistence agriculture in areas near their settlement on Barbuda, but their impacts included timber removal, likely on scales greater than in previous periods, given that they exported their materials offshore. The pollen record of Freshwater Pond may corroborate historical records of natural resource exploitation on the island. Around the time of the first permanent English settlement, *Piper* pollen reaches its highest percentages in the core and *Cecropia* pollen grains are also present, suggesting disturbance to and canopy gaps in moist vegetation, likely forests growing in the Highlands (Figure 3). Frequent or extended droughts, similar to those in the modern record (1950–2016, Herrera and Ault, 2017; Jackson, 2001), might have exacerbated the negative impacts of European land uses on soils and vegetation, such as reduction of seed trees through harvesting and increased livestock browsing and grazing that together would have greatly diminished recruitment and growth of woody plants on the island. While human activities alone can reduce biomass, the combination of human impacts and recurring droughts on Barbuda may have more dramatically reduced available fuels, the extent and intensity of fires, and thereby the abundance of charcoal in our sediment record. Further, European arrival in the mid-17th century in conjunction with extended droughts during the LIA may have caused the crossing of an ecological threshold, in which some of the island's taller closed forests were converted into the low thorny woodlands that dominate the land cover today.

Local fire history of Freshwater Pond, Barbuda from macroscopic charcoal

The sustained presence of sedimentary macroscopic charcoal (>125 µm) at Freshwater Pond indicates regular biomass burning near the study site from extrapolated 2050 BC to 1640 CE (4000–310 yr BP; Figure 3) is further evidence of the long history of human manipulation of Barbuda's landscape. Macroscopic (> 125 µm) charcoal is often deposited within a few hundred meters of a fire. Most of our charcoal fragments fell into the > 125–250 µm size class, which has been found to be wind-transported for several kilometers in the western U.S.A. (Whitlock and Millspaugh, 1996). Though charcoal deposition has not been studied in the Caribbean, it seems possible that easterly trade winds or strong onshore sea breezes could have transported some charcoal fragments from fires in Ceramic Age sites in southeastern Barbuda (Figure 1) to

Freshwater Pond. We interpret our macrocharcoal record as evidence of burning of mangroves or other vegetation adjacent to the pond though some of the charcoal could have arrived by slope wash from burning in the nearby Highlands that grade gently toward Freshwater Pond, and some may have originated or have been blown in from archaeological sites.

The burning near the pond could have been associated with shifting agriculture, since more organic wetland soils near the pond may have represented some of the best available for cultivation during dry seasons or periods of extended droughts when waters receded; however, archaeological studies have not thus far produced evidence of manioc or maize cultivation including seeds, starch grains, or phytoliths (Bain et al. 2017). In addition, we found no pollen evidence of cultivated plants, such *Zea mays* or *Manihot esculenta,* but pollen/spore preservation was poor during the Ceramic Age when peoples who practiced shifting agriculture occupied the island, and pollen of cultivated plants is usually rare in pollen records. A modern pollen study of *Zea mays* deposition revealed that, depending upon area of maize under cultivation, wetland/lake surface area, characteristics of riparian vegetation, and other landscape characteristics, surface sediment samples just meters away from maize cultivation may contain little or no maize pollen (Lane et al., 2011). Lacking corroborating evidence of agriculture as an origin of Freshwater pond macrocharcoal, we interpret charcoal production and burning of fuelwood as the most likely provenance of our sedimentary macrocharcoal.

Our discovery of charred *Rhizophora mangle* (red mangrove) fragments in Freshwater Pond was not surprising given that mangrove species were a common source of fuel wood for indigenous Caribbean peoples (Newsom and Wing, 2004). Thus, charcoal production may have occurred on site in the mangroves fringing the pond. The FP2 pollen record (Figure 3), likely heavily representing vegetation adjacent to the pond and on the southwestern portion of the

Highlands due to the pond's small size (Sugita, 1994), indicates the presence of seasonally dry tropical forest taxa, such as *Celtis* and *Bursera,* between ~540 and 1450 CE, that were probably also burned by early inhabitants.

Variations in the sedimentary macrocharcoal concentrations from Freshwater Pond may relate to changing land use near the core site, but could also reflect changes in taphonomy (deposition processes) associated with shifting water levels and surface extent of the pond. Variations in lake size tied to effective rainfall (precipitation minus evaporation) would impact proximal fuel sources as the pond's fringing vegetation became closer or more distant from the core location. In any case, plentiful charred particles in the Freshwater Pond sediment core, particularly between extrapolated 1550 BCE (3500 yr BP) and 1250 CE (Figure 3), attests to a long history of burning near the study site by indigenous peoples. While the lowest section (65–84 cm) of the FP2 core remains undated, charcoal in that section represents burning dating to a period before ~150 BCE (2100 yr BP), the result of a radiocarbon date from material at 65 cm. Indigenous populations at the Seaview archaeological site by ~100 BCE, burned wood and produced charcoal fragments. Inhabitants may have remained or intermittently occupied Barbuda until as recently as ~1130 CE (Bain et al., 2017; Watters et al., 1992).

The sharp decline in local fire activity at the core site after 1250 CE precedes our interpreted transition from shallow mangrove wetland to lacustrine environment that occurred at the onset of the LIA (Burn et al., 2016) by a century and a half (Figures 2 and 3). The Indian Town Trail archaeological site was occupied as recently as 1130 CE, though the island was likely abandoned by indigenous populations by the 1500s (Bain et al., 2017; Harris, 1963). Abandonment would support the explanation of a dramatic decrease in anthropogenic ignitions and sedimentary charcoal. Other archaeological records from the circum-Caribbean note the abandonment Lesser Antilles islands in the 1300s (Wilson, 2007) and may corroborate our interpretation that charcoal decline was caused by decreasing human ignitions.

Low concentrations of monotypic charcoal deposited in the period following interpreted island abandonment, from the late 1200s through the mid-1600s CE, may represent secondary deposition (remobilization) of charcoal (Enache and Cumming, 2007), rather than fire activity, transported by water from lowland areas adjacent to the core site, or possibly from the southern slopes of the Highlands. Soon after European arrival, the island's population became concentrated in the small village of Codrington several kilometers to the north (Figure 1), human burning becoming too distant from Freshwater Pond to contribute large charcoal fragments. Historical records indicate that small-scale agriculture was limited to the Highlands and areas adjacent to Codrington Village, both distant from Freshwater Pond. In contrast to many of the Caribbean islands, plantation agriculture (mostly sugar cane) never became widely established on Barbuda due to the island's shallow soils and unpredictable rainfall (Bain et al., 2017; Harris, 1963; Watters, 1980a).

Human impacts, vegetation history, and precipitation variability on Barbuda

The pollen and spore data of Freshwater Pond, combined with macrocharcoal results, point to a long history of human disturbance to the vegetation near Freshwater Pond, including forests and slopes of the Highlands, the dry shrublands of the surrounding lowlands, and the fringing mangroves. An absence of pollen, spores, and carbonate microfossils from the basal sediments prevented a temporally complete reconstruction of Freshwater Pond's environmental and vegetation history. Crumpled pollen grains with thinned exines (evidence of oxidizing conditions), in pollen slides spanning the Archaic/Ceramic Ages, suggested repeated wetting and drying cycles at the study site before ~1450 CE (Campbell, 1999; Delcourt and Delcourt, 1980; Twiddle and Bunting, 2010; Tweddle and Edwards, 2010). As Freshwater Pond is a hydrologically-closed system, we interpret abundant damaged pollen grains deposited prior to ~1450 CE as evidence of generally drier conditions in the northeastern Caribbean prior to the onset of the LIA.

While most pollen/spores in this section were damaged beyond identification in sediments of the lower core (84–51 cm), the presence of a few better-preserved pollen grains and spores attest to the establishment of a shallow mangrove wetland that supported a herbaceous cover of ferns, sedges, and aroids by ~750 BCE (2700 yr BP; Figure 3). Shrubland and perhaps forests surrounded the wetland, as documented by the presence of Fabaceae and Moraceae pollen, with the presence of *Cecropia* pollen suggesting canopy gaps and succession in moist forests, likely growing in the Highlands and slopes of the Highlands. Pollen of *Burser*a, an important tree of Neotropical dry forests, is rare in Freshwater Pond sediments but present in samples dating to ~540 and 1040 CE (Figure 3). By 1450 CE, the onset of the LIA, Freshwater Pond transitioned from a shallow wetland to lacustrine environment.

Though pollen and spores are better preserved in sediments dating from ~1450 CE to present, abundant damaged pollen signals seasonal or occasional drying of the pond during this period. At ~1450 CE, red mangrove pollen (*Rhizophora mangle*) and buttonwood (*Conocarpus erectus*) attained the highest percentages they would reach for several centuries, perhaps reflecting wetland establishment and mangrove expansion tied to increased effective precipitation (Burn et al., 2016) and indigenous abandonment of the site and subsequent vegetation succession. The probable abandonment of large Ceramic Age sites on the island ~200 years previously (Bain et al., 2017; Harris, 1963) and subsequent forest recovery may be revealed by the presence of *Cecropia* and *Piper* pollen in sediments dating to 1450 CE. Rarer pollen types, including *Celtis*, *Eugenia*, *Vitex*, Scrophulariaceae, and Asteraceae, representing tropical dry forest trees (*Celtis* and *Vitex*), evergreen shrubland (*Eugenia*), and herbaceous taxa of open environments (Scrophulariaceae and Asteraceae; Smith et al., 2004), corroborate our interpretation of forest canopy gaps and more open vegetation typical of a disturbed landscape that had recently been abandoned. Trees typical of Neotropical dry forests were likely more prevalent on the Barbudan landscape prior to or at European colonization. On Barbuda and other islands of the Caribbean, *Bursera*, *Celtis*, *Eugenia*, and *Vitex* were extensively harvested by indigenous peoples for charcoal, fuel, and timber and were certainly exploited by Europeans, sometimes as timber exports (Bain et al., 2017; Harris, 1963; Newsom and Wing, 2004). After ~1450 CE, pollen of these tropical dry forest taxa are absent from sediments of Freshwater Pond, suggesting local absence from vegetation near the core site.

By ~1610 CE (42 cm), we interpret drier conditions at Freshwater Pond from declines in pollen of mangrove taxa pollen and other moist habitat indicators (aroids, fern spores), increases in forest/shrub pollen and pollen of herbaceous taxa (Scrophulariaceae and Asteraceae) representative of open environments, increased fungal spores, and abundant damaged pollen grains and spore. The pollen record corroborates an interpreted drought from decreases in *Pyrgophorus parvulus* (a freshwater gastropod) and stable oxygen isotope data from ostracod valves of the same sediment core (Burn et al., 2016). Another drier period is interpreted for ~1710 CE (30 cm) from maxima in the stable oxygen isotope record and decreases in freshwater gastropod shells (Burn et al., 2016), and increases in fungal spores and highest pollen concentrations of Fabaceae pollen, indicating increased input from shrubland surrounding Freshwater Pond. Moraceae pollen decreased to the lowest amounts observed in our core, while

Piper remains relatively high, suggesting a more open vegetation with an increased dominance of shrub and herbaceous vegetation, as indicated by high Fabaceae and Araceae pollen. Later dry periods at ~1850 CE and in recent decades follow the same pattern, with maxima in the stable oxygen isotope and decreases in the carbonate microfossil record, as well as decreases in wetland and herbaceous vegetation and increase in fungal spores (Figure 3).

Interestingly, fungal spore counts were the greatest predictor of changes in precipitation at Freshwater Pond, with slight increases coinciding with interpreted dry events from Burn et al. (2016). Increases in fungal spores may be tied to exposed and decaying aquatic vegetation or may indicate greater use of the site by grazing animals during periods of drought. In general, decreases in pollen and spores of wetland and herbaceous vegetation and relative increases in forest and shrub types signal drier versus wetter periods, suggesting dieback of vegetation immediately surrounding or growing within the pond and greater input from surrounding shrubland and forest. Interpreting the pollen record of Freshwater Pond is complicated by low pollen and spore counts and traces of human activities throughout the period documented by our sediment core. While evidence of indigenous agriculture is lacking from both the sediment and archaeological records, timber removal and charcoal production certainly impacted the pre-European landscape against a backdrop of changing hydrologic conditions at the core site.

Conclusions

Our multiproxy analysis of sediments from Freshwater Pond, Barbuda, provides the first fire history and the first vegetation history documenting inland vegetation from the Lesser Antilles. Macroscopic charcoal from our sediment core documents thousands of years of biomass burning by indigenous peoples near Freshwater Pond, likely through the selective cutting of mangrove and species typical of Neotropical seasonal forests. While pollen and spores are poorly preserved for much of Freshwater Pond's history, our record provides the first data from inland terrestrial ecosystems of the Lesser Antilles from the prehistoric through Post-Colonial periods and indicates a long history of disturbance from interpreted forest canopy gaps, likely tied to indigenous and Colonial human activities. Ongoing archaeological investigations indicate that the island has a long history of human occupation, from the Archaic age to present. Prehistoric human impacts included biomass burning near Freshwater Pond, probably to support the large settlements of Saladoid and post-Saladoid peoples who occupied the island. Indigenous use of Freshwater Pond and surrounding areas decreased by ~1250 CE, as evidenced by a significant decrease in macroscopic charcoal, in agreement with archaeological records that indicate the indigenous population of the island was severely reduced by the time of British occupation in the 1600s. Other archaeological sites from the Lesser Antilles also indicate population decreases and site abandonment around 1300 CE. Though our results must be interpreted with caution due to high amounts of damaged pollen, our pollen record suggests that indigenous and Colonial use of natural resources may have reduced populations of tree species on Barbuda, or at least near our study site, particularly timber species which were probably more abundant in the past. Our results show that mid- to late-Holocene fire regimes of lowland ecosystems of the Lesser Antilles may be largely controlled by human activities, with decreases in regional burning after ~1610 CE likely also tied to reduced fuel conditions associated with repeated droughts during the Little Ice Age against a legacy of charcoal production and timber removal by indigenous and European populations. Our multiproxy dataset, including the archaeological, and sedimentary stable isotope and charcoal records, and our review of the literature, suggest that past fire regimes in the

Neotropics must be evaluated within appropriate contexts of spatial scale, location, and human history to gain the fullest understanding of drivers of fire activity.

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Figure Captions

Figure 1. *Top:* Location of Barbuda within the northeastern Lesser Antilles. *Bottom:* Location of Freshwater Pond and prehistoric (black circles) and historical (gray circles) archaeological sites on the island. The dashed lines denote the approximate boundary of the Highlands. Map recreated from Bain et al. (2017).

Figure 2. Lithology, age-depth model, and loss-on-ignition data for sediment core FP2. Figure recreated from Burn et al. (2016).

Figure 3. Pollen, spores, and charcoal data from the FP2 sediment core. Black circles denote presence of pollen, spores, or macroscopic charcoal for depth levels for which we did not perform full counts. Horizontal gray bars represent periods of interpreted drought from previous analysis of this sediment core (Burn et al., 2016). Horizontal black lines note boundaries of cultural periods, labeled on the right.

Table 1. Cultural and climate history of the Caribbean, with representative archaeological sites on Barbuda (unless otherwise noted), associated human activities, and probable impacted ecosystems.

Cultural period	Age	Archaeological sites[a,I,j,k,l]	Human Activities	Ecosystems Impacted	Climate
Lithic	~4050 BCE (6000 yr BP)	Greater Antilles (Cuba, Hispaniola) only[i]	Fisher-gatherer-foragers	Marine, coastal	Moist [e,f,g]
Archaic	~3000–500 BCE (4,950–2450 yr BP)	Strombus line Burton's Field Cattle Field The River Salt Pond, Antigua	Fisher-gatherer-foragers	Marine, coastal: fished, collected shellfish and wild plants Seasonal or sporadically occupied settlements	Moist until ~1250 BCE (3200 yr BP)[efg] Drying trend last ~5,400 yrs[e] Multi-centennial variability ~3550 BCE (5500 yr BP) though overall increased precipitation since ~1250 BCE (3200 yr BP)[d]
Ceramic	~500 BCE–1492 CE (2450–458 yr BP)	Seaview Indian Town Trail Sufferers & Welches	Ceramic-producing agriculturalists	Marine, inland: shifting agriculture Sedentary and large populations Island abandonment by ~1300 CE?[a]	Drying after ~1250 BCE (3200 yr BP)[e,f,g] Multi-centennial variability, overall increased precipitation since ~1250 BCE (3200 yr BP)[d]
Colonial	post-1492–1850s CE	Highland House The Castle	Livestock (horses, cattle, sheep, goats), timber, lime, charcoal, crops	First permanent British settlement ~1660 CE[a] Agricultural activities (limited to vicinity of Codrington Village) except island-wide animal grazing	Little Ice Age (1400-1800 CE): variable precipitation to arid/drought[b,c,h]

[a]Bain et al., 2017; archaeology of Barbuda
[b]Burn et al., 2016; Freshwater Pond, Barbuda
[c]Fensterer et al.; 2012, Stalagmite, Cuba
[d]Fritz et al., 2011; Grand Etang and Lake Antoine, Grenada
[e]Haug et al., 2001; Cariaco Basin, Venezuela
[f]Higuera-Gundy et al. 1999; Lake Miragoâne, Haiti
[g]Hodell et al., 1991; Lake Miragoâne, Haiti
[h]Lane et al., 2011; Laguna Felipe, Cordillera Central, Dominican Republic
[i]Newsom and Wing, 2004; archaeology of Caribbean
[j]Rousseau et. Al, 2017; archaeology of Barbuda
[k]Siegel et al. 2015; Trinidad, Grenada, Martinique, and Guadeloupe

Table 2. FP2 (0-84 cm) radiocarbon date results through the facilities at the National Ocean Sciences Accelerator Mass Spectrometry Facility (NOMAS) at Woods Hole Oceanographic Institution and the Scottish Universities Environmental Research Centre (SUERC) at the University of Glasgow. Calibrated samples ages were determined by the Clam 2.2 (Blaauw, 2010) calibration program and calibrated by the Intcal13 dataset (Reimer et al. 2009, Stuiver and Reimer 1993). Table recreated from Burn et al. (2016).

Lab No.	Depth (cm)	Material dated	$\delta^{13}C$ (‰)	^{14}C yr BP	2σ Calibrated yr CE	Probability (%)
SUERC–37169	27–30	*Ruppia maritima* achenes	-15 (est.)	242 ± 30	1936–1954	7.4
					1762–1802	28.0
					1738–1751	0.9
					1631–1682	52.4
					1525–1558	6.7
SUERC–37170	47–49	*Ruppia maritima* achenes	-15 (est.)	347 ± 30	1463–1533	39.1
					1536–1635	55.8
OS–81963	63–64	Woody fragment	-25.17	1959 ± 30	103–122	4.4
					40 BCE–88	91.0
OS–81964	64–65	Woody fragment	-26.05	2121 ± 40	211–42 BCE	83.1
					229–220 BCE	0.9
					352–295 BCE	11.4

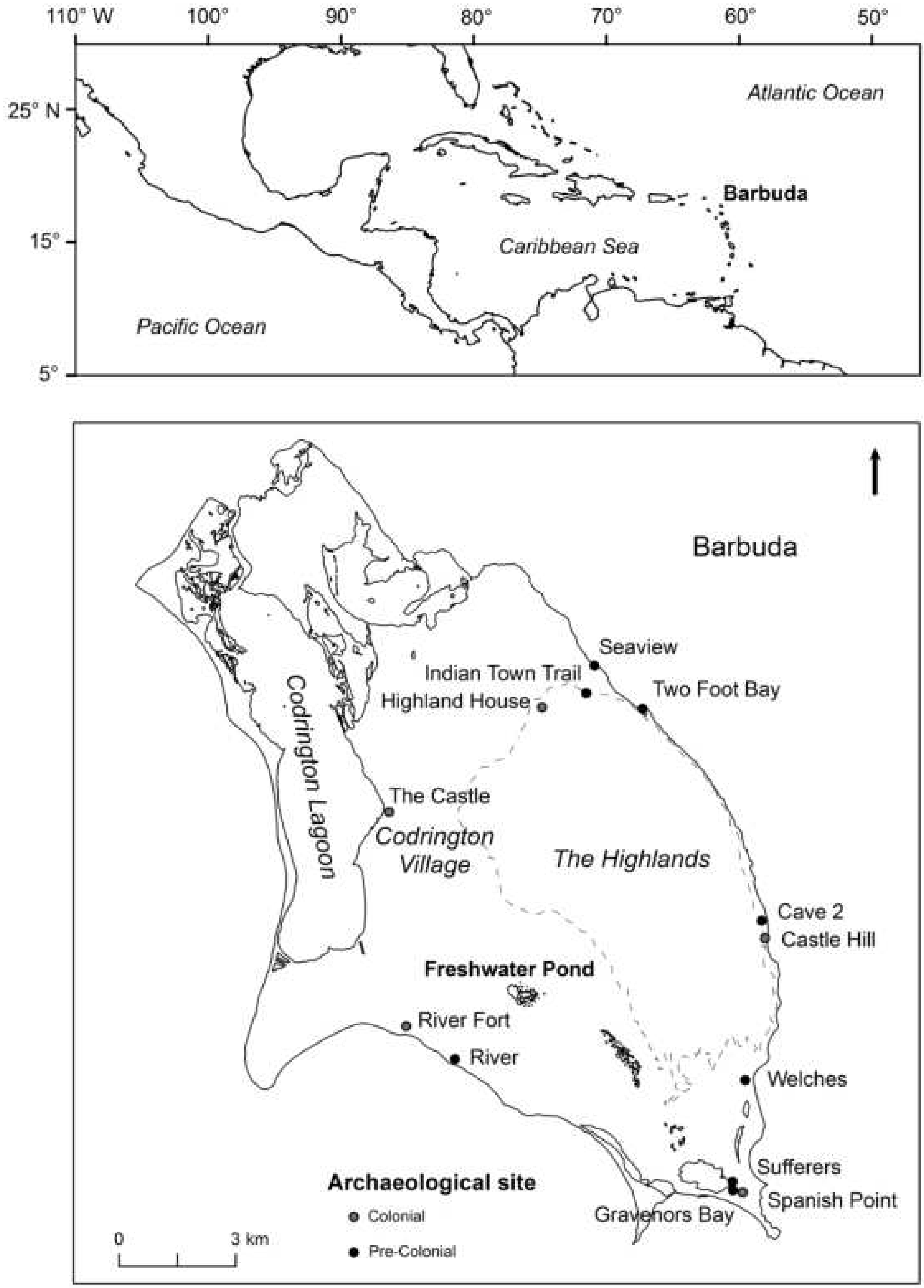
110° W
100°
90°
80°
70°
60°
50°
25° N
15°
5°
Atlantic Ocean
Barbuda
Caribbean Sea
Pacific Ocean
Barbuda
Seaview
Indian Town Trail
Two Foot Bay
Highland House
Codrington Lagoon
The Castle
Codrington Village
The Highlands
Cave 2
Castle Hill
Freshwater Pond
River Fort
River
Welches
Sufferers
Archaeological site
Spanish Point
Gravenors Bay
Colonial
Pre-Colonial
0
3 km

Figure 1

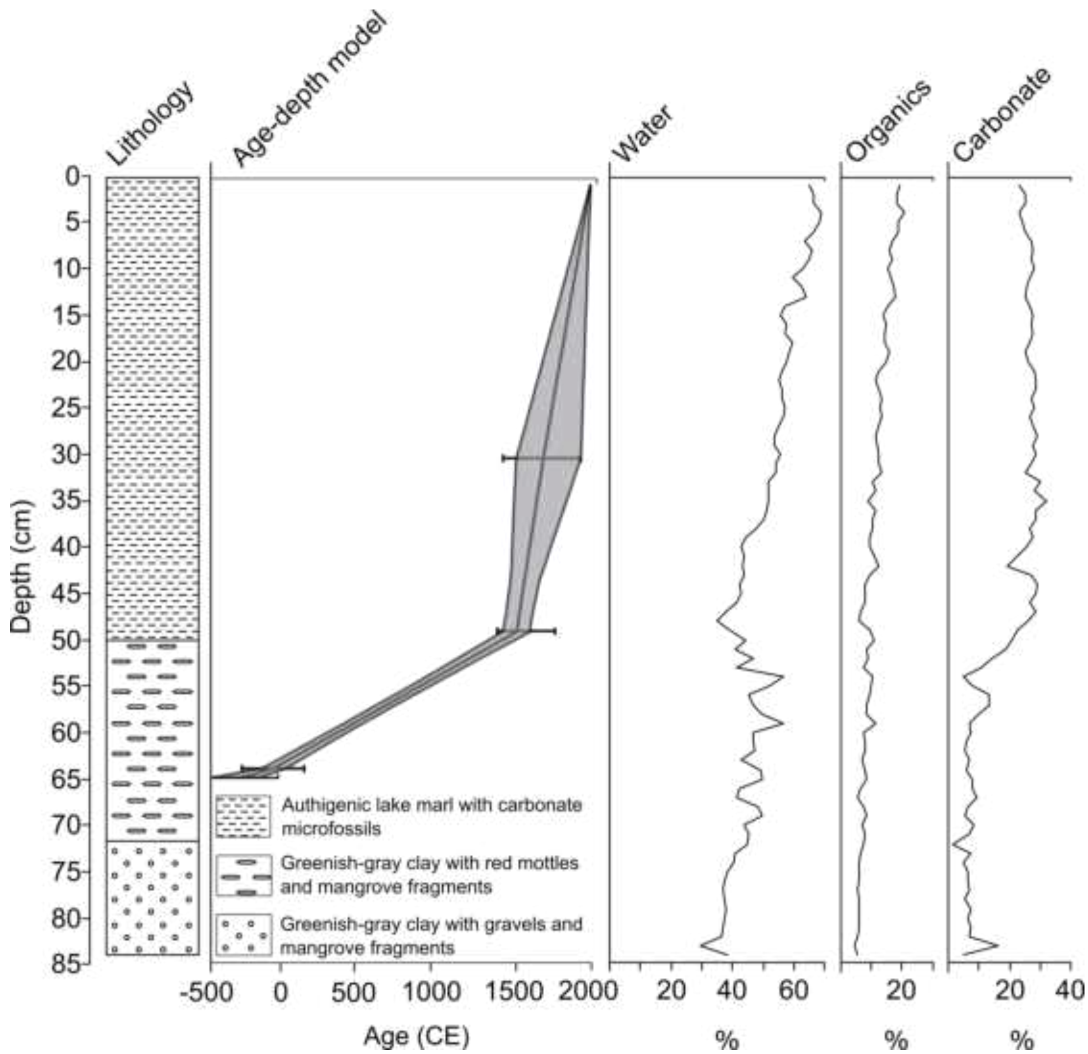
Lithology
Age-depth model
Water
Organics
Carbonate
Depth (cm)
Age (CE)
%
%
%
Authigenic lake marl with carbonate microfossils
Greenish-gray clay with red mottles and mangrove fragments
Greenish-gray clay with gravels and mangrove fragments

Figure 2

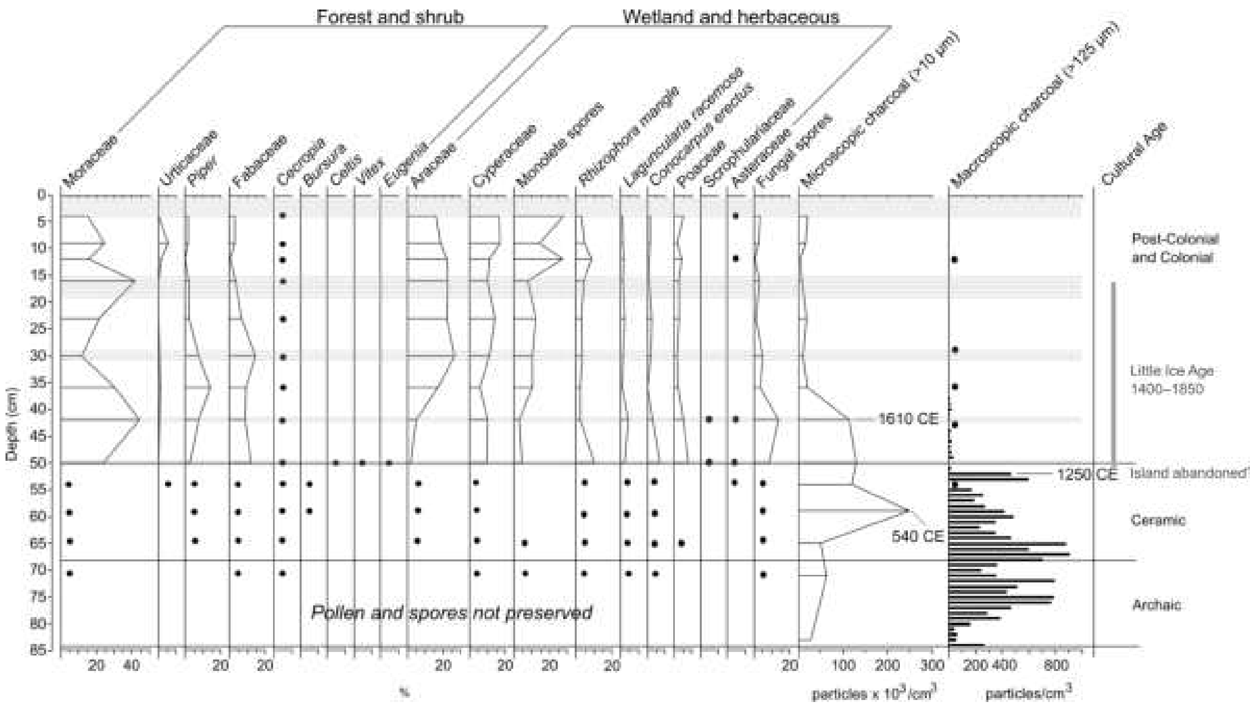
Forest and shrub
Wetland and herbaceous
Moraceae
Urticaceae
Piper
Fabaceae
Cecropia
Bursura
Celtis
Vitex
Eugenia
Araceae
Cyperaceae
Monolete spores
Rhizophora mangle
Laguncularia racemosa
Conocarpus erectus
Poaceae
Scrophulariaceae
Asteraceae
Fungal spores
Microscopic charcoal (>10 μm)
Macroscopic charcoal (>125 μm)
Cultural Age
Depth (cm)
Post-Colonial and Colonial
Little Ice Age 1400–1850
1610 CE
1250 CE
Island abandoned?
Ceramic
540 CE
Archaic
Pollen and spores not preserved
%
particles x 10³/cm³
particles/cm³

Figure 3

Chapter 4

The application of modern pollen data from surface samples to interpretation of sedimentary pollen in seasonally-dry lowlands of southwestern Dominican Republic

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Abstract

This research on modern pollen from a seasonally-dry Caribbean lowland region represents the first study of samples from lowland vegetation in the Greater Antilles. Published studies of surface pollen from the Caribbean islands are rare, limiting the interpretation of stratigraphic pollen records from the region. We analyzed surface pollen from several lowland plant communities of Parque Nacional Sierra Martín García, Dominican Republic, including mudflat, lagoon, mangrove, thorn forest, and tropical dry forest. Anemophilous pollen from tropical dry, humid broadleaf, and pine forest taxa (i.e., Urticaceae/Moraceae, *Pinus occidentalis, Cecropia*) contributed relatively high amounts of pollen to sample sites downslope, especially in non-forested sites. The terrestrial mangrove, *Conocarpus erectus*, was over-represented in the pollen record while white and black mangroves were under-represented. Some important trees of tropical dry forests, including *Guaiacum officinale*, and *G. sanctum* were present locally but 'silent' in the pollen record. Cactus and bromeliads, common on the regional landscape, were also under-represented in the pollen rain. Mudflats were indicated by pollen of *Batis maritima* and Amaranthaceae, while thorn forests tended to be dominated by Fabaceae, particularly *Mimosa* spp. and *Prosopis juliflora*. Pollen of food plants was rare in surface pollen, even for a sample location with a subsistence garden. Non-metric multidimensional scaling (NMDS) of pollen from surface samples revealed clusters (i.e. similarity of pollen spectra) containing samples from non-forested versus forested vegetation types and could further distinguish our sample from tropical dry forest near the ecotone of more moist forest as taxonomically unique. Our modern pollen results also aided in the interpretation of stratigraphic 'fossil' pollen in the study of nearby Laguna Alejandro, representing the past ~1,500 years of pollenshed vegetation history. This study informed our ideas on vegetation-pollen representation in different plant communities of a seasonally-dry Caribbean lowland landscape and may help to refine interpretations of sedimentary pollen within similar study areas.

Key Words: Modern pollen, Caribbean, Dominican Republic, Tropical dry forest, Non-metric Multidimensional Scaling, Pollen analysis

Introduction

Analysis of pollen and spores from lake sediments is one of the most widely adopted techniques for reconstructing regional vegetation, climate, and disturbance histories over long time periods. In tropical study sites, interpretation of stratigraphic pollen from sediment cores is complicated by high species richness, low taxonomic resolution of many pollen types, the diversity of plant life forms occupying a variety of environmental settings, and the abundance of insect-pollinated taxa that produce far less pollen than wind-pollinated taxa (Gosling et al., 2009; Bush and Rivera, 2001; Bush, 2000; Rodgers and Horn, 1996; Gentry, 1995; Bush, 1991). Analysis of contemporary pollen rain (modern pollen) from surface soils and sediments can improve our understanding of stratigraphic (fossil) pollen records, but some regions and vegetation types remain little studied. Modern pollen spectra reflect present-day vegetation communities and allow separation of major plant community types when applied to stratigraphic pollen spectra from sediment cores obtained within similar pollen source area. (Gosling et al., 2009; Rodgers and Horn, 1996; Webb, 1974).

Several modern pollen studies represent Central America (Figueroa-Rangel et al., 2016; Bhattacharya et al., 2011; Correa-Metrio et al., 2011; Ortuño et al., 2011; Bush and Rivera, 2001; Bush, 2000; Rodgers and Horn, 1996; Islebe and Hooghiemstra, 1995; Jacobs, 1982; and references therein) and South America (Guimarães et al., 2017; Burn et al., 2010; Gosling et al., 2009; Urrego et al., 2010, 2009; Kuentz et al., 2007; Reese and Liu, 2005; Weng et al., 2004; Markgraf et al., 2002; and references therein), but a notable gap exists for the Greater and Lesser Antilles islands, which are represented by only a single published study from montane pine forests and grasslands of the Cordillera Central, Dominican Republic (Kennedy et al., 2005). The high-elevation vegetation types studied by Kennedy et al. (2005) are quite unlike lowland and coastal environments of the Caribbean islands, which to date are lacking published modern pollen research.

Several modern pollen studies from tropical America have focused on highland sites characterized by moist/wet forest types and grasslands or coastal sites dominated by mangroves, but tropical dry forests are poorly represented (Burn et al., 2010; Urrego et al., 2010, 2009; Kuentz et al., 2007; Bush, 2000; Weng et al., 2004; Islebe and Hooghiemstra, 1995). Tropical dry forests were once the most extensive forest type of the Americas and Caribbean but are highly threatened, having been largely converted to urban areas, savanna, and legume-dominated thorn forest or scrub (García-Fuentes et al., 2015; Sánchez-Azofeifa and Portillo-Quintero, 2011; Roth, 1999; Murphy and Lugo, 1995). Estimates suggest that less than half (44%) of tropical dry forests remain in Latin America (Sánchez-Azofeifa and Portillo-Quintero, 2011). Human disturbance of lowland dry forests complicated the analysis of modern pollen rain in western Mexico, where the pollen spectra causing were dominated by disturbance species (Jacobs, 1982). In Costa Rica, Rodgers and Horn (1996) were only able to obtain a single sample from within Fabaceae and Rubiaceae-dominated tropical dry forest due to the conversion of this forest type to agriculture. Correa-Metrio et al. (2011) cited a long history of human disturbance in the region as a possible influence on lack of unique pollen assemblages along environmental gradients for tropical seasonal forests of the Yucatan Peninsula. These studies point to the need for modern pollen studies from tropical dry forests, especially those less disturbed by people.

Analyses of pollen taxonomic assemblages has led to the successful separation of tropical vegetation types in tropical regions of South and Central America (Gosling et al., 2009; Bush, 2000; Rodgers and Horn, 1996; Bush, 1991) indicating that Neotropical vegetation communities do produce characteristic pollen rains. In spite of the growing number of modern pollen studies from mainland tropical America, relatively few studies (Iglesias et al., 2017; Correa-Metrio et al., 2012; Burn et al., 2010; Gosling et al., 2009) have examined the application of modern pollen analysis to the interpretation of stratigraphic pollen analyzed from sediment cores. In one example, vegetation communities surrounding lakes in Bolivia were reflected in surface pollen from their surface sediments when a taxa assemblage approach was combined with thresholds for overrepresented, wind-pollinated taxa, such as the Moraceae family, *Cecropia*, and *Schefflera* (Gosling et al., 2009). When applied to fossil pollen from the lake sediments, broad vegetation formations were identifiable, even for past vegetation communities compositionally dissimilar to those currently at the study site (Gosling et al., 2009).

This first study of modern pollen spectra from lowlands environments of the Greater Antilles had two main objectives: 1. To determine whether modern pollen spectra from surface samples could separate and identify vegetation types in coastal and lowland vegetation of semi-arid southwestern Dominican Republic; and 2. To explore the application of modern pollen data to a stratigraphic pollen record from sediments of Laguna Alejandro in the same region. We used non-metric multidimensional scaling (NMDS) to determine whether the studied vegetation communities were represented by identifiably characteristic pollen spectra and then applied the results of our analysis to interpretation of fossil pollen contained in Laguna Alejandro's sediments. The deficiency of modern pollen studies from the insular Caribbean, especially lowlands and tropical dry forest areas, presently limits the confidence and precision of sedimentary pollen-based paleoenvironmental reconstructions from this region, which have suggested major changes in precipitation, vegetation, and human-environment interactions during the late-Quaternary and Holocene periods (Burn et al., 2016; Holmes et al., 2016; Piperno, 2011; Peros et al., 2007; Haug et al., 2001; Higuera-Gundy et al., 1999). Here we contribute to the knowledge of how modern pollen spectra relate to local and regional vegetation in a tropical dry forest region, where such relationships have yet to be examined.

Study Area

The Dominican Republic (Figure 1, centroid 18.9˚ N, 70.4˚ W) occupies the eastern two-thirds of Hispaniola, a member of the Greater Antilles islands in the Caribbean Sea. The distribution of rainfall on the island is bimodal, with two rainy (April–June and September–November) and dry seasons (December–March and July; García-Fuentes et al., 2015). A series of northwest to southeast trending mountain chains block the onshore flow of humid ocean air masses (northeastern trade winds) and create a strong rainshadow effect for southwestern Hispaniola, with locally higher moisture availability linked to orographic precipitation (Izzo et al., 2010; Bolay, 1997).

Our study area (centroid 18.313097˚ N, 71.030802˚W; Figure 1) is located in the semi-arid southwestern Dominican Republic at the eastern edge of the Enriquillo Valley, a paleo-sea channel that became isolated from the Caribbean Sea ~4,000 years ago (Greer and Swart, 2006). Modern pollen samples were collected within Parque Nacional Sierra Martín García (SMG), an isolated coastal massif rising 1,343 m asl, and surrounding lowlands including Lagunas de la Sierra and Alejandro (informally named). Laguna de la Sierra is a shallow lagoon intermittently connected to Bahia de Neiba and also fed by ephemeral streams (arroyos) originating from SMG and channelized flow from the Yaque del Sur river. Surrounding land is seasonally inundated and sparsely vegetated by shrubs and herbs. Laguna Alejandro is also a shallow coastal lagoon at the base of SMG isolated from the sea by a narrow barrier of rock and fossilized coral. Coastal areas and lowlands of SMG and the Enriquillo Valley receive as little as 400–700 mm precipitation annually, while higher elevations of SMG may receive up to 800–1200 mm/yr linked to orographic precipitation from onshore breezes. Average monthly temperatures range from 25–28˚C (Izzo et al., 2010).

The lowlands and lower slopes of SMG are predominantly covered by thorn forests or 'scrub' typical of disturbed tropical dry forests in the southwestern Dominican Republic, with rare patches of less disturbed forest that contain higher numbers of old growth dry forest species, including *Bursera simaruba* (Burseraceae), *Guaiacum* spp. (Zygophyllaceae), and *Phyllostylon rhamnoides* (Ulmaceae) (Cano-Ortiz et al., 2015; García-Fuentes et al., 2015; García et al. 2007). While differences in the composition of tropical dry forests in the Dominican Republic can result from variations in substrate (Cano-Ortiz et al., 2015; i.e. growing on serpentine soils or limestone), another important factor is human disturbance, which has reduced the number of large hardwoods, such as *Bursera simaruba*, *Guaiacum* spp., and members of the mahogany family (Meliaceae), and promoted expansion of thorn forest associations dominated by legumes, particularly *Prosopis juliflora* and *Acacia macrantha* (García-Fuentes et al., 2015; Roth, 1999). Domestic logging for production of charcoal has caused proliferation of succulents and cactus in tropical dry forests of Dominican Republic, while cattle and goat grazing have dramatically increased the proportion of leguminous trees, especially *Prosopis juliflora* (García-Fuentes et al., 2015). The abundance of these legumes (Fabaceae) is strongly proportional with the degree of disturbance (García-Fuentes et al., 2015).

Tropical dry forests transition to humid broadleaf forests at ~500 m elevation on SMG with increasing moisture availability and improved edaphic conditions (García et al., 2007). We observed a concurrent transition in soils, with thick O horizons at the dry-humid broadleaf transition compared with the thin and mineral soils on limestone bedrock at lower elevations. Seasonally inundated areas and mangroves on the coasts have unique species compositions including mangroves species (*Avicennia germanins*, *Laguncularia racemosa*, *Rhizophora mangle*) the terrestrial mangrove *Conocarpus erectus*, and salt-tolerant succulent herbs and shrubs.

The park is only sparsely occupied due to its remoteness and harsh climatic conditions, with some areas affected by mining, charcoal production, livestock grazing, fishing, and subsistence agriculture (Perdomo et al., 2010; García et al., 2007). During sampling, a saltpan operation occupied the eastern side of L. Alejandro and a canal had been recently built on the western edge to release water. We accessed a network of single-track vehicle paths in the coastal and lower elevations of SMG to collect our surface samples. We observed evidence of logging in upland forests of the park during our 2013 visit and encountered a subsistence garden (conuco) and smoke from a small fire.

Materials and Methods

Field methods

We collected modern pollen samples during the winter dry season of 2013 when seasonally inundated lands are exposed. At each site, we noted the dominant taxa and all known species, the topographic/geomorphic position (alluvial fan, coastal barrier, etc.), and location information (elevation, latitude, and longitude) recorded using a sub-meter accuracy Trimble GPS unit (Table 1). At each sample site, the field team employed the "10 pinch" method (Kennedy et al., 2005; Rodgers and Horn, 1996; Adam and Mehringer, 1975) for collecting modern pollen from soils: ten random "pinches" of the top 1–2 cm of the soil/sediment surface from a small area with approximately 100 m^2 of relatively homogenous vegetation were gathered, bagged, and mixed to represent the pollen rain of the area over the approximately the past 1–10 years (Rodgers and Horn, 1996). In sites with deep leaf litter, we collected material from the litter/soil interface. We collected modern pollen from surface sediments in lakes or waterlogged sites using a Mudsnapper dredge, to capture the mud/water interface. All samples were stored in whirl packs at 6 °C at Virginia Tech (VT) prior to further processing.

Vegetation Types

Tropical dry forest

We retrieved two samples from mature tropical dry forest growing on the alluvial fans emanating from SMG. The uppermost sample location (Sample 1, ~480 masl), was a dense closed-canopy forest of ~10–15+ m height near the boundary with humid broadleaf forest. Dominant tree taxa included Sapotaceae spp., *Guaiacum officinale*, and *G. sanctum*. We observed freshly cut stumps of both mature *Guaiacum* trees and saplings in this area and a subsistence garden growing squash (Cucurbitaceae). Sample 2 was collected lower on the slope (~280 masl) in an ecotonal area between less and more disturbed dry forests. Canopy trees included *Bursera simaruba,* Fabaceae spp., Moraceae spp., and *Guaiacum*. The shrub layer included species of *Ilex,* Myrsinaceae, and Myrtaceae. Lianas and bromeliads were abundant including *Tillandsia* spp.

Thorn forest

Thorn forests form an extensive vegetation type in the driest areas of the country, throughout the Enriquillo Valley and extending into the Azua Valley, where annual precipitation is low (<700 mm/yr) and evapotranspiration greatly exceeds precipitation (Cano-Ortiz et al., 2015; García-Fuentes et al., 2015; García et al., 2007). These forests represent disclimax communities resulting from human disturbance to tropical dry forest (García-Fuentes et al., 2015; García et al., 2007; Roth, 1999). At our study site, thorn forests are located on drier soils at the base of Sierra Martín García in eastern edge of the Enriquillo Valley. Vegetation is of low height (generally <5 m), with abundant spiny shrubs and small trees and cacti, many endemic (Cano-Ortiz et al., 2015). Characteristic species include *Prosopis juliflora*, *Mimosa* spp., other leguminous species, *Agave antillarum, Bursera simaruba*, and Cactaceae spp. such as *Opuntia cubensis*, *Harrisia nashi*, *Pilocereus polygonus* (García-Fuentes et al., 2015; García et al., 2007). These forests are sometimes inundated after tropical storms and during the wet season, as indicated by high-resolution satellite imagery. We obtained four samples (3, 4, 5, 6) from sites near sea-level at the base of the mountain. Sample 4 was collected near L. Alejandro from an arroyo deposit just behind a stand of *Rhizophora mangle*.

Beach

On drier coastal sites just inland from the shore, shoreline plants that can tolerate high salinity (halophytes), onshore winds, and periodic inundation by seawater give way to short-statured tree and shrubs dominated by drought-deciduous and evergreen species, including thorny types and cacti. Most shoreward are *Rhizophora mangle* mangroves growing in areas protected from direct wave action. Sprawling herbaceous vegetation included *Batis maritima*, *Sesuvium portulacastrum*, grasses, sedges, and other taxa representing the families Amaranthaceae and Malpighiaceae. *Bursera simaruba* often emerged from the low and dense canopy formed by *Coccoloba uvifera, Guaiacum officinale,* and representatives of Melastomataceae, Fabaceae, and Apocynaceae. We collected Sample 7 from highly mineral soil in beach vegetation.

Mudflat

Seasonal lagoons/mudflats are located along the coasts of Bahia de Neiba at the base of SMG, where the Yaque del Sur river forms an extensive system of tidally and seasonally inundated wetlands sparsely vegetated by halophytes. Some main constituents include the herbs *Sesvium portulacastrum* (Aizoaceae), *Heterostachy ritteriana* (Amaranthaceae), *Batis maritima* (Bataceae) and *Heliotropium curassavicum* (Boraginaceae). Drier areas less frequently inundated support *Prosopis juliflora* and cacti such as *Consolea monoiforms*. The mangrove species *Conocarpus erectus* (buttonwood), *Avicennia germinans* L. (black mangrove), and *Rhizophora mangle* (red mangrove) are located along the coast of Bahia de Neiba and fringe the lagoons with more regular access to water, including Laguna Alejandro (García et al., 2007). At the time of sampling during the driest season, seasonally flooded lagoons were sparsely vegetated mudflats, dominated by a single herb (*Batis maritima*). We obtained four samples (Samples 8–11) from this vegetation type.

Mangrove

Red mangroves (*Rhizophora mangle*) grow as thickets of small shrubs to large trees with branched prop roots. While red mangroves can advance seaward to 1m depth, they generally grow in shallow and muddy coastlines protected from direct wind and wave action. They tolerate a wide range of salinities from fresh to 44 ppt, but above 65 ppt the trees begin to die and above 90 ppt the trees are dead (Nellis, 1994). Droughts can also kill red mangroves that colonized salt flats and similar areas during the rainy season. Black mangroves (*Avicennia germinans*) grow as small shrubs to large trees and are easily distinguished from the other mangrove species by their pneumatophores. Adult black mangroves are very salt tolerant and may tolerate hypersaline conditions of 100 ppt (Nellis, 1994). Black mangroves are primarily found on silty, saturated soils along tidal coasts at higher elevations than red or white mangroves, as they can be killed if the pneumatophores are submerged for a long time period. White mangroves (*Laguncularia racemosa*) are evergreen trees to 25 m and prefer moist and silty soil but are not as salt tolerant as black and red mangroves. At salinities higher than sea water, white mangroves are often replaced by black mangroves (Nellis, 1994). Buttownwood (*Conocarpus erectus*) is found near salt water but cannot tolerate sites as wet as white and black mangroves. Unlike the other true mangrove species, buttonwood can survive periods of drought and may occur some distance from the water (Nellis, 1994). We obtained two samples from mangroves. Sample 12 was obtained from within a monospecific stand of *Rhizophora mangle* and 13 from a stand of canopy height *Conocarpus erectus* forest at the base of SMG.

Lagoon

Surface samples were also obtained from the center and inland edge of Laguna Alejandro (14 and 15) to examine the representation of the pollenshed in the sedimentary record. Due to the hypersalinity of L. Alejandro and inundation of surrounding mudflats during the spring tides and storm events, no vegetation grows in the lake or around the edges. During the dry season, we observed maximum water depths of 4 m at Alejandro but satellite imagery shows that the lake's surface area expands into the surrounding mudflats during the wet-season and tropical storms.

Laboratory methods

Samples were mixed thoroughly before sampling. Subsamples of 15–45 ml (15 ml for sediments, 45 ml for soils) were removed and soaked in deionized water, and then washed through 250 µm screens to remove coarse organic debris and large mineral grains. The sieved material was centrifuged down and the remaining pollen-rich material stirred (Kennedy et al., 2005). We then removed and processed 2 ml samples for pollen analysis using a modified heavy liquid technique (10% hydrochloric acid for the removal of carbonates, 10% potassium hydroxide to break up organics and for the removal of humic acids, 10% sodium hexametaphosphate to disperse clays, 2.2 specific gravity sodium polytungstate, 49% hydrofluoric acid for the removal of silicates, acetolysis solution, safranin stain; Traverse, 2007; Faegri and Iverson, 1989). Tablets with a known number of *Lycopodium* spores (one tablet containing 18,584 ± 371 spores) were added to each sample to allow calculation of pollen concentrations (Stockmarr, 1971).

We made slides of the residue and identified and counted a minimum of 300 pollen grains and spores (with spore abundance ranging from an absence to a maximum of 8% of total sum) from the fifteen slides with sufficient pollen preservation. Counts were made at 400x magnification using a Leica compound light microscope. Indeterminate grains were tallied and classified as either damaged or obscured while pollen types we could not identify were categorized as ‘unknown’. Identification of pollen and spores were aided by our own pollen/spore reference slides from the Dominican Republic and other tropical areas, published references (Buril et al., 2010; Lima et al., 2008; Bush and Weng, 2006; Willard et al., 2004; Colinvaux et al., 1999; Palacios-Chávez et al., 1991; Roubik and Moreno, 1991; Hooghiemstra, 1984; Sorsa and Huttunen, 1975), and online pollen databases with photographs and descriptions (Davis, 2001). While we were able to distinguish *Trema*, *Celtis* spp., *Cecropia*, and *Urera* spp., we grouped all other Urticales-type pollen grains, which are psilate to granulate and have variable numbers of pores, into the category of Moraceae/Urticaceae pollen. We were able to discriminate *Acacia*, *Caesalpinia*, *Mimosa* spp., and *Prosopis juliflora;* other types we grouped at subfamily or family (Fabaceae) level. Identification of *Zea mays subsp. Mays* pollen grains followed Lane et al. (2008) with Poaceae pollen grains greater than 62 μm in diameter identified as maize. We graphed pollen and spore data into four broad categories (Dry, humid, and pine forest, thorn forest, mangroves and coastal, and herbs and grasses) in the stratigraphic plotting software TILIA v. 2.0.41 (Grimm, 1990).

In order to test the ability of our modern pollen and spore data to classify fossil pollen data from sediment cores into vegetation/ecosystem types, we conducted pollen analysis on a previously collected sediment core. In 2012, we collected overlapping sediment profiles (sediment core ALJ202, 0–220cm) in clear PVC tubes from the center of the lake using a Colinvaux-Vohnout piston corer until the sediment could no longer be penetrated. At Virginia Tech, the cores were stored at 6 °C until photographed and X-radiographs (x-rays) taken to provide detailed stratigraphy. Core sections were described on core logs, noting sediment stratigraphy, texture, and Munsell colors.

We conducted loss-on-ignition analysis (Dean, 1974) at 1 cm intervals throughout the profile to determine the fractions of water, organic matter, and carbonates in each level. In order to provide chronological control for the profile, plant macroremains and charcoal from six depths (Table 2) were removed and sent for Accelerator Mass Spectrometry (AMS) radiocarbon dating through the facilities at Woods Hole Oceanographic Institution and University of Arizona. Sample ages were calibrated using the Intcal13 dataset (Reimer et al. 2013) and the Bayesian age-depth modeling program Bacon (ESM1; Blaauw and Christen, 2011).

To document the vegetation history of the study site, we removed 1 cm^3 samples from 26 depths throughout the sediment profile, using changes in sediment stratigraphy to guide sampling. We processed sediment samples using a modified heavy liquid technique, previously described. We scanned slides of pollen residue and identified and counted a minimum of 300 pollen grains and spores per slide at 400x magnification using a Leica compound light microscope from 10 depth levels with sufficient preservation and density. Indeterminate grains were tallied and classified as either damaged (e.g., crumpled or corroded) or obscured. Pollen/spore data were graphed and analyzed using the specialized pollen plotting software TILIA v. 2.0.41 (Grimm, 1990).

Numerical analyses

We expressed our individual pollen and spore types as percentages of our total counts excluding unknown and indeterminate types. In Past 3.15 software (Hammer et al., 2001), we included our thirty-eight pollen and spore types with amounts greater than or equal to 1% abundance for at least two samples. We then performed non-metric multidimensional scaling (NMDS) using the Bray-Curtis dissimilarity index. Like other ordination techniques, NMDS is useful in revealing structure and patterns within datasets. This technique is frequently used in ecology as it avoids assumptions of linear relationships among variables and is thus well-suited for non-normal datasets (McCune and Grace, 2002). In paleoecological and paleontological studies involving analysis of pollen and spores, NMDS has proved a useful technique for examining compositional differences in pollen spectra dating to the Holocene and older time periods (Moss et al., 2016; Salzmann et al., 2011; Harrington, 2008; and references therein). The Bray-Curtis index is advised when examining species abundance data as the index takes into account taxon presence/absence and abundance and rank orders pairs of samples based upon their similarity values (Beals, 1984). In the resulting 2D scatterplot, samples are arranged to best represent these values, with samples closer together in multidimensional space interpreted as more compositionally similar than samples further away from each other. The software also computes the “stress” parameter, giving the user an indicator of the goodness of fit when interpreting the NMDS results, with stress levels greater than 0.2 indicating a poor fit, and levels below 0.05 as excellent or high confidence when interpreting similarity values (McCune and Grace, 2002).

Results

Modern pollen

We identified 186 pollen and 13 spore morphologic types (including *Selaginella*). Pollen concentrations (grains/ml; Figure 2) varied greatly, from a low of 9,161 for our beach sample (sample 7) to a maximum of 199,778 for one of our thorn forest samples (sample 4). Concentrations were generally low, with 11 of 15 samples below ~44,000 grains/ml. Considered by vegetation type, our mangrove samples had the overall highest pollen concentrations, with 168,349 and 78,724 grains/ml. In general, pollen concentrations varied within and between ecosystem types, suggesting differences in pollen influx and preservation are tied to site specific factors versus vegetation type alone.

Taxonomic diversity also varied considerably, with a minimum found at a thorn forest (sample 6) containing only 15 identifiable pollen and spore types and tropical dry forest (sample 2) with a maximum of 69 types (Figure 2). By vegetation type, our tropical dry forest samples had the overall great diversity. The main features of the pollen spectra in each vegetation type are described below.

Tropical dry forest

Samples from mature dry forest are distinguishable from other vegetation types by the high biodiversity of pollen taxa, including pollen from tropical dry (*Bursera simaruba*, *Cordia*, Urticaceae/Moraceae), humid broadleaf (*Begonia*, *Cecropia*, Urticaceae/Moraceae), and pine forest (*Pinus occidentalis*) taxa, and the lack of pollen from thorn forest, mangrove, and halophytic vegetation. While we grouped Urticaceae and Moraceae, most of the pollen is likely from the mulberry family (Moraceae), as much of the Urticaceae/Moraceae category is dominated by psilate, spheroidal pollen with inconspicuous, non-annulate pores while the Urticaceae family, including those types found on Hispaniola, are dominated by scabrate to granulate types with annulate pores, types relatively rare in our record (Sorsa and Huttunen, 1975). One exception to the Urticaceae/Moraceae category is our treatment of *Urera* as a separate pollen type.

Spectra from the highest elevation of SMG (Sample 1) was dominated by *Celtis* spp. (~22%) and *Pouteria/Sideroxylon* (~17%, Sapotaceae) pollen. At least two species of *Celtis* are found in our study area, including *C. iguanaea* (a liana) and *C. trinervia* (a tree) though the genus is treated as an important tree of secondary tropical dry forests in the Miragoâne record (Higuera-Gundy et al., 1999). *Pouteria/Sideroxylon* spp. are trees of seasonally-dry to mesophytic forests of the Neotropics (Newsom and Wing, 2004) and were present locally. Trees from the mulberry family (Moraceae) were present locally and likely account for the importance of Moraceae/Urticaceae pollen for this sample. Also present locally and represented in the pollen spectra was *Bursera simaruba*. The conuco was represented in the pollen spectra by small amounts of *Dioscorea* (yams) and *Ipomoea* (sweet potato). Forest canopy-gap/disturbance indicators and other taxa suggestive of more open vegetation included small amounts of *Cecropia*, short-spine Asteraceae, *Piper*, Scrophulariaceae, *Solanum*, and *Trema* pollen grains.

Slightly lower in elevation, our other tropical dry forest sample (2), at the ecotone of less and more disturbed dry forest, had an increased presence of Fabaceae pollen (*Caesalpinia*, ~10%). Dominant taxa also included *Euphorbia* (~16%), *Piper* (13%), along with *Bignoniaceae* (~6%), *Begonia* spp. (~5%), and Urticaceae/Moraceae (~4%). *Caesalpinia* is a dry-adapted genus found in tropical dry forests (Higuera-Gundy et al., 1999) and lowland woodlands (Newsom and Wing, 2004) and is likely the legume we observed growing at the study site. *Agave*, *Bursera simaruba*, *Ilex*, Moraceae, and Myrtaceae, all present locally, were present in the pollen spectra in relatively small amounts while bromeliads and *Guaiacum* spp. were present in the local vegetation but absent from the pollen record. Pollen of disturbance indicators and more open vegetation (*Cecropia*, *Piper*, *Peperomia*, Scrophulariaceae, and *Solanum*) were also present in this sample's pollen spectra.

Thorn forest

Thorn forest samples nearer to SMG (3 and 4) contained a relatively high diversity of pollen taxa though lower than our tropical dry forest samples (Figures 2 and 3). Pollen spectra from these samples included many dry (*Bursera simaruba*) and humid forest (*Cecropia*, Urticaceae/Moraceae), thorn forest (*Mimosa*), and mangrove and coastal vegetation pollen types, reflecting the proximity of these samples at the ecotones of several vegetation types. Pollen spectra were dominated by wind-pollinated *Conocarpus erectus* (~34 and 37%), as well as *Mimosa* spp. (~18 and 4%, growing upslope) and *Bursera simaruba* (9%, Sample 3). *Rhizophora mangle* was present in small amounts at Sample 4, obtained behind a monospecific stand of red mangroves. Sedge pollen contributed 22% of the total pollen of Sample 4. Absent from the pollen rain was *Coccoloba uvifera*, present as canopy height trees at both sample sites, and *Guaiacum* spp., common in beach and dry forest areas at our study site. Vegetation that produces a lot of pollen and/or whose pollen is dispersed by the wind were absent locally but contributed relatively high pollen amounts to our sample locations, including Urticaceae/Moraceae (~6 and 23%, respectively). Sample 3 contained Melastomataceae pollen (~2%), relatively rare in our record though we did encounter canopy-height trees of the family at the sample location.

Sample 6 was dominated by a single leguminous species, *Prosopis juliflora* (93%). While wind-dispersed pollen types from upland forests were present (*Pinus occidentalis*), this sample is notable for a lack of Urticaceae/Moraceae pollen, found in all other samples. Sample 5 was dominated by the local pollen signal, specifically Cyperaceae (~35%), and a diversity of pollen types from forest, coastal, and herbaceous types. Sample 5 also contained cactus pollen, rare in the pollen record. While cactus is an important element of the lowland vegetation at the study site, cactus pollen was rare in the pollen record with sample 5 containing the highest percentage (Figure 3).

Beach

Pollen spectra from our singular beach sample (7) contained a relatively high diversity of pollen taxa, with spectra representing wind-dispersed pollen types from upland (humid and pine), dry, and thorn forest, and coastal zones, including Urticaceae/Moraceae (~14%), *Pinus occidentalis* (4%), *Mimosa* (~5%), and *Conocarpus erectus* (11%). Pollen representing local vegetation was also present, dominated by sedges (~16%), Malpighiaceae (~4%), and *Peperomia* (4%). Absent from the pollen spectra but present locally were Cactaceae, *Coccoloba uvifera*, and *Guaiacum sanctum*.

Mudflat

We analyzed four samples from mudflats. Pollen spectra of our samples are dominated by wind-dispersed tree and shrub species from dry, humid, pine, and thorn forest upslope, including Urticaceae/Moraceae (~2 to 39%), *Pinus occidentalis* (~2 to 10%), and *Mimosa* (Sample 8: ~90%). Pollen of other tropical dry and humid forest tree species contributed to our pollen spectra, including *Bursera simaruba*, *Cecropia, Celtis, Cordia,Trema, and Trichilia* spp.. Local vegetation also contributed pollen, including palms, mangroves, sedges, and grasses. While vegetation of the mudflats was dominated by halophytes including *Amaranthaceae* and *Batis maritima*, cactus, and black and button mangroves, pollen of these types were underrepresented in the pollen record. Amaranthaceae pollen was absent from sample 8, it reached maximum percentages of ~4% in our other coastal lagoon/mudflat samples. While Amaranthaceae was present in other ecosystem types, including mangroves and beach, *Batis maritima* was only present in our coastal mudflat and lagoon samples, from ~1 to 2%, and is indicative of this ecosystem type. Cactus pollen, rare in our pollen record, was present in our coastal lagoon and mudflat samples, though as single grains. *Conocarpus erectus* and *Rhizophora mangle* pollen were also present in our samples, while pollen of *Avicennia germinans* was absent from all four samples.

Mangrove

Pollen spectra of sample 12, obtained within a monospecific stand of *Rhizophora mangle*, is dominated by pollen of *Conocarpus erectus* (37%) though this sample also contained the highest percentage of red mangrove pollen (~6%) in our samples. Both species rely upon wind to disperse pollen and as such produce prolific amounts of pollen. The red mangrove sample also contained pollen from upland moist forest trees and shrubs (Urticaceae/Moraceae, 21%) and sedges (~18%). The pollen spectrum from sample 13, a monospecific stand of *Conocarpus erectus*, was dominated *Prosopis juliflora* pollen (~34% growing upslope), followed by *Conocarpus erectus* (~30%) pollen.

Lagoon

Two lagoon samples contained sufficient pollen for analysis. Sample 14 was obtained near the inland edge of L. Alejandro while 15 was obtained near the center of the lake, nearest the sample location of sediment core ALJ202. Similar to other samples, wind-pollinated species of forest and mangrove ecosystems dominate our lagoon samples, including Urticaceae/Moraceae (~43 and 54%), *Pinus occidentalis* (~18 and 10%), as well as other tropical dry forest species including *Cecropia* (~4 and 10%), *Bursera simaruba*, palms, and *Piper* spp. Herbaceous pollen of local vegetation is also present in small amounts, including grasses, sedges, and short-spine Asteraceae. Taxonomic diversity (Figure 2) was greater for the sample obtained from the inland edge of the lake versus the center and included rare pollen taxa from dry and humid forest taxa and probable cultivars (Convolvulaceae, Cucurbitaceae; Figure 3).

Alejandro sediment core

Core chronology and description

Our AMS radiocarbon dating results indicate that sediments began accumulating at the core site by ~1,500 cal yr BP (Table 2). Results from the two uppermost samples (35–37 and 70–71 cm) were discarded as they dated to ~2,000 cal YBP, older than the bottom of the core and probably reflect older carbon deposited into the lake. Presence of alluvial fans terminating in the landward margin of the lake and storm-generated overwash fans on the coastal barrier and seaward margin of the lake both provide possible mechanisms for the introduction of older carbon into the water body. A coarse clastic layer (21–54 cm, Figure 4) may be linked to hurricane-generated overwash and deposition of sand and gravel from the coastal barrier to the core site. The bottom three dates were in order and are in general agreement with previously obtained results from a different sediment core obtained near the seaward edge of the lake (LeBlanc et al., 2017).

We divided lake core ALJ202 into two zones based upon sediment stratigraphy and loss on ignition data. Zone 1 encompasses 0–81 cm (~520 cal yr BP to present) and Zone 2 82–220 cm (~1500–530 cal yr BP). Loss-on-ignition results (Figure 4) indicate organic content of our core ranges between 8–29%, with the lowest values coinciding with the clastic layer deposited 21–54 cm. Zone 2 has overall higher organic, carbonate, and water content while Zone 1 is dominated by silicates, comprising up to a maximum of 89% of the sediment at 32 cm. Basal sediments (220 cm) to 111 cm are dominated by finely-laminated, silty-peat, before transitioning to silty-peat characterized by soft laminations from 111 to 81 cm. Above 81 cm, the core is dominated by silt lacking laminations and from 52 cm to the top of the core, sediments are clastic. A peat deposit (174–163 cm) suggests lower water and salinity levels than present and indicates the lagoon was a mangrove swamp in the past.

Stratigraphic pollen results

Of the 26 levels processed for pollen analysis, ten contained sufficient pollen for analysis (Figure 5). Pollen samples from sediments between 54 and 80 cm (~510–310 cal yr BP/1640–1440 CE) were poorly preserved (exines thinned) and not analyzed. Our zones delimited by sediment stratigraphy are also useful for describing pollen results. Pollen concentrations (Figure 2) varied widely throughout the core, from a minimum of 17,135 grains/ml in our uppermost sample (9–10 cm) to a maximum of 303,213 grains/ml at 82.5–83.5 cm. Pollen concentrations were overall higher for Zone 2, ranging from 70,206 to 303,213 grains/ml while concentrations for Zone 1 ranged from 17,135 to 87,488 grains/ml. Taxonomic diversity is overall lower for Zone 2 (82–220 cm, ~530–1500 cal yr BP) in comparison to Zone 1, with an average of 21 versus 41 types, respectively.

Pollen spectra for Zone 2 (Figure 5) is dominated by thorn forest types, specifically *Mimosa* spp., comprising 56 to 84% of our pollen. Pollen of dry and humid forest vegetation (Urticaceae/Moraceae) and sedges are also important components of the pollen spectra of Zone 2. Pollen types indicative of forest canopy gaps or more open vegetation (*Cecropia, Trema, Piper, Urera, Solanum*) are found in small amounts of Zone 2. Pollen of *Urera*, an evergreen shrub to small tree often in secondary growth (Fern, 2014) was not identified in our modern pollen samples but is found in our stratigraphic pollen record in sediments representing ~1,300–190 cal yr BP cm. Pollen of mangroves and coastal vegetation are present in small amounts in our oldest sediments dating to ~1,500 cal yr BP, indicating these vegetation types were established at the study site by that time.

Zone 1 (0–81 cm, present day to ~520 cal yr BP) shows a drastic decrease in pollen of thorn forest vegetation and an increase in pollen of dry and humid forest and successional types, particularly Urticaceae/Moraceae and *Urera* pollen, for sediments representing ~250–115 cal yr BP/1700–1840 CE. These sediments, deposited between 46 and 29 cm, occurred within a clastic layer interpreted as a hurricane overwash deposit (Figure 4). For this time period, Urticaceae/Moraceae represent 32–44% and *Urera* 4–24% of our pollen sums. Pollen of other disturbance/gap indicators, including *Cecropia*, *Piper*, *Trema*, and *Solanum* are present, suggesting forest canopy gaps. Pollen of mangrove and coastal vegetation is also present, in slightly higher amounts versus Zone 2. Presence of *Guaiacum sanctum* pollen, rare in our modern and fossil pollen, is found in sediments deposited ~250 cal yr BP (46 cm). Thorn forest types were still present near the core site, as revealed by *Mimosa* spp. pollen in all depth levels analyzed for the zone. *Prosopis juliflora* pollen, absent in older sediments, is present in small amounts at ~190 cal yr BP and sediments deposited within recent decades (9–10 cm). Cactus pollen is also present after ~115 cal yr BP and in our uppermost sediments analyzed. Two grains of maize pollen were identified in sediments deposited ~190 cal yr BP. Our uppermost level analyzed, in sediments deposited in the last several decades (9–10 cm) is dominated by pollen of pine (33%) and *Bursera simaruba* (10%). While pollen of *Cecropia* was absent, pollen of *Piper*, *Trema*, and *Solanum* were present. A thin clastic layer deposited in this level suggests another hurricane strike to the study site.

Non-metric Multidimensional Scaling results

Non-metric multidimensional scaling (NMDS) results revealed clear differences in modern pollen spectra, with samples from more open/lacustrine conditions clustering together (Figure 6). Clustering of three of four mudflat and both lagoon samples indicates the groups are compositionally similar to each other though distinct as the groups remain separated when displayed in multidimensional space. Another cluster contains samples from multiple vegetation types, including tropical dry forest, thorn forest, mudflat, mangrove, and beach. These samples were all obtained near the base of SMG at the boundaries of several ecotones, and all received relatively high inputs of pollen from lowland (thorn and dry) and upland (humid and pine) forests and mangrove pollen, particularly *Conocarpus erectus*, explaining the compositional similarity of pollen spectra observed from these very different vegetation types. Notably, some samples from within the same vegetation type, such as mangrove (samples 12 and 13) and tropical dry forest (samples 1 and 2), are relatively far apart in multidimensional space, reflecting the high taxonomic diversity of tropical lowlands. Samples 5 and 6 (thorn forests) and 13 (mangrove), obtained at the western edge of SMG's pollenshed, contain less pollen from dry, humid, and pine forests in comparison to our other samples and explain their unique positions in multidimensional space. Sample 1, from dry forest near the boundary with humid forest, also occupies unique multidimensional space apart from the other forested samples, reflecting the abundance of pollen types from dry and humid forests found only in this sample. A stress level of 0.09091 indicates a good fit (McCune and Grace, 2002).

In order to examine the compositional similarity of our pollen from sediments of Alejandro to pollen from surface soils and sediments, we re-ran the NMDS and included our sediment core data. A stress level of 0.09833 indicates a good fit and thus we used the results an interpretive aid. In the combined analysis, the tropical dry forest samples did not cluster together but do occupy unique multidimensional space along axis 2, reflecting the high taxonomic diversity of dry forests and distinct compositional differences of dry and thorn forests. Similar to the modern pollen only model, the same three mudflat and both lagoon samples cluster together in the combined model, while a third cluster contains both mangrove samples and the two thorn forest samples (3 and 4) obtained near the base of SMG, reflecting the high contribution of *Conocarpus erectus* pollen to all 4 sample locations.

When applied to the sediment core samples, the combined ordination shows distinct clustering of all samples from Zone 2 (Figure 6) near each other and proximal to surface samples 6 (thorn forest) and 8 (mudflat). Pollen spectra of samples 6 and 8 are both dominated by Fabaceae (*Mimosa* spp. and *Prosopis julifora*) pollen while pollen from zone 2 of the sediment core was dominated by *Mimosa* spp. The only exception is pollen spectra from 179 cm of Zone 2, more taxonomically similar to modern sample 13 (mangrove), reflecting the increase in Urticaceae/Moraceae pollen for sediments deposited at 179 cm.

Interpreting pollen of Zone 1 is less straight forward. Samples from 46 and 38.5 cm cluster together and relatively near both lagoon samples as well as thorn forest sample 4 and mangrove sample 12 modern pollen samples. Similar to our surface mudflat and lagoon samples, pollen from 38.5 and 46 cm is dominated by Urticaceae/Moraceae pollen but high amounts of *Urera* pollen in these depths, relatively rare in Zone 2 and extremely rare (limited to two pollen grains) in the modern pollen rain, may explain these samples unique position in multispectral space. Pollen from 30 cm is located near thorn forest sample 4 and mangrove sample 12, reflecting the decrease in *Urera* pollen, dominance of Urticaceae/Moraceae from upland forests, and highest amounts of *Mimosa* spp. pollen for Zone 1. Our uppermost pollen sample from 10 cm lies nearest our beach modern pollen sample in multidimensional space. Pollen spectra from 10 cm is dominated by *Pinus* pollen, unique for our site's 1,500 year history. Pollen of *Bursera simaruba* and grasses also reached their highest abundances in the core at this depth level. Samples from Zone 1 occupy relatively unique multispectral space, and therefore are compositionally dissimilar to modern pollen rain and vegetation conditions presently at the study site.

Discussion

Application of modern pollen to interpretation of sedimentary pollen records

Our NMDS results reveal that for much of Zone 2 (~1500–530 cal yr BP), Alejandro's pollen spectra was compositionally similar to Fabaceae dominated mudflat and thorn forest modern pollen samples. Zone 2 pollen is dominated by *Mimosa* spp. and representatives of tropical dry forest, mangrove and coastal vegetation types. Modern pollen analysis at SMG demonstrates that *Mimosa* spp. pollen currently derives from thorn forest growing upslope of our lagoon and mudflat sites, whose open conditions allow for a high input of pollen rain from the pollenshed in addition to local sources. We interpret the combined (modern pollen and core) NMDS results as demonstrating that Laguna Alejandro only recently (after ~530 cal yr BP) exhibited deeper-water lagoon conditions, and instead consisted of a shallow-water lagoon, perhaps also of lesser spatial extent, from ~1,500 to at least 530 cal yr BP. The absence of pollen from halophytes we might expect to grow on mudflats, such as *Batis maritima* and Amaranthaceae, may suggest arroyos from SMG drained into Alejandro to allow more permanent and fresh to brackish-water conditions.

Shallow water conditions are confirmed by sediment characteristics, including the presence of peat, likely mangrove, in sediments of Zone 2, and confirmed by low amounts of mangrove pollen in this core section. A previously analyzed sediment core from the northwestern section of Alejandro, ~50 m from the water's edge, also documented mangrove peat throughout the sediment profile and confirm shallow water conditions (Kar, 2010). Isolated patches of white and red mangroves (excluding the terrestrial mangrove, *Conocarpus erectus*) currently grow around the perimeter of the lake. Tropical dry, humid, and pine forests were established on slopes of SMG by ~1,500 cal yr BP, as demonstrated by pollen of Urticaceae/Moraceae, *Pinus*, and *Celtis*, with the presence of disturbance indicators (*Cecropia* and *Trema*) suggesting forest canopy gaps. The dominance of *Mimosa* spp. pollen in the record suggests the plants vegetated lowlands near the core site, perhaps growing in locations now inundated by L. Alejandro or transported by wind and water from upslope. Modern pollen sample 3, on the western edge of Alejandro, contains pollen from *Mimosa* growing upslope. While we were unable to identify which species of *Mimosa* we observe in the sediment core, there are at least four species endemic to the West Indies (Acevedo-Rodriguez and Strong, 2012), sprawling annual vines to shrubs that prefer open conditions and whose seeds can be transported by running water, such as from arroyos draining from the alluvial fans at the base of SMG.

After ~530 cal yr BP, NMDS results for Zone 1 samples are interpreted as resulting from dramatic changes in hydrologic condition and consequent changes in pollen representation. Pollen was poorly preserved from ~510–310 cal yr BP/1640–1440 CE, suggesting very shallow water to exposed sediments at the core site, coincident with the latter half of the Little Ice Age (1400–1850s CE), associated with variable precipitation and periods of drought in the Caribbean (Burn et al., 2016; Fensterer et al. 2012). Following this period of interpreted low water levels, the pollen spectra exhibits a shift from thorn forest (*Mimosa* spp.) to dry and humid forest (Urticaceae/Moraceae, *Urera* spp.) types dominating much of Zone 1 until recent decades. NMDS suggested pollen spectra of sediments deposited ~250 and 190 cal yr BP (46 and 38.5 cm) were compositionally most similar to pollen spectra from L. Alejandro's surface as well a mangrove and a thorn forest sample; all dominated by Urticaceae/Moraceae, buttonwood, and sedge pollen.

We interpret this shift in pollen spectra from Zone 2 to 1 as an indicator of change in Alejandro's hydrologic condition, from a shallow, perhaps narrow lagoon following the coastline to deeper water and probably more extensive spatial extent similar to current hydrologic conditions and explaining the similarity of pollen spectra (i.e. abundance of Urticaceae/Moraceae) for the lagoon's surface pollen spectra. A greater surface extent of the lagoon would also explain a decrease in pollen from vegetation proximal to the core site (i.e. *Mimosa*) as the core site became less sensitive to pollen sources nearby and allow increased pollen rain from vegetation upslope (i.e. Urticaceae/Moraceae). Not only would a change in hydrologic condition explain the shift in spectra, but also the increase in taxonomic diversity characteristic of Zone 1, reflecting the greater representation from taxonomically rich upland forests (Figure 2). Overall low pollen concentrations for this core section may be tied to the largely clastic nature of Zone 1 sediments.

Multiple hurricane strikes at the study site may explain the addition of multiple, discrete clastic layers deposited in Zone 1 between surface sediments and 54 cm, including multiple thin clastic layers in the top 13 cm (last ~5 decades) as well as a large deposit from 21–54 cm, encompassing three of four depth levels (29–30, 37.5–38.5, and 46–46 cm) analyzed in this core section. Our age-depth model (ESM1) provides a date of ~307 cal yr BP or ~1643 CE for the bottom of the 21–54 cm clastic layer. Hurricanes struck Santo Domingo/southern Hispaniola at 1631 and 1680 CE (Millas, 1968) and could be the storm we document at ~1643 in our core. The hurricane strike ~307 cal yr BP was also documented in a core obtained near the seaward of Alejandro (LeBlanc et al., 2017). Hurricane winds and storm surge may have also mechanically damaged lowland vegetation, decreasing input of pollen from surrounding thorn forest vegetation (i.e. *Mimosa*) and increasing pollen of wind-dispersed types within the watershed, including Urticaceae/Moraceae.

By ~190 cal yr BP, *Prosopis juliflora* first appears in the Alejandro sedimentary record. These shrubs to small trees are often a component of legume-dominated scrub forests of Hispaniola, the result of human cutting and burning of tropical dry forests (García-Fuentes et al., 2015; Roth, 1999). Maize (*Zea mays*) pollen is also present in these sediments, indicating cultivation at the study site. Pollen in sediments deposited in the last few decades (9–10 cm) are unique in comparison to our sediment core and modern pollen samples, dominated by *Pinus* and also containing relatively high amounts of *Bursera simaruba* and Urticaceae/Moraceae. A recent study by Herrera and Ault (2017) revealed that the Caribbean has experienced at least four severe droughts since 1950, the most recent from 2013–2016. Repeated droughts in recent decades likely favored pine and *Bursera simaruba*, with photosynthesizing bark, over deciduous broadleaf species. Additionally, thin-walled and psilate grains of Urticaceae/Moraceae may have been oxidized if Alejandro's sediments were exposed while the larger and easily identifiable pollen of pine and *Bursera* may be less susceptible to oxidation damage.

Our modern pollen analysis also allows the reexamination of a previously published stratigraphic pollen record from Laguna Alejandro, obtained near the coastal barrier of the lake (LeBlanc et al., 2017). LeBlanc et al. documented hurricane generated overwash deposits and tropical storm precipitation events in the lake core from geologic and isotopic proxies, and examined pollen from sediments below and above the events to examine hurricane impacts to vegetation. In general, hurricane strikes were followed by decreases in Fabaceae (Mimosoideae) and increases in Urticaceae/Moraceae pollen, interpreted as destruction of lowland forests (i.e. decreases in pollen of legumes) and expansion of scrub vegetation (i.e. increases in Urticales pollen). Our modern pollen work indicates that Urticaceae/Moraceae pollen in our lake core is likely Moraceae pollen from trees growing in upland tropical dry to moist forest and Fabaceae pollen represents woodlands growing in lowlands of Sierra Martín García. Thus, hurricane strikes likely mechanically damaged or drowned leguminous woodlands in low-lying areas through high winds and lowland flooding, leading to decreases in Fabaceae pollen to the sedimentary record post-hurricane. Increases in Urticaceae/Moraceae pollen post-hurricane were likely tied to increased dominance in the pollen shed as a result of both decreased Fabaceae and increased water levels and spatial extent of Alejandro, allowing a greater input of pollen rain from sources further away from the core site.

Pollen representation

Anemophilous pollen from all forest types (thorn, tropical dry, humid broadleaf, and pine) was over-represented in sites located downslope, especially non-forested locations such as mudflat and lagoon. *Pinus occidentalis* pollen was found in all fifteen samples though absent from the local vegetation at all sites. Urticaceae/Moraceae, *Cecropia*, and *Pinus occidentalis* pollen, representing tropical dry, humid, and pine forests growing on Sierra Martín García, reached highest inputs in surface sediments of Laguna Alejandro while also contributing significant amounts of pollen to mudflat pollen spectra. Our findings are similar to other modern pollen studies from Central (Bhattacharya et al., 2011) and South America (Guimarães et al., 2017; Jones et al., 2011). In Bolivian savanna sites, Jones et al. found high amounts of Moraceae pollen originating from evergreen forests bordering the savanna. In the southeastern Amazon, pollen of wet forests dominated surface lake sediments though savanna vegetation encompassed the majority of the watershed (Guimarães et al., 2017). In wetland sites of Central America, Bhattacharya et al. (2011) also found high proportions of wind-dispersed forest types, including oak (*Quercus*) and pine, despite the absence of these vegetation types locally. Urticaceae/Moraceae, *Cecropia*, and *Bursera simaruba* were also well-represented in fallow pasture and savanna ecosystem types where these trees were absent locally (Bhattacharya et al., 2011). Conversely, at our study site, *Bursera simaruba* was present from beach to upland tropical dry forests, and was under-represented in our singular beach sample, perhaps due to preservation issues in sandy, exposed sites.

At our lowland sites nearer the coast, pollen of wind-dispersed *Conocarpus erectus* dominated sites vegetated by black (*Avicennia germanins*) and red mangroves (*Rhizophora mangle*) while white mangroves (*Laguncularia racemosa*) and *Conocarpus erectus* grew adjacent to these sites. It is surprising that wind-dispersed pollen of *Rhizophora mangle* is not better represented in our lowland and coastal sites as these mangroves flower throughout the year and produce a lot of pollen (Nellis, 1994). Our results are in contrast to a study from mangroves of a Colombian island, where the local pollen signal (mangroves and beach) represented >90% of the pollen spectra (Urrego et al., 2010) though our choice of sampling site at the location of several ecotones explain lowland coastal sites dominated by mangrove and upland forest pollen spectra. Low amounts of *Rhizophora mangle* pollen in our sample from a red mangrove stand may suggest that sampling occurred before flowering, and thus pollen was not incorporated into sediment, as well as preservation issues at the sample location. Phuphumirat et al. (2015) experimented with pollen preservation in mangrove sediments and found degradation of pollen after short amounts of time (months) in sediments related specific environmental factors and pollen grain characteristics.

Some important vegetation types present locally were under-represented in the pollen spectra. In tropical dry forests and beach vegetation, canopy-height *Coccoloba uvifera* and *Guaiacum officinale* were important to dominant components of the vegetation. While *Guaiacum* was present but rare in the pollen record, *Coccoloba* was absent. Palms were also under-represented in tropical dry forests, mangroves and coastal vegetation types, even when they dominated the canopy. Bromeliads, also important in lowland to upland tropical dry forest sites were rare in the pollen spectra. On the beach, in thorn and tropical dry forests, bordering mudflats and lagoons, several species of cactus were present and abundant on the landscape. In pollen spectra from all of these environments, cactus pollen was poorly represented, suggesting that even a single pollen grain from Cactaceae should be interpreted as local presence of the family. At our mudflat sampling locations, both *Batis maritima* and Amaranthaceae were present locally, with *Batis* forming extensive colonies. In the pollen record, both of these types were poorly represented in comparison to their importance on the landscape, reflecting the poor pollen dispersion of these herbs and over-representation by pollen representative of forest.

While we noted the presence of a conuco at the uppermost tropical dry forest site, pollen of food plants was rare in the record, both at the tropical dry forest site and represented in the surface sediments of Laguna Alejandro. In sites that are composed largely of closed-canopy forests, and in watersheds that are largely forested, small agricultural plots are not likely to leave a signature in the pollen record and additional proxies of human activities must be used. In this study, we found that signals of human activity within a watershed may not produce a signature in lake sediments, especially from a sediment core obtained in the center of a relatively large lake. While we found no pollen of cultivars in surface sediments from the center of Alejandro, small amounts of pollen from Cucurbitaceae and Convolvulaceae, both important food plant families, were found in surface sediments near the inland edge of the lake. In a study of modern maize pollen deposition in lakes, Lane et al. (2010) found that maize growing near lakes was not always represented in lake sediments, even for those samples obtained near shorelines. In this study we interpret the two maize pollen grains identified in our lake sediments as indicating that corn was grown relatively close to the lake to be incorporated into our core obtained from the center of the lake.

Conclusion

Though preliminary, this study presents the first analysis of modern pollen and spores from lowland environments of the southwestern Dominican Republic. Non-metric multidimensional scaling results show that pollen spectra from non-forested (mudflat and lagoon) locations are taxonomically distinct from forested, even with the overrepresentation of taxa from dry, humid, and pine forests in the modern pollen spectra. While tropical forests are taxonomically diverse, severely degraded thorn forests can be distinguished from tropical dry forest by presence of leguminous (especially *Prosopis juliflora* and *Mimosa*) and cactus pollen. While absent locally, *Pinus* pollen was present in every surface sample. In sample locations near the coast, *Conocarpus erectus* pollen was over-represented and all other mangrove types under-represented, especially black and white mangroves. Other underrepresented pollen types included important hardwoods of beach and tropical dry forests, including *Guaiacum sanctum* and *G. officinale*, as well as *Coccoloba uvifera* and bromeliads. Amaranthaceae and *Batis maritima* pollen, though under-represented in mudflats, were indicators of these environments. While we encountered at least one garden plot in forests of the park, pollen of cultivars was rare at that sample location and in surface sediments of Laguna Alejandro, suggesting that small-scale human activity may be difficult to ascertain in pollen records of relatively large lakes.

The results from this study aided in the interpretation of sedimentary pollen from a center core obtained of Laguna Alejandro. Ordination results agreed with a previous interpretation that pollen spectra of older (Zone 2) sediments represented shallow-water conditions, with recent changes in hydrology and pollenshed, explaining the shift in importance from *Mimosa* to Urticaceae/Moraceae in our stratigraphic pollen. Modern pollen rain from thorn and dry forests also revealed provenance of Fabaceae (*Mimosa* and *Prosopis julifora*) and Urticaceae/Moraceae at the study site. LeBlanc et al. (2017) interpreted decreases in Fabaceae (Mimosoideae) and increases in Urticaceae/Moraceae pollen post-hurricane as destruction of lowland forests (i.e. decreases in pollen of legumes) and expansion of scrub vegetation (i.e. increases in Urticales pollen). Our modern pollen work reveals that Urticaceae/Moraceae pollen in our lake core is likely from tropical dry to moist forest and Fabaceae pollen (particularly *Mimosa*) represents thorn forests growing in lowlands of Sierra Martín García. Additional modern pollen samples from a variety of ecosystem types of the Caribbean islands are still sorely needed. Here we demonstrate that broad Neotropical vegetation types possess taxonomically distinct pollen rain and that results of modern pollen analysis can refine interpretations of past changes in environment and ecosystem recovery from disturbance events.

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Figure captions

Figure 1. A. The Dominican Republic (DR, dark gray) occupies the eastern two-thirds of the island of Hispaniola. B. The study area (box) in the semi-arid southwestern DR lies in the rainshadow of the Cordillera Central. C. Location of modern pollen samples and sediment core ALJ202 within Laguna Alejandro.

Figure 2. Modern (top) and sediment core ALJ202 (bottom) pollen concentrations and taxonomic diversity.

Figure 3. Percentage pollen diagram for modern pollen spectra. Black circles note presence of rare (<1%) types.

Figure 4. Alejandro sediment core ALJ202 photographs, x-rays, and loss-on-ignition results. Light gray box represents coarse clastic deposits described in text, likely from hurricane-generated storm surge that breached coastal barrier and pushed sediments form near-shore environments into Laguna Alejandro.

Figure 5. Alejandro sediment core ALJ202 pollen analysis results. Black circles note presence of rare (<1%) types.

Figure 6. (Top) Results of NMDS ordination on surface soil and sediment samples. (Bottom) Combined ordination of modern pollen samples and sediment core pollen, denoted by filled black circles. Dashed ellipses represent clusters of taxonomically similar modern pollen samples. Diagonal line shows division between clusters of pollen results for sediments of Zones 1 and 2.

Table 1. Sample location, ecosystem, and material type.

Sample	Label	Vegetation type	Sample type	Latitude	Longitude
1	MP2	Tropical dry forest	Soil	18.350207563	-71.029339482
2	MP5	Tropical dry forest	Soil	18.336410927	-71.038105911
3	MP12	Thorn forest	Soil	18.302587078	-71.005859281
4	SS01	Thorn forest	Sediment	18.314951687	-71.037308575
5	MP 8	Thorn forest	Soil	18.346722655	-71.139296931
6	MP 9	Thorn forest	Soil	18.348839249	-71.133733303
7	MP13	Beach	Soil	18.309530035	-71.032981213
8	MP 6	Mudflat	Sediment	18.318416587	-71.049254140
9	MP 7	Mudflat	Sediment	18.324061512	-71.060543338
10	MP 15	Mudflat	Sediment	18.321934870	-71.057989700
11	SS07	Mudflat	Sediment	18.322652282	-71.059884430
12	MP 01	Mangroves	Sediment	18.312865418	-71.022801664
13	MP 10	Mangroves	Sediment	18.338037266	-71.097634399
14	SS 04	Lagoon	Sediment	18.313570716	-71.032030187
15	SS 05	Lagoon	Sediment	18.314660391	-71.033190313

Table 2. ALJ202 radiocarbon date results from the National Ocean Sciences Accelerator Mass Spectrometry Facility (NOMAS) at Woods Hole Oceanographic Institution and the Accelerator Mass Spectrometry Laboratory at the University of Arizona. Calibrated samples ages were determined by the Calib 7.0.2 calibration program and calibrated by the Intcal13 dataset (Reimer et al. 2009, Stuiver and Reimer 1993). Weighted means were calculated using the Bayesian age-depth modeling program Bacon (Blaauw and Christen 2011).

Sample	Depth (cm)	^{14}C Yr BP	2σ Calibrated yr BP	Probability (%)	Weighted mean
AA101338	35–37	2200 ± 37	2323–2125	1.000	–
AA101339*	55–56	–	–	–	–
AA101340	70–71	1970 ± 350	2762–1255	0.996	–
			1205–1186	0.003	
			1250–1240	0.001	
AA101341	125	918 ± 39	923–758	0.980	858
			753–745	0.020	
ALJ202178**	178	1400 ± 20	1338–1289	1.000	1309
AA101342	218–219	1490 ± 47	1423–1301	0.806	1549
			1521–1456	0.178	
			1442–1431	0.017	

* Sample failed at lab due to equipment malfunction

**Sample dated through NOMAS

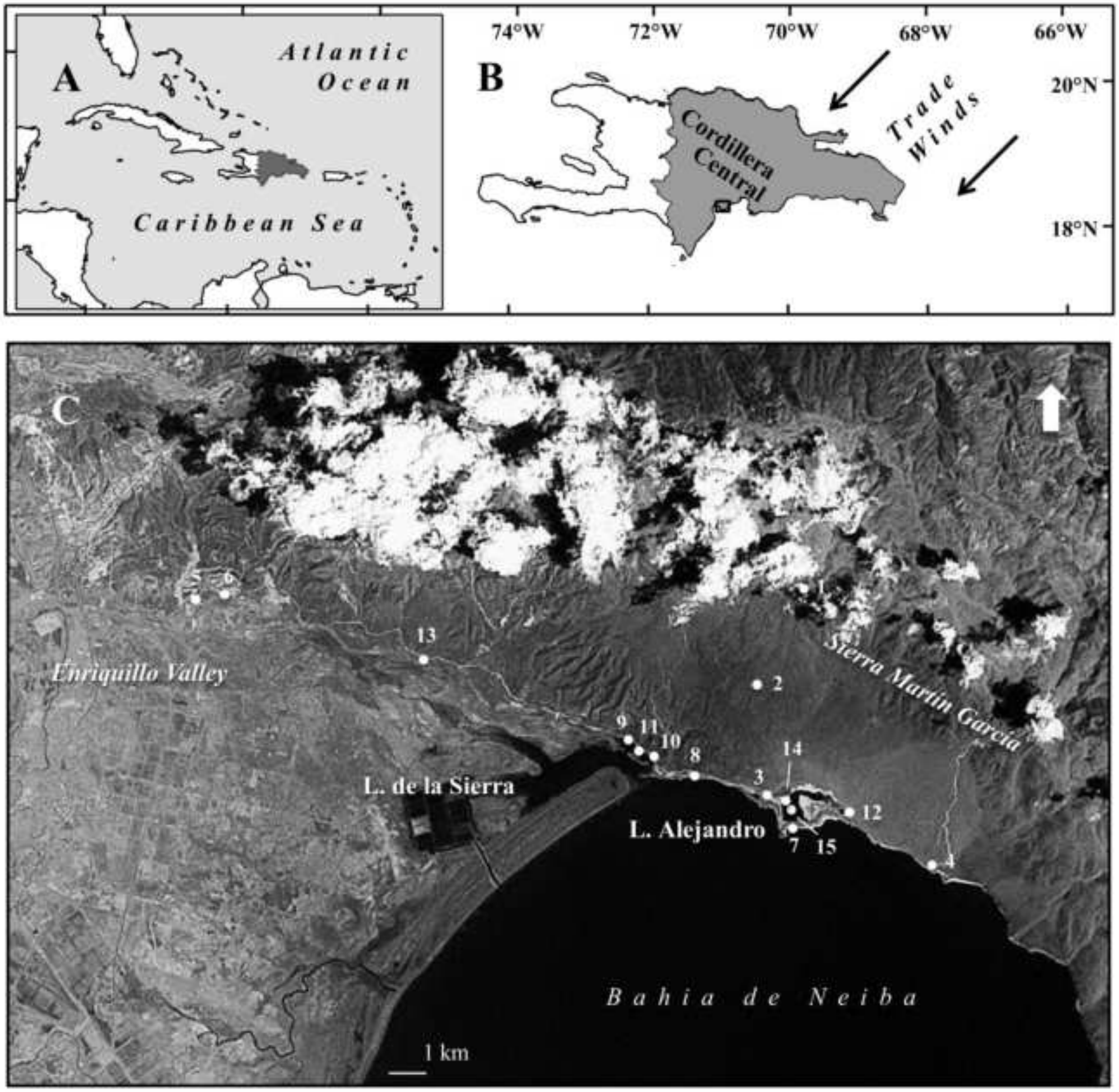

A
Atlantic Ocean
Caribbean Sea
B
74°W
72°W
70°W
68°W
66°W
20°N
18°N
Cordillera Central
Trade Winds
C
13
Enriquillo Valley
2
Sierra Martín García
9
11
10
8
14
3
L. de la Sierra
12
L. Alejandro
7
15
4
Bahia de Neiba
1 km

Figure 1

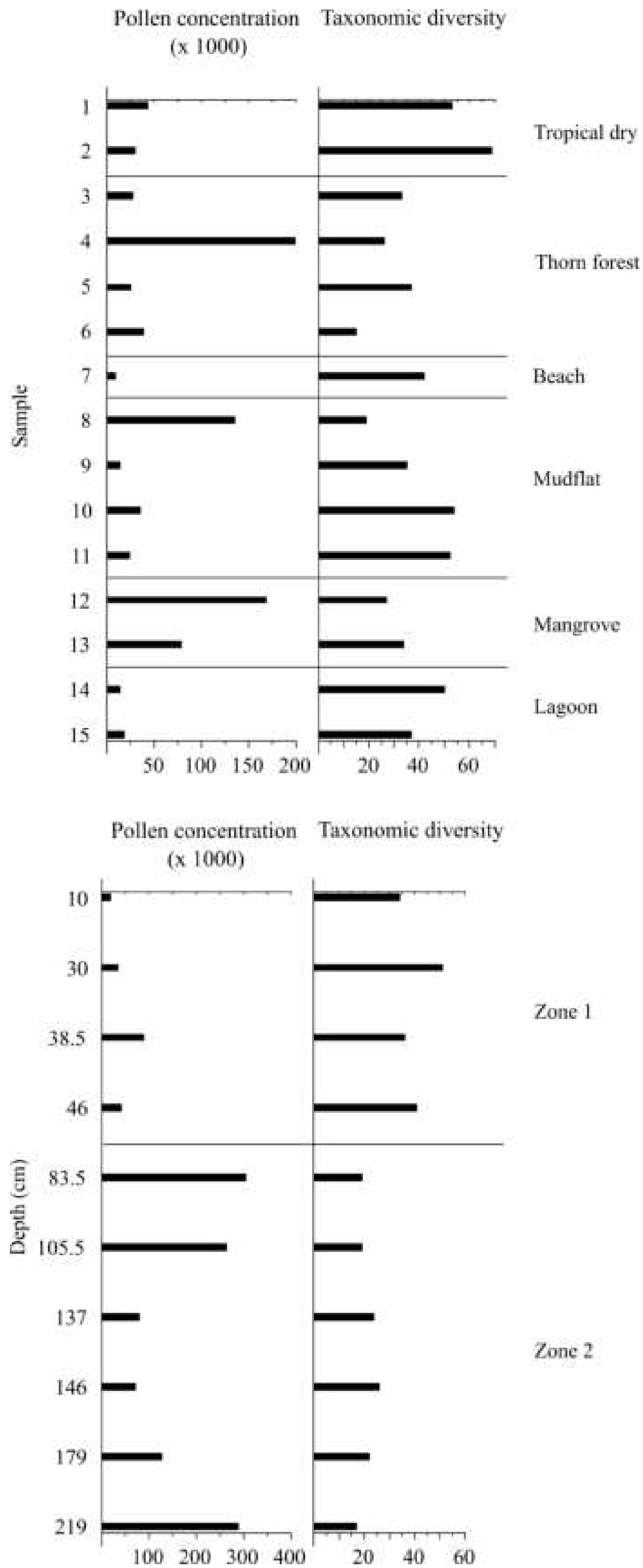

Pollen concentration (x 1000)
Taxonomic diversity
Sample
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
50 100 150 200
20 40 60
Tropical dry
Thorn forest
Beach
Mudflat
Mangrove
Lagoon
Pollen concentration (x 1000)
Taxonomic diversity
Depth (cm)
10
30
38.5
46
83.5
105.5
137
146
179
219
100 200 300 400
20 40 60
Zone 1
Zone 2

Figure 2

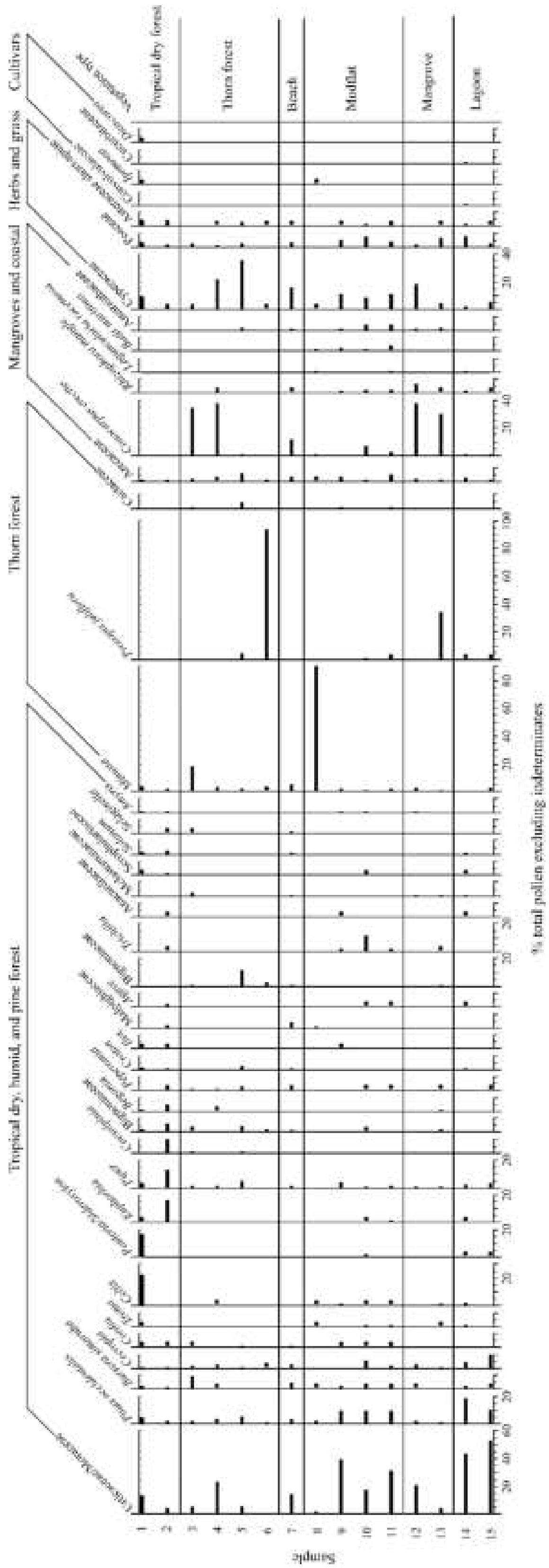

Tropical dry, humid, and pine forest
Thorn forest
Mangroves and coastal
Herbs and grass
Cultivars
Tropical dry forest
Thorn forest
Beach
Mudflat
Mangrove
Lagoon
% total pollen excluding indeterminates
Sample

Figure 3

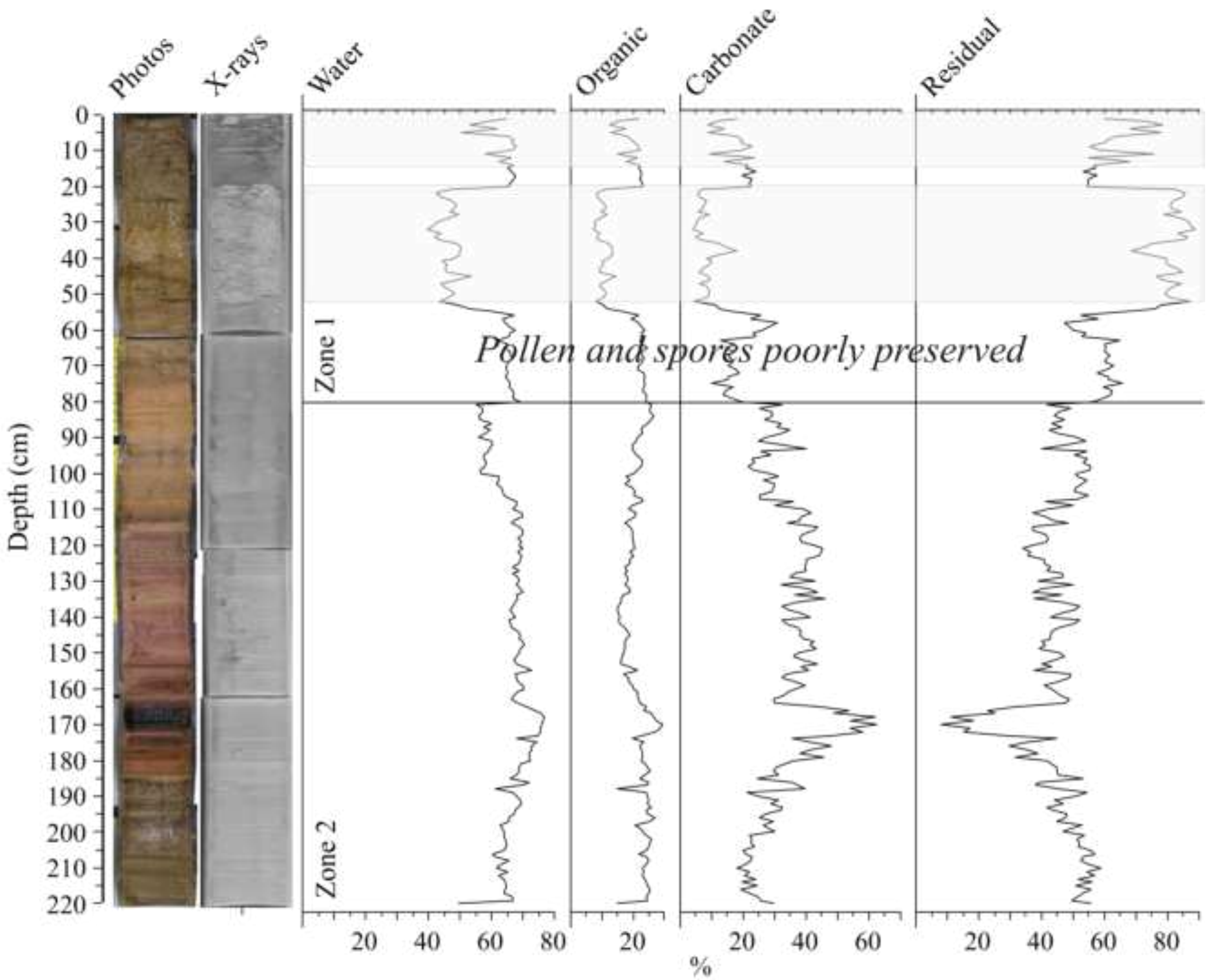
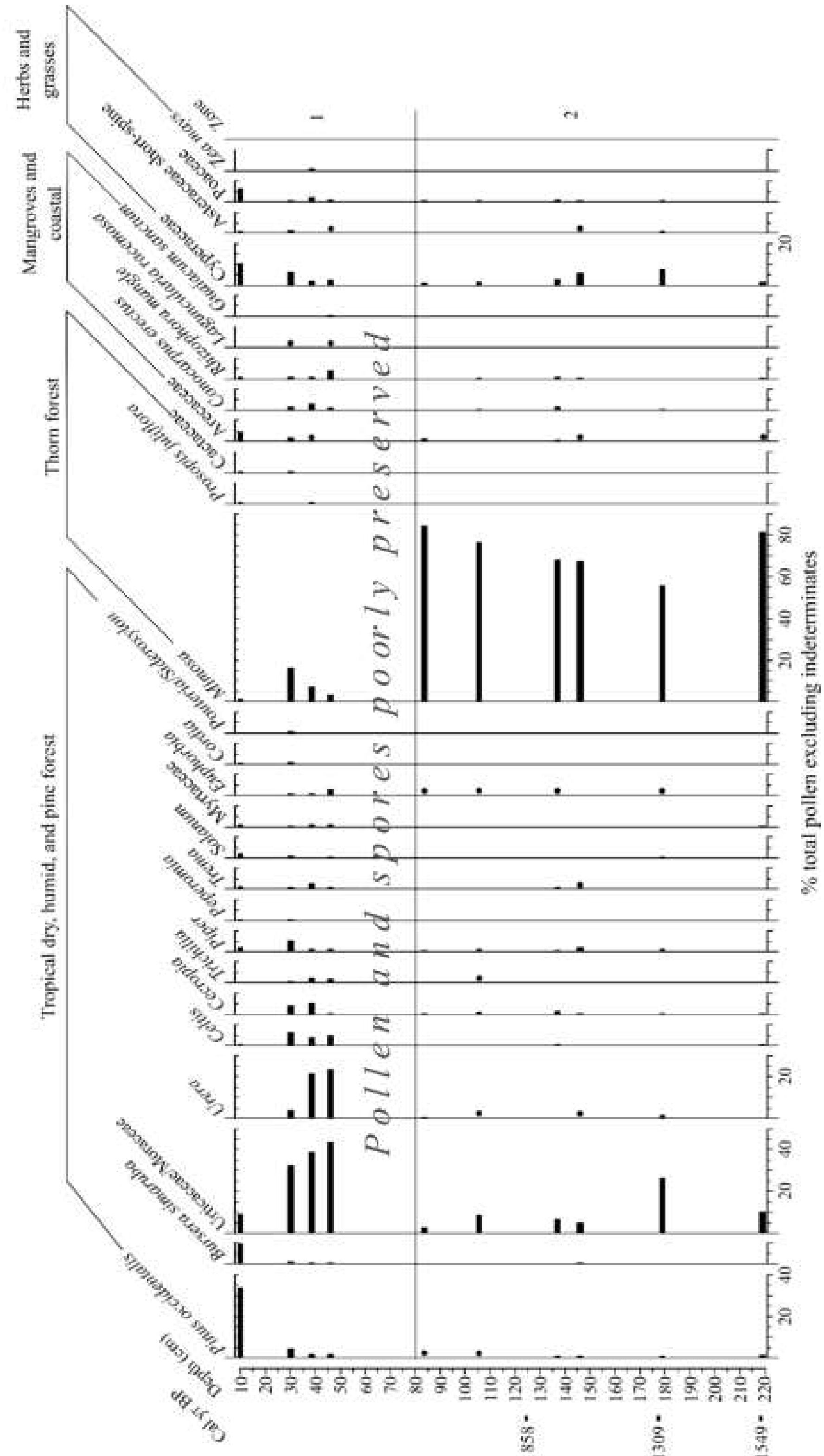

Photos
X-rays
Water
Organic
Carbonate
Residual
Depth (cm)
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
160
170
180
190
200
210
220
Zone 1
Zone 2
Pollen and spores poorly preserved
20
40
60
80
20
20
40
60
20
40
60
80
%

Figure 4



Herbs and grasses
Mangroves and coastal
Thorn forest
Tropical dry, humid, and pine forest
Cal yr BP
Depth (cm)
Pinus occidentalis
Bursera simaruba
Urticaceae/Moraceae
Urera
Celtis
Cecropia
Trichilia
Piper
Peperomia
Trema
Solanum
Myrtaceae
Euphorbia
Cordia
Pouteria/Sideroxylon
Mimosa
Prosopis juliflora
Cactaceae
Arecaceae
Conocarpus erectus
Rhizophora mangle
Laguncularia racemosa
Guaiacum sanctum
Cyperaceae
Asteraceae short-spine
Poaceae
Zea mays
Zone
1
2
Pollen and spores poorly preserved
% total pollen excluding indeterminates
858
1309
1549

Figure 5

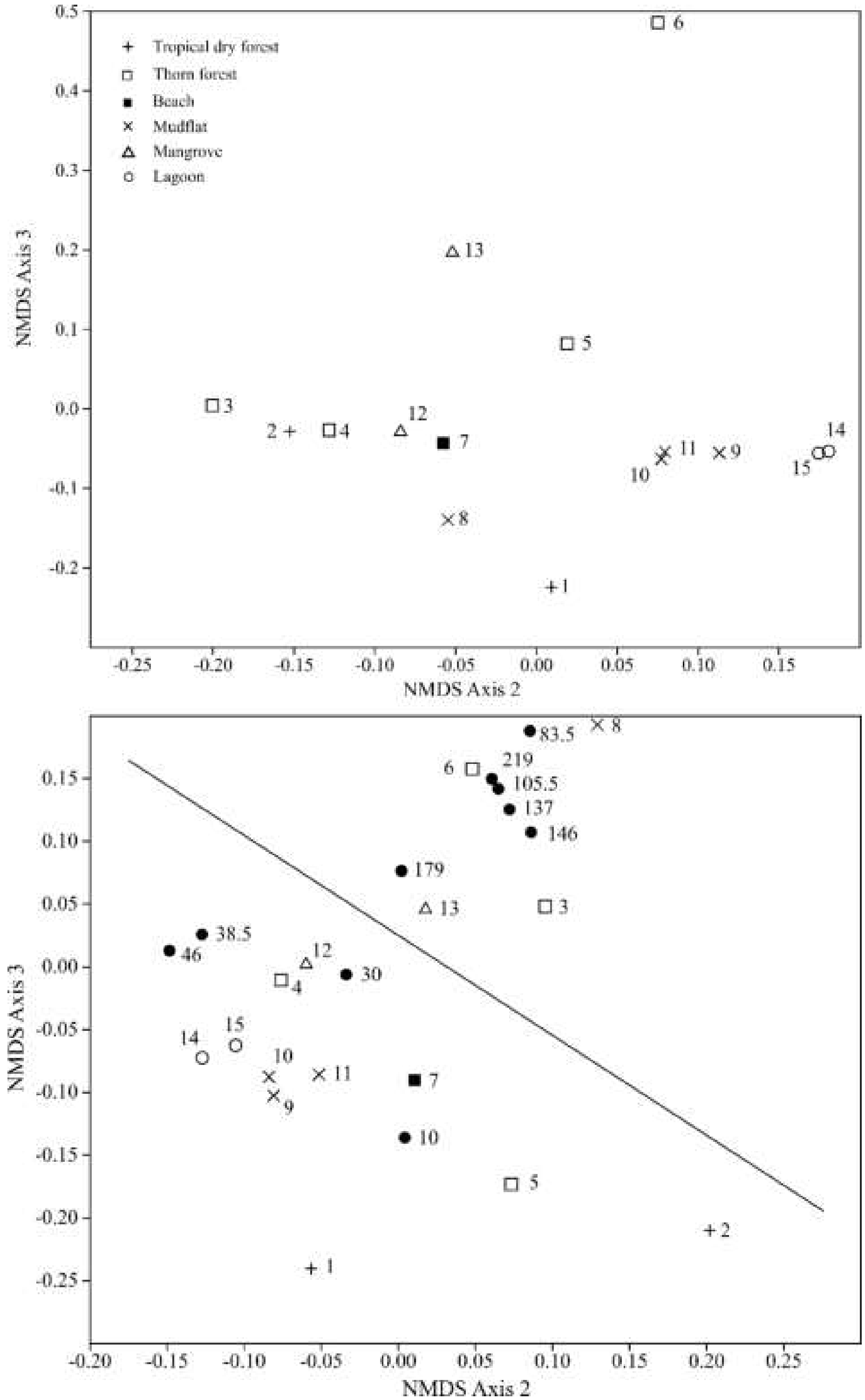
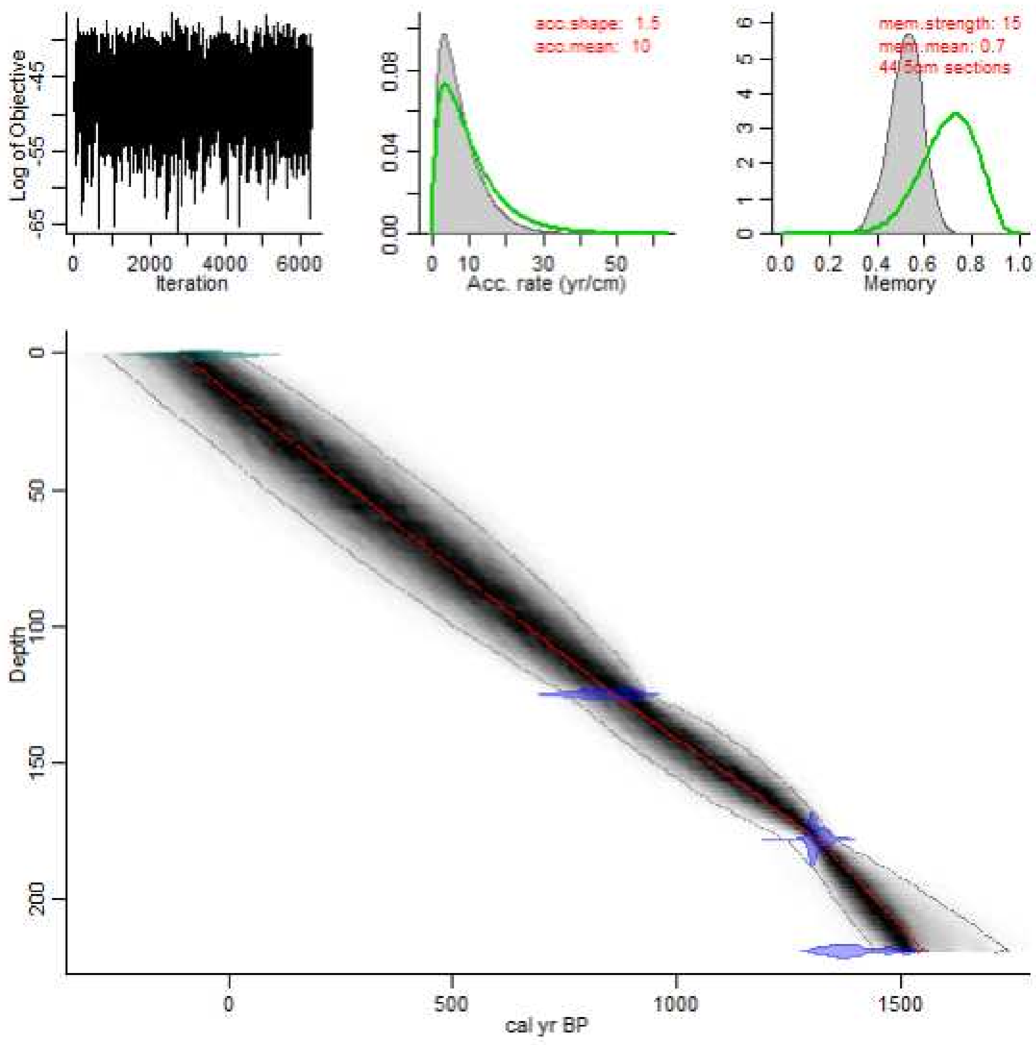

Tropical dry forest
Thorn forest
Beach
Mudflat
Mangrove
Lagoon
NMDS Axis 3
NMDS Axis 2
83.5
219
105.5
137
146
179
38.5
46
30
10

Figure 6

ESM1. Age-depth model for the ALJ202 sediment core created using Bayesian age modeling software Bacon (Blaauw and Christen, 2011). (Top Left) Log of objective shows no systematic structure across neighboring iterations, suggesting a good model run. (Top Middle) and (Top Right) show prior initial guesses (green) and posterior (gray) distributions for accumulation rate (i.e., sedimentation rate) and memory (how the accumulation rate is thought to have changed over time), respectively. (Bottom) shows calibrated dates (blue), with the mean age model (red) and 95% confidence interval of dates for a given depth (dashed lines) (6). Grayscale intensity indicates likelihood of an age for a given depth, with darker values indicating more likely calendar ages.



Chapter 5: Conclusions

Conclusions

This dissertation contributed to the late-Holocene environmental history of lowland sites of the northeastern Caribbean from multiproxy analysis of sediment cores and modern pollen from surface soils and sediments. Several knowledge gaps were addressed, including the vegetation and fire history of lowland tropical-seasonal vegetation, responses to tropical cyclone activity, and human activities at the study sites.

Both the Laguna Alejandro (Dominican Republic) and Freshwater Pond (Barbuda) sedimentary pollen records contributed to the late-Holocene vegetation history of lowland tropical-seasonal vegetation. Pollen and spores from Freshwater Pond (chapter 3), whose spectra from basal sediments must be interpreted with caution due to preservation issues, provides the first vegetation history from the island and suggests over two millennia of disturbance to vegetation growing near the core site as revealed by pollen of *Cecropia*. Recent archaeological investigations on Barbuda (Bain et al., 2017; Rousseau et al., 2017) document a long history of human exploitation of the island's terrestrial and marine environments, beginning with seasonal occupation of the island in the Archaic Age through the Post- Colonial time periods.

Pollen spectra from L. Alejandro (chapters 2 and 4) reconstructed over 1,500 years of vegetation history from analysis of two sediment cores; one near the seaward edge of the lagoon and another near the center. Spectra from both cores was dominated by spectra of Fabaceae (Mimosoideae) and Urticaceae/Moraceae. Analysis of modern pollen (chapter 4) from lowland environments of Sierra Martín García (SMG), L. Alejandro, and surrounding areas revealed main pollen spectra of the major vegetation types (tropical dry forest, thorn forest, mangrove, mudflat, and lagoon) and refined our interpretation of the site's vegetation history. Modern pollen analysis revealed *Mimosa* spp. pollen dominating the older sediments of L. Alejandro were likely derived from thorn forests growing near L. Alejandro and that Urticaceae/Moraceae pollen was most likely Moraceae pollen dispersed by trees growing in tropical dry and humid broadleaf forests of SMG. My modern pollen results also refined a previous (chapter 2) interpretation of changes in pollen spectra related to tropical storm activity. I previously interpreted decreases in Fabaceae (Mimosoideae) and increases in Urticaceae/Moraceae pollen post-hurricane as destruction of lowland forests (i.e. decreases in pollen of legumes) and expansion of scrub vegetation (i.e. increases in Urticales pollen). However, with provenance of *Mimosa* and *Urticaceae/Moraceae* revealed, I interpret decreases in *Mimosa* and increases in Urticaceae/Moraceae pollen post-hurricane as reflecting both destruction/drowning of *Mimosa*-dominated lowland thorn forest and mudflats, which received *Mimosa* pollen from thorn forests upslope, tied to lowland flooding from tropical storms. Increases in L. Alejandro's spatial extent allowing an increase in wind-dispersed pollen from forests growing further from the core site, such as tropical dry and humid forests vegetating the alluvial fans of emanating from SMG.

Though we did not complete floristic surveys, a comparison of the major vegetation types and dominant vegetation encountered with its pollen spectra revealed over- and under-represented taxa at the study site. Comparison of floristic diversity of stratigraphic pollen from Alejandro in comparison to modern pollen spectra also revealed changes in floristic diversity at the study site through time, with *Urera* pollen once a major component of pollen spectra from tropical dry forests (Linares-Palomino et al., 2011) over the past ~500 years to absent from sediments representing the most recent decades. *Prosopis juliflora*, a major component of thorn forests on the island, a disclimax community resulting from human disturbance to tropical dry forest, first appears in the sediments of L. Alejandro ~190 cal yr BP (1760 CE), and may represent human disturbance to tropical dry forests, as maize pollen is also present in sediments dating. While we encountered at least one garden plot in forests of the park, pollen of food plants was rare at that sample location and in surface sediments of Laguna Alejandro, suggesting that small-scale human activity may be difficult to ascertain in pollen records of relatively large bodies of water.

Humans also likely impacted vegetation growing near Freshwater Pond (chapter 3) as revealed by the abundance of larger (macroscopic) charcoal isolated from pond sediments, with consistent abundance in sediments representing ~150 BCE (2100 cal. yr BP) to ~1250 CE suggesting primarily human ignitions. While no pollen of food plants was observed in the sedimentary record to provide more direct evidence of human activities near the core site, the archaeological record (Bain et al., 2017; Rousseau et al., 2017) supports the interpretation of primarily anthropogenic fire, with excavations of Pre-Columbian horticulturalist settlements on the island coinciding with plentiful charcoal in the sedimentary record. Indigenous use of Freshwater Pond and surrounding areas decreased by ~1250 CE, as suggested by a significant decrease in macroscopic charcoal, in agreement with archaeological records that indicate the indigenous population of the island was severely reduced, with possible island abandonment, by the time of British occupation in the 1600s. Decreases in regional burning after ~1610 CE, as revealed by smaller charcoal particles in Freshwater Pond's sediment may be tied to reduced fuel conditions associated with repeated droughts during the Little Ice Age (Burn et al., 2016) against a legacy of charcoal production and timber removal by indigenous and European populations (Bain et al., 2017).

Conversely, sediments of Laguna Alejandro (chapter 2) documented fire activity as related to tropical storms and precipitation variability during the late-Holocene. Multiproxy analysis of a sediment core near the seaward edge of Alejandro provided a 1000-year record of inferred tropical cyclone and storm activity. We interpreted at least ten hurricanes from geological evidence, loss-on-ignition data, and the stable oxygen isotope record; a new proxy data source for identification of tropical storms (Lane et al., 2017; Lawrence et al. 2008). A hurricane landfall ~330 cal yr BP initiated a major change in state at our core site from shallow mangrove wetland to deeper water/lacustrine conditions, possibly linked to lowland flooding, mangrove drowning, and peat collapse at the core site. An interpreted higher frequency of hurricanes during the past three centuries agrees with other sedimentary and historical records from the region, with increased storm activity probably linked to a more southerly position of the Intertropical Convergence Zone (ITCZ) during the LIA (Fensterer et al., 2012; McCloskey and Liu, 2012; Peros et al., 2015; Baldini et al., 2016). A latitudinally depressed ITCZ during the LIA may also explain the interpreted shift in climate to more variable precipitation. Regional fire activity appeared to be linked to storm events and moisture variability, with increased regional fire activity during the more moist Medieval Warm Period (MWP) and depressed fire activity during the LIA. Local fires increased with increased fuel availability after tropical storm events, except during the more arid LIA when hurricane landfalls did not always lead to increased fire activity within the watershed, a finding similar to results from sediments of a coastal mangrove lagoon in Cuba (Peros et al., 2015).

The dissertation's modern pollen analysis will aid in the analysis of other sedimentary pollen records from the circum-Caribbean, strengthening interpretations of vegetation, climate, environment, and human histories from the region. Reconstruction of fire histories from lowland, tropical-seasonal vegetation of Barbuda and the southwestern Dominican Republic will be of interest to land managers, especially as tropical dry forests represent a high conservation priority throughout the Neotropics. Pollen and charcoal analysis from sediments of Laguna Alejandro provide a rare vegetation and fire history for a site with tropical dry and humid forests, with only small-scale human agricultural activities documented within the watershed for the period of record. The L. Alejandro record can be contrasted to the Freshwater Pond record, which revealed thousands of years of biomass burning and interpreted vegetation disturbance. Pollen analysis revealed increased floristic diversity for tropical dry forest sites versus thorn forests and can inform land managers of taxa for restoration efforts. Reconstruction of tropical storm activity for the southwestern Dominican Republic, possible links to changes in regional climate, and fire and vegetation responses will be of interest to land managers considering current and future predicted global climate change and associated changes in tropical cyclone activity. My research documenting a change in environmental conditions from wetland to lacustrine linked to a hurricane landfall will be of interest to land and natural resource managers of tropical and sub-tropical coastal zones, especially considering current and projected sea-level rise and hurricane activity.

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