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Reconstructing Late Holocene Fire, Agriculture, and Climate from Sediment Records in Costa Rica and the Dominican Republic

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To the Graduate Council:

I am submitting herewith a dissertation written by Erik Nicholas Johanson entitled "Reconstructing Late Holocene Fire, Agriculture, and Climate from Sediment Records in Costa Rica and the Dominican Republic." I have examined the final electronic copy of this dissertation for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Doctor of Philosophy, with a major in Geography.

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Reconstructing Late Holocene Fire, Agriculture, and Climate from Sediment Records in Costa Rica and the Dominican Republic

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DEDICATION

This dissertation is dedicated to my wife, Jessie, and our daughter, Lilia.

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ABSTRACT

We use multiple proxies from sediment cores to identify periods of climate stress during the late Holocene across the circum-Caribbean region and to determine how fire activity and signals of Pre-Columbian agriculture coincide with these arid periods. We examine evidence of aridity from stable carbon isotope ratios and shifts in elemental composition, along with pollen and microscopic charcoal, at Bao Bog in the highlands of Hispaniola. We infer two major periods of aridity (3600–2300 and 1040–850 cal yr BP), with the later period associated with the late phase of the Terminal Classic Drought. A third, less marked interval of aridity corresponds to the Little Ice Age from 550–100 cal yr BP. Southward shifts in the mean latitudinal position of the Intertropical Convergence Zone coincide with the arid periods in the Bao Bog record, which we interpret as also coinciding with a lowering of the elevation of the Trade Wind Inversion.

We also produce three new records that show environmental change, maize agriculture, and fire history in southern Pacific Costa. Our 4300-year record from Laguna Los Mangos shows the earliest evidence of *Zea mays* subs. *mays* in the region at ca. 3300 cal yr BP, following a 1000-year period when the area around the lake was largely forested, with slight or no agricultural activity. The Laguna Los Mangos record contains evidence of the transition to maize agriculture and a later decline associated with the onset of the LIA and Spanish contact. From Laguna Danta and Laguna Carse

we developed high-resolution records of fire history and maize agriculture spanning the Little Ice Age. We found that fires occurred during the Little Ice Age and were influenced by human activity related to agriculture, but that fires persisted following agricultural decline, suggesting climate as a driver of fire in the lowlands. The continuation of fire into the Little Ice Age contradicts a recent global synthesis of fire activity and suggests local variability in fire response to climate.

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CHAPTER 1

INTRODUCTION

1.1 Introduction

Lake and wetland sediments are natural archives of past conditions that contain organic and inorganic particles and geochemical signatures that reveal past changes in climate and environmental conditions, including human modification of the landscape, such as forest clearance and agriculture, and natural and human-set fires (Cohen, 2003; Horn, 2007; Roberts, 2014). Pollen grains of cultigens in lake sediments and fragments of charcoal examined on pollen slides are key proxies for reconstructing the timing, presence, and scale of prehistoric agriculture in the Neotropics (Bush et al., 1992; Clement and Horn, 2001; Horn, 2006; Islebe et al., 1996; Northrop and Horn, 1996), but other proxies analyzed in tandem with pollen can provide complementary data on maize agriculture. Bulk sedimentary stable carbon isotope analyses ($\delta^{13}C_{OM}$) of Costa Rican lake-sediment cores (Lane et al., 2004; 2008; 2009; Taylor et al., 2013a) showed sensitivity to changes in the extent of tropical forest and cultivated land within watersheds, with forest conversion resulting in a shift to more positive isotope values associated with the replacement of C_3 tropical forest taxa with C_4 plants such as maize and agricultural weeds. High-resolution analyses of macroscopic charcoal in lake sediments also contribute to understanding of the timing and nature of prehistoric agriculture (Dull, 2007; Nevle et al., 2011; Power et al., 2008; Whitlock and Larson, 2001). Analyses of $\delta^{13}C_{OM}$ and macroscopic charcoal in sediment profiles contribute to more robust reconstructions of past agricultural activity than can be achieved through pollen or microscopic charcoal analysis alone.

In the Neotropics, separating climate signals from signals of human impact, such as agriculture or forest clearance, based on pollen alone can be difficult (Horn, 2007). Several proxies interpreted together can potentially indicate drought in a sediment record, though human-induced changes in watersheds can mimic signals of drought (Horn, 2007). Fossil pollen deposited in lacustrine environments tends to preserve well, resulting in high pollen concentrations and low indeterminate pollen counts. During droughts that reduce lake levels, pollen in exposed sediments is oxidized, resulting in sediments with low pollen concentrations and many damaged, indeterminate grains. Even if the core site itself is not exposed, oxidized pollen from surrounding exposed shores will wash into the core site, increasing percentages of indeterminate pollen, which can indicate intervals of drought (Delcourt and Delcourt, 1980). Shifts in the elemental composition of sediments and the organic content, or changes in charcoal influx, can also indicate intervals of drought. Stable carbon isotope ratios in sediments are sensitive to changes in the proportions of C_3 and C_4 plants in watersheds, with values becoming more positive with increased importance of C_4 plants in the local vegetation. Because C_4 plants are more efficient during photorespiration, which provides C_4 plants an advantage in moisture-limited environments (Cerling, 1999; Ehleringer and Cerling, 2002; Johnson et al., 2007), increases in the ratio of C_4 plants in watersheds can signal periods of drier climate. The photosynthesis of C_3 plants can also be affected by drought, with a reduction in ^{13}C discrimination resulting in increased $\delta^{13}C_{OM}$ values.

Using stable carbon isotope values to interpret climate is problematic for environments with anthropogenic activity, as many agricultural activities can shift carbon isotope values. In the neotropical lake basins that are the focus of two of my dissertation chapters, shifts in stable carbon isotope values appear to be largely driven by shifts between tropical moist forests composed of trees that use the C_3 photosynthetic pathway and agricultural landscapes that include cultigens (maize) and agricultural weeds that are C_4 plants. However, in the remote highlands of the Dominican Republic that is the study site for my first dissertation chapter, we see no evidence of agriculture or forest clearance. In the absence of an anthropogenic source for changes in watershed vegetation, the shifts in stable carbon isotope ratios can be interpreted as proxies for climate, with drier intervals resulting in an increase in the $\delta^{13}C_{OM}$ value of C_3 plants or increasing the cover of the few C_4 herbs expected at the site.

Several regional droughts have been identified in the circum-Caribbean region. The Terminal Classic Drought (TCD, 1200–850 cal yr BP) consists of a series of multidecadal droughts. The TCD has been invoked to explain the collapse of the classic Maya civilization (Hodell et al., 2005), but its effects were not restricted to the Yucatan Peninsula (Lane et al., 2014). The Little Ice Age (LIA, 550–100 cal yr BP) is a recent climate event that reduced both annual temperatures and precipitation in much of the northern hemisphere, including the Neotropics (Haug et al., 2001; Lamb, 1965; Lane et al., 2011). In Costa Rica, evidence exists of cool and less productive conditions from 1580 to 1860 CE, based on a chironomid reconstruction from Laguna Zoncho in southern

Pacific Costa Rica (Wu et al., 2016). Geochemical and microfossil records from the eastern Caribbean show variability in precipitation, but overall drier conditions during the LIA (Burn and Palmer, 2013; Burn et al., 2016). Proxy indicators of drought can be compared to established regional paleoclimate records to support interpretations or identify climate mechanisms responsible for shifting climate conditions.

In the Diquís archaeological area of southern Pacific Costa Rica, several studies examined evidence of prehistoric forest clearance, maize agriculture, and fire (Anchukaitis and Horn, 2005; Clement and Horn, 2001; Kerr, 2014; Lane et al., 2008; Taylor et al., 2013a; 2013b). Recent work is focused on interpreting climate from stable isotopes and other proxies (Wu et al., 2016) and on understanding how past climate affected human society in the region. Lake-sediment records are key to understanding the history of maize agriculture and the agricultural use of fire; how Spanish contact and the subsequent spread of diseases affected human population, agriculture, and fire; and the extent to which climate drove changes in the environment and in human activities.

The Diquís archaeological area of Costa Rica is part of the Greater or Gran Chiriquí archaeological region that comprises sites in western Panama as well as southern Pacific Costa Rica. Previous lake-sediment studies are from sites in the southeastern portion of the Diquís subregion, mainly near the modern border with Panama. This dissertation contributes to efforts to understand the interplay of climate, human activity, and fire in the Diquís subregion through the development of new proxy records from three sites located in the northwestern portion of the area, further from the

modern border with Panama and at lower elevation. My new records improve the spatial distribution of sites in the region, important for identifying regional variability in climate, fire, and human activity across time. The new records also contribute some unique proxies. From Laguna Danta and Laguna Carse, I developed macroscopic charcoal records at very high resolution, previously unavailable for the region. At Laguna Los Mangos, I developed the first records of elemental composition for Costa Rican lakes. Finally, with the work at Laguna Los Mangos, I have extended the paleoenvironmental record for southern Pacific Costa Rica into the period prior to the spread of maize agriculture at ca. 3200 cal yr BP. All other lake-sediment records begin with maize already established in the region. The addition of three new records that include new proxies and extend further back in time contributes to the understanding of local effects of droughts and the Spanish contact on agriculture and fire in southern Pacific Costa Rica.

1.2 Sediment Profiles: Chronologies and Proxies

1.2.1 Age-depth Modeling

Establishing a chronology for a sediment profile from a lake or wetland requires an age-model based on the provenience of radiocarbon dates sampled strategically across the profile. In linear age modeling, a common modeling technique, lines are calculated to connect the measure of central tendency of the calibrated radiocarbon ages

(Telford et al., 2004), such as the weighted mean age or the median age. The result produces ages for sediment intervals between dated horizons based on consistent sedimentation rates calculated between pairs of dates. Linear models contain abrupt changes in sedimentation rate centered on dated horizons that are likely artificial and a product of the location of the dated material.

Age modeling using Bayesian statistics, as in the Bacon age-modeling package for R, is an alternative to linear age-depth modeling that addresses some caveats of linear modeling while offering some limitations of its own (Blaauw and Christen, 2011). The Bacon age-model uses the IntCal 13.14 calibration dataset (Reimer et al., 2013; Stuiver and Reimer, 1993) and outputs the weighted mean in cal yr BP for the entire core profile in 1-cm intervals.

Modeling the age-depth relationships for our core sites using Bayesian techniques requires the incorporation of a prior distribution for sediment accumulation rates, which is suggested after an initial examination of estimated basal age and profile depth. The degree of memory, or autocorrelation, related to the accumulation rates above and below any given depth can be adjusted within the model, but with default values suggested by the authors based on a global sample of sediment records (Blaauw and Christen, 2011). Using Markov Chain Monte Carlo simulations, the Bayesian technique can model a range of possible sediment accumulation histories across multiple iterations (Blaauw and Christen, 2011). This age-depth modeling approach quantifies the uncertainty associated with a given radiocarbon date while also

incorporating the chronology of the lower depths to constrain the age range at a given level (Blaauw and Christen, 2011).

Bayesian age-depth modeling offers several advantages over that of traditional linear age-modeling including the ability to: (1) quantify and incorporate age uncertainty; (2) use the law of superposition to constrain large calibrated age ranges by taking into consideration ages associated with lower levels; (3) discount reported dates as outliers; and (4) smooth the age-depth model based on thousands of simulations. A disadvantage is that the user may have less control over their own judgments as to the true age of a particular level in the core. For example, forcing the model to accept a known date can prove challenging if it is located in an outlier position.

1.2.2 Stable Carbon and Nitrogen Isotopes

Stable carbon isotope ratios ($\delta^{13}C_{OM}$) in lake sediments are influenced by the photosynthetic pathway of watershed vegetation (Boom et al., 2007; Lane et al., 2004). The interpretation of these isotope ratios allows the reconstruction of the dominant photosynthetic pathway of vegetation in a watershed. The carbon isotope ratio refers to the proportion of two naturally occurring stable isotopes, ^{12}C (98.89 %) and ^{13}C (1.11 %), that are typically expressed in ratio form (R = $^{13}C/^{12}C$) relative to Vienna-Pee Dee belemnite (V-PDB) marine-carbonate standard (Johnson et al., 2007):

$$\delta^{13}C \text{ (per mil)} = 1000\ [(R_{sample} / R_{standard}) - 1]$$

Naturally occurring isotopic fractionation results in variations in this ratio based on preferential discrimination of ^{13}C by plants during photosynthesis, leading to plant tissue that is isotopically depleted in ^{13}C relative to the surrounding atmosphere (Boutton, 1991; 1996; O'Leary, 1981). Differences between the two main photosynthetic pathways—Calvin-Benson (C_3) and Hatch-Slack (C_4)—include less discrimination against $^{13}CO_2$ in C_4 plants relative to C_3 plants, which results in differential fractionation in the plant tissue, and subsequently in soil organic matter derived from these plants (Bender, 1968; Ehleringer and Cerling, 2002; Johnson et al., 2007; O'Leary, 1981; 1988; Smith and Epstein, 1971). As C_3 plants are more discriminatory against the heavier ^{13}C molecules, they are isotopically lighter with isotopic values ranging from –32 to –20 ‰. The isotopically heavier C_4 plants possess isotopic values that range from –11 to –14 ‰. The mechanism that allows C_4 plants to be less discriminatory results in C_4 plants being more efficient in warm climates and in open areas with high light levels.

Stable carbon isotope ratios in lakes and wetlands can be interpreted in different ways based on the environmental and archaeological history of an area. In an area dominated by C_3 plants without human disturbance and maize agriculture, stable carbon isotope ratios may indicate moisture stress. Alternatively, in an area with known maize agriculture, stable carbon isotope ratios may indicate the timing and scale of cultivation in the watershed.

Changes in stable nitrogen isotope ratios ($\delta^{15}N_{OM}$) in sediment profiles can reflect a wide variety of processes that occur within and outside of the lake or wetland

(McLauchlan et al., 2014; Talbot, 2001). The nitrogen isotope values refer to the proportion of two naturally occurring stable isotopes in ratio form (R = $^{15}N/^{14}N$) relative to atmospheric air:

$$\delta^{15}N \text{ (per mil)} = 1000\ [(R_{\text{sample}} / R_{\text{standard}}) - 1]$$

Values can increase after major peaks in fire activity and then subsequently decline as forests recover and terrestrial N availability declines (Dunnette et al., 2014). Fires can lead to nitrogen losses due to volatilization where ^{14}N is preferentially released to the atmosphere resulting in more positive sedimentary N stable isotope ratios ($\delta^{15}N_{OM}$) and percent N (Dunnette et al., 2014; Johnson et al., 1998; Nave et al., 2011; Saito et al., 2007; Turekian et al., 1998). Greater nitrogen shifts are expected from canopy fires in coniferous vegetation than from agricultural fires or surface fires, as expected for most wildfires in a tropical moist forest. Research has shown that the magnitude of shifts in nitrogen biochemistry in a watershed is directly related to the intensity of the fire event as reconstructed from soil and vegetation (Stephan et al., 2015), which suggests that lower-intensity burns may produce less discernable shifts in nitrogen proxies in sediment profiles.

Biological processes in lacustrine environments related to within-lake productivity changes can also affect nitrogen signals (Talbot, 2001). These changes can indicate shifts in nitrogen during primary productivity or relate to the bacteria in the system (e.g. nitrification or denitrification). Also significant is the anthropogenic effect on nitrogen, which is broad and can relate to agricultural practices and fertilization or

even human excrement in a watershed or near-lake environment. Regional and global-scale variations in nitrogen deposition and cycling are also influenced by human actions (Holtgrieve et al., 2011; McLauchlan et al., 2014; 2013). The interpretation of nitrogen in sediment profiles must also account for diagenesis in organic lake sediments, which can shift $\delta^{15}N_{OM}$ values enough to influence interpretations of environmental change influencing sedimentary nitrogen (Brahney et al., 2014).

1.2.3 Elemental Composition

Changes in the elemental composition of lake or wetland sediments as revealed by XRF analyses can indicate intervals of changing climate or anthropogenic influences in the watershed. XRF results are influenced by the organic composition of the sediments. Core sections with higher organic content will produce a decreased count for all measured elements, while counts will be higher in more mineral-rich sections (Calvert, 1983; Lowemark et al., 2011; Rollinson, 1993). To circumvent this issue, researchers often normalize or standardize elemental data of interest against another element. Lowemark et al. (2011) suggested that aluminum is an ideal normalizing element because it is abundant, resists weathering, and is minimally affected by biological and redox processes. The examination of key elements in sediment cores normalized to Al can contribute to paleoclimate and agricultural interpretations based on other proxies.

1.2.4 Charcoal

Charcoal data from sediment cores are used to assess links between climate, vegetation, fire, and anthropogenic activities in the past (Whitlock and Larson, 2001). Charcoal is a direct data source for fire reconstruction and enters the lacustrine record when particulate charcoal is either washed into the lake basin or enters from atmosphere fallout. Charcoal in tropical sediments is commonly considered to reflect the local environment; however, as small charcoal can be transported long distances in the atmosphere, microscopic charcoal reflects both local and extralocal fires (Carcaillet et al., 2002). Analyzing larger (macroscopic) charcoal particles when present in sufficient abundance ensures that the record is one of local fires, but examining microscopic charcoal also provides useful indices of changing fire activity. In Costa Rica, microscopic charcoal records differ across ecosystem regions, and microscopic and macroscopic charcoal records from the same lakes show similar patterns, suggesting that much of the microscopic charcoal may derive from local fires; however, more research that compares size fractions of charcoal in sediment cores is needed (Horn, personal communication).

1.2.5 Pollen

Pollen analysis is predicated on the assumption that sedimentary pollen assemblages provide an accurate reconstruction of key vegetation changes through time (Bennett and Willis, 2001). Whether this would be true for the sediments of tropical

lakes was once in question (Flenley, 1973), but decades of research have established the validity of the method. Neotropical lake sediments contain abundant well-preserved pollen (Flenley, 1979), representing not just wind-pollinated plant taxa, but also many insect-pollinated plants (Bush, 1995). As in temperate areas, tropical pollen interpretations rely on the presence and abundance of taxa deemed indicative of certain environmental conditions (Bush, 1995) or that characterize particular vegetation types (Rodgers and Horn, 1996). Pollen counts are reported as percentages relative to the entire assemblage, allowing evaluation of changes through time. Pollen also serves as an indirect data source for determining fire activity in the past, as fluctuations in plant taxa or vegetation types associated with fire suggest fire activity in the local area (Whitlock and Larson, 2001).

1.3 Study Area Descriptions

This dissertation investigates the sediment records of four sites located in two study areas: a bog (Bao Bog 1) located in the highlands of the Dominican Republic, and three lakes (Lagunas Los Mangos, Danta, and Carse) located in the southern Pacific region of Costa Rica.

1.3.1 Highlands of the Dominican Republic

The WNW-ESE trending Cordillera Central of the Dominican Republic, which extends into Haiti as the Massif du Nord, is the highest mountain range in the

Caribbean, with three peaks reaching over 3000 m and an area of about 60 x 20 km that extends above 2000 m (Horn et al., 2000; Orvis et al., 1997). Two national parks meet along the crest, Parque Nacional Armando Bermúdez on the northeastern side, which includes the Valle de Bao study site, and Parque Nacional de Juan Carlos Ramírez on the southwest side (Clark et al., 2002).

Climate in the highland (> 2000 m) largely follows the dominant bimodal precipitation pattern of the circum-Caribbean. Two rainfall maxima (May–June and September–October) are separated by a weaker or secondary dry season termed a "mid-summer drought" (July–August) and a stronger boreal winter dry season (January–March) (Gamble et al., 2007). Precipitation in Hispaniola is strongly influenced by proximity to the ITCZ with the heaviest precipitation corresponding to the time of the most northerly position of the ITCZ during its seasonal migration. For highland sites influenced by the TWI, the northern (southern) position of the ITCZ lifts (lowers) the TWI elevation and increases (decreases) high elevation convective activity and rainfall (Martin and Fahey, 2014).

The high-elevations of the Cordillera Central have an annual precipitation of 1900 mm (or 192 mm per month) for the windward slopes, but that is reduced to 80 mm per month during the prominent winter dry season (Sherman et al., 2005). Northeasterly trade winds deliver moisture to the windward northeastern slopes of the Cordillera Central with the drier leeward southwestern slopes receiving at times half the rainfall and experiencing a more distinct dry season (Horst, 1992; Kennedy et al., 2005).

At windward sites below 2000 m and at some protected locations above 2000 m, the humid montane broadleaf forests and mixed pine/broadleaf forests are dominated by a diversity of broadleaf evergreen species with some native pine. Forests above 2000 m are largely pine forests, dominated by the single canopy species *Pinus occidentalis* Swartz or Hispaniolan pine (Speer et al., 2004). The lower limit of pine dominance coincides with occasional freezing temperatures at most sites above 2100 m (Kennedy et al., 2005). Above 2500 m, open woodlands and elfin forest replace the pines, which is coincident with the elevation where the trade wind inversion limits precipitation (Sherman et al., 2005). Within the pine forest occur areas of open savanna vegetation dominated by the tussock grass *Danthonia domingensis* Hack. & Pilg. and other herbs. The Valle de Bao study site is a large example of a highland savanna. Other, smaller areas of savanna on the drier southwestern slope of the Cordillera Central occupy distinct geomorphic settings that resemble features known from the African highlands as dambos (Clark et al., 2002).

Disturbances in the highland ecosystem are related to fire, landslides, and tropical storm events. Pines with multiple fire scars provide evidence of recurrent fires during the historic period (Martin and Fahey, 2006; Speer et al., 2004). While the earliest evidence of human activity on the island of Hispaniola likely dates to ca. 6000 cal yr BP (Wilson et al., 1998) and European colonization occurred in 1492 C.E., evidence of anthropogenic disturbances in the Cordillera Central region is largely confined to the last ~150 years (Kustudia, 1998). Charcoal in soils and sediments from highland savanna

environments and wetlands document fires during the late Pleistocene and Holocene that predate evidence of human activity in the Dominican highlands and were likely ignited by lightning. Several radiocarbon dates predate human colonization of Hispaniola, and could only have resulted from lightning (Horn et al., 2000).

1.3.2 Southern Pacific Costa Rica

The three lake sites in the Southern Pacific Zone of Costa Rica—Laguna Carse, Laguna Los Mangos, and Laguna Danta—are within a 12 km diameter study area of moderate topographic relief. The study area is classified as tropical moist forest using the Holdridge Life Zone System (Holdridge, 1967; Tosi, 1969) with the elevation of the lakes between 365 and 470 m. The pre-disturbance watershed vegetation is estimated to be tropical forest composed primarily of species that use the C_3 photosynthetic pathway. The lakes appear to have formed from landslides (Horn et al., in preparation). Such events are common in the area (Alvarado et al. 2009a; 2009b).

The study area is located within the Diquís subregion of the Greater or Gran Chiriquí archaeological region that encompasses southern Pacific Costa Rica and parts of western Panama. The archaeological record of the Diquís subregion includes two major cultural periods. The older Aguas Buenas Period (300 BCE to 800 CE) preceded the more recent Chiriquí Period, which began at 800 CE and ended with the arrival of the Spanish by 1500 CE (Corrales, 2000). The Chiriquí Period is considered to represent

a complex hierarchical society with high population levels that were supported by maize agriculture (Corrales, 2000).

1.4 The Dissertation

The goal of this dissertation research was to use multiple proxies from sediment cores to identify periods of climate stress, specifically drought, during the late Holocene at sites within the circum-Caribbean region and to determine how fire activity and signals of pre-Columbian agriculture coincide with these arid periods. The dissertation is organized as a set of three manuscripts intended for publication. These manuscripts address four primary objectives of my research:

(1) Evaluate evidence of aridity in a sediment record from a high-elevation site, and to assess relationships between this evidence and regional proxy records linked to the migration dynamics of the Intertropical Convergence Zone (ITCZ) and to changes in the height of the Trade Wind Inversion (TWI).

(2) Document environmental conditions and fire history in southern Pacific Costa Rica prior to the arrival of maize agriculture, and add to regional evidence on the timing of the spread and later decline of maize agriculture in the region.

(3) Compare the timing of agricultural decline at three new sites in the southern Pacific of Costa Rica to the onset of the LIA and the arrival of Spanish in the New World.

(4) Identify the influence of climate change on fire activity across the LIA and compare the findings with regional trends and climate interpretations derived from a recent global synthesis (Power et al., 2013), which revealed some contradictions and uncertainties for the northern Neotropics.

Chapter 2 addresses the first objective through analysis of stable carbon isotopes and elemental composition in a core from a highland bog in the Dominican Republic that was undisturbed by anthropogenic action until historic times. The core examined was recovered, dated, and examined for pollen and charcoal by Kennedy et al. (2006) in previous research. My new analyses were motivated by recent studies at other highland sites in the northern neotropics (Crausbay et al., 2015; Lane and Horn, 2013) that explored relationships between sedimentary proxies and climate drivers including shifts in the mean latitudinal position of the ITCZ and TWI dynamics.

Chapter 3 contributes to the second objective by presenting a unique 4300-year record of environmental change and fire activity at Laguna Los Mangos. The Laguna Los Mangos record covers a ~1000 year interval that precedes the earliest evidence of maize agriculture in the region at ca. 3200 cal yr BP (Horn, 2006), with the record capturing the transition to maize agriculture and its later decline.

Chapters 3 and 4 contribute to both objectives 3 and 4. In Chapter 4, I present two high-resolution records of fire history and signals of maize agriculture from Laguna Danta and Laguna Carse that together span the LIA. My record from Laguna Los Mangos (Chapter 3) also spans the Little Ice Age but extends back much further in time

to offer a longer term perspective on environmental change in southern Pacific Costa Rica. I also compare the three study lakes located in the northwestern lowlands of the southern Pacific region to existing records in the southeastern edge of the region to consider spatial differences in fire activity and agricultural decline (Chapter 4). I summarize the main conclusions of my study in Chapter 5.

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CHAPTER 2

IDENTIFYING PERIODS OF ARIDITY IN A 4000-YEAR SEDIMENT RECORD FROM A HIGHLAND BOG IN THE DOMINICAN REPUBLIC

This chapter is in preparation for journal submission. My use of "we" in this chapter includes my co-authors, Sally P. Horn and Chad S. Lane. I am first author, and my contributions to this project include experimental design, data collection and analyses, and writing the manuscript.

2.1 Abstract

We carried out stable isotope and elemental analyses of a previously studied sediment profile from a highland bog in the Cordillera Central, Dominican Republic to identify periods of aridity and to explore how dynamics of the Intertropical Convergence Zone and Trade Wind Inversion affect aridity at sites near the inversion elevation. We infer two major periods of aridity (3600–2300 and 1040–850 cal yr BP), with the later period associated with the Terminal Classic Drought. A third, less marked interval of aridity corresponds to the Little Ice Age from 550–100 cal yr BP. Interpretations are based on $\delta^{13}C_{OM}$, pollen preservation, charcoal influx, pollen and spore influx, and ratios of titanium and iron to aluminum in the sediment profile, and on comparisons to regional paleoclimate records. Southward shifts in the mean latitudinal position of the Intertropical Convergence Zone coincide with the arid periods in the Bao Bog record, which we interpret as also coinciding with a lowering of the elevation of the Trade Wind Inversion. During the Terminal Classic Drought, the Bao Bog record indicates only the effects of the late phase with no indication of drought conditions during the early phase for the highlands of Hispaniola.

2.2 Introduction

Over the past 25 years, paleoenvironmental researchers have investigated the relationships between climate change across the Holocene and changes in environments and human activities in the Greater Antilles (Burn et al., 2016; Burney et al., 1994; Caffrey et al., 2015; Crausbay et al., 2015; Higuera-Gundy, 1999; Hodell et al., 1991; Holmes, 1998; Kennedy et al., 2006; Lane et al., 2014; 2009a; 2011b; 2008; Peros et al., 2007; Street-Perrott et al., 1993). Most previous work has focused on sites located below 1000 m elevation, in keeping with the geography of the region. As is the case for the Central American mainland (Horn, 2007), many of the paleoenvironmental records from low and middle elevations in the Caribbean are from watersheds with a long history of human occupation, which can make it difficult to tease apart influences of climate and human activity in the records, especially using traditional proxies such as pollen and charcoal. However, records from wetlands in the mountains of Hispaniola (Crausbay et al., 2015; Kennedy et al., 2006) provide evidence of past environmental conditions in highland environments where the imprint of human activity is less and thus our ability to resolve climate potentially greater.

Palynological and geochemical analyses of sediment cores recovered from bogs and other wetlands in the Caribbean highlands allow for the development of local records of past vegetation, fire, and other environmental conditions. Climate reconstructions based on these local paleoenvironmental records can contribute to understanding of regional patterns of paleoclimate across the broader circum-Caribbean

region, in which important climate teleconnections existed during the Holocene extending from the Greater Antilles to Central and South America (Curtis and Gamble, 2007; Gamble and Curtis, 2008; Gamble et al., 2007; Metcalfe et al., 2000).

A powerful climate driver in the Neotropical region is variation in the mean seasonal positions of the Intertropical Convergence Zone (ITCZ). For highland settings in the northern Neotropics, the latitudinal shifts in the mean summer position of the ITCZ have large impacts on precipitation and also alter the elevation of the Trade Wind Inversion (TWI), a temperature inversion closely associated with the moist trade winds, the dry descending air of the Hadley Cell circulation, and sea surface temperatures (Cao et al., 2007; Crausbay et al., 2015; Lane and Horn, 2013; Schubert et al., 1995).

Several climate episodes or events characterized by warming or cooling temperatures, some beginning or ending abruptly, have occurred over the past millennium and have been shown or hypothesized to have affected moisture availability, vegetation, and fire regimes in the Caribbean and wider Neotropics. The Medieval Climate Anomaly (MCA) from 1050–700 cal yr BP was followed by a global cooling event, the Little Ice Age (LIA), from about 550–100 cal yr BP (Haug et al., 2001; Lamb, 1965; Lane et al., 2011b). During the LIA, evidence exists for severe El Niño events in the Pacific (Haberle and Lusty, 2000) that likely caused periods of environmental stress in the circum-Caribbean.

The Terminal Classic Drought (TCD, 1200–850 cal yr BP), is a prominent climate anomaly that consists of a series of multidecadal droughts overlapping the MCA that

affected Central and South America and the Caribbean (Hodell et al., 2005b; Lane et al., 2014). The TCD can be subdivided into an early phase (1180–1080 cal yr BP) and late phase (1030–850 cal yr BP) with a 50-year period of moister conditions separating the phases (Hodell et al., 2005b).

Closely associated with the classic Maya "collapse" in Mesoamerica, the TCD is apparent in paleoclimate records from across the circum-Caribbean, including Hispaniola (Haug et al., 2003; Hodell et al., 2005a; 1995; Lane et al., 2009a; 2014; Webster et al., 2007). Evidence of the TCD and other arid intervals in lake-sediment cores can consist of distinct layers of differing particle size, with coarser sediments, or more charcoal, deposited at core sites during periods of aridity and lowered lake levels (Horn, 1993); evidence of ped formation or other pedogenic processes if lake level lowering exposes the core site (Lane et al. 2009a); and shifts in climate proxies developed from oxygen isotope analyses of biogenic carbonates (Lane et al., 2009a) and from compound-specific analyses of hydrogen isotope ratios in lake sediments (Lane et al., 2014).

Analyses of marine sediment cores from the anoxic Cariaco Basin, off the coast of Venezuela, have provided highly resolved records of Caribbean paleoclimate. Titanium (Ti) and iron (Fe) concentrations were used to develop a 14,000-year record of variations in the hydrological cycle in the northern Neotropics (Haug et al., 2001). The record has been interpreted as a proxy for the mean latitudinal position of the ITCZ, with a more northerly position of the ITCZ leading to greater precipitation in northern Venezuela, increased erosion, and greater sediment deposition in the marine basin. Increased Ti

content in the record, reflecting greater terrigenous input from erosion, is interpreted as indicating a more northerly position of the ITCZ (Haug et al., 2001). As migrational dynamics of the ITCZ affect precipitation through the region, the Cariaco Ti record has been used to interpret periods of regional aridity for the circum-Caribbean region. At 3800–2800 cal yr BP, high-amplitude fluctuations in the Ti record indicate reduced precipitation (Haug et al., 2001). Similar patterns in the Ti concentration are visible during the TCD and LIA for the Cariaco Basin record. Proximity to the ITCZ can affect the mean TWI elevation as well as precipitation. For the highlands of Hispaniola, a more southerly mean position of the ITCZ would reduce rainfall and also decrease the elevation of the TWI with the descending dry air of the Hadley circulation (Cao et al., 2007).

El Niño–Southern Oscillation (ENSO) events also influence the TWI with negative phase ENSO, or El Niño events, lowering the TWI elevation and causing the TWI to be more persistent (Cao et al., 2007). From the sediments of Laguna Pallcacocha in the southern Ecuadorian Andes, Moy et al. (2002) developed a 12,000-year record of ENSO variability that documents ENSO activity on a timescale of 2–8 years. The ENSO record was based on the identification of light-colored, inorganic clastic laminae in the sediment core that correspond to episodes of high rainfall during El Niño events.

Periods of greater El Niño frequency show reduced precipitation linked to a lowering of the TWI in the high-elevation volcanic setting of Hawaii (Cao et al., 2007). The lower TWI elevation allows for less vertical cloud development and associated

precipitation because a reduction occurs in the elevation range between the upper TWI and the lower Lifting Condensation Level, the elevation at which rising air masses reach maximum relative humidity (Cao et al., 2007). Despite strong differences between Pacific and Atlantic atmospheric dynamics, the inferred effects of ENSO events on the TWI in Hawaii may extend to the broader tropics and also affect highlands of the circum-Caribbean region.

The ranges of plant species and the elevational limits of different forest formations are also limited by these atmospheric circulation systems that sharply affect moisture availability. The location of the TWI and the associated steep climate gradient affect vegetation composition by affecting precipitation, cloud cover, and humidity (Loope and Giambelluca, 1998). For example, the upper limit of the Tropical Montane Cloud Forest (TMCF) in the Neotropics is constrained by the position of the TWI, where rising humid air meets dry descending air, causing abrupt changes in biota (Cao et al., 2007; Crausbay et al., 2015; Schubert et al., 1995). For many tropical island locations with TMCF, an abrupt shift in vegetation occurs at the TWI elevation from TMCF to a grass or shrubland vegetation type, corresponding to the steep climate gradient (Hamilton et al., 1995). Additionally, the ranges of plant species growing on high elevation slopes below the TWI interface will shift both up and down slope with fluctuations of the TWI elevation. However, upslope movements of species ranges in response to warming temperatures can be limited above the TWI because of the sharp decline in moisture above the TWI (Loope and Giambelluca, 1998).

In the Bao valley in the highlands of Hispaniola, located below the TWI elevation on the windward flanks of the Cordillera Central of the Dominican Republic, Kennedy et al. (2006) investigated the sediments of a small montane bog at ~1800 m elevation. The ~4000-year Bao Bog record showed long-term dominance of pine vegetation and repeated fires during the late Holocene. The Bao Bog record also showed indications of intervals of aridity or enhanced seasonal drying between ~3700 and 1200 cal yr BP. This interpretation, based on evidence from pollen and sediment deposition, may signal the influence of the ITCZ and TWI in this highland environment.

More recently, Crausbay et al. (2015) developed a paleoenvironmental record of the last ~5900 years at the nearby Arrepentimientos site (19.028 °N, 70.924 °W) that offers a second-high elevation environmental and climate history for comparison. The Arrepentimientos site, a small high-elevation forest hollow at ~2455 m, is located 13 km southeast of the Bao Bog site. Research at the Arrepentimientos site (Crausbay et al., 2015) focused on the upper limits of the Tropical Montane Cloud Forests (TMCF) and the effects of the Trade Wind Inversion (TWI) on vegetation and fire history.

The Arrepentimientos record supported a link between TWI position and vegetation composition as the record showed a transition from the middle Holocene to present from TMCF to grasslands to pine forests associated with a lowering of TWI elevation. As the mean latitudinal position of the ITCZ moved southward from ~5900 cal yr BP to present and the TWI elevation lowered in response, the percentage of TMCF taxa declined in the Arrepentimientos record (Crausbay et al., 2015). While supporting

the link between montane vegetation and TWI elevation as influenced by the ITCZ, the Arrepentimientos record showed no support for a hypothesis that the upper limit of cloud forest taxa is controlled by El Niño-driven droughts (Crausbay et al., 2015).

Stable carbon and hydrogen isotope analyses of sediments from Lago de las Morrenas 1 in Costa Rica, together with previous pollen and charcoal analyses, supported the hypothesis that changes in the migration of the Intertropical Convergence Zone (ITCZ) over the course of the Holocene affected the hydrology of the high-elevation páramo ecosystem (Lane and Horn, 2013; Lane et al., 2011a). The findings showed that millennial-scale ITCZ dynamics in the circum-Caribbean region extended beyond the tropical lowlands to also affect highland environments and that these ITCZ dynamics likely contributed to the fire dynamics recorded in the Costa Rican páramo (Horn, 1993; League and Horn, 2000). The Lago de las Morrenas 1 record also suggested a relationship between the ITCZ position and the elevation of the TWI for the highlands of Costa Rica, in which ITCZ position affects the TWI elevation (Lane and Horn, 2013).

In this study, we describe new proxy analyses on the Bao Bog core that build on the initial Kennedy et al. (2006) work. Research questions are: (1) Can we identify intervals of aridity in the Bao Bog record using stable carbon isotopes ($\delta^{13}C_{OM}$) and elemental composition (XRF) along with existing proxies of pollen and microscopic charcoal? (2) Do intervals of aridity in the Bao Bog sediments coincide with regional droughts such as the Terminal Classic Drought (1200–850 cal yr BP) and the Little Ice Age (550–100 cal yr BP)? (3) Do shifts in the position of the Intertropical Convergence

Zone over the late Holocene and the associated effect on Trade Wind Inversion elevation affect the paleohydrology of the highland valley study site? And (4) Does ENSO activity also affect the TWI elevation and moisture stress in the highlands of Hispaniola?

2.3 Study Area

Bao Bog (19.0685 °N, 71.0342 °W, ~1800 m) is located in Valle de Bao, Dominican Republic on the windward flanks of the high peaks of the Cordillera Central (Figure 2.1). Valle de Bao has a treeless valley bottom valley that is dominated by *Danthonia domingensis* Hack. & Pilg. and other C3 grasses with patches of *Rubus* spp. (blackberry) on the valley floor. The valley slopes support forests dominated by Hispaniolan pines (*Pinus occidentalis* Swartz) with cold air drainage apparently limiting the encroachment of woody vegetation on the valley bottom (Kennedy et al., 2006).

Climate in the high elevations of the Cordillera Central largely follows the dominant bimodal precipitation pattern of the circum-Caribbean. Two rainfall maxima (May–June and September–October) are separated by a weaker or secondary dry season termed a “mid-summer drought” (July–August) and a stronger boreal winter dry season (January–March) (Gamble et al., 2007). Precipitation in Hispaniola is strongly influenced by proximity to the ITCZ with the heaviest precipitation corresponding to the time of the most northerly position of the ITCZ during its seasonal migration. For highland sites influenced by the TWI, the northern (southern) position of the ITCZ lifts (lowers) the TWI elevation and increases (decreases) high elevation convective activity and

rainfall (Martin and Fahey, 2014). The high-elevations of the Cordillera Central have an annual precipitation of 1900 mm (or 192 mm per month) for the windward slopes, but precipitation is reduced to 80 mm per month during the prominent winter dry season (Sherman et al., 2005).

While the earliest evidence of human activity on the island of Hispaniola likely dates to ca. 6000 cal yr BP (Fitzpatrick, 2015; Wilson et al., 1998) and European colonization occurred in 1492 C.E., evidence of anthropogenic disturbances in the Cordillera Central region is largely confined to the last ~150 years (Kustudia, 1998). Historical records indicate that slash and burn agriculture was introduced into the mountainous pine forests of the Cordillera Central around the start of the 20th century (Darrow and Zanoni, 1990). Pines were commercially logged beginning in the early 1900s and continuing until the banning of the practice in 1962 by the Dominican Republic government (Darrow and Zanoni, 1990). Logging activity in the Cordillera Central region did not extend to the slopes surrounding Bao Bog.

2.4 Bao-1 1997 Core Site and Previous Analyses

The Bao-1 1997 core site is a small peat bog (Bao Bog 1) at the topographically low portion of the valley floor. The bog sediments were recovered in 1997 as a series of successive one-meter drives using a Colinvaux-Vohnout (C-V) locking-piston corer (Colinvaux et al., 1999). At the time of coring, 15–20 cm of water was present at the core site with the uppermost sediment being dark organic peat (Kennedy et al., 2006). The

sediment was transported to the Laboratory of Paleoenvironmental Research at the University of Tennessee, Knoxville in the original sampling tubes (5-cm diameter). The near surface sediments were collected from a separate hole (<2 m away) with a PVC tube (5-cm diameter) and extruded in 2-cm intervals into plastic bags while in the field.

The C-V core sections were opened in the Laboratory of Paleoenvironmental Research with a modified table-mounted router. The sediments were photographed and their texture and color were described on core logs. The total profile sampled was 340 cm long, with the bottom-most sediments exhibiting characteristics of a paleo-surface with different depositional context compared to the modern bog. Prior analyses focused on samples from 0 to 40 cm in the PVC core of near-surface sediments; from 40 to 103 cm in C-V Core Section I; and from 103 to 126.5 cm in C-V Core Section II (Kennedy et al., 2006).

Pollen, charcoal, and loss on ignition (LOI) analyses were conducted at 4-cm intervals. In the LOI analysis, samples were ignited for one hour at 550 and 1000 °C to estimate organic and carbonate content (Dean, 1974). Samples for pollen and microscopic charcoal analysis were processed using standard pollen preparation techniques (HF, HCl, KOH, acetolysis, safranin stain) (Faegri and Iversen, 1989), with *Lycopodium* tablets added as controls (Stockmarr, 1971). Pollen residues were mounted on microscope slides in silicone oil, and then counted to a minimum of 400 pollen grains exclusive of indeterminate pollen and spores. Microscopic charcoal fragments greater

than 50 μm in maximum dimension were counted during the pollen counts. Only completely black, opaque, angular fragments were tallied.

Twelve samples were submitted from the upper organic section of the Bao-1 1997 core for AMS radiocarbon dating (Table 2.1). Dated samples consisted of terrestrial macrofossils, most commonly seeds; clearly identifiable wood fragments; or twigs, buds, or leaves; with charcoal fragments also used for dating. Some of the dated material was interpreted to represent redeposited materials that may correspond to high precipitation or tropical storm events. The Bao-1 1997 core contained 50 pollen types identified by Kennedy et al. (2006). Pollen preservation varied through the core with the highest indeterminate pollen percentages located in the lower, less organic sediments that date older than ~1800 cal yr BP. The pollen record is dominated by pine (*Pinus*), grass (*Poaceae*), and sedge (*Cyperaceae*) for the entirety of the 4000-year vegetation history. Microscopic charcoal was abundant through the record, indicating a long history of fires set by lightning or humans. Kennedy et al. (2006) proposed an interval of enhanced seasonal drying from ca. 3700–1200 cal yr BP at Bao Bog based on low pollen influx, poor pollen preservation, and low organic content in this part of the record.

2.5 Methods

2.5.1 Age-depth modeling

A new age model was created for the Bao Bog profile using Bayesian statistics in the Bacon age-modeling package for R (Blaauw and Christen, 2011). For this model, we used 11 dates (Table 2.1) and a surface date of –47 corresponding to the time of core collection in March 1997. The Bacon age-model uses the IntCal 13.14 calibration dataset (Reimer et al., 2013; Stuiver and Reimer, 1993); we set program parameters to provide the weighted mean age in cal yr BP for the entire profile at 1-cm intervals. We used the weighted mean age modeling output to plot the Kennedy et al. (2006) pollen data by age for comparison to new proxies. We also used the age modeling output to calculate sediment accumulation rates that we used to express pollen and charcoal data from Kennedy et al. (2006) as influx values. For each sample in the core profile, the accumulation rate calculation used the difference in modeled weighted mean ages between the sample depth and a point 1 cm below that depth.

2.5.2 Stable carbon and nitrogen isotope analysis

Bulk sedimentary organic carbon ($\delta^{13}C_{OM}$) and nitrogen ($\delta^{15}N_{OM}$) isotope values were measured on Bao Bog sediments at intervals of ca. 2 cm (~30 years). The sampling resolution for isotope analyses was about twice the resolution of the prior pollen and microscopic charcoal analyses (4-cm intervals, ~60 years). As in the Kennedy et al.

(2006) analysis, we sampled the 0 to 40 cm section of near–surface sediments collected with the PVC corer; C-V Core Section I (40–103 cm); and C-V Core Section II (103 to 126.5 cm). Samples of 1 cm^3 volume were dried at 50 °C overnight and then ground to a fine powder with a mortar and pestle to sufficiently homogenize the samples to be representative of the of the bulk sediment. The ground samples were split into a non-acidified fraction for $\delta^{15}N_{OM}$ and XRF analyses and an acidified fraction for $\delta^{13}C_{OM}$ analysis. Fractions for acidification were lightly moistened with distilled H_2O and then acid–fumigated in desiccators with 12M HCl for 2–3 hours. The acidified samples were then vented overnight before being placed on a hotplate to dry the samples, with samples reground as needed.

The analysis of the samples used a Thermo Delta V Plus mass spectrometer at the University of North Carolina Wilmington Isotope Ratio Mass Spectrometry (UNC-WIRMS) Laboratory. All isotopic compositions are reported in standard δ-per mil notation with nitrogen relative to atmospheric air and carbon relative to the Vienna-Pee Dee belemnite (V-PDB) marine-carbonate standard, where $R = {}^{13}C/{}^{12}C$ or ${}^{15}N/{}^{14}N$ and:

$$\delta^{13}C \text{ (per mil)} = 1000\ [(R_{sample} / R_{standard}) - 1]$$

$$\delta^{15}N \text{ (per mil)} = 1000\ [(R_{sample} / R_{standard}) - 1]$$

Reported carbon isotope ratios correspond to the acidified fraction while reported nitrogen isotope ratios correspond to the non-acidified fraction. The reported C:N ratio uses the percent carbon values for the acidified fraction and the percent nitrogen values

for the non-acidified fraction. All isotope values include error, which is expressed as the standard deviation for the duplicate samples at the same stratigraphic level.

2.5.3 X-ray fluorescence

We carried out elemental analysis of the Bao Bog sediment core samples that corresponded to the pollen and microscopic charcoal sampling intervals of 4 cm (~60 years) with tighter sampling (2 cm) around the 80–100 cm interval of the profile. Powdered samples from 38 levels of the profile were loaded into cells and analyzed using energy dispersive EDXRF technology in an Olympus BTX Profiler (Olympus BTX Profiler, 2013).

EDXRF excites all of the elements in the sample simultaneously, while an energy dispersive detector along with a multi-channel analyzer is used to simultaneously collect the emitted fluorescence radiation from the sample and then differentiate the energies of the characteristic radiation from each of the sample elements (Potts and Webb, 1992). The XRF analysis produces percent values for a combined all light elements category and for 32 specific elements (Mg, AL, Si, P, S, Cl, K, Ca, Ti, V, Cr, Mn, Fe, Co, Ni, Cu, Zn, As, Se, Sr, Zr, Mo, Ag, Cd, Sn, Sb, W, Pt, Hg, Pb, Th, U).

Elemental analyses based on XRF analyses of wet sediment cores has become common in paleoenvironmental research with the development of core scanners that automate data collection (Zolitschka et al., 2002). However, a variety of factors can lead to large variations in XRF data output when scanning wet sediment cores. For example,

sediment water content, core surface roughness, grain size variations, and time between analyses influence the reliability of comparisons of XRF data within cores or across sites (Böning et al., 2007; Lowemark et al., 2011; Tjallingii et al., 2007; Weltje and Tjallingii, 2008). However, the XRF data obtained for the Bao core are not subject to these issues, as they are based on the analysis of samples that are removed from core sections and dried and ground before being loaded into cells for analysis with the BTX profiler.

Whether analyzed dry in cells or wet in cores, XRF results are influenced by the organic composition of the sediments. Core sections with higher organic content will produce a decreased count for all measured elements, while counts will be higher in more mineral-rich sections (Calvert, 1983; Lowemark et al., 2011; Rollinson, 1993). To circumvent this issue, researchers often normalize or standardize elemental data of interest against another element. Lowemark et al. (2011) suggested that aluminum is an ideal normalizing element because it is abundant, resists weathering, and is minimally affected by biological and redox processes. For our Bao bog analyses, we report XRF data as the ratio of values in ppm against Al in ppm.

2.5.4 Proxy Diagrams

Diagrams that showed isotope values, sediment accumulations rates, and other characteristics of the Bao Bog core were created using the C-2 software (Juggins, 2007). In each diagram, we shaded the TCD (1200–850 cal yr BP) and LIA (550–100 cal yr BP),

based on reported dates (Haug et al., 2001; Lamb, 1965; Lane et al., 2011b). We also indicated a period of aridity that we identified earlier in the record.

2.6 Results

2.6.1 Age-Depth Model

The Bayesian age-depth model rejected three radiocarbon dates while fitting the remaining dates (Figure 2.2). These rejected dates that are too young for their stratigraphic positions were all measured on charred macrofossils and were interpreted as redeposited charcoal by Kennedy et al. (2006). The new age model shows a major shift in sedimentation rate from 1350 to 1150 cal yr BP. Before 1350 cal yr BP, sediment accumulated at the site at the rate of 0.02–0.03 cm/year. After 1150 cal yr BP, sediment accumulated at the rate of about 0.06 cm/year. Our model indicates the following time intervals for the sediment types noted by Kennedy et al. (2006) (Figure 2.3). The organic-rich sand silt (10YR 3/1) with occasional clasts of redeposited organic sediment and coarse sand from 126.5 to 103 cm corresponds to the interval from 4000 to 3100 cal yr BP. A thin layer of fine-grained mineral silt that is lighter in color (10YR 4/1) from 103 to 100 cm corresponds to the interval from 3100 to 2950 cal yr BP. From 100 to 94 cm, the sediment is again dark, organic-rich sandy silt (10YR 3/1), but with greater mottling throughout (10YR 4/6) and abundant redeposited peat and mineral soil clasts. This material was deposited from 2950–2550 cal yr BP. The upper 94 cm of the core,

spanning 2550 cal yr BP to modern, is a dark, fine-textured silty peat (10YR 2/1) that grades upward to peat with a lower silt content (10YR 2/2). The upper 20 cm of this interval, from 250 cal yr BP to modern, is rich in undecayed plant material.

2.6.2 Pollen and Spore Percentages and Pollen and Charcoal Influx

Pollen and spore percentages from Kennedy et al. (2006), replotted by age using the Bacon age model (Figures 2.4, 2.5), show some shifts during the times of the TCD and LIA. For example, pollen percentages for *Pinus* (pine) and *Arceuthobium* (mistletoe) both increase during the TCD, and *Trema* increases during the LIA. Pollen and spore influx values, calculated using pollen and spore counts from Kennedy et al. (2006) and accumulation rates from the Bacon age model, are initially high (base of the record older than ~3700 cal yr BP), but overlying sediments (~3700–1300 cal yr BP) have very low influx values, except for one higher value at about 3250 cal yr BP (Figure 2.6). The uppermost section of the profile (younger than ~1300 cal yr BP) shows the highest pollen and spore influx. Charcoal influx values mirror the pollen and spore influx values. Charcoal influx declines at ~3200 cal yr BP and stays low until ~1300 cal yr BP. After 1300 cal yr BP, charcoal influx values are generally high until the last ca. 150 years.

2.6.3 Organic Matter, Organic Carbon, Nitrogen, and C:N ratios

Organic matter content and organic carbon and nitrogen values and ratios vary through the Bao Bog profile (Figure 2.3). The organic matter (OM) content, based on

LOI, varies from 16% to 46% (data from Kennedy et al., 2006), with lowest organic content in the basal sediments. Organic carbon and nitrogen percentages for the Bao Bog record generally parallel the OM content. Sharp increases in organic carbon occurred at ~1040 cal yr BP and ~250 cal yr BP. The C:N ratio (Figure 2.3) shows a gradual increase from the base to ~1100 cal yr BP, with a sharp increase at roughly 1000 cal yr BP and a decreasing trend in the ratio after 1000 cal yr BP.

2.6.4 Stable Carbon and Nitrogen Isotope Ratios

The Bao Bog isotope samples (n=60) for $\delta^{13}C_{OM}$ exhibited ratios varying from –28.9‰ to –19.8‰ (Figure 2.7). The basal portion of the core from 4000–2300 cal yr BP shows the most positive $\delta^{13}C_{OM}$ values (χ = –24.0‰). At ca. 2400 cal yr BP, a pronounced shift occurs toward more negative $\delta^{13}C_{OM}$ values (χ = –28.1‰), which are maintained until 1040 cal yr BP. The upper portion of the core, from 1040 cal yr BP to modern, exhibits $\delta^{13}C_{OM}$ values (χ = –26.2‰) that shift twice from more negative to less negative $\delta^{13}C_{OM}$ values and then back to more negative values. The first of these shifts toward less negative $\delta^{13}C_{OM}$ occurs between 1040 and 850 cal yr BP, coincident with the late phase of the TCD in the circum-Caribbean (Hodell et al., 2005b; Lane et al., 2014). The second shift, smaller and more gradual, is toward less negative $\delta^{13}C_{OM}$ values from 550–200 cal yr BP, during the LIA. Sedimentary stable N isotope ratios ($\delta^{15}N_{OM}$) for Bao Bog vary from 1.0‰ to 2.9‰ (Figure 2.7). The $\delta^{15}N_{OM}$ values generally mirror the $\delta^{13}C_{OM}$

values with the most positive $\delta^{15}N_{OM}$ values occurring in the early arid interval for Bao Bog, the TCD, and the last part of the LIA.

2.6.5 X-ray Fluorescence

The elemental composition of the Bao-1 1997 core samples shows some variability in key elements across time (Figure 2.8). These shifts in elemental composition (expressed as ratios against Al) are small in magnitude except during the last ~200 years (after ca. 150 cal yr BP). The large modern shifts in composition are potentially associated with regional atmospheric pollution. The Ti/Al record exhibits the highest value near the base of the core (~3600 cal yr BP) before decreasing with some variability until ~2100 cal yr BP. The Ti/Al ratio increases from ~2100 cal yr BP until ~1350 cal yr BP, when a sharp decline begins that lasts until ~1100 cal yr BP, followed by a sharp, but isolated increase at ~1040 cal yr BP. Another decline begins at 750 cal yr BP and is maintained during the LIA until the top of the profile.

The Fe/Al record shares some trends with the Ti/Al record. The maximum Fe/Al value occurs in the basal sediments at ~3750 cal yr BP and the ratio decreases upward to ~3000 cal yr BP, after which the value increases and stays above the mean for the record until ~1200 cal yr BP. After 1200 cal yr BP, values decline and then stabilize at ~900 cal yr BP before decreasing again after ~600 cal yr BP. The Fe/Al ratio then increases from ~370 cal yr BP until the top of the profile. The Fe/Al ratios in the Bao Bog profile show lower values during the basal arid interval and the LIA, and a decline across the TCD.

Ca/Al ratios show a decline at ~3600 cal yr BP with values remaining below the mean value until ~2400 cal yr BP. Another decline occurs from ~1350–1100 cal yr BP, before values rise slightly to above the mean value. A third sharp decline occurs at ~600 cal yr BP, after which values remain low until ~200 cal yr BP. The Zn/Al record mostly mirrors the Ti/Al record until ~300 cal yr BP, after which Ti/Al values decrease while Zn/Al values increase.

2.7 Discussion

2.7.1 Stable Carbon Isotopes and Aridity in the Highlands of Hispaniola

Prior pollen analysis (Kennedy et al. 2006) indicated a relatively stable vegetation history at Bao Bog with the bog surface and valley bottom primarily supporting grasses (Poaceae) and sedges (Cyperaceae) and surrounding mountain slopes supporting pines (*Pinus*) with a grass understory. The dominant grass in the valley, *Danthonia domingensis,* is a C_3 plant and this may be the case for all other grasses that have been collected in the highland pine forests and savannas (Table 2.2) (Hager and Zanoni, 1993; Osborne et al., 2014). The possible exception is *Panicum*, which Zanoni (1993) listed for the highlands (without species identification), and which includes some C_4 species. The genera of sedges known from the highlands are commonly C_3 species, but also include some C_4 species, such as *Bulbostylis subaphylla* and potentially *Cyperus flavus* (Table 2.2)

(Bruhl and Wilson, 2007; Hager and Zanoni, 1993; Osborne et al., 2014; Zanoni, 1993). The modern importance of C_4 plants at the site is probably low.

The $\delta^{13}C_{OM}$ values measured on the Bao Bog sediments provide additional information about past vegetation and environmental conditions. Stable carbon isotopes in lake sediments are influenced by the photosynthetic pathway of watershed vegetation (Boom et al., 2007; Lane et al., 2004). The carbon isotope ratio refers to the proportion of two naturally occurring stable isotopes, ^{12}C (98.89%) and ^{13}C (1.11%), that are typically expressed in ratio form ($^{13}C/^{12}C$) (Johnson et al., 2007). Naturally occurring isotopic fractionation results in variations in this ratio based on preferential discrimination of ^{13}C by plants during photosynthesis, leading to plant tissue that is isotopically depleted in ^{13}C relative to the surrounding atmosphere (Boutton, 1991; 1996; O'Leary, 1981). Differences between the two main photosynthetic pathways—Calvin-Benson (C_3) and Hatch-Slack (C_4)—include less discrimination against $^{13}CO_2$ in C_4 plants relative to C_3 plants, which results in differential fractionation in the plant tissue, and subsequently in soil carbon (Bender, 1968; Ehleringer and Cerling, 2002; Johnson et al., 2007; O'Leary, 1981; 1988; Smith and Epstein, 1971). As C_3 plants are more discriminatory against the heavier ^{13}C molecules ($^{13}CO_2$ during gas exchange), they are isotopically lighter with isotopic values ranging from –35 to –20‰. The isotopically heavier C_4 plants possess isotopic values that range from –14 to –10‰ (Bender, 1971; O'Leary, 1981). Physiological differences between C_4 and C_3 plants result in a reduced discriminatory ^{13}C preference,

which allows C_4 plants to be more efficient in warm climates and in open areas with high light levels.

In a locality such as Bao Bog, where vegetation is dominated by C_3 plants and there is no evidence of agricultural activity that would introduce C_4 crops, the stable carbon isotope ratio can indicate moisture stress or signs of environmental aridity. Such increases in moistures stress in C_3 plants may shift the $\delta^{13}C_{OM}$ content by as much as 3–6‰ as those C_3 plants lose their ability to discriminate against the heavier ^{13}C (Johnson et al., 2007; Tieszen, 1991). We hypothesized that C_3 plants should fix more ^{13}C during periods of aridity or enhanced seasonal drying in the Bao Valley, therefore producing heavier isotopic fractions (positive shift toward C_4 values). If sedges in the valley include C_4 species, possible increases in their abundance during drier periods would further shift isotope ratios toward C_4 values.

The Bao Bog record shows an interval near the base of the record of increased $\delta^{13}C_{OM}$ values that we interpret as evidence of an arid interval from 3600–2300 cal yr BP. This interval is followed by a decrease in $\delta^{13}C_{OM}$ values, suggesting a wetter interval until ~1040 cal yr BP. At ~1040 cal yr BP, the record shows a more positive $\delta^{13}C_{OM}$ signal that we interpret as a shift to drier conditions coincident with the late phase of the TCD. At the traditional end of the TCD (850 cal yr BP) a negative shift in $\delta^{13}C_{OM}$ values occurs, indicating somewhat moister conditions. Across the LIA, $\delta^{13}C_{OM}$ values show a gradual increase, but the shift in $\delta^{13}C$ values is less than shifts during our interpreted arid periods from 3600–3200 and 1040–850 cal yr BP.

Our interpretation of aridity between 3600 and 2300 cal yr BP from $\delta^{13}C_{OM}$ values supports the earlier interpretation of enhanced seasonal drying based on high indeterminate pollen values, low pollen and spore influx, and low organic contents in the lower part of the Bao record (Figures 2.5 and 2.6) (Kennedy et al., 2006). More pronounced seasonal drying of the bog surface would be unfavorable for pollen preservation and organic matter accumulation. The lower charcoal influx during this dry period may also relate to climate, through a possible effect of seasonally drier conditions on the accumulation of fine fuels that support fires.

At 2550 cal yr BP, the bog stratigraphy shifts to dark silty peat from lighter organic silt (Figure 2.3). The $\delta^{13}C_{OM}$ values indicating moisture stress at Bao Bog are highest during the basal sediments preceding the peat portion of the stratigraphy, suggesting that sediment type may influence our $\delta^{13}C_{OM}$ values. However, $\delta^{13}C_{OM}$ values remain high until after 2400 cal yr BP, overlapping with peat sediments. The similar timing of the transition to peat and reduced signals of aridity in the record is consistent with our interpretation of an arid period from 3600–2300 cal yr BP, followed by a wetter period until the TCD.

The elemental composition of the Bao Bog sediments shows patterns of relative decline in Fe and Ti during the inferred arid interval from 3600–2300 cal yr BP and during the TCD and LIA. We interpret the decline in Ti and Fe, normalized to Al, in the Bao Bog sediments during the inferred arid interval to correspond to lower average precipitation and reduced sediment weathering compared to the earlier (4050–3600 cal

yr BP) and later (2300–1200 cal yr BP) intervals of inferred wetter conditions. Declines in Ca/Al ratios could indicate a drop in wetland productivity (Turner et al., 2015) during the basal arid interval, TCD, and LIA.

Elemental composition of the uppermost Bao Bog sediments shows a large increase in many heavy elements. Roughly corresponding to the last 100–150 years, the shifts in Fe/Al, Ca/Al, and Zn/Al may signal anthropogenic inputs into the atmosphere. These recent shifts require further study.

The Bao Bog record shows evidence for another period of aridity corresponding to the TCD (1200–850 cal yr BP). Within the Bao Bog record, nearly all climate proxies, including the $\delta^{13}C_{OM}$ curve, show shifts in their values associated with the late phase of the TCD (1030–850 cal yr BP). The early phase of the TCD (~1200–1080) is not well represented in the Bao Bog proxy records, suggesting an absence of climate stress during the early phase in the highlands of Hispaniola. However, Laguna Castilla on the leeward slope of the Cordillera Central, ~800 m lower in elevation (Figure 2.1), shows evidence of both the early and late phase of the TCD.

Climate proxies also show the effects of the LIA in our record. The similarity in proxy responses between the well-established TCD and LIA climate events and the inferred arid interval (3600–2300 cal yr BP) supports our interpretations of aridity in the highlands of Hispaniola. Our proxy analyses refine the timing and strengthen the case of a period of aridity in the basal portion of the Bao Bog profile as previously inferred from pollen and charcoal evidence (Kennedy et al., 2006). Whereas Kennedy et al. (2006)

interpreted the period from 3700–1300 cal yr BP as arid, we consider the arid period to be from 3600–2300 cal yr BP with a wetter period between 2300 cal yr BP and the TCD.

2.7.2 Trade Wind Inversion and Inter Tropical Convergence Zone Position in the Caribbean Antilles

The mean latitudinal position of the ITCZ is hypothesized to have an effect on both seasonal precipitation in the Caribbean highlands and the elevation of the TWI, which also influences moisture availability near the TWI elevation. Existing paleorecords in the circum-Caribbean indicate millennial-scale ITCZ dynamics in the circum-Caribbean region extended beyond the tropical lowlands to also affect the hydrology of highland sites. In the highlands, the latitudinal migration of the ITCZ affects seasonal rainfall amounts, as in the lowlands, and also the elevation of the TWI, with more ITCZ activity lifting the TWI (Crausbay et al., 2015; Lane and Horn, 2013; Lane et al., 2009b). To evaluate whether these relationships are evident in the Bao Bog record, we compared patterns of shifts in $\delta^{13}C_{OM}$ with the Cariaco Basin Ti concentration record (Haug et al., 2001) and the Laguna Pallcacocha ENSO record (Moy et al., 2002) for the TCD and the earlier arid interval (3600 to 2300 cal yr BP) (Figure 2.9).

The Cariaco Basin titanium record is interpreted to be a proxy for the average latitudinal position of the ITCZ, with lower Ti concentrations corresponding to periods of more southerly ITCZ position. In the most recent 4000 years of the Cariaco record, Ti concentrations are highest from 4000–3600 cal yr BP. Cariaco Basin sediments deposited

from 3600 to 2000 cal yr BP show depressed Ti values with great variability. Ti concentrations are stable from 2000 cal yr BP until ~1200 cal yr BP, after which values decline until ~900 cal yr BP with a sharp positive spike at ~800 cal yr BP. This decline in Ti concentrations at 1200 cal yr BP is interpreted by Haug et al. (2001) to correspond to the onset of the TCD. Another more recent decline in the Cariaco Ti record is associated with the LIA and begins at ~600 cal yr BP.

During the basal arid interval and the TCD in the Bao Bog record, the Cariaco Basin record shows shifts toward lower percent Ti values, indicating more southerly mean latitudinal positions of the ITCZ (Haug et al., 2001). While the ITCZ does not migrate far enough northward in the boreal summer to the directly intersect Hispaniola, the northward extent of the ITCZ, as reflected by its mean annual position, strongly influences precipitation. A southerly mean position of the ITCZ results in lower precipitation amounts compared to a more northerly mean position of the ITCZ and also decreases the elevation of the TWI as a result of the descending dry air of the Hadley circulation (Cao et al., 2007).

Negative phase ENSO, or El Niño events, are linked to a lower elevation and more persistent TWI in the circum-Caribbean (Cao et al., 2007). The Laguna Pallcacocha ENSO record shows a general shift toward more frequent El Niño events over time until the peak is reached at ~1300 cal yr BP (Moy et al., 2002). After ~1300 cal yr BP, ENSO events decline as evidenced in both the ENSO 100-year windows and Red Color Intensity datasets. The arid interval (3600–2300 cal yr BP) in the Bao Bog record

corresponds to an increase in ENSO activity, which could produce drier conditions for the highlands of Hispaniola by affecting the elevation of the TWI. ENSO activity also increases during the TCD; however, the increase in activity occurs later, at roughly the time of the late phase of the TCD from 1030–850 cal yr BP (Hodell et al., 2005b). The timing of the shift to drier conditions at ~1040 cal yr BP in the Bao Bog $\delta^{13}C_{OM}$ curve coincides with the late phase of the TCD. From our proxies, the early TCD from ~1200–1080 cal yr BP may not have strongly affected Bao Bog.

The phase of the North Atlantic Oscillation (NAO), the strength of the Atlantic meridional overturning circulation (AMOC), shifts in the Walker Circulation, and sea-surface temperatures may all play a role in ITCZ positioning and TWI elevation in the highlands of Hispaniola (Haug et al., 2003; Kennett et al., 2012; Lane et al., 2011b; Peterson and Haug, 2006; Trouet et al., 2009). Both of the regional paleoclimate records used in this study, the Cariaco Ti record and Laguna Pallcacocha ENSO record, relate to ITCZ and TWI positions, which are controlled by atmospheric mechanisms that are not fully understood. The inferred ITCZ and TWI positions are interpreted to affect precipitation and TWI elevation in the highlands of Hispaniola. A lower TWI elevation reduces convective activity and would further enhance drought conditions and moisture stress for sites near the TWI elevation boundary.

The Bao Bog record, located below the TWI at ~1800 m, shows evidence of two periods of aridity during its history that were very likely driven by mean ITCZ position and the associated elevation of the TWI. The early arid interval (~3600–2300 cal yr BP)

and the TCD (1200–850 cal yr BP) in the Bao Bog record correspond to high-amplitude fluctuations in the Cariaco Ti record that indicate shifts in the ITCZ that likely affected precipitation in the Cordillera Central region. The Bao Bog record also shows some evidence of aridity associated with the LIA (550–100 cal yr BP).

The Laguna Pallcacocha record of ENSO activity shows fluctuations in the number of El Niño events that correspond with the early arid interval and the late TCD. We interpret the correspondence between ENSO activity and aridity to indicate that ENSO does influence the elevation and persistence of the TWI. The Bao Bog record shows some correspondence between El Nino events and an interpreted lowered and more persistent TWI. However, the Pallcacocha record shows two intervals of increased ENSO activity during the wetter period from 2300–1200 cal yr BP that seem not to match proxies in the Bao record indicating that this relationship is not consistent across the entire late Holocene.

2.8 Conclusions

Using $\delta^{13}C_{OM}$ values, elemental composition (Ti/Al, Fe/Al, Ca/Al, Zn/Al), organic content, and pollen and charcoal proxies, we identified several periods of aridity in the Bao Bog record. An interpretation of aridity from 3600–2300 cal yr BP, followed by a wetter period between 2300 cal yr BP and the TCD is supported by multiple sediment proxies. The Bao Bog record also shows the effects of the TCD in the Highlands of Hispaniola as constrained to the late phase of the TCD from ca. 1030–850 cal yr BP. The

absence of an early phase of the TCD in the Bao Bog record contrast with a paleoclimate record at the nearby, but lower elevation Laguna Castilla site (Lane et al., 2014), which shows evidence of moisture stress for both the early and late phase of the TCD.

We compared the $\delta^{13}C_{OM}$ record with two regional paleoclimate records, the Cariaco Basin titanium concentration record and the Laguna Pallcacocha ENSO record, to evaluate the effects of ITCZ migrational dynamics and changing TWI elevations on the hydrology of Bao Bog. The two most prominent periods of aridity in the Bao Bog record, the ~1300-year arid interval (3600–2300 cal yr BP) and the late phase of the TCD (1030–850 cal yr BP), both correspond to intervals of a more southerly ITCZ position, which is expected to be associated with a lower TWI elevation. The Bao Bog record also showed some relationship between inferred aridity and the Laguna Pallcacocha ENSO record, suggesting reduced precipitation or lowered TWI elevation during some, but not all, intervals of enhanced El Niño activity. Highland locations in Hispaniola experienced aridity across the late Holocene at intervals coincident with southerly shifts in ITCZ position and a lowering of the TWI elevation.

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2.11 Appendix

Table 2.1. Radiocarbon determinations from the Bao-1 1997 profile.

Lab number [a]	Depth (cm)	$\delta^{13}C$	Uncalibrated ^{14}C age (^{14}C yr BP)	±2 σ cal. age range BP
AA40257	17	–25.5	191 ± 31	302–1
AA40258	17	–26.1	167 ± 43	292–1
AA43339	39	–24.2	2126 ± 59 [b]	2309–2003
AA40256	41	–26.4	553 ± 66	659–504
AA43340	59	–23.9	1816 ± 57 [c]	1879–1606
AA39458	48	–25.5	3016 ± 49 [b]	3355–3068
Beta-155839	76	–25.2	1300 ± 40	1302–1099
Beta-155840	87	–25.9	2260 ± 50	2350–2152
Beta-13524	99.5	–24.9	5210 ± 50 [b]	6178–5896
AA40253	106	–26.6	3083 ± 38	3379–3183
AA40254	113	–24.8	3348 ± 38	3688–3479
AA40255	126	–24.5	3690 ± 86	4345–3730

Calibration dataset used for ±2 σ cal. age range BP is IntCal 13.14c (Reimer et al., 2013; Stuiver and Reimer, 1993).

[a] Analyses were performed by the NSF Arizona AMS Facility (AA) and by Beta Analytic, Inc. (Beta).

[b] Samples interpreted as redeposited charcoal by Kennedy et al., 2006.

[c] Sample not included in age-depth modeling as pollen, charcoal, elemental analysis, and stable isotopes were sampled from Core Section I below the 40-cm depth.

Table 2.2. Photosynthesis pathway for common grasses and sedges in Valle de Bao.

Family	Taxon [a]		Photosynthetic Type [b]
Poaceae	*Danthonia*	*domingensis*	C3
Poaceae	*Calamagrostis*	*leonardii*	C3
Poaceae	*Agrostis*	*hyemalis*	C3
Poaceae	*Agrostis*	*perrenis*	C3
Poaceae	*Deschampsia*	*domingensis*	C3
Poaceae	*Panicum*	sp.	C3/C4
Cyperaceae	*Carex*	*longii*	C3
Cyperaceae	*Carex*	*polystachia*	C3
Cyperaceae	*Carex*	*angustior*	C3
Cyperaceae	*Cyperus*	*flavus*	C3/C4
Cyperaceae	*Bulbostylis*	*subaphylla*	C4

[a] Grass and sedge species mentioned in Hager and Zanoni, 1993 and Zanoni, 1993.

[b] Information from Osborne et al., 2014 and Bruhl and Wilson, 2007.

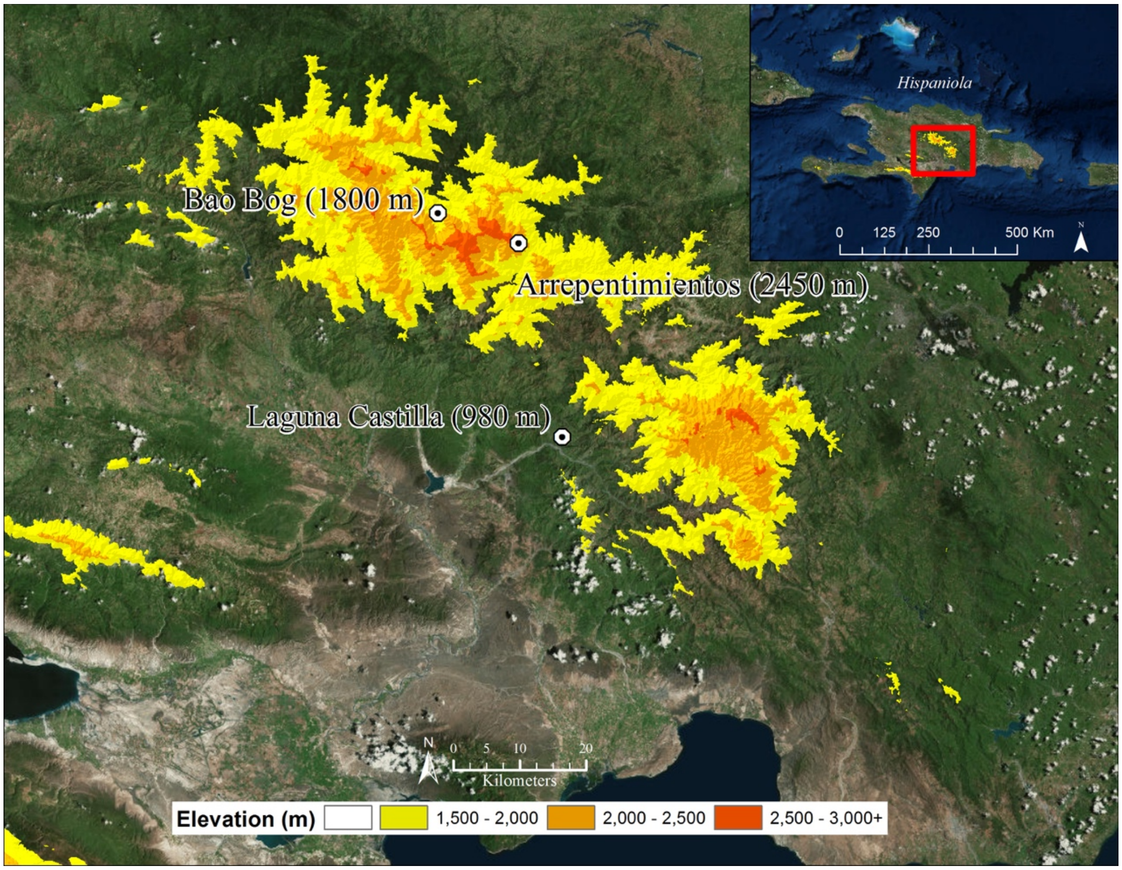

Figure 2.1. Location of Bao Bog and nearby sites in the Cordillera Central, Dominican Republic. Sources: ESRI, DigitalGlobe, i-cubed, EarthStar Geographics, CNES/Airbus DS, USGS, USDA, AEX, Getmapping, Aerogrid, IGN, IGP, swisstopo.

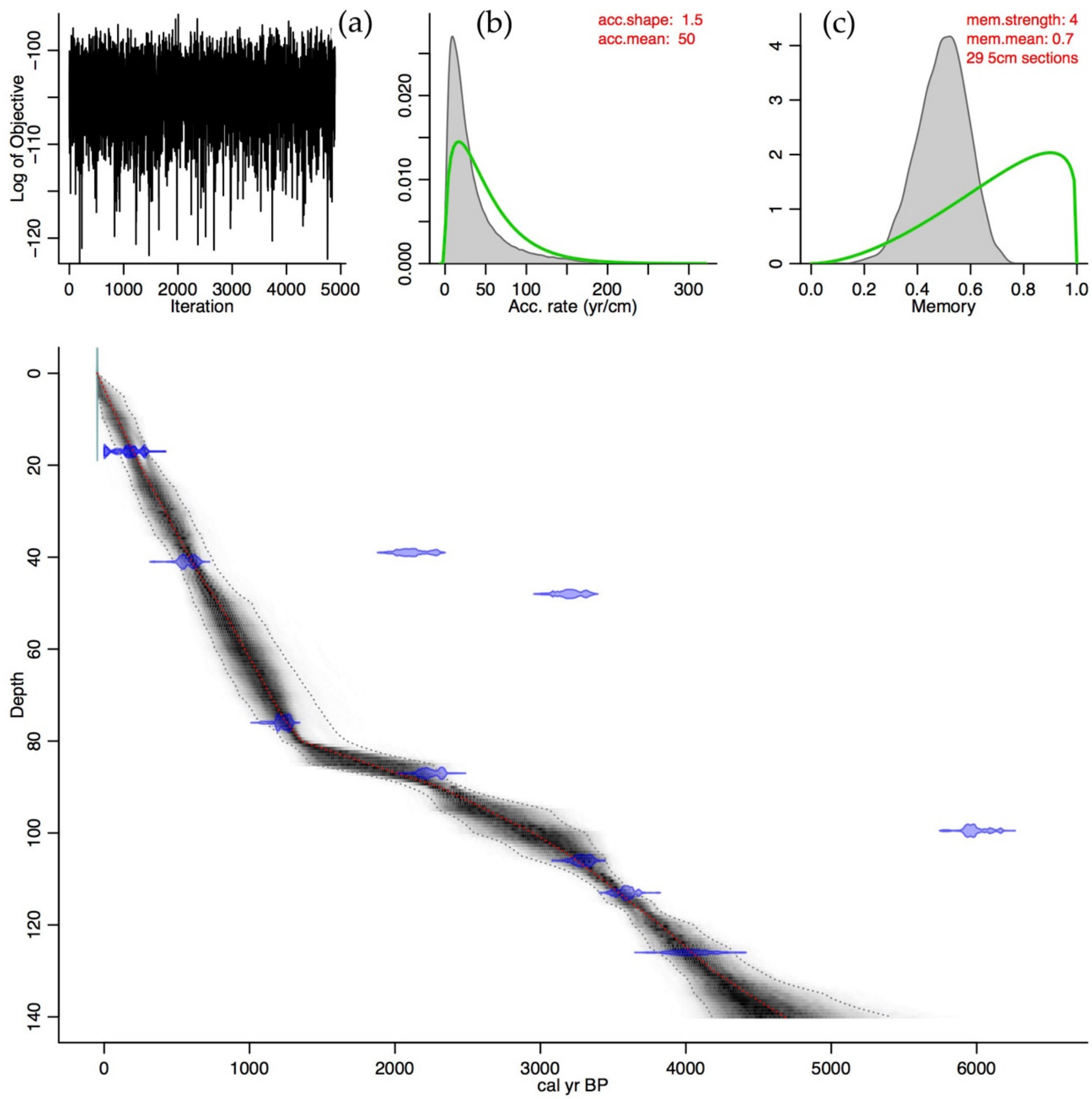

Figure 2.2. Age-depth model for Bao-1997 core from Bao Bog, Dominican Republic. (a) MCMC iterations with stationary distributions ideal. (b) The accumulation rate consists of a gamma distribution with adjusted accumulation shape and mean values (Blaauw and Christen, 2011). (c) The memory value, or autocorrelation, defines how much the accumulation rate of a particular depth in a core depends on the depth above it. Assuming a low memory or autocorrelation, the accumulation rate would change greatly over time (highly variable environmental conditions), while a high memory implies a more constant accumulation (Blaauw and Christen, 2011).

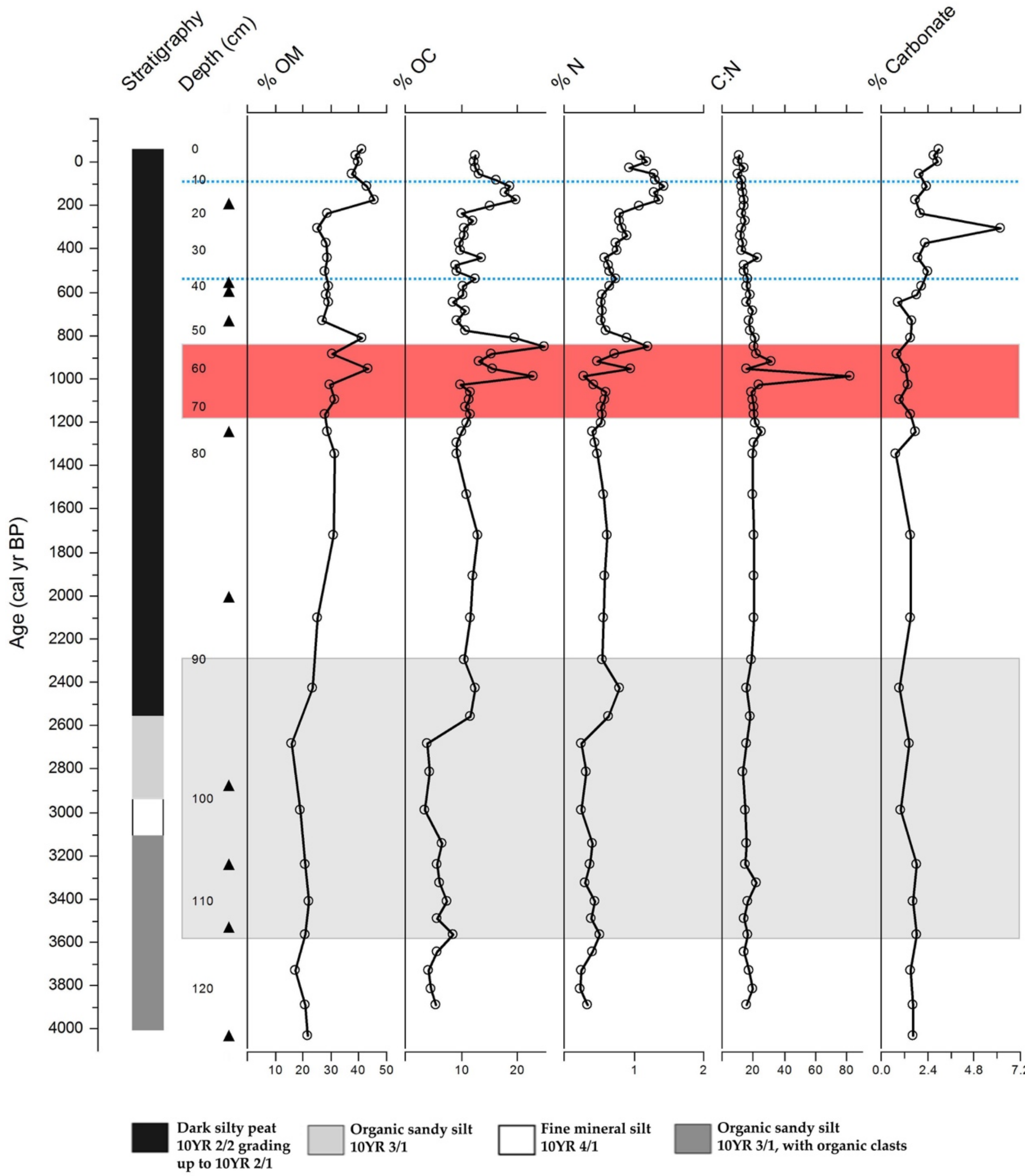

Figure 2.3. Stratigraphy and sediment composition based on LOI and geochemical analyses for the Bao Bog profile. % OM data from Kennedy et al. (2006). Black triangles show positions of radiocarbon dates. Blue dotted line represents the LIA; red shaded interval represents the TCD; gray shaded interval represents the early arid interval from Bao Bog.

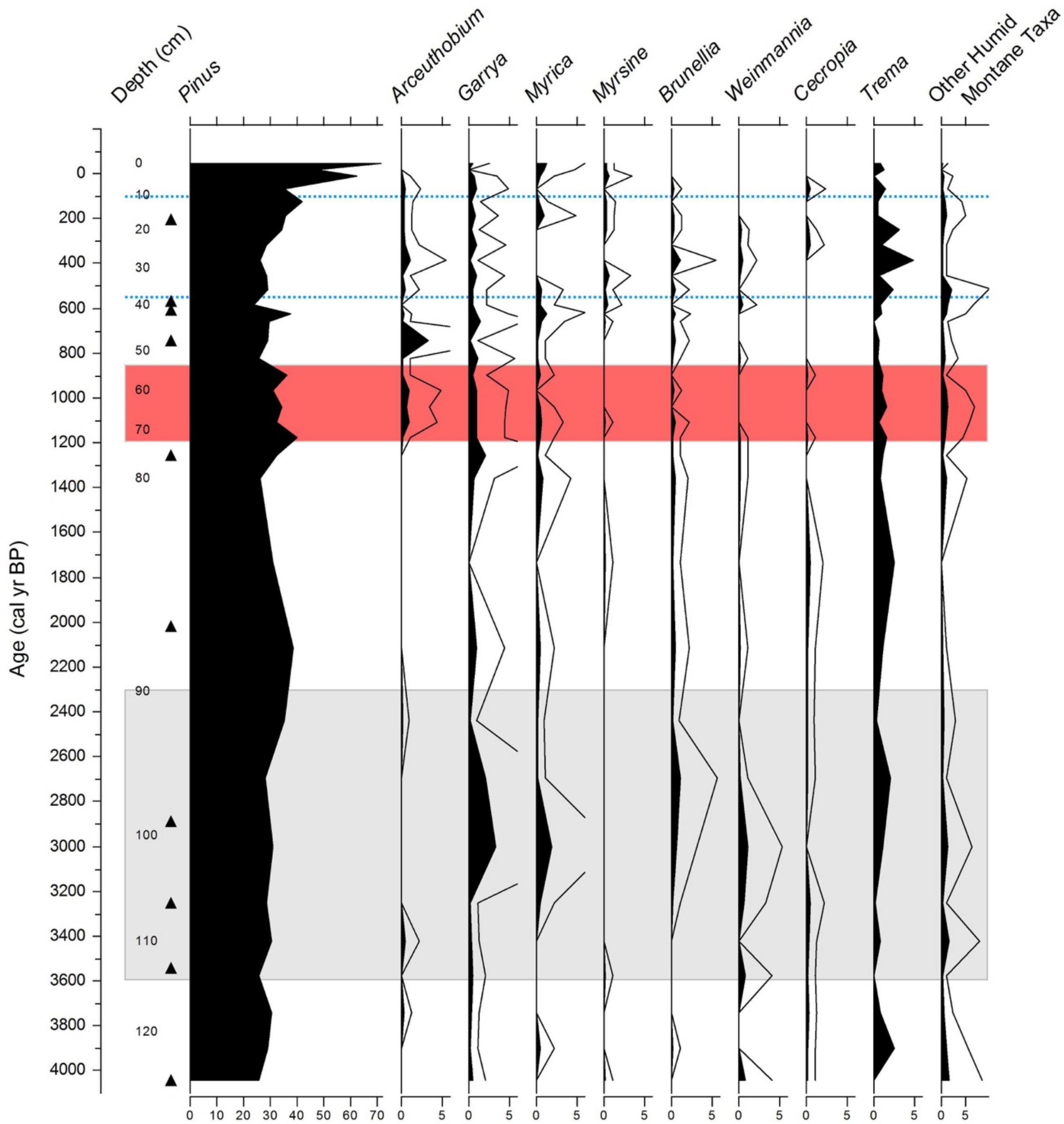

Figure 2.4. Pollen percentages for tree and shrub taxa plotted by age for the Bao-1 1997 core (Kennedy et al., 2006). The "Other Humid Montane Taxa" group includes *Ilex*, *Hedyosmum*, *Didymopanax*, *Alchornea*, *Juglans*, Melastomataceae, *Bocconia*, *Piper*, *Zanthoxylum*, and Solanaceae. Black lines represent a 5x exaggeration. Black triangles show positions of radiocarbon dates. Note scale changes. Blue dotted line represents the LIA; red shaded interval represents the TCD; gray shaded interval represents the early arid interval from Bao Bog.

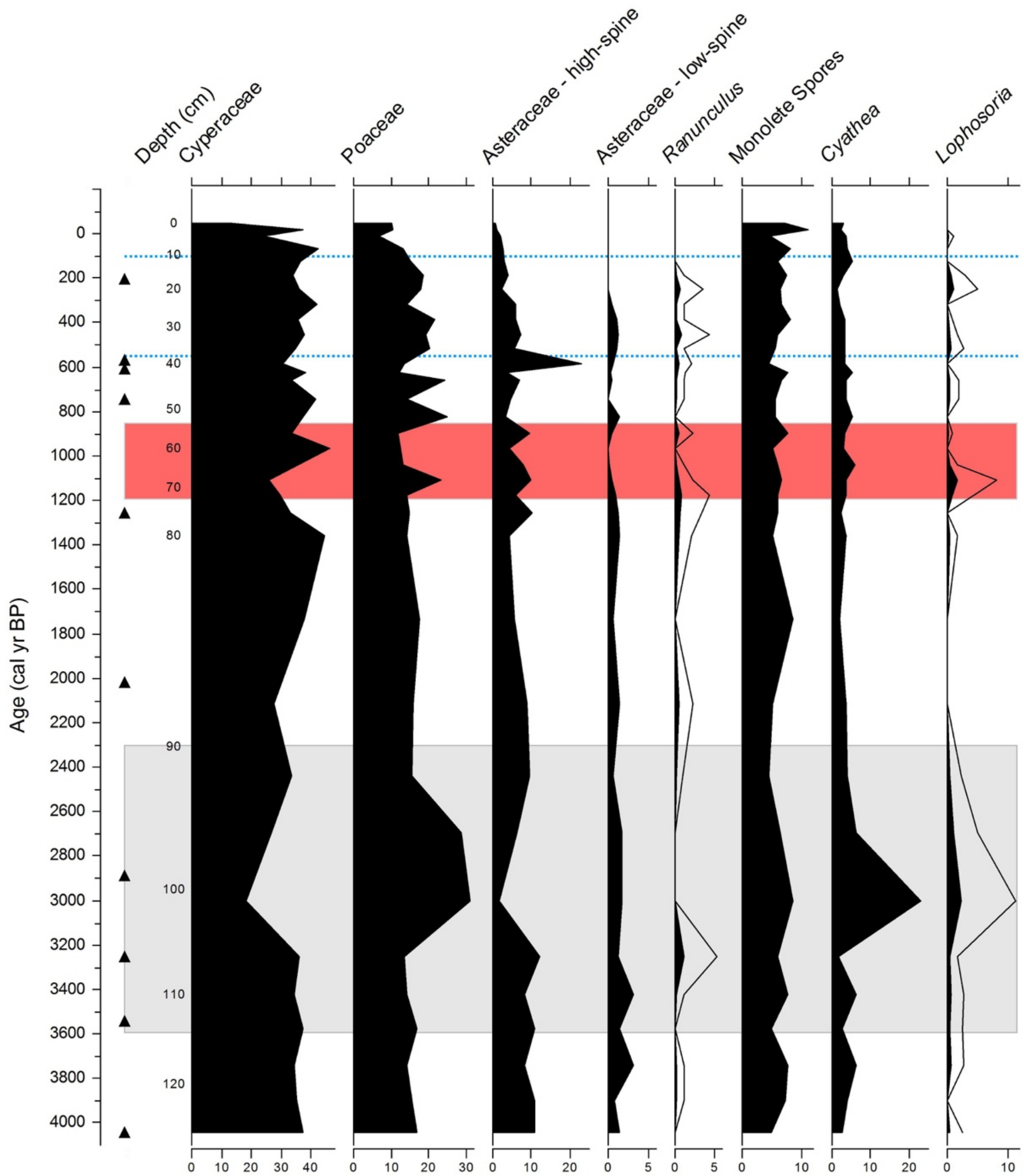

Figure 2.5. Pollen and spore percentages for selected, mainly herbaceous taxa and pteridophytes plotted by age for the Bao-1 1997 core (Kennedy et al., 2006). Black lines represent a 5x exaggeration. Black triangles show positions of radiocarbon dates. Note scale changes. Blue dotted line represents the LIA; red shaded interval represents the TCD; gray shaded interval represents the early arid interval from Bao Bog.

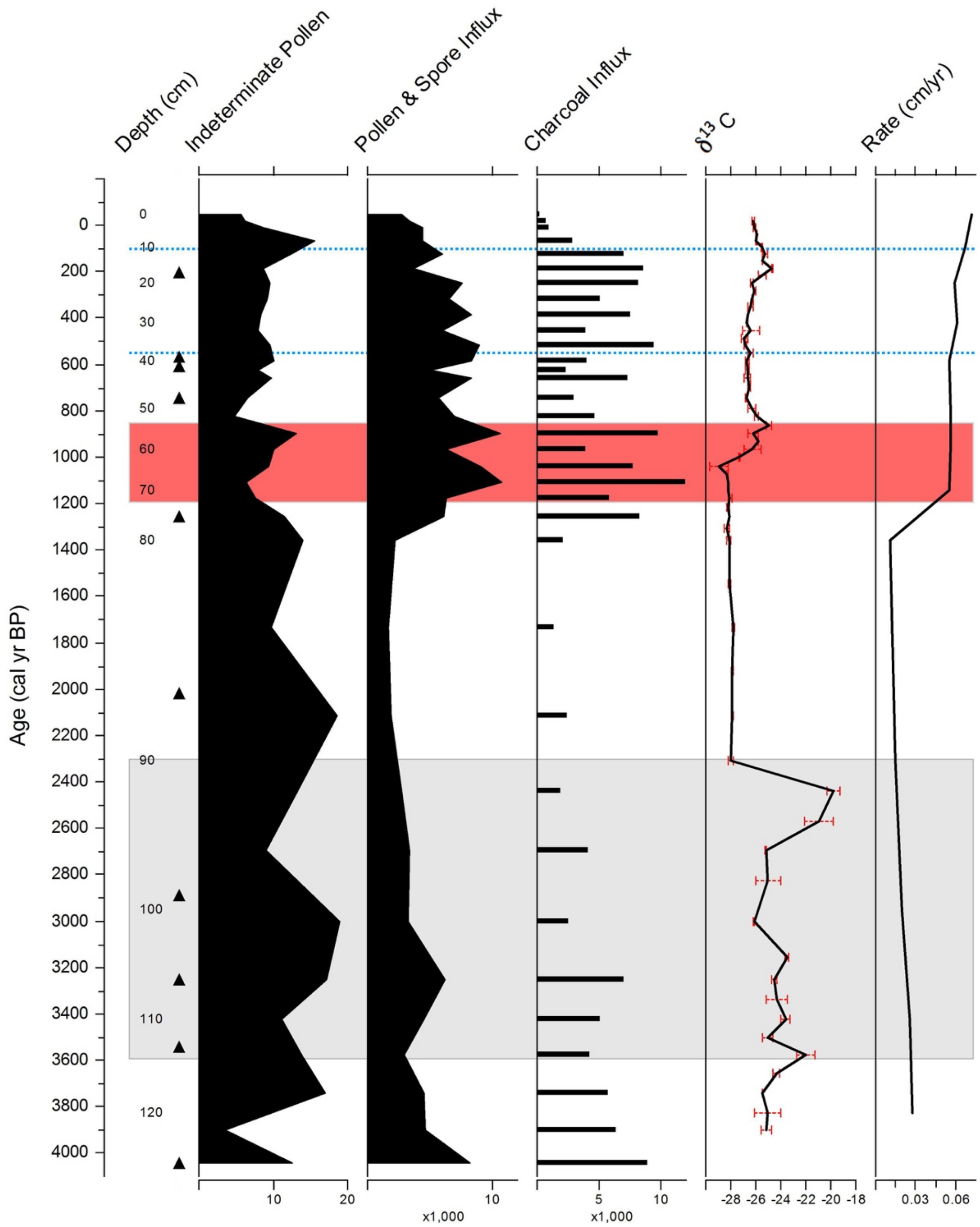

Figure 2.6. Indeterminate pollen percentages, pollen and spore influx and charcoal influx, and sedimentation rate for Bao Bog profile with the stable carbon isotope curve from Figure 2.7 for comparison. Black triangles show positions of radiocarbon dates. Blue dotted line represents the LIA; red shaded interval represents the TCD; gray shaded interval represents the early arid interval from Bao Bog.

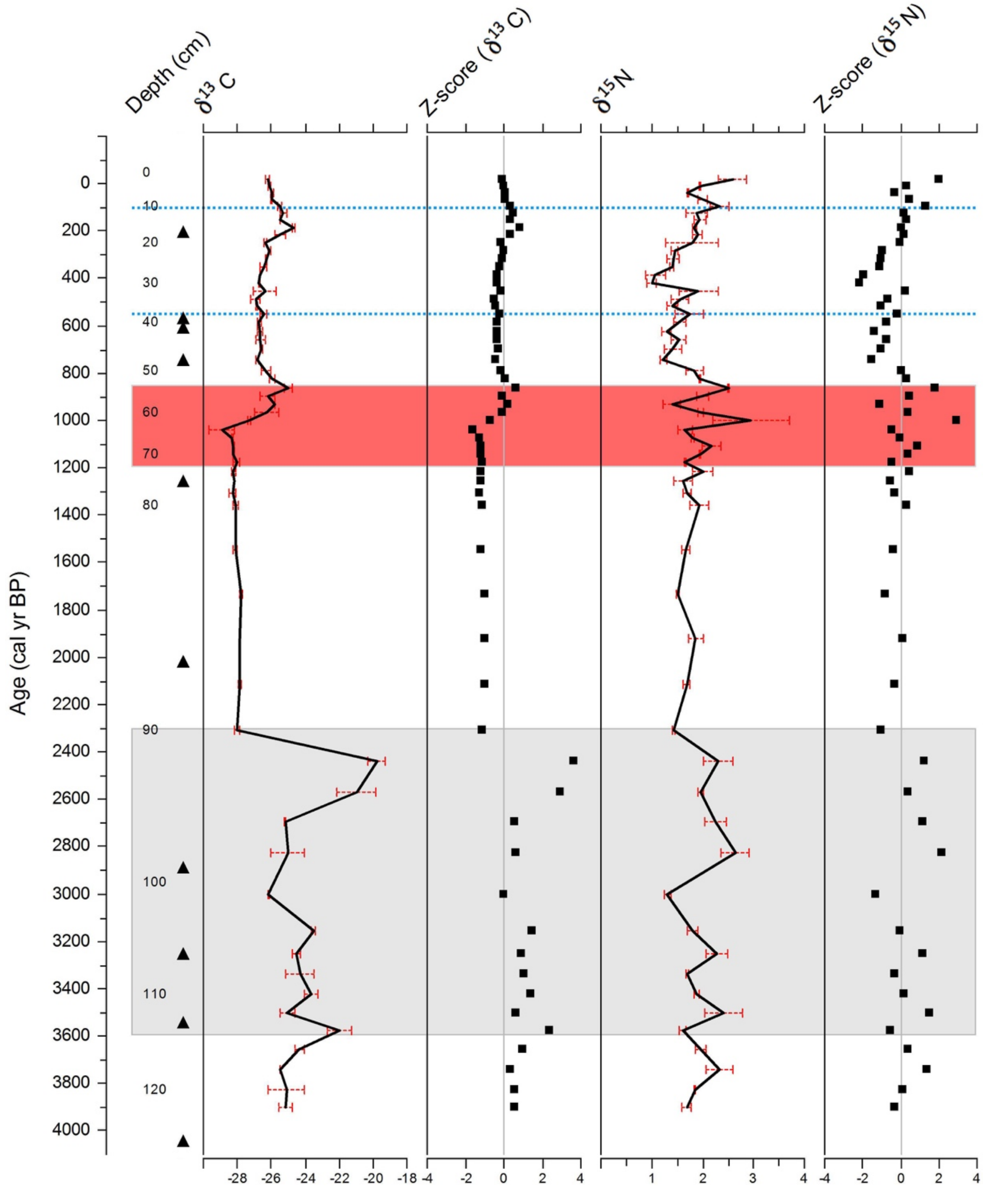

Figure 2.7. Stable carbon and nitrogen isotope curves for the Bao-1 1997 core with Z-scores denoting magnitude of change in values from the data mean. Black triangles show positions of radiocarbon dates. Blue dotted line represents the LIA; red shaded interval represents the TCD; gray shaded interval represents the early arid interval from Bao Bog.

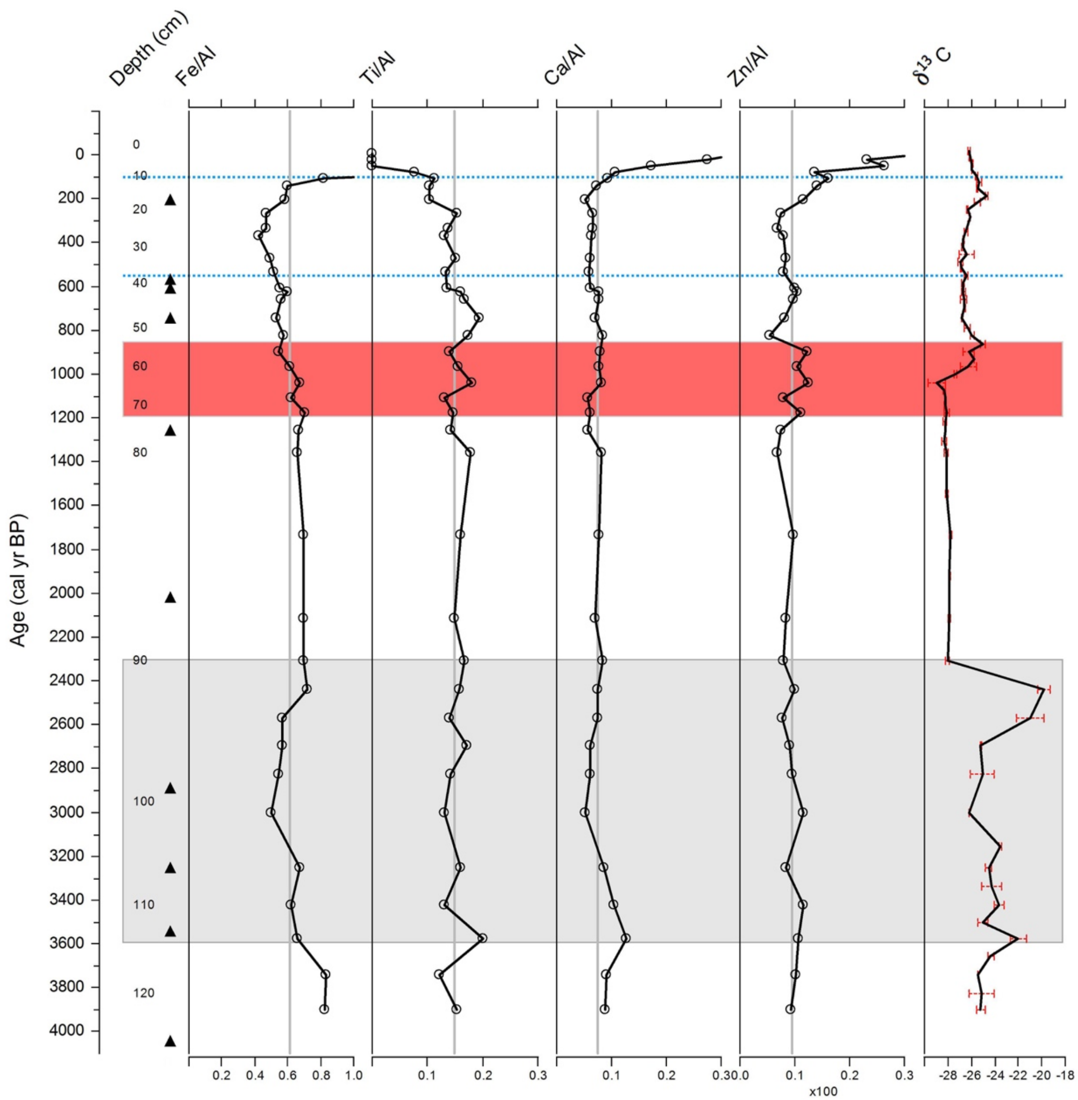

Figure 2.8. Bao Bog elemental composition from XRF analysis. Percent element composition for Fe, Ti, Ca, and Zn are normalized by percent Al. Means calculated for samples >12 cm depth. Note scale changes for Zn/Al (x100) where 0.1 is 0.001. Fe/Al ratios above 1 are truncated with the ratios equal to 3.5, 6.0, 6.3, and 9.1 at 80, 51, 22, and -6 cal yr BP. The uppermost Ca/Al ratio value is also truncated with the ratio at -6 cal yr BP equal to 0.4. Modern spikes in heavy metals may correspond with anthropogenic emissions in the atmosphere. Stable carbon isotope curve from Figure 2.7 included for comparison. Black triangles show positions of radiocarbon dates. Blue dotted line represents the LIA; red shaded interval represents the TCD; gray shaded interval represents the early arid interval from Bao Bog.

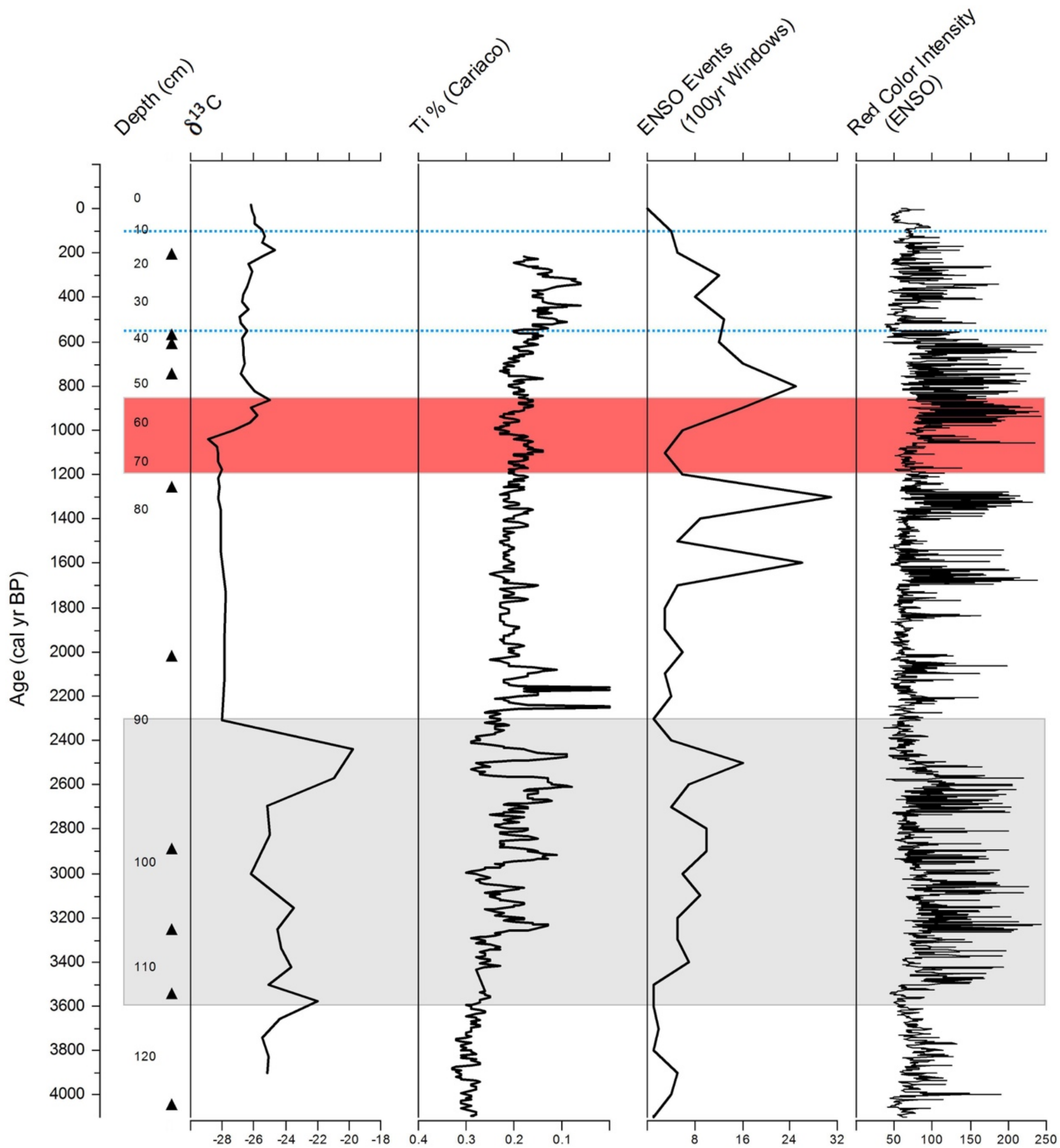

Figure 2.9. Bao Bog stable carbon isotope composition compared to regional precipitation and ITCZ proxies for the chronology of the Bao Bog record. Ti % data are from the Cariaco Basin record (Haug et al., 2001). ENSO data are from the Laguna Pallcacocha record (Moy et al., 2002). The Red Color Intensity time series reconstructs warm ENSO events in the Laguna Pallcacocha sedimentary record with red quantifying the distribution and concentration of laminae in in the Laguna Pallcacocha sediment record (Moy et al., 2002). Black triangles show positions of radiocarbon dates for Bao Bog. Blue dotted line represents the LIA; red shaded interval represents the TCD; gray shaded interval represents the early arid interval from Bao Bog.

CHAPTER 3

PRECOLUMBIAN AGRICULTURE, FIRE, AND SPANISH CONTACT: A 4300-YEAR RECORD FROM LAGUNA LOS MANGOS, COSTA RICA

This chapter is in preparation for journal submission. My use of "we" in this chapter includes my co-authors, Sally P. Horn and Chad S. Lane. I am first author, and my contributions to this project include experimental design, data collection and analyses, and writing the manuscript.

3.1 Abstract

We present a lake-sediment record of pre-Columbian agriculture and fire history from the lowlands of southern Pacific Costa Rica that captures the arrival of maize agriculture at ca. 3300 cal yr BP in the Diquís subregion of the Gran Chiriquí archaeological region. Our 4300-year record from Laguna Los Mangos begins 1000 to 2000 years earlier than other lake records from the region and provides the first microfossil and geochemical evidence of vegetation and fire prior to the establishment of maize agriculture. This early portion of the record shows evidence of fires associated with land clearance or field preparation and maintenance for tubers or other crops, or with hunting, or that were wildfires ignited unintentionally by people or by lightning or volcanism. With early maize by 3200 cal yr BP at Laguna Zoncho in the southeastern section of the Diquís subregion, our discovery of early maize agriculture at 3300 cal yr BP in the Laguna Los Mangos record in the northwestern portion of the Diquís subregion indicates a rapid adoption of maize agriculture in the region after the initial introduction. Prehistoric agriculture and fire activity at Los Mangos declines in the last ca. ~500 years, coinciding with the Little Ice Age and Spanish contact in Costa Rica.

3.2 Introduction

Southern Pacific Costa Rica composes the Diquís subregion of the Gran Chiriquí archaeological region, an important area of similar cultural traditions in southern Pacific Costa Rica and western Panama. Several lakes in this region have been cored to develop paleoenvironmental records, including Laguna Zoncho (Clement and Horn, 2001; Filippelli et al., 2009; Haberyan and Horn, 2005; Lane et al., 2004; Taylor et al., 2013a; 2013b; Wu et al., 2016), Laguna Santa Elena (Anchukaitis and Horn, 2005; Kerr, 2014), Laguna Vueltas (Horn et al., 2011; Horn and Haberyan, 2016) and Laguna Gamboa (Horn, 2006; Horn et al., 2013). However, these lakes are all in the southeastern part of the Diquís subregion, and their records begin near or after the arrival of maize in the region (Horn et al., 2006). The Laguna Los Mangos record covers the entire Late Holocene, which is formally defined as beginning at 4200 cal yr BP (Walker et al., 2012).

Diffusionist models have long been used to explain the origin of cultural traditions in Costa Rica, with the Diquís subregion considered to be heavily influenced by Mesoamerican cultures from the north and Andean cultures from the south at differing times and to differing extents (Haberland, 1984; Linares and Ranere, 1980; Stone, 1977). However, a growing emphasis by archaeologists working in southern Costa Rica is to recognize an independent, local cultural tradition from the archaeological record in the Gran Chiriquí region (Corrales, 2000; Palumbo, 2009). New long-term records of environmental change, fire history, and agriculture from the western lowlands of the Diquís subregion are critical to the issue of the timing and

spatial variability of pre-Columbian land use and modification. A paleoenvironmental record that extends further back in time is also needed to establish a baseline for the fire activity and vegetation composition prior to the introduction of full-scale maize agriculture in the region.

Early plant domestication and agricultural investment are hypothesized to occur around areas on the landscape considered to be rich in resources, with examples of such rich ecosystems including river floodplain corridors and at the margins of lakes and wetlands (Smith, 2016). In addition to the ecological importance of lakes to early agricultural societies, lake-sediment records are critical for documenting the timing of the domestication and dissemination of maize through the New World. The cultural importance of maize and the ability to infer human presence from the presence of maize in a sediment record (Horn et al., 2006) add to the importance of tracing the timing and route of maize dissemination.

Genetic evidence indicates domesticated maize (*Zea mays* subsp. *mays*) derives from an early annual teosinte grass (*Zea mays* subsp. *parviglumis*) indigenous to central Mexico (Doebley, 1990; 2004; Matsuoka et al., 2002). The cultural processes that precipitated the domestication of maize and the precise location of the domestication process are not clearly known, but evidence suggests people domesticated maize in the Central Balsas River Valley in Mexico around 9500–8800 cal yr BP (Piperno and Flannery, 2001; Piperno et al., 2009). Other early sites with evidence of maize agriculture indicate a faster dispersal into northern South America, possibly as early as 7800–6000

cal yr BP (Pagán-Jiménez et al., 2015) and a slower movement northward into the modern southwestern U.S sometime around 5000 cal yr BP (Fearn and Liu, 1995; Fritz, 1993) and eventually the Eastern Woodlands of North America circa 1800 cal yr BP (Chapman and Crites, 1987; Hart and Lovis, 2012). The traditional model of southward diffusion indicates that maize moved through modern Costa Rica and Panama to reach South America (Piperno et al., 2000; Ranere et al., 2009).

The earliest evidence of maize in Costa Rica comes from maize pollen in lake sediments in the northwestern lowlands. AMS dating of small charcoal particles associated with the earliest maize pollen at Laguna Martínez indicates maize cultivation at 5500 cal yr BP (Arford and Horn, 2004; Horn, 2006), an age slightly earlier than the age of 5090 cal yr BP based on charcoal associated with maize macrofossils found in an excavation for the Arenal Prehistory archaeological project (Sheets and McKee, 1994). Evidence of early maize in southern Pacific Costa Rica comes from the sediments of Laguna Zoncho, where maize pollen is present from the time of lake formation ca. 3200 cal yr BP (Clement and Horn, 2001).

Macrobotanical maize remains are sparse in the Gran Chiriquí archaeological region with some found associated with the Curré Phase of the Sinancrá Period in Costa Rica (Hoopes, 1996; Palumbo, 2009). From the macrobotanical maize evidence, which predates similar evidence in western Panama by as much as 1000 years, archaeologists have hypothesized an agricultural diffusion from the lowlands of southern Pacific Costa Rica eastward into Panama (Cooke, 2005; Cooke and Sanchez Herrera, 2004; Palumbo,

2009). Early maize starch evidence from stone tools (Dickau et al., 2007) predates macrobotanical evidence of maize in western Panama, which could indicate preservation issues at archaeological sites. The use of manos and metates, or other food processing tools, may be well preserved archaeologically; however, grinding tools may be related to the processing of foraged foods or early non-maize cultivars such as manioc, and are therefore problematic as a temporal marker for early maize.

Archaeologists have generally found or hypothesized a pattern of low-level use of maize following its initial adoption in an area, followed by an increase in maize cultivation (Smith, 1992). Uncertainty surrounds whether the delay in intense use is the product of physical limitations of early-domesticated maize, a lack of cultural tolerance in introducing a new staple crop, or limited technology, with intensive use coinciding with maize becoming a storable food resource (Smith, 1992). The initial motivation of early maize cultivation is also unclear with certain proponents suggesting alcohol production using the sugary pith of the stalk as the initial impetus for domestication and use with grain consumption as a secondary consideration (Smalley and Blake, 2003). Available dates for macrobotanical and microfossil evidence of maize in Costa Rica indicate a limited time delay between the age of maize pollen and recovered maize kernels and cobs, suggesting that maize was not distributed solely for stalk sugar (e.g. alcohol production), but equally for its grain potential (Horn, 2006).

In addition to defining the time of earliest maize agriculture in the southern Pacific region of Costa Rica, reconstructing long-term changes in agriculture and fire

activity can help define the archaeological record of the region and can contribute to understanding how societies dealt with shifts in climate. The sediment record from Laguna Zoncho, 65 km from Laguna Los Mangos, shows evidence of a decline in agriculture associated with the Terminal Classic Drought (TCD, 1200 to 850 cal yr BP) (Taylor et al., 2013a). The TCD is a prominent climate anomaly consisting of a series of multidecadal droughts that are closely associated with the classic Maya "collapse" in Mesoamerica (Hodell et al., 2005a), but that had effects across the circum-Caribbean (Lane et al., 2014). Records from other lakes in the region, including Laguna Danta (Chapter 4), Laguna Vueltas (Horn et al., 2011; Horn and Haberyan., 2016), and Laguna Santa Elena (Anchukaitis and Horn, 2005; Kerr, 2014) showed agricultural declines associated with Spanish contact at ca. 1500 CE and the onset of the Little Ice Age (LIA, 550–100 cal yr BP). The LIA was a global cooling event that also affected the Neotropics (Haug et al., 2001; Lamb, 1965; Lane et al., 2011). Research from some sites indicates extended drought conditions across the region during the LIA (Hodell et al., 2005b; Lane et al., 2011; Peterson and Haug, 2006), while elsewhere researchers have noted a highly variable, but overall drier climate during the LIA, at least for island sites in the Caribbean (Burn et al., 2016). Chironomid assemblages in the sediments of Laguna Zoncho show evidence of cool and less productive conditions in southern Pacific Costa Rica from ca. 1480 to 1860 CE (Wu et al., 2016).

The effects of climate on landscapes, vegetation, and fire regimes were not necessarily the same across the entire southern Pacific region, with cultural response to

climate or other stresses likely to have been equally varied spatially. Additional paleoenvironmental records are necessary to understand these effects across the region and how elevation and proximity to western Panama may have influenced cultural history. Western Panama was the site of several important population centers of the Gran Chiriquí archaeological region and also the location of Volcán Barú, whose multiple eruptions during the late Holocene may have affected human settlement (Anchukaitis and Horn, 2005). Further studies of lake-sediment records are also needed to understand environmental conditions including vegetation composition and fire activity prior to the spread of maize agriculture in the region.

In this research, we use a 4300-year record of pollen, microscopic charcoal, stable carbon and nitrogen isotopes, and elemental composition from Laguna Los Mangos to answer the following questions: (1) How does the timing of the earliest evidence of maize agriculture fit with existing evidence suggesting maize cultivation in the Diquís subregion by 3200 cal yr BP? (2) What was the vegetation and fire history of the Laguna Los Mangos watershed before the arrival of maize agriculture and what changes occured during intervals of maize cultivation? (3) How do the Laguna Los Mangos agricultural and fire records coincide with other sites in the broader Diquís subregion, and what patterns in human response to Spanish contact and to climate events such as the LIA are suggested by the comparisons between sites?

3.3 Study Site

Laguna Los Mangos is located in an area of moderate topographic relief in the Fila Costeña mountain range of southern Pacific Costa Rica (Figure 3.1). To the north is the Cordillera de Talamanca, reaching 3819 m at its highest point. The Valle de El General lies between the two ranges. The geology of the study area includes Tertiary igneous and sedimentary rocks. Laguna Los Mangos is located within the Curré formation comprised of Upper Miocene conglomerates, sandstones, and shale (Alvarado et al., 2009a; 2009b). The lake appears to have formed from a landslide (Horn et al., in preparation). Such events are common in the area (Alvarado et al., 2009a; 2009b).

The study area is classified as tropical moist forest in the Holdridge Life Zone System (Holdridge, 1967; Tosi, 1969), indicating an average annual temperature above 24 °C and annual precipitation between 2000 and 4000 mm. Prior to forest clearance, the watersheds of both lakes would have supported tropical moist forest composed primarily of species that use the C_3 photosynthetic pathway. The original littoral vegetation could have included some sedges in the genus *Cyperus*, a genus that includes both C_3 and C_4 species in Costa Rica (Bruhl and Wilson, 2007; Tucker, 1983a; 1983b), but we expect that C_4 plants occupied only a small percentage of the watershed prior to forest clearance for maize agriculture. Maize (*Zea mays* subsp. *mays*) uses the C_4 photosynthetic pathway, as do herbaceous weeds associated with maize agriculture. Maize is cultivated today on a steep slope adjacent to Laguna Los Mangos (Figures 3.2

and 3.3), but watershed vegetation also includes other crops, cattle pasture, and some patches of forest.

3.3.1 The Archaeology of the Diquís Subregion

The archaeological record of the Diquís subregion of the Greater or Gran Chiriquí archaeological region includes three major cultural periods associated with ceramic technology, following several earlier hunter-gatherer and transitional periods (Figure 3.4). The 4300-year chronology of Laguna Los Mangos begins during the early Boquete Phase (2300–1500 BCE) of the Archaic Period for the Greater Chiriquí archaeological region (Corrales, 2000). The Boquete Phase is associated with distinct lithic technology focused on grinding implements, potentially indicating an early form of horticulture based on tubers and fruits and seeds from trees, with limited alterations of existing forests (Ranere 1980). The Boquete Phase is not well represented within the Diquís subregion, but horticulture involving tubers and tree fruits is hypothesized as a precursor of maize agriculture in many areas of the Neotropics.

The Sinancrá Period (1500–300 BCE) marks the transition in the Greater Chiriquí region from preceramic hunter-gatherers focused on early horticulture to sedentary agriculturalists with ceramic technology (Corrales, 2000). The Curré and Darizara Phases are represented by ceramic traditions with distinctly different vessel forms and motifs. Evidence exists of the Darizara Phase near the Costeña Range at the Ni Kira Site and evidence of the Curré Phase at the Curré site near the Térraba Middle Basin

(Corrales, 2000). Corrales (1989) suggested these phases represent early horticulturalism primarily based on tool form and an absence of metates and manos, which are nearly ubiquitous at sites with maize agriculture in Costa Rica. Paleoenvironmental evidence from pollen analysis at Laguna Zoncho indicated early maize agriculture in the Diquís region by ~1250 BCE (Horn, 2006). The timing of the presence of maize pollen puts the transition to maize agriculture within the Sinancrá Period for the Diquís subregion, in keeping with the archaeological interpretation of the period as marking the transition to sedentary agriculture (Corrales, 2000).

The La Concepción Phase (500/300 BCE to 300/400 CE) is closely associated with the later Aguas Buenas Period, each beginning at roughly the same time and persisting concurrently for a time before the La Concepción Phase ends and the Aguas Buenas Period continues (Corrales, 2000). The La Concepción Phase is represented by zoned bichrome pottery commonly decorated with zoomorphic motifs (Corrales, 2000; Hoopes, 1996; Snarskis, 1981).

The Aguas Buenas Period (300 BCE to 800 CE) shares the zoned bichrome ceramic technique with the La Concepción Phase, representing a near identical ceramic form across the Greater Chiriquí region. Based on archaeological work in the region that included analyses of macrobotanical remains and phytoliths, the Aguas Buenas Period is considered to represent a mixed-agriculture system with evidence of maize cultivation complementing the cultivation of other crops and the gathering of wild plant resources, hunting, and fishing. (Corrales, 2000; Drolet, 1988). During this period, social

stratification and warfare are inferred from iconography on ceramic vessels and carved metates (Linares et al., 1975).

The more recent Chiriquí Period (800–1500 CE) ended with the arrival of the Spanish (Corrales, 2001). Based on archaeological evidence of complex funerary practices and patterns in settlement organization, the Chiriquí Period is considered to represent a complex hierarchical society with high population levels that were supported by maize agriculture (Corrales, 2000). Regional settlement hierarchies with defined territories were interpreted as representing a chiefdom level of social organization (Drolet, 1988). Much of the evidence for warfare during the period was extrapolated from iconography and ethnohistoric accounts of conflict and palisaded villages (Corrales, 2000). The adoption of a bright polychrome ceramics tradition denotes the Chiriquí Period (Palumbo, 2009). The ubiquity of Diquís Spheres, locally produced petrospheres, in the subregion is a major archaeological characteristic attributed to the Chiriquí culture (Palumbo, 2009), but possibly dating to the earlier Aguas Buenas Period (Lothrop, 1963). The Diquís Spheres were typically located in open areas likely functioning as public spaces with nearby cobble-stone circles interpreted as house foundations (Corrales, 2000). Agricultural fields, most commonly for maize cultivation based on paleoenvironmental and archaeological evidence, would be located near these large village sites (Corrales, 2000; Drolet, 1988). Spanish contact in the New World (ca. 1500 CE) and initial direct exploration of the Pacific Coast of Costa Rica (ca. 1519) had a dramatic impact on the Chiriquí culture with estimated population

loss in Central America of 90–95% following contact (Dobyns, 1966; Lovell and Lutz, 1995). When the Spanish arrived in the Diquís subregion, they noted reliance on large-scale agriculture, extensive fortifications, and frequent conflicts among territorial chieftains (Guardia, 1913).

Limited archaeological studies have been conducted near Laguna Los Mangos with most of the work being archaeological survey efforts in advance of a state-sponsored electrical project. The Instituto Costarricense de Electricidad (ICE) is in the process of planning and developing a large hydroelectric dam known as the El Diquís Project, which if completed will flood roughly 7363 hectares of land, 915 hectares within indigenous territories, and displace 1547 people (Campregher, 2009). Currently, archaeologists working for ICE are conducting archaeology in the region to create an inventory before any flooding occurs, on lands within the proposed reservoir and in an adjacent buffer zone. Laguna Los Mangos is located in this buffer zone. No systematic archaeological surveys have been conducted in the watershed of Laguna Los Mangos, by ICE teams or any other. However, an established archaeological site with a mound tradition is located less than 5 km from Laguna Los Mangos. Archaeological evidence of closer settlement exists in the form of an elaborate carved metate located only a few hundred meters from the edge of the lake (Figure 3.4). Both of these sites are attributed to the later Chiriquí Period.

3.3.2 Laguna Los Mangos

Laguna Los Mangos (9.0895° N, 83.4665° W, 475 m) is located in the Pilas District in the canton of Buenos Aires, Puntarenas Province. Laguna Los Mangos is a small lake with a surface area of 0.3 ha and a maximum depth of 0.5 m as determined by our bathymetric survey in July 2014 (Figure 3.4).

3.4 Materials and methods

3.4.1 Core Collection, Processing, and LOI

We recovered sediment cores from Laguna Los Mangos in July 2014. Cores were recovered from the deepest portion of the lake from an anchored floating platform using a Colinvaux-Vohnout (C-V) locking piston corer (Colinvaux et al., 1999). We began our first C-V core at 30 cm below the mud-water interface. We did not collect a mud-water interface core, but did collect a surface grab sample from the uppermost lake sediments.

We returned the core sections to the cold room (4–5 °C) in the Laboratory of Paleoenvironmental Research at the University of Tennessee, Knoxville still encased in their original aluminum coring tubes. In the lab, we opened the core tubes longitudinally using a modified wood shaper, photographed the core sections, and described sediment colors (Munsell) and textures on core logs. The organic matter and carbonate content of the sediments were estimated using loss on ignition (LOI) (Dean, 1974). Samples for LOI were extracted from the core sections at ca. 16 cm intervals,

placed in pre-weighed ceramic crucibles, and weighed before being dried at 100 °C for 24 hours. The samples were cooled and reweighed to determine water content, and then ignited in a furnace at 550 °C for one hour to estimate organic matter and 1000 °C for one hour to estimate carbonate content.

3.4.2 Radiocarbon Dating and Age-depth Modeling

We selected six macrofossils from the Laguna Los Mangos sediment profiles for AMS radiocarbon dating. Age models were produced from the radiocarbon results with the Bacon age-modeling package for R (Blaauw and Christen, 2011), which uses Bayesian statistics and the IntCal 13.14 calibration dataset (Reimer et al., 2013; Stuiver and Reimer, 1993). Parameters were changed to limit autocorrelation to correctly model the apparent shift in sedimentation rate at ~160 cm core depth. The Bacon age model provided a weighted mean age in cal yr BP at 1-cm intervals in the Los Mangos profile.

3.4.3 Pollen and Microscopic Charcoal Analyses

Samples for pollen and microscopic charcoal analysis were taken at ~16-cm intervals and processed using standard pollen preparation techniques (HF, HCl, KOH, acetolysis, safranin stain) (Faegri and Iversen, 1989), with *Lycopodium* tablets added as controls (Stockmarr, 1971). Pollen residues were mounted on microscope slides in silicone oil, and then counted at 400x magnification to a minimum of 250 pollen grains exclusive of fern spores and indeterminate pollen and spores. The presence or absence

of maize on pollen slides was determined by scanning slides in their entirety at low (100x) magnification. Initial maize scans of a single slide were completed for all sample levels (n=37). Below the oldest level with maize presence from the initial scan, four additional slides were scanned for each sample level (n=15) to pinpoint the timing associated with the arrival of maize in the watershed. Five slides with no maize presence represents absence of maize agriculture. For the maize scans, only grains with diameters >63 μm and visible pores were counted as maize pollen. Undomesticated *Zea* (teosinte) produces pollen in this size range (Anchukaitis and Horn, 2005; Clement and Horn, 2001; Taylor et al., 2013a), but the biogeographic ranges of native teosintes do not include southern Pacific Costa Rica. Microscopic charcoal point counting was conducted on the same pollen microscope slides (n=37) using an Olympus BH2 microscope at 400x magnification and a modified point-counting method (Clark, 1982). Only completely black, opaque, angular fragments were tallied as charcoal during the point counts.

3.4.4 Stable Carbon and Nitrogen Isotope Analysis

The stable carbon and nitrogen isotope ratios of the bulk sedimentary organic carbon ($\delta^{13}C_{OM}$) and nitrogen ($\delta^{15}N_{OM}$) were measured at intervals of ~16 cm. Samples of 1 cm^3 volume were dried at 50 °C overnight and then ground to a fine powder with a mortar and pestle to sufficiently homogenize the samples to be representative of the bulk sediment. The ground samples were split into a non-acidified fraction for $\delta^{15}N_{OM}$

and an acidified fraction for $\delta^{13}C_{OM}$ analysis. Inorganic carbon in the bulk sediment interferes with the measurement of organic ^{13}C unless those carbonates are removed through an acidification process (Harris et al., 2001). Fractions for acidification were lightly moistened with distilled H_2O and then acid–fumigated in desiccators with 12 M HCl for 2–3 hours for the Laguna Los Mangos samples. The acidified samples were then vented overnight before being placed on a hotplate to dry the samples, with samples reground as needed. Samples were loaded into tin capsules in 100% duplicates for all sample intervals for both acidified (n=80) and non-acidified (n=80) samples.

The isotopic analysis of the samples used a Costech 4010 elemental analyzer interfaced with a Thermo Delta V Plus mass spectrometer at the University of North Carolina Wilmington Isotope Ratio Mass Spectrometry facility at the Center for Marine Science of the University of North Carolina Wilmington. All isotopic compositions are reported in standard δ-per mil notation with nitrogen relative to atmospheric air and carbon relative to the Vienna-Pee Dee belemnite (V-PDB) marine-carbonate standard, where R = $^{13}C/^{12}C$ or $^{15}N/^{14}N$ and:

$$\delta^{13}C \text{ (per mil)} = 1000\,[(R_{sample} / R_{standard}) - 1]$$

$$\delta^{15}N \text{ (per mil)} = 1000\,[(R_{sample} / R_{standard}) - 1]$$

Reported carbon isotope ratios correspond to the acidified fraction while reported nitrogen isotope ratios correspond to the non-acidified fraction. The reported C:N ratio, percent organic carbon, and percent nitrogen use values for percent carbon from the acidified fraction and percent nitrogen from the non-acidified fraction. The C:N ratio is

used to reconstruct the source of organic matter (e.g. terrestrial or aquatic) in the sediment profile of the lakes (Talbot, 2001; Sharp, 2007). A C:N ratio of ~10–20 marks the transition from primarily aquatic (< 10) and primarily terrestrial (> 20) (Meyers and Teranes, 2002). All isotope values include error, which is expressed as the standard deviation for the duplicate samples at the same level.

3.4.5 X-ray fluorescence

We carried out elemental analysis of the Laguna Los Mangos sediment profile at ~16 cm intervals corresponding to depths sampled for pollen, microscopic charcoal, and stable carbon and nitrogen isotope analyses. Powdered samples from 40 levels of the profile were loaded into cells and analyzed using energy dispersive EDXRF technology in an Olympus BTX Profiler (Olympus BTX Profiler, 2013).

EDXRF excites all of the elements in the sample simultaneously, while an energy dispersive detector along with a multi-channel analyzer is used to simultaneously collect the emitted fluorescence radiation from the sample and then differentiate the energies of the characteristic radiation from each of the sample elements (Potts and Webb, 1992). The XRF analysis produces percent values for a combined all light elements category and for 32 specific elements (Mg, AL, Si, P, S, Cl, K, Ca, Ti, V, Cr, Mn, Fe, Co, Ni, Cu, Zn, As, Se, Sr, Zr, Mo, Ag, Cd, Sn, Sb, W, Pt, Hg, Pb, Th, U).

Elemental analyses based on XRF analyses of wet sediment cores has become common in paleoenvironmental research with the development of core scanners that

automate data collection (Zolitschka et al., 2002). However, a variety of factors can lead to large variations in XRF data output when scanning wet sediment cores. For example, sediment water content, core surface roughness, grain size variations, and time between analyses influence the reliability of comparisons of XRF data within cores or across sites (Böning et al., 2007; Lowemark et al., 2011; Tjallingii et al., 2007; Weltje and Tjallingii, 2008). However, the XRF data obtained for the Laguna Los Mangos core are not subject to these issues, as they are based on the analysis of samples that were removed from core sections and dried and ground before being loaded into cells for analysis with the BTX profiler.

Whether analyzed dry in cells or wet in cores, XRF results are influenced by the organic composition of the sediments. Core sections with higher organic content will produce a decreased count for all measured elements, while counts will be higher in more mineral-rich sections (Calvert, 1983; Lowemark et al., 2011; Rollinson, 1993). To circumvent this issue, researchers often normalize or standardize elemental data of interest against another element. Lowemark et al. (2011) suggested that aluminum is an ideal normalizing element because it is abundant, resists weathering, and is minimally affected by biological and redox processes. For our Laguna Los Mangos analyses, we report XRF data as the ratio of values in ppm against Al in ppm.

3.5 Results

3.5.1. The Danta and Carse Sediment Profiles

We recovered a 760-cm sediment core from Laguna Los Mangos (Figure 3.7). The base of the profile consists of dense, fine mineral sediment, greenish gray (Munsell GLEY 1 6/5GY) in color. The profile shows some variable colors and sediment texture, which ranges from fine mineral silts and clays to coarse organic sediment with large wood fragments. The sediment profile shows some intervals of fine laminations in the silty sediment. The two largest wood fragments occur at depths of ca. 590 and 410 cm in the profile.

3.5.2 Radiocarbon Ages and Age-Depth Models

The radiocarbon dates on the Laguna Los Mangos profile indicate that it spans the entirety of the late Holocene as delineated by Walker et al. (2012), with a modeled basal age slightly preceding the proposed start of the Late Holocene at 4200 cal yr BP (Table 3.1, Figure 3.8). The Bacon age-depth model fitted all dates and indicated a sharp change in sedimentation rate for the uppermost 160 cm (~260 cal yr BP). Laguna Los Mangos has a mean sediment accumulation rate of 0.17 cm/yr until the shift at 160 cm to 0.4 cm/yr for the uppermost sediment. Based on the age model, the large wood fragments in the core correspond to ages of ca. 3600 cal yr BP and 2600 cal yr BP.

3.5.3 Organic Matter, Organic Carbon, Nitrogen, and C:N ratios

In the Laguna Los Mangos record, organic matter (OM) percentages generally increase upward in the core until ca. 3000 cal yr BP, then generally decrease until stabilizing near the OM mean (χ = 45.17) at ~1700 cal yr BP (Figure 3.9). OM percentages then decrease again at ~1160 cal yr BP, which roughly corresponds to the onset of the TCD. Organic matter percentages decline across the TCD until the time of Spanish contact at ca. ~400 cal yr BP, after which time they increase until the top of the record at ca. 1950 C.E. LOI analysis of the surface grab sample (not shown in diagram) indicated an organic content of 24%, much lower than the content of the uppermost core sample analyzed (43%), and likely the result of accelerated erosion recently in the watershed (Figure 3.3). Percent organic carbon and percent nitrogen values show matching trends that strongly mirror the organic matter curve based on LOI analysis. C:N ratios in the Laguna Los Mangos record show some variation, with one sharp rise at ~2900 cal yr BP. This peak in the C:N ratio indicates an increase in terrestrial carbon influx possibly linked to a deforestation event in the watershed (Kaushal and Binford, 1999). The C:N ratios for both lakes indicate a combination of terrestrial and aquatic carbon inputs over their histories.

3.5.4 Pollen and Microscopic Charcoal

Pollen and spore percentages in the Laguna Los Mangos profile show an early pre-maize environment (~4300–3500 cal yr BP) characterized by high percentages of tree

and shrub pollen and monolete and trilete fern spores, and low percentages of herb pollen (Figure 3.10). From ~3500 to 2900 cal yr BP, tree and shrub taxa decline, while herbaceous plant taxa increase. Pollen percentages for Poaceae, Cyperaceae, and Amaranthaceae and Asteraceae (graphed together) all reach peak values by 2900 cal yr BP. These families include many weedy species and we interpret their expansion to indicate strong human modification of the landscape as forests were cleared for early maize agriculture in the Laguna Los Mangos watershed. Near the top of the profile, pollen percentages show evidence of forest recovery and agricultural decline.

Maize pollen shows the earliest evidence of maize cultivation in the Laguna Los Mangos watershed at ca. 3300 cal yr BP, which coincides with the positive shift in $\delta^{13}C$ ratios. Maize pollen was present on 11 of 97 slides spanning 37 sample levels scanned in their entirety for the presence of maize. The maximum maize grain diameter was 75 μm with most of the maize grains approximately 66 μm in diameter.

Tree and shrub pollen types at Laguna Los Mangos include taxa characteristic of modern tropical moist and wet forests, along with some types derived from premontane or montane forests at somewhat higher elevation (Janzen, 1983; Kapelle, 2016). The generally greater abundance of monolete as compared to trilete fern spores through the profile is in line with modern pollen data from moist and wet forests at low to high elevation in Costa Rica (Rodgers and Horn, 1996). The high (>20%) total fern spore percentages in a few levels near the base of the profile exceed values found by Rodgers and Horn (1996) in modern pollen samples from lowland forests in Costa Rica, but are

consistent with percentages found in some sections of lake-sediment profiles from Laguna Santa Elena in the southern Pacific zone (Anchukaitis and Horn, 2005) and Laguna Bonillita in the Caribbean lowlands (Northrop and Horn, 1996).

The charcoal record for Laguna Los Mangos indicates that fire activity was variable across the Late Holocene in the southern Pacific lowlands of Costa Rica (Figure 3.10). Prior to evidence of early maize agriculture, charcoal area influx shows a peak at ca. 4050–3950 cal yr BP. Charcoal area influx values show additional fires at ca. 3300–3200 cal yr BP; this charcoal slightly precedes the earliest maize pollen and may correspond to initial forest clearance and agriculture in the Laguna Los Mangos. Charcoal area influx values shows a large peak at ~2450 cal yr BP and again at ~1000 cal yr BP. Following the ~1000 cal yr BP large fire event, which coincides with the TCD, charcoal area influx remains high until the onset of the LIA and Spanish contact after ~530 cal yr BP, when charcoal area influx declines dramatically.

3.5.5 Stable Carbon and Nitrogen Isotope Ratios

Stable carbon isotope ratios ($\delta^{13}C_{OM}$) for Laguna Los Mangos show a C_3-dominant environment from ~4300–3500 cal yr BP with values (χ = –29.6‰) remaining below the profile mean of –27.5‰ (Figure 3.11). $\delta^{13}C_{OM}$ values are stable around the profile mean until a shift at ~3200 cal yr BP. At ca. ~3200 cal yr BP a large positive shift reveals an increase in C_4 plant dominance near the lake with a peak value of –24.5‰ from 2900 to 2800 cal yr BP. Following the peak, $\delta^{13}C_{OM}$ values become slightly more negative, but

remain above the profile mean. At ~700 cal yr BP, a moderate positive shift occurs, following the end of the TCD. Ratio values then decline by 480 cal yr BP to slightly below the mean until historic times, with twentieth century agriculture shifting the $\delta^{13}C_{OM}$ values toward a C_4 signal. The decline following the ~700 cal yr BP positive peak coincides with the onset of the LIA and Spanish contact at 550–500 cal yr BP.

Sedimentary N stable isotopes ratios ($\delta^{15}N_{OM}$) for Laguna Los Mangos are highly variable during the basal interval of negative $\delta^{13}C_{OM}$ values (~4300–3500 cal yr BP). A positive $\delta^{15}N_{OM}$ peak of 4.1‰ at ~4200 is then following by sharp negative shift to 0.7‰ by ~3850 cal yr BP. A second positive peak to 3.5‰ by ~3750 cal yr BP is followed by a decline to below the profile mean of 1.8‰. These low values are maintained until the onset of the LIA and Spanish contact at 550–500 cal yr BP, when $\delta^{15}N_{OM}$ values increase to roughly the profile mean.

3.5.6 X-ray Fluorescence

The elemental composition of the Laguna Los Mangos sediment profile shows large shifts at the time of initial maize agriculture (~3200 cal yr BP) and during recent historic times (Figure 3.12). From ca. 3200–3000 cal yr BP, large positive shifts occur in P/Al, Zn/Al, and Ca/Al ratios, and a negative shift is shown by the Si/Al ratio. The Fe/Al curve show large positive shifts just after at ca. 2800 cal yr BP. The uppermost samples show a large, sharp positive shift coinciding with the twentieth century that potentially represent anthropogenic emissions into the atmosphere.

3.6 Discussion

3.6.1 The Timing of the Earliest Maize Agriculture in the Diquís Subregion

Pollen grains of *Zea mays* subs. *mays* in the basal lake sediments at Laguna Zoncho, deposited at ca. 3200 cal yr BP, are the earliest existing evidence of maize agriculture in the Diquís subregion and in the wider Gran Chiriquí archaeological region of southern Pacific Costa Rica and western Panama (Clement and Horn, 2001; Horn, 2006; Taylor et al., 2013a). The maize pollen at Laguna Zoncho predates the oldest archaeologically-recovered maize macrofossils in the region by more than a millennium (Clement and Horn, 2001; Corrales, 2000). That maize pollen is present in the lowest lacustrine sediments suggests that maize already may have been in cultivation in the region when the lake formed, e.g., before ca. 3200 cal yr BP. If so, paleoenvironmental records that extend farther back in time could reveal an earlier introduction of maize into the region.

The Laguna Los Mangos sediment profile contains a 4300-year record of forest clearance and the introduction of maize agriculture in the watershed. The earliest maize pollen detected occurs in sediments with an estimated age of 3281 cal yr BP, indicating the presence of maize in southern Pacific Costa Rica somewhat earlier than the first microfossil evidence of maize at Laguna Zoncho. We interpret the similar timing of botanical evidence of early maize at Laguna Los Mangos and Laguna Zoncho to indicate

that maize entered the Gran Chiriquí archaeological region at ca. 3300 cal yr BP and quickly became widely adopted across the Diquís subregion.

The Laguna Los Mangos record shows direct evidence of maize agriculture through pollen presence and stable carbon isotope ratios. Coinciding with maize pollen presence, the stable carbon isotope ratio curve shifts strongly toward less negative values, indicating an increase in C_4 vegetation in the watershed. We interpret this shift to reflect the establishment of fields of maize and the spread of C_4 agricultural weeds in the watershed. After 3300 cal yr BP, pollen percentages increase for the herbaceous plant families Poaceae, Amaranthaceae, and Asteraceae, which we interpret as linked to forest clearance and agricultural activities near Laguna Los Mangos (the first two families include C_4 species). At this time, pollen percentages for many tree and shrub taxa decline, supporting the idea of forest clearance near the lake.

The Laguna Los Mangos record shows additional evidence of human modification in the watershed in shifts in charcoal influx and elemental composition, and in the distribution of large wood fragments in the core. The charcoal record indicates fire activity preceding and coinciding with the first presence of maize pollen in the profile, which we interpret as related to anthropogenic forest clearance and field preparation for maize cultivation. Shifts in elemental composition from XRF analysis at ca. 3200 cal yr BP also provide evidence of a strong change in the watershed at Laguna Los Mangos, likely a result of forest clearance for agricultural fields. The large wood fragments at ca. 3600 cal yr BP and 2600 cal yr BP (and the smaller wood fragments

distributed between them; Figure 3.7) also suggest forest clearance. The wood at ca. 3600 cal yr BP corresponds to a positive shift in stable carbon isotope values, and the wood at ca. 2600 cal yr BP is close to the position of a charcoal peak and also matches a positive shift in stable carbon isotope values.

3.6.2 The Environment Preceding Maize Agriculture

The Laguna Los Mangos record contains a 1000-year record of environmental conditions and fire history before the first pollen evidence of maize cultivation at the site. The highest percentages of *Alchornea*, Melastomataceae-Combretaceae, and diporate Urticales pollen occur in this pre-maize period (~4300–3300 cal yr BP), together with the lowest percentages of pollen of grasses, sedges, and other herbaceous plants. We interpret the pre-maize environment at Laguna Los Mangos to have supported forests to the edge of the lake, without the ring of herbaceous plants now present. *Bursera, Piper, Ficus, Virola, Anacardium,* and *Sapium* occurred near the lake.

Conditions shifted markedly with clearance for initial maize agriculture, but people likely used and modified the watershed to a lesser degree prior to maize agriculture. The fire history of this period shows burning prior to maize agriculture. Evidence of early horticulture or agriculture in the watershed is not visible in the Laguna Los Mangos record; however, pollen of cultigens other than maize (for example manioc) is rarely preserved in Neotropical lake-sediment records (Clement and Horn, 2001).

3.6.3 A Regional Perspective on Agriculture and Fire in the Diquís Subregion

Laguna Los Mangos shows evidence for the introduction of maize agriculture into the region at ca. 3300 cal yr BP and a decline in agriculture (based on $\delta^{13}C_{OM}$ ratios) associated with the LIA and Spanish contact (~550–450 cal yr BP). A large peak in fire activity coincides with the decline, followed by lower charcoal influx. We interpret these proxies to show the effects of the cool LIA (Wu et al., 2016) limiting productivity and population decline from disease spread following Spanish contact in the region.

Paleoenvironmental records from other lakes in the Diquís subregion (Laguna Danta, Laguna Vueltas, and Laguna Santa Elena) show similar patterns of agricultural decline at ca. ~550–450 cal yr BP (Chapter 4; Anchukaitis and Horn, 2005; Horn, 2006). However, not all show a decline in fire activity during the LIA as is commonly documented for the circum-Caribbean (Power et al., 2013). The nearby Laguna Danta and Laguna Carse records show continued fire activity until the late LIA (after 300 cal yr BP) (Chapter 4), while Laguna Vueltas and Laguna Santa Elena show sharp declines in their fire histories at ca. ~500 cal yr BP (Anchukaitis and Horn, 2005; Horn, 2006).

Laguna Zoncho, which shares evidence for early maize pollen in the region, shows signals of agricultural decline associated with the TCD (at 1150–970 cal yr BP and 860–640 cal yr BP) (Taylor et al., 2013a; 2015). For Laguna Los Mangos, agricultural proxies signal a small decline by ~1400 cal yr BP (preceding the TCD) with a subsequent increase in agriculture by ~700 cal yr BP (following the TCD). While both records show varying declines around the TCD, only Laguna Los Mangos shows an agricultural

decline coinciding with the LIA and Spanish contact. At Laguna Zoncho, maize agriculture was inferred to already be of less importance in the watershed by this time (Taylor et al., 2013a).

Laguna Los Mangos and Laguna Zoncho show coinciding shifts in $\delta^{13}C_{OM}$ associated with initial maize establishment, and some similarities in shifts in organic matter content, particularly the upswing associated with reforestation during the colonial period (Figure 3.13). Shifts in these and other proxies at both sites show some temporal association with climate events such as the TCD and LIA. At both sites charcoal:pollen ratios show sharp declines coinciding with the LIA and Spanish contact. The range in $\delta^{13}C_{OM}$ values over the two records is similar, but with the Laguna Zoncho record showing much larger declines in agricultural intensity. Signals of maize agriculture at Laguna Los Mangos decline, but to reduced degree, supporting our interpretation of continual maize agriculture after the initial introduction.

3.7 Conclusions

We present a Late Holocene record of environmental change with the introduction of maize agriculture. From the Laguna Los Mangos record, we present evidence of the timing of maize introduction in southern Pacific Costa Rica and the Gran Chiriquí archaeological region at ca. 3300 cal yr BP. The presence of maize pollen at the northwestern lowland site of Laguna Los Mangos and the southeastern mid-elevation site of Laguna Zoncho (Clement and Horn, 2001; Taylor et al., 2013a; 2013b; 2015)

supports our interpretation of a rapid and widespread adoption of maize agriculture in the southern Pacific region following the initial introduction of this key cultigen.

The Laguna Los Mangos record also shows a pre-maize environment that changed with the introduction of maize agriculture. We show a forested landscape surrounding Laguna Los Mangos with some fire activity persisting for 1000 years. Preceding and at the time of the earliest pollen evidence of maize introduction, the record shows evidence of forest clearance for agriculture and an increase in C_4 vegetation at the site. Charcoal evidence, large shifts in elemental composition of the lake sediments, and increases in grasses and herbs, some related to agricultural disturbance, also coincide at the approximate time of maize introduction.

Maize agriculture at Laguna Los Mangos decreases slightly following an initial peak shortly after maize was introduced in the watershed as inferred from the stable carbon isotope ratios. Maize pollen presence from levels distributed across the profile following the initial evidence at ca. 3300 cal yr BP suggests continued maize cultivation across the Late Holocene, during the Sinancrá, Aguas Buenas, and Chiriquí archaeological periods. Compared to Laguna Zoncho, which experienced two periods of pronounced agricultural decline (from 1150–970 and 860–640 cal yr BP), our agricultural proxies at Laguna Los Mangos indicate only two, small declines, from ~1400–1000 cal yr BP and from 480 cal yr BP to modern historic times. Both records show lowered agricultural signals during the TCD, but only the Laguna Los Mangos

record indicates an increase in maize agriculture following the TCD and a subsequent decline coinciding with the LIA and Spanish contact.

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3.10 Appendix

Table 3.1. Radiocarbon determinations from the Laguna Los Mangos 2014 core.

Lab Number [a]	Depth (cm)	Uncalibrated ^{14}C Age (^{14}C yr BP)	±2 σ Cal. Age Range [b] (cal yr BP)	Area Under Probability Curve	Material
DAMS-014532	160	159 ± 26	35–1	0.188	wood
			118–69	0.114	
			157–131	0.114	
			230–165	0.409	
			247–244	0.003	
			285–250	0.172	
UGAMS-21108	298	2130 ± 25	2027–2005	0.431	leaf
			2156–2036	0.884	
			2296–2267	0.073	
DAMS-014533	399	2457 ± 27	2545–2364	0.494	wood
			2619–2556	0.193	
			2704–2629	0.313	
UGAMS-21106	487	3030 ± 25	3270–3160	0.741	leaf
			3340–3286	0.259	
UGAMS-21107	605	3460 ± 25	3660–3648	0.125	leaf
			3726–3689	0.467	
			3762–3750	0.113	
			3821–3793	0.295	
UGAMS-19461	734	3760 ± 25	4036–3997	0.094	leaf
			4164–4078	0.764	
			4181–4166	0.029	
			4231–4197	0.114	

[a] Analyses were performed by Direct AMS (D-AMS) and by the Center for Applied Isotope Studies at UGA (UGAMS).

[b] Calibrations were made using CALIB version 7.0.4 (Stuiver and Reimer, 1993) and the IntCal 13 dataset (Reimer et al., 2013).

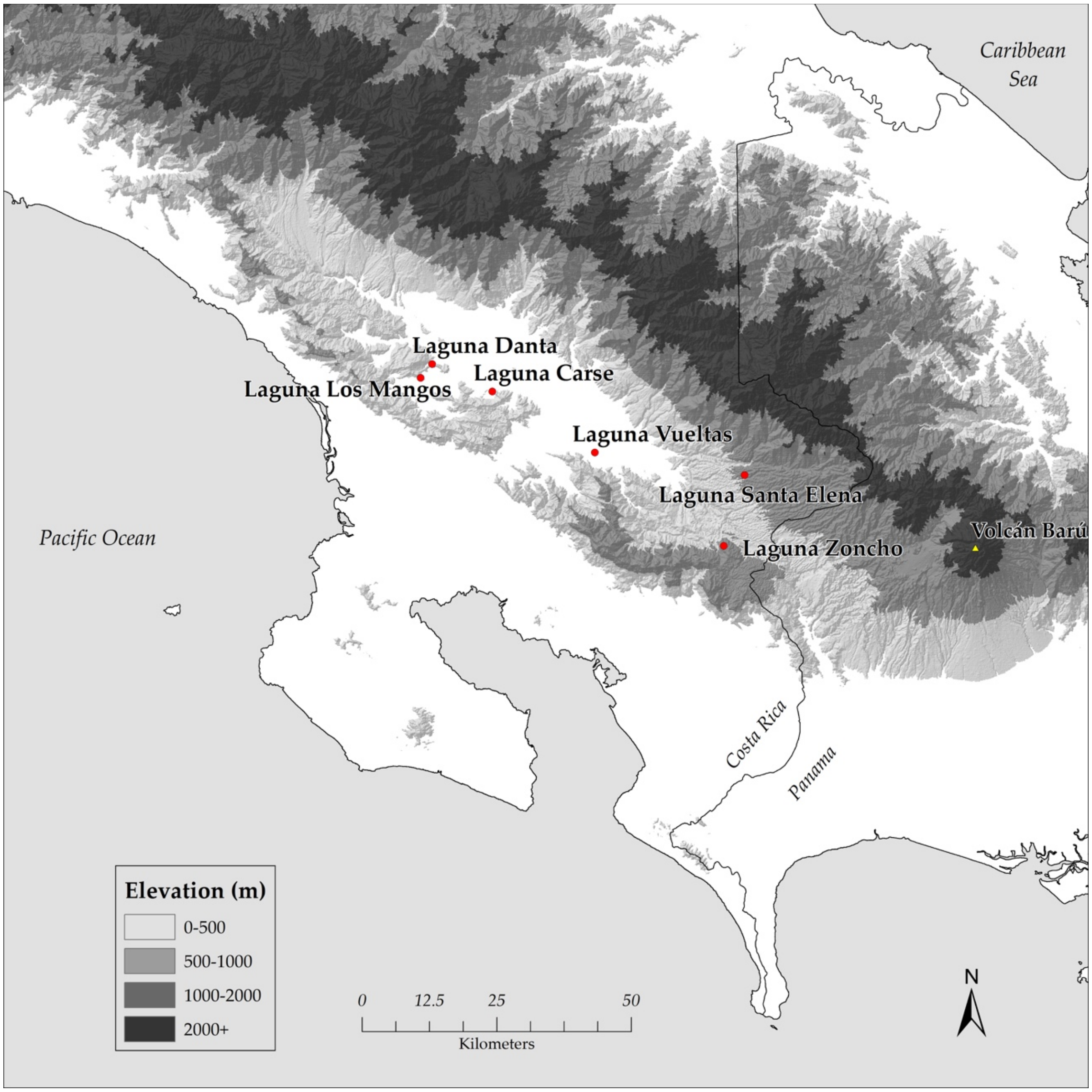


Figure 3.1. Location of Laguna Los Mangos and other lakes sampled for paleoenvironmental research in southern Pacific Costa. Elevation data from CIAT-CSI SRTM (http://srtm.csi.cgiar.org).

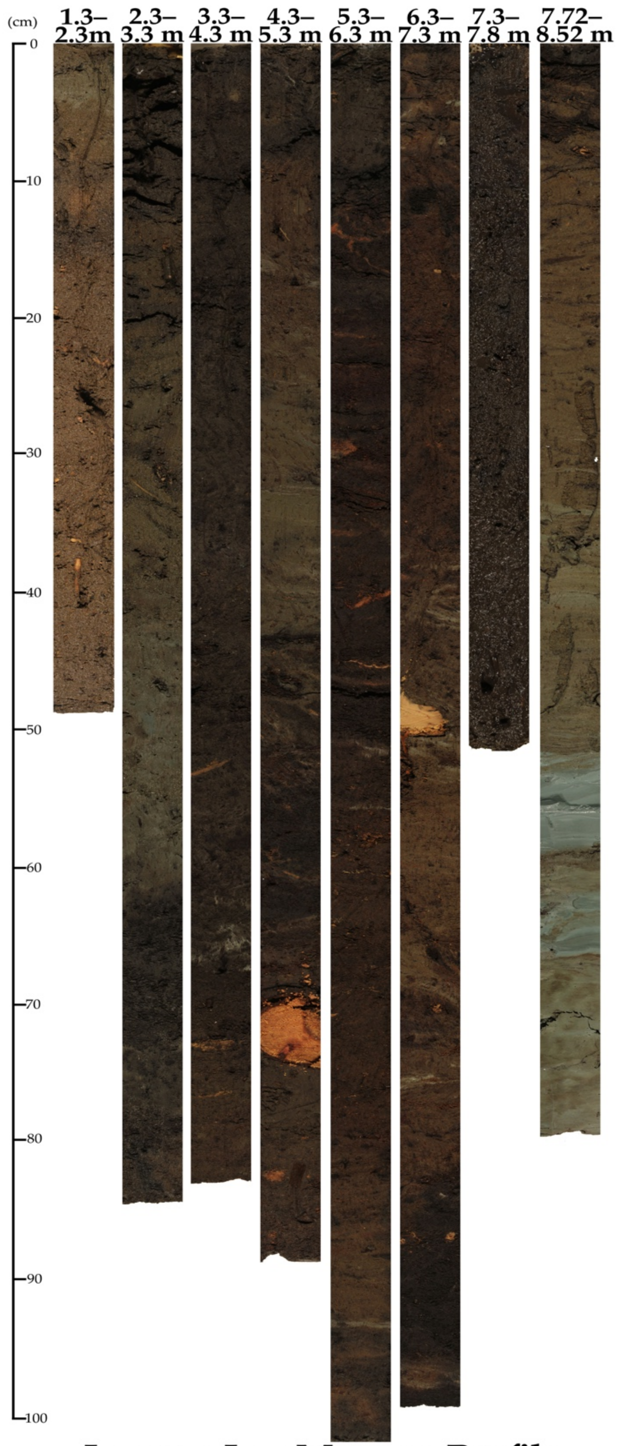
Figure 3.2. Modern agricultural setting of Laguna Los Mangos showing maize on the slope on the right. Photograph taken during July 2014 fieldwork by Erik Johanson.

Figure 3.3. Laguna Los Mangos during the dry season in March 2014, showing low water level and steep unprotected slope. We attribute high recent sedimentation rates to modern agricultural activity, including cultivation of this steep slope. Photograph taken in March 2014 by Sally Horn.

Figure 3.4. Diquís subregion of the Greater (or Gran) Chiriquí archaeological region. Locations of archaeological sites based on (Snarskis, 2003).

Figure 3.5. Petroglyph metate located within a few hundred meters of Laguna Los Mangos. Positioned on a ridge to overlook the valley bottom, the petroglyph metate has decoration on the working surface that likely signifies a ceremonial use. Photograph taken in March 2014 by Erik Johanson.

Figure 3.6. Bathymetry of Laguna Los Mangos with coring location indicated. Lake depths (shown in cm) surveyed in March 2014 with bathymetry calculated using a spline function. Aerial Imagery modified from ESRI, DigitalGlobe.



Laguna Los Mangos Profile

Figure 3.7. Sediment core sections from Laguna Los Mangos. Depth ranges above photos are drive depths including water depth and height of platform.

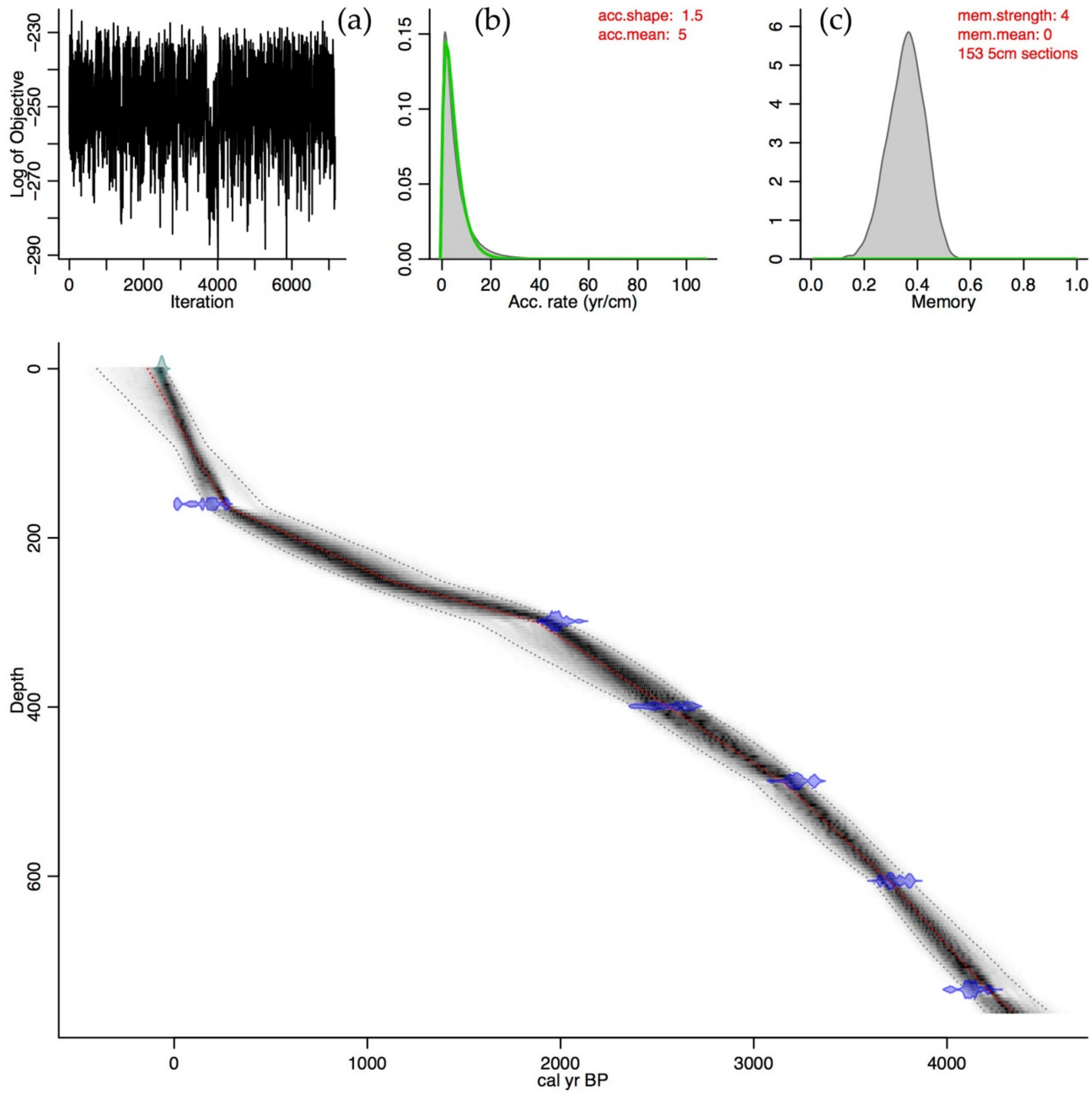


Figure 3.8. Age-depth model for Laguna Los Mangos 2014 profile from southern Pacific Costa Rica. (a) MCMC iterations with stationary distributions ideal. (b) The accumulation rate consists of a gamma distribution with adjusted accumulation shape and mean values (Blaauw and Christen, 2011). (c) The memory value, or autocorrelation, defines how much the accumulation rate of a particular depth in a core depends on the depth above it. Assuming a low memory or autocorrelation, the accumulation rate would change greatly over time (highly variable environmental conditions), while a high memory implies a more constant accumulation (Blaauw and Christen, 2011).

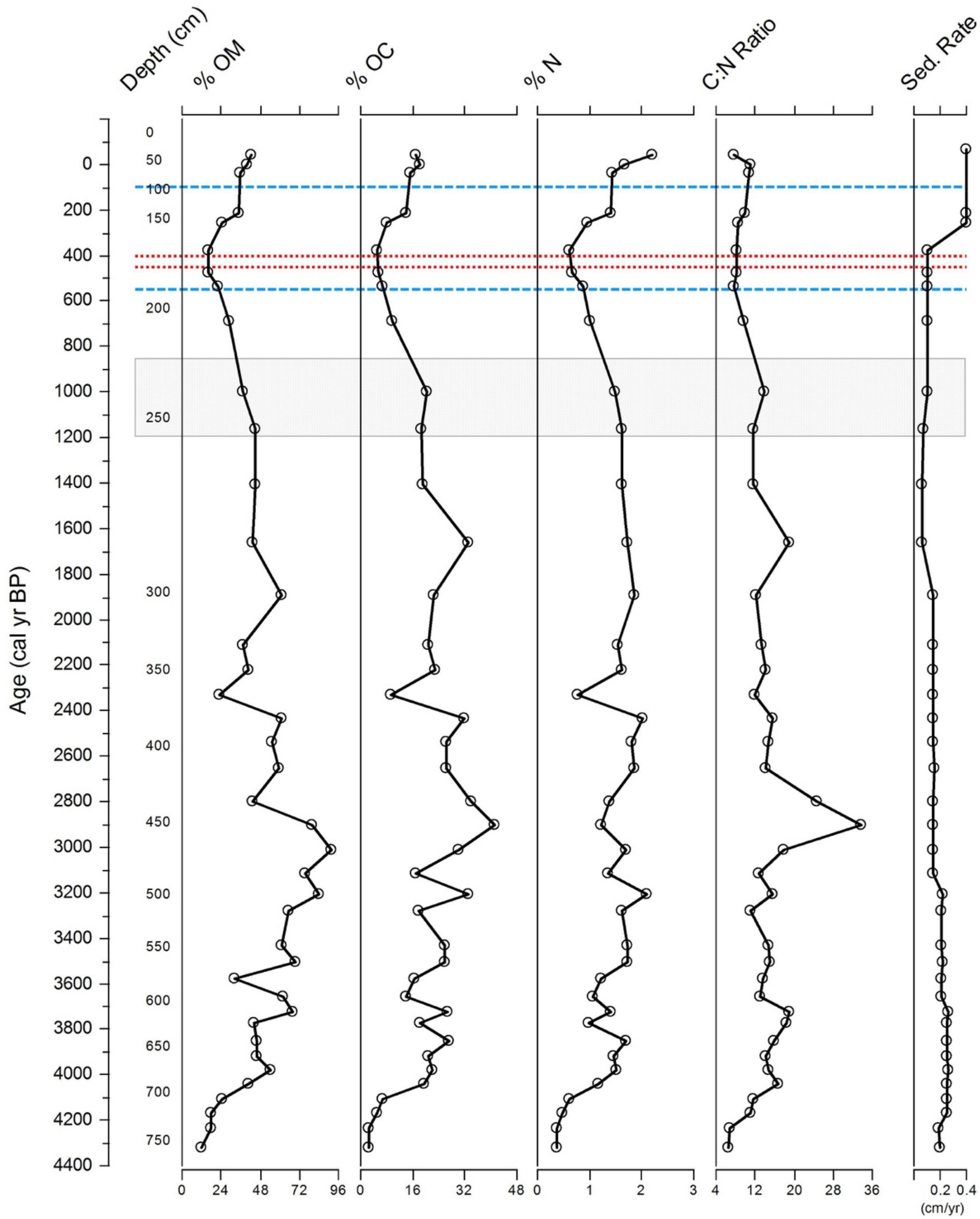


Figure 3.9. Laguna Los Mangos sediment composition based on LOI and geochemical analyses, and sediment accumulation rate based on the Bacon age model. Red dotted lines bracket the timing of Spanish contact (~450–400 cal yr BP). Blue dashed lines delineate the LIA (~550–100 cal yr BP). Gray stipple zone marks the TCD (1200–850 cal yr BP).

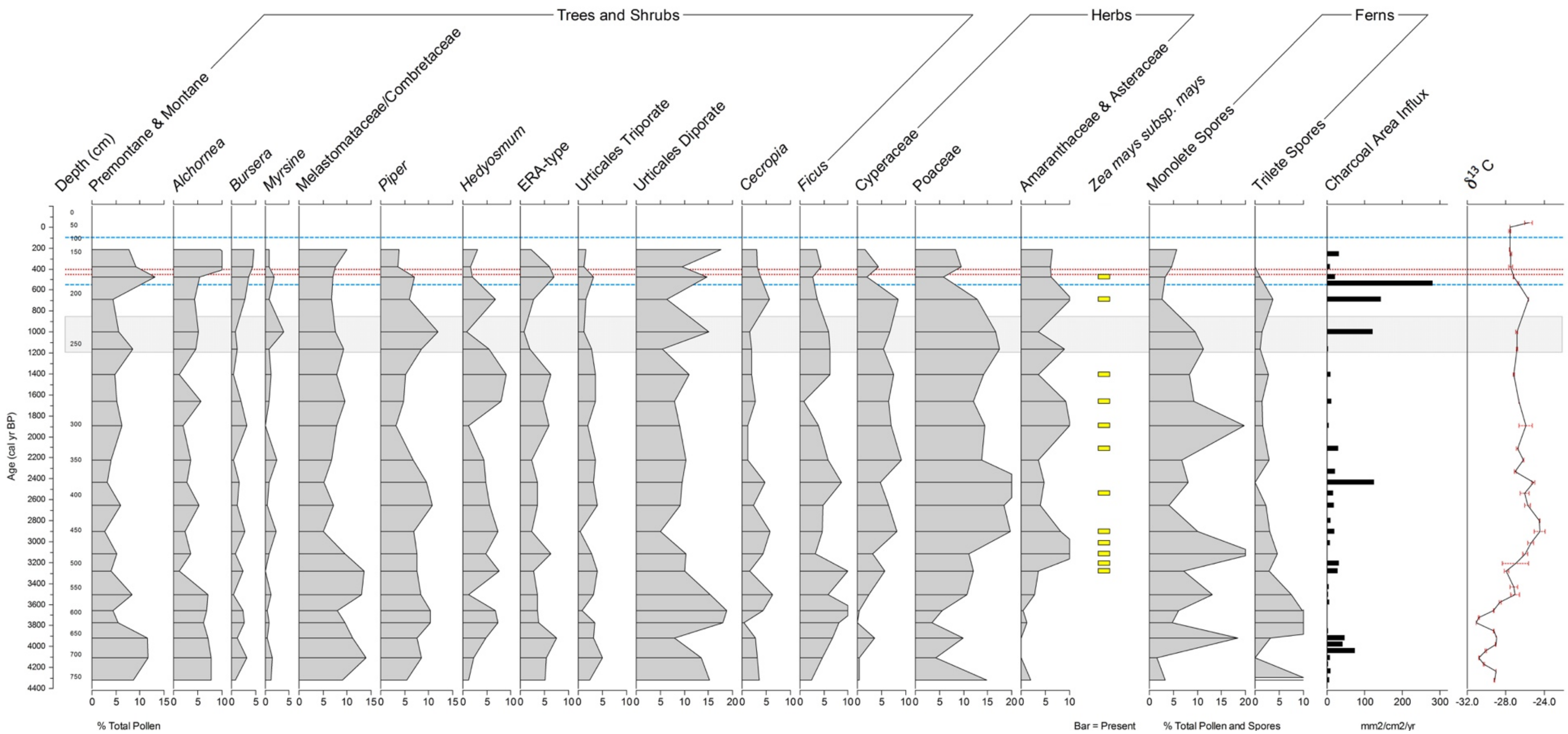


Figure 3.10. Laguna Los Mangos pollen and microscopic charcoal diagram, showing curves for individual taxa and composite classes, *Zea mays* subs. *mays* presence, charcoal area influx. Stable carbon isotope curve from Figure 3.11 added to facilitate comparison. Pollen percentages calculated as percent total pollen (excluding indeterminates and fern spores), while fern spore percentages are calculated as the percent of total pollen and fern spores. The composite curve for premontane and montane taxa includes *Quercus*, *Weinmannia*, *Myrica*, *Alnus*, and *Ulmus*. ERA-type (Horn, 1985; 1986) includes tricolporate reticulate taxa in several families including the Euphorbiaceae, Rutaceae, and Anacardiaceae families. At Laguna Los Mangos the most common ERA-type genera may be *Anacardium* and *Sapium*. The order Urticales includes the Moraceae, Urticaceae, and Ulmacease families. The Urticales Triporate curve includes *Celtis.* The Urticales diporate curve includes *Trema*. Red dotted lines bracket the timing of Spanish contact (~450–400 cal yr BP). Blue dashed lines delineate the LIA (~550–100 cal yr BP). Gray stipple zone marks the TCD (1200–850 cal yr BP).

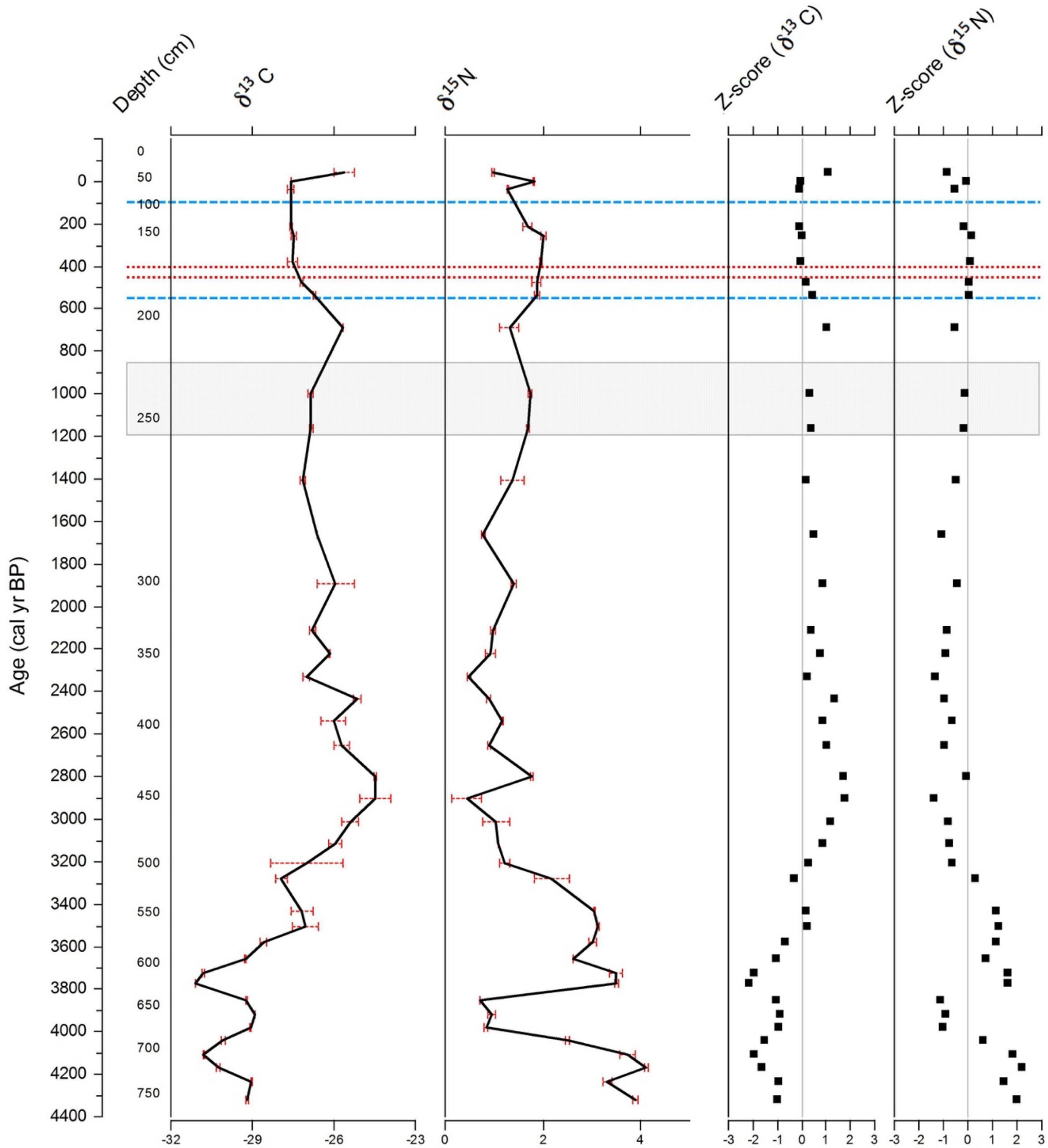


Figure 3.11 Stable carbon and nitrogen isotope curves for Laguna Los Mangos with Z-scores denoting magnitude of change in values from the data mean. Red dotted lines bracket the timing of Spanish contact (~450–400 cal yr BP). Blue dashed lines delineate the LIA (~550–100 cal yr BP). Gray stipple zone marks the TCD (1200–850 cal yr BP).

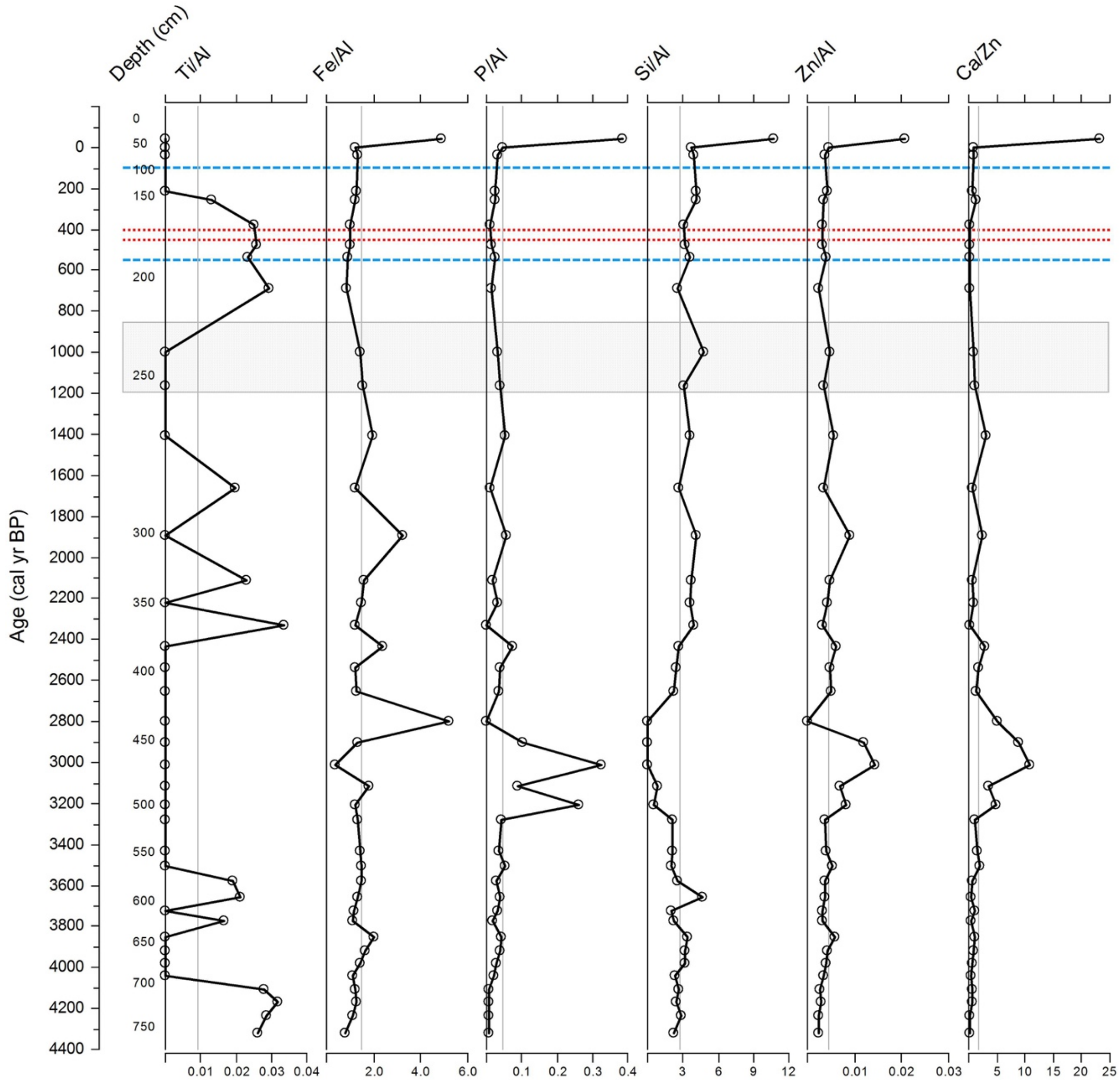


Figure 3.12 Laguna Los Mangos elemental composition from XRF analysis. Percent element composition for Ti, Fe, P, Si, Zn, and Ca are normalized by percent Al. Means calculated for samples >41 cm depth. Note scale changes. Red dotted lines bracket the timing of Spanish contact (~450–400 cal yr BP). Blue dashed lines delineate the LIA (~550–100 cal yr BP). Gray stipple zone marks the TCD (1200–850 cal yr BP).

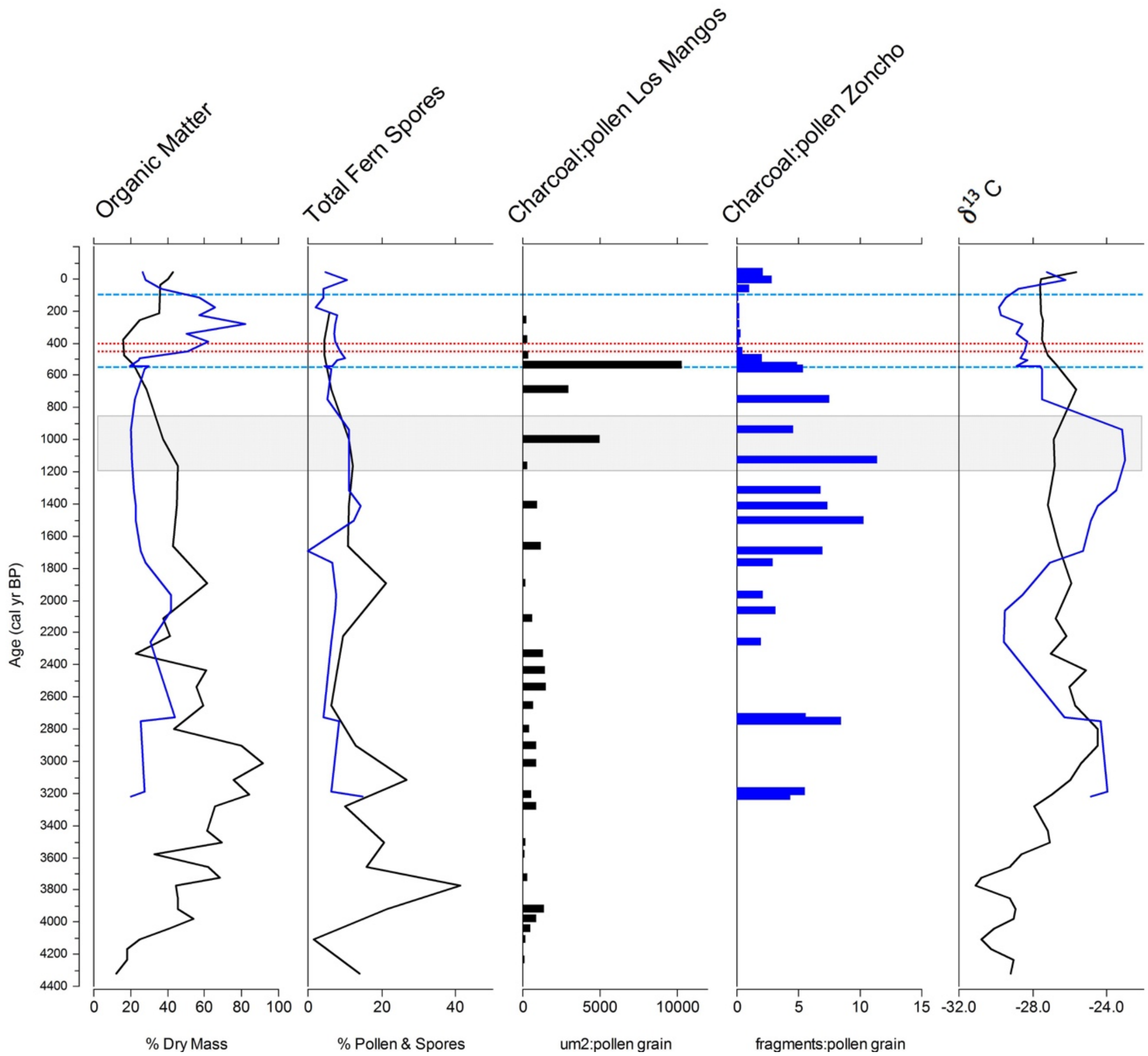


Figure 3.13. Comparison of regional sites in southern Pacific Costa Rica. Laguna Los Mangos (black) and Laguna Zoncho (blue). Red dotted lines bracket the timing of Spanish contact (~450–400 cal yr BP). Blue dashed lines delineate the LIA (~550–100 cal yr BP). Gray stipple zone marks the TCD (1200–850 cal yr BP).

CHAPTER 4

FIRE HISTORY ACROSS THE LITTLE ICE AGE IN SOUTHERN PACIFIC COSTA RICA

This chapter is in preparation for journal submission. My use of "we" in this chapter includes my co-authors, Sally P. Horn, Chad S. Lane, Maureen Sánchez, and Jacob Cecil. I am first author, and my contributions to this project include experimental design, data collection and analyses, and writing the manuscript.

4.1 Abstract

We present two high-resolution records of Late Holocene fire history from lakes in the lowlands of southern Pacific Costa Rica, and compare them with evidence of prehistoric agriculture in the same cores and with records of regional paleoclimate. Macroscopic charcoal influx in Laguna Danta and Laguna Carse shows several major and minor peaks across the last ~800 years, but does not show the decline at the time of the Little Ice Age and Spanish contact evident in other charcoal records from the region. Stable carbon isotope values in sediments indicate that agricultural activity declined at this time at Laguna Danta, but the association between fire and indigenous agriculture at the study sites is not strong. Instead, drought appears to be a primary driver of fire in the lowlands of southern Pacific Costa Rica. Peaks in macroscopic charcoal at Laguna Danta coincide with shifts in the mean latitudinal position of the Intertropical Convergence Zone in the Caribbean as reconstructed from the Cariaco Ti record. We interpret our charcoal records to indicate both human use of fire in agricultural settings and wildfires in intact forests driven by regional changes in climate.

4.2 Introduction

Fire activity and agricultural practices in southern Pacific Costa Rica has changed over the last 750 years because of demographic and social changes precipitated by the arrival of the Spanish and as a result of changes in climate. Previous researchers attributed declines in indigenous agricultural activity and fire evident in lake-sediment records from the region to local population declines associated with European contact, multidecadal droughts, or some combination of both (Anchukaitis and Horn, 2005; Clement and Horn, 2001; Horn, 2006; Taylor et al., 2013a). Declines in population could be associated with higher morbidity rates from conflict related to Spanish contact or with the introduction and propagation of Old World diseases throughout the region. Alternatively, population declines could suggest emigration out of affected locations driven by changes in local climate conditions and social stresses.

Changes to the size or social organization of human communities in the region should affect the fire history and agricultural practices of the region as captured in lake-sediment records. At Laguna Vueltas in southern Pacific Costa Rica, agriculture and fire both declined at the time of Spanish arrival (Horn, 2006; Horn et al., 2011). However, proxy records from Laguna Zoncho and Laguna Santa Elena in southern Pacific Costa Rica indicate evidence of agricultural decline and an inferred population reduction in advance of Spanish arrival likely driven by climate (Anchukaitis and Horn, 2005; Kerr, 2014; Taylor et al., 2013a). Cooler and drier conditions during the Little Ice Age (LIA, 550–100 cal yr BP) may have driven changes in fire regimes. LIA shifts in climate could

have affected fire both directly, by influencing biomass production and burning conditions for wildfires, and indirectly, by affecting where people lived and their use of fire in agriculture.

The LIA represents a significant climate event that reduced both annual temperatures and precipitation in much of the northern hemisphere, including the Neotropics (Haug et al., 2001; Lamb, 1965; Lane et al., 2011). Titanium concentrations in marine sediment cores from the Cariaco Basin off Venezuela provide evidence that the LIA had a strong effect on the circum-Caribbean region (Haug et al., 2001; Peterson and Haug, 2006). The Cariaco Ti record is a proxy for terrestrial erosion driven by variations in precipitation linked to the mean annual latitudinal position of the Intertropical Convergence Zone (ITCZ) (Haug et al., 2001). During the LIA, there was a weakening of the Walker circulation (Conroy et al., 2008) and a southward displacement of the ITCZ with an associated cooling of air and sea surface temperatures and a weakening of the Central American monsoon (Haug et al., 2001; Lane et al., 2011; Sachs et al., 2009). These effects of the LIA produced a pronounced 450-year period of low Ti concentrations in the Cariaco basin that is interpreted as evidence of a prolonged dry period in the circum-Caribbean (Peterson and Haug, 2006). Stable isotope records from the Yucatan Peninsula (Hodell et al., 2005) and the Dominican Republic (Lane et al., 2011) show evidence of extended drought during the LIA (Hodell et al., 2005; Lane et al., 2011). In Costa Rica, Wu et al. (2016) produced a record of mean annual air temperature from chironomid assemblages in the sediments of Laguna Zoncho that shows cool and less

productive conditions in southern Pacific Costa Rica from ca. 1480 to 1860 CE. However, geochemical and microfossil records from lakes in Jamaica (Burn and Palmer, 2013) and Barbuda (Burn et al., 2016) show variability in precipitation, but overall drier conditions during the LIA at these Caribbean island sites.

European contact in the southern Pacific region of Costa Rica occurred shortly after 1500 CE with the Spanish exploration of the Isthmus of Panama in 1501 CE and the initial arrival of the Spanish on the Pacific coast of Costa Rica in 1519 CE (Guardia, 1913; Nunley, 1960). The arrival of the Spanish and subsequent disease spread would have influenced fire activity in the Neotropics. Estimates suggest 90–95 percent of the agricultural population was lost following the European contact with the New World (Dobyns, 1966; Lovell and Lutz, 1995). The dramatic reduction in the agricultural population contrasts with the steadily increasing demographic pressure on forests from anthropogenic burning through the Holocene up until European colonization (Dull et al., 2010). Highlighting the possible role of pre-industrial populations in global carbon cycles, Dull et al. (2010) proposed that the abrupt post-Columbian decline in population in the Neotropics was itself the cause of the LIA. In the view of Dull et al. (2010), the cessation of agricultural burning by humans and forest recovery following the decimation of indigenous populations across North and South America caused a reduction in global carbon dioxide levels large enough to cool the planet and create the interval of lower global temperatures recognized as the Little Ice Age. Others, however,

have interpreted the Little Ice Age to have resulted from natural variations in earth systems not caused by humans (Mann et al., 2009).

With respect to the drop off in burning seen at many neotropical sites at the time of European contact, Power et al. (2013) concluded that this change in fire activity may have been driven more by LIA climate cooling than by changes in human population. Their study looked at changes in fire activity across North America (including Mexico and Central America), South America, and the Caribbean, based on a synthesis of charcoal records from the Americas and comparison with charcoal records from other sites around the world, paleoclimate data, and estimates of population change. Power et al. (2013) found a strong correspondence between the LIA decline in burning in southern Mexico, Central America, and the Caribbean and the precipitation decline in the Cariaco record, which suggested that the LIA reduced burning by limiting fuel availability. As noted by Power et al. (2013), this finding is at odds with the observation that fire is more prevalent in tropical systems with intermediate levels of precipitation and fuel loads; the correspondence between drought and low fire activity also contradicts the observation that fire in most neotropical ecosystems has largely occurred during intervals of reduced rainfall (Power et al., 2010). The conflict led Power et al. (2013) to suggest that the Cariaco record may not fully capture the complexity of climate across the LIA in southern Mexico, Central America, and the Caribbean. They called for a more detailed study, at higher resolution, of charcoal records from the area to explore the relationship

between LIA climate change and biomass burning in this part of the Americas. Such a study requires the development of additional records, such as the ones we present here.

Charcoal and stable carbon isotope records from lacustrine sediments provide evidence of local effects of human activity in the Neotropics, specifically fire history and agricultural activity. Fires recorded in sediment profiles can include fires set intentionally, associated with forest clearance or agricultural or subsistence activities; fires that ignite by accident in mature or secondary vegetation, perhaps indirectly related to anthropogenic actions; or fires set by lightning or volcanism that burn either intact or human-modified vegetation. Charcoal is a direct proxy for fire reconstruction and enters the lacustrine record when particulate charcoal is either washed into the lake basin or enters from atmosphere fallout. Analysts study microscopic charcoal (<125 micrometers) on slides prepared for pollen analysis, and larger, macroscopic charcoal particles concentrated from cores by sieving. Because small charcoal particles can be transported long distances in the atmosphere, microscopic charcoal may derive from both local and extralocal sources (Carcaillet et al., 2002). Larger, macroscopic charcoal particles are, in contrast, interpreted to represent local fires that occurred within the lake watershed or close by (Whitlock and Larson, 2001).

Charcoal data from sediment cores are used to assess links between climate, fire, and anthropogenic activities in the past (Whitlock and Larson, 2001). Combining high-resolution charcoal analysis with geochemical analyses provides a means to identify possible drivers of changing fire activity in the lowland Neotropics. Stable carbon

isotopes ratios ($\delta^{13}C_{OM}$) in lake sediments are influenced by the photosynthetic pathways of the plants that compose the watershed vegetation (Boom et al., 2007; Lane et al., 2004). The interpretation of these isotope ratios allows the reconstruction of the dominant photosynthetic pathway of vegetation in a watershed. Previous analyses by Lane et al. (2004; 2008) of stable carbon isotope ratios in Costa Rican lake-sediment cores showed that the $\delta^{13}C_{OM}$ proxy is sensitive to changes in the extent of tropical forest and cultivated land within watersheds, with forest conversion resulting in a shift to more positive isotope values associated with the replacement of C_3 tropical forest taxa with C_4 plants such as maize and agricultural weeds. Bulk carbon $\delta^{13}C_{OM}$ analysis offers a method, in addition to pollen analysis, to detect prehistoric forest clearance and maize agriculture in small neotropical watersheds (Lane et al., 2004; 2009; 2008; Taylor et al., 2013a; 2013b).

In this paper, we present high-resolution charcoal records of fire history across the LIA from two lowland neotropical lakes, Laguna Danta and Laguna Carse. We also present stable carbon isotope evidence of agricultural activity. We compare our records to each other and examine how changes in proxies may correspond with the LIA and the arrival of the Spanish in southern Pacific Costa Rica. We focus on the relationship between fire history at Laguna Danta and Carse and (1) evidence of human presence and activity from archeological and historical records; (2) evidence of changes in the extent of agriculture in the watersheds from stable carbon isotope analysis; (3) regional climate trends; (4) fire history at nearby sites reconstructed from charcoal analyses at lower resolution; and (5) global patterns of fire activity.

4.3 Study Sites

Laguna Danta (470 m) and Laguna Carse (370 m) are located 12 km apart in an area of moderate topographic relief in the Fila Costeña mountain range of southern Pacific Costa Rica (Figure 4.1). To the north is the imposing Cordillera de Talamanca, reaching 3819 m at its highest point; the Valle de El General lies between the two ranges. The geology of the study area includes Tertiary igneous and sedimentary rocks. Laguna Danta is located along the boundary between the Curré formation (Upper Miocene conglomerates, sandstones, and shale) and the Grifo Alto formation (Upper Miocene and Pliocene plutonic rocks and breccias); Laguna Carse is located within the Grito Alto formation (Alvarado et al., 2009a; 2009b). Both lakes owe their origin to landslides (Horn et al., in preparation), which are common in the area (Alvarado et al., 2009a).

The study area is classified as tropical moist forest in the Holdridge Life Zone System (Holdridge, 1967), indicating an average annual temperature above 24 °C and annual precipitation between 2000 and 4000 mm. Prior to forest clearance, the watersheds of both lakes would have supported tropical moist forest composed of species that use the C_3 photosynthetic pathway. The original littoral vegetation could have included some sedges in the genus *Cyperus*, a genus that includes both C_3 and C_4 species (Bruhl and Wilson, 2007; Tucker, 1983), but we expect that C_4 plants occupied only a small percentage of the watersheds prior to forest clearance for maize agriculture. Maize (*Zea mays* subsp. *mays*), brought into southern Pacific Costa Rica by pre-Columbian peoples by 3200 cal yr BP (Horn, 2006), uses the C_4 photosynthetic pathway,

as do herbaceous weeds associated with maize agriculture. Maize is cultivated today near both lakes, but watershed vegetation consists primarily of cattle pasture with patches of forest.

The study area is located within the Diquís subregion of the Greater or Gran Chiriquí archaeological region that encompasses southern Pacific Costa Rica and parts of western Panama. The archaeological record of the Diquís subregion includes two major cultural periods. The older Aguas Buenas Period (300 BCE to 800 CE) occurred preceded the more recent Chiriquí Period, which began at 800 CE and ended with the arrival of the Spanish by 1500 CE (Corrales, 2000). The Chiriquí Period is considered to represent a complex hierarchical society with high population levels that were supported by maize agriculture (Corrales, 2000). The ubiquity of Diquís Spheres, locally produced petrospheres, in the subregion is a major archaeological characteristic attributed to the Chiriquí culture, but possibly dating earlier (Lothrop, 1963).

Following initial coastal exploration by the Spanish of the Pacific Coast of Costa Rica in 1519 CE, a second Spanish party in 1522–1523 CE explored the coast on foot, and visited several Boruca villages a short distance inland (Nunley, 1960). The first expedition by the Spanish into the interior of Costa Rica occurred in 1524 and ended unsuccessfully on the eastern slopes of the Cordillera de Talamanca; the eventual Spanish conquest of the Diquís subregion was effected by Coronado in 1562–1563 CE (Guardia, 1913; Nunley, 1960). Cartago was officially established as the colonial capital by the Spanish in 1564, which marked the colonization of Costa Rica (Nunley, 1960).

When the Spanish arrived in the Diquís subregion, they noted reliance on large-scale agriculture, extensive fortifications, and frequent conflicts among territorial chieftains (Guardia, 1913).

Communities in the early colonial period in Costa Rica adopted subsistence agricultural practices similar to those used in pre-Columbian times, but with the introduction of some Old World cultivars and techniques of cultivation (Nunley, 1960). The capital of Cartago was isolated with crude roads developed to enable commerce to the Caribbean and Pacific coasts and to the Isthmus of Panama (Nunley, 1960). The settlement of Costa Rica by the Spanish was spatially variable with some regions extensively affected while others received minimal direct contact and settlement. Independence from Spain allowed for coffee agriculture to expand after 1821, but only after the completion of the Inter-American highway in the 1940s did settlement and modern agricultural practices expand significantly in southern Pacific Costa Rica (Nunley, 1960).

Limited archaeological studies have been conducted near the study lakes of Laguna Danta and Laguna Carse with most of the work being archaeological survey efforts in advance of a state-sponsored electrical project. The Instituto Costarricense de Electricidad (ICE) is in the process of planning and developing a large hydroelectric dam known as the El Diquís Project, which if completed will flood roughly 7363 hectares of land, 915 hectares within indigenous territories, and displace 1547 people (Campregher, 2009). Currently, archaeologists working for ICE are conducting archaeology in the

region to create an inventory before any flooding occurs, on lands within the proposed reservoir and in an adjacent buffer zone, in which the study lakes are located. No systematic archaeological surveys have been conducted in the watershed of either Laguna Danta or Laguna Carse, by ICE teams or any other. However, when we visited Laguna Danta in June 2013 archaeologists noticed a few ceramic sherds in an agricultural field adjacent to the lake that they attributed to the later Chiriquí Period. Additionally, we were told of the existence of several archaeological sites near Laguna Ojo de Agua, a small lake 1 km east of Laguna Danta, where we observed ceramic sherds and a large lithic biface artifact in a nearby roadcut.

Laguna Danta and Laguna Carse are located near the modern-day Térraba indigenous reservation in an area that is closely associated with the pre-Columbian settlement range of the Boruca indigenous community (Stone, 1962; 1949). Around 1697 CE part of the Térraba indigenous community was relocated by the Spanish from settlements on the Caribbean slope of the Cordillera de Talamanca to the valley of the Río Grande de Térraba, also known as the Diquís valley (Pittier, 1941; Stone, 1962). The modern indigenous reservations of the Térraba and Boruca are located within or near the Diquís valley, which was an important trade route during both pre-Columbian and colonial times as it offered a corridor for movement through difficult surrounding terrain.

4.3.1 Laguna Danta and Laguna Carse

Laguna Danta (9.1122° N, 83.4480° W, 470 m) and Laguna Carse (9.0669° N, 83.3472° W, 365 m) are located in the Pilas District and Boruca District, respectively, in the canton of Buenos Aires, Puntarenas Province. Laguna Danta has a surface area of 1.7 ha and a maximum depth of 5 m as determined by our bathymetric survey in June 2013 (Figure 4.2). Laguna Carse has a similar surface area of 1.5 ha and a maximum depth of 5 m from our July 2014 bathymetric survey (Figure 4.3). Laguna Carse is near the indigenous communities of Bijagual, Ceibón, and Doboncragua in the Térraba-Boruca Indigenous Reserve. Nearly 3000 indigenous people live within the Puntarenas Province of Costa Rica (OIRSA, 2005).

4.4 Methods

4.4.1 Core Collection, Processing, and LOI

We recovered sediment cores from Laguna Danta and Laguna Carse in March 2014 and July 2014, respectively. Cores were taken from the deepest portion of each lake from an anchored floating platform using a Colinvaux-Vohnout (C-V) locking piston corer (Colinvaux et al., 1999). At Laguna Danta, we used a plastic tube fitted with a rubber piston to collect the uppermost 46 cm; at Laguna Carse, we began our first C-V core at 51 cm below the mud-water interface and did not collect a mud-water interface core.

We returned the core sections to the cold room (4–5 °C) in the Laboratory of Paleoenvironmental Research at the University of Tennessee, Knoxville still encased in their original aluminum coring tubes. In the lab, we opened the core tubes longitudinally using a modified wood shaper, sliced the sediments lengthwise using a thin wire, photographed the core sections, and described sediment colors (Munsell) and textures on core logs. The organic matter and carbonate contents of the sediments were estimated using loss on ignition (LOI) (Dean, 1974). We extracted samples for LOI from the core sections at ca. 16 cm intervals, placed them in pre-weighed ceramic crucibles, and weighed them before being dried at 100 °C for 24 hours. The samples were cooled and reweighed to determine water content, and then ignited in a furnace at 550 °C for one hour to estimate organic matter and at 1000 °C for one hour to estimate carbonate content.

4.4.2 Radiocarbon Dating and Age-depth Modeling

We selected 9 macrofossils from the Laguna Danta and Laguna Carse sediment profiles for AMS radiocarbon dating. We then produced age models from the radiocarbon results using the Bacon age-modeling package for R (Blaauw and Christen, 2011), which uses Bayesian statistics and the IntCal 13.14 calibration dataset (Reimer et al., 2013; Stuiver and Reimer, 1993). The Bacon age model provided a weighted mean age in cal yr BP at 1-cm intervals in the two profiles.

4.4.3 Macroscopic Charcoal

We carried out macroscopic charcoal analysis at contiguous 2-cm intervals in the Laguna Danta sediment profile and in the lower portion (772–552 cm) of the Laguna Carse sediment profile. Above 552 cm in the Carse profile, we sampled macroscopic charcoal at 8-cm intervals. We sampled four cm^3 of sediment from each level by using a rectangular prismatic sampler to remove two contiguous samples (each 1 cm x 1 cm x 2 cm) over a 2-cm interval in the core. We then reacted the sediment with 50 mL of 3% hydrogen peroxide overnight to remove and bleach some non-charred organic matter (Schlachter and Horn, 2009). Following this treatment, samples were dried at 110 °C for >16 hours to comply with USDA protocols for working with foreign soils in our lab. Following sterilization, samples were rehydrated with 50 mL of 5% sodium metaphosphate solution for 24–48 hours. The Laguna Danta samples (n=177) and Laguna Carse samples (n=136) were sieved using 500- and 125-μm mesh sieves and the contents on the sieves were transferred to Petri dishes and dried at 50 ºC for 24 hours. Few charcoal particles were retained on the 500 μm sieve, so we focused our analysis on charcoal in the 125–500 μm size range. We identified and counted charcoal fragments in dry samples using a dissecting microscope; charcoal was identified as black angular material with a characteristic sheen.

4.4.4 Stable Carbon and Nitrogen Isotope Analysis

Stable carbon ($\delta^{13}C_{OM}$) and nitrogen ($\delta^{15}N_{OM}$) isotope ratios were measured at intervals of ca. 12 cm (Laguna Danta) and 16 cm (Laguna Carse). Samples of 1 cm^3 volume were dried at 50 °C overnight and then ground to a fine powder with a mortar and pestle to sufficiently homogenize the samples to be representative of the bulk sediment. The ground samples were split into a non-acidified fraction for $\delta^{15}N_{OM}$ and an acidified fraction for $\delta^{13}C_{OM}$ analysis. Inorganic carbon in the bulk sediment interferes with the measurement of organic ^{13}C unless those carbonates are removed through an acidification process (Harris et al., 2001). Fractions for acidification were lightly moistened with distilled H_2O and then acid–fumigated in desiccators with 12 M HCl for 2–3 hours for the Laguna Carse samples and for 24 hours for the Laguna Danta samples because of the higher carbonate levels in the latter. The acidified samples were then vented overnight before being placed on a hotplate to dry the samples with samples reground as needed. Samples were loaded into tin capsules with 100% duplicates for all intervals for both acidified (n=70 for Danta; n=78 for Carse) and non-acidified (n=70 for Danta; n=78 for Carse) samples.

The isotopic analysis of the samples used a Costech 4010 elemental analyzer interfaced with a Thermo Delta V Plus mass spectrometer at the University of North Carolina Wilmington Isotope Ratio Mass Spectrometry facility at the Center for Marine Science of the University of North Carolina Wilmington. All isotopic compositions are reported in standard δ-per mil notation with nitrogen relative to atmospheric air and

carbon relative to the Vienna-Pee Dee belemnite (V-PDB) marine-carbonate standard, where $R = {}^{13}C/{}^{12}C$ or ${}^{15}N/{}^{14}N$ and:

$$\delta^{13}C \text{ (per mil)} = 1000\ [(R_{sample} / R_{standard}) - 1]$$

$$\delta^{15}N \text{ (per mil)} = 1000\ [(R_{sample} / R_{standard}) - 1]$$

Reported carbon isotope ratios correspond to the acidified fraction while reported nitrogen isotope ratios correspond to the non-acidified fraction. The reported C:N ratio, percent organic carbon, and percent nitrogen use values for percent carbon from the acidified fraction and percent nitrogen from the non-acidified fraction. The C:N ratio is used to reconstruct the source of organic matter (e.g. terrestrial or aquatic) in the sediment profile of the lakes (Talbot, 2001; Sharp, 2007). A C:N ratio of ~10–20 marks the transition from primarily aquatic (< 10) to primarily terrestrial (> 20) organic matter (Meyers and Teranes, 2002). All isotope values include error, which is expressed as the standard deviation for the duplicate samples at the same stratigraphic level.

4.5 Results

4.5.1. The Danta and Carse Sediment Profiles

In total, we collected a 434-cm sediment profile from Laguna Danta and a 714-cm sediment profile from Laguna Carse (Figure 4.4). The basal sediments of the Laguna Danta profile contain large angular rock fragments that we interpret as landslide deposits. At Carse, the base of the profile consists of dense, fine mineral sediment, white

(Munsell 2.5 YR 8/1) in color. The Laguna Danta profile shows variable colors and sediment texture, which ranges from coarse organic sediment to fine mineral silts and clays. The Laguna Carse profile is fairly consistent, with most of the core consisting of silty sediments. The sediment profiles for both lakes show intervals of fine laminations, especially in Laguna Carse.

4.5.2 Radiocarbon Ages and Age-Depth Models

The radiocarbon dates on the two profiles show one age reversal in Laguna Danta and indicate that both profiles are fairly young (Table 4.1). The Bacon age-model rejected one radiocarbon date that was too old for its stratigraphic position while fitting the remaining dates (Figures 4.5 and 4.6). The Laguna Danta sediment profile has a modeled basal age of ~800 cal yr BP and the Laguna Carse sediment profile has a modeled basal age of ~350 cal yr BP. The Laguna Danta profile contains a record of pre-LIA fire activity, the entirety of the LIA, Spanish contact, and the interval from the end of the LIA in 1850 CE to present, while the Laguna Carse record covers the second half of the LIA until ca. 1980 CE. Mean sediment accumulation rates are 0.5 cm/yr for Laguna Danta and 1.8 cm/yr for Laguna Carse. These rates are much higher than modeled for other lakes in southern Pacific Costa Rica (Anchukaitis and Horn, 2005; Clement and Horn, 2001) and provide an opportunity to develop records of fire history at very high temporal resolution.

4.5.3 Organic Matter, Organic Carbon, Nitrogen, and C:N ratios

In the Laguna Danta record, organic matter (OM) percentages generally increase upward in the core, with low values before the LIA, and highest average values after the LIA (Figure 4.7). The Laguna Carse record begins at roughly the midpoint of the LIA and shows a similar pattern of higher OM values after the LIA, at least initially (Figure 4.8). Percent organic carbon and percent nitrogen values show matching trends in each profile. In the Laguna Carse record, the organic carbon and nitrogen values strongly mirror the percent organic matter curve based on LOI analysis. C:N ratios in the Laguna Danta (Figure 4.7) and Laguna Carse (Figure 4.8) records show only slight variation, with one sharp rise in the Laguna Carse record at ~160 cal yr BP. This peak in C:N ratio suggests an increase in terrestrial carbon input possibly linked to a deforestation event in the watershed (Kaushal and Binford, 1999). The C:N ratios for both lakes indicate a combination of terrestrial and aquatic carbon inputs over their histories.

4.5.4 Macroscopic Charcoal

The Laguna Danta macroscopic charcoal record (Figure 4.9) shows local fire activity at a resolution of ca. 4 years for the last 750 years. The record includes major peaks in charcoal, interpreted to indicate peaks in fire activity, at ~600 cal yr BP, ~500 cal yr BP, and from 350–300 cal yr BP, with lesser peaks at ~660, ~450, and ~400 cal yr BP. The earliest charcoal peak (~600 cal yr BP) occurs roughly 50 years prior to the onset of the LIA, on the rising edge of a prominent positive shift in the $\delta^{13}C_{OM}$ curve that we

interpret to indicate agricultural expansion in the Laguna Danta watershed. The second major charcoal peak (~500 cal yr BP) coincides with a sharp decline in maize agriculture as inferred from the $\delta^{13}C_{OM}$ curve. The third, broad charcoal peak from ca. 350–300 cal yr BP indicates high fire activity for a prolonged period. Between these major peaks, minor peaks in charcoal at 450 and 400 cal yr BP bracket the timing of the arrival of the Spanish in southern Pacific Costa Rica.

The Laguna Carse macroscopic charcoal record (Figure 4.10) shows local fire activity at a resolution of ca. 1 year between 340 and 250 cal yr BP and 4 years for the last ~250 years. The Laguna Carse record contains peaks in charcoal at ~325 and 300 cal yr BP, at ~225–200 cal yr BP, and between ~40 cal yr BP and -20 cal yr BP. The first major charcoal peak (~325 cal yr BP) coincides with the broad charcoal peak in the Laguna Danta record. The charcoal peak at Laguna Carse from ~225–200 cal yr BP occurs just in advance of a large positive shift in the $\delta^{13}C_{OM}$ curve (~200 cal yr BP). The pattern indicates increased forest clearance and burning of the landscape for agriculture, followed by an increase in maize cultivation and a positive shift in $\delta^{13}C_{OM}$. This agricultural activity at Laguna Carse coincides with a period of increasing $\delta^{13}C_{OM}$ values at Laguna Danta. The multiple charcoal peaks in the upper 2 m of the Laguna Carse record are likely associated with modern agricultural practices near the lake, which based on the charcoal data must include some burning of pastures or nearby agricultural fields.

4.5.5 Stable Carbon and Nitrogen Isotope Ratios

The stable carbon isotope ratios for Laguna Danta (Figure 4.9) and Laguna Carse (Figure 4.10) show periods of inferred increases in maize agriculture followed by declines and forest recovery. At Laguna Danta, a major shift toward more positive $\delta^{13}C_{OM}$ values occurs between 620 and 580 cal yr BP. This +10‰ shift in $\delta^{13}C_{OM}$ represents a major change in the watershed vegetation interpreted to signal initial clearance of C_3 forests and their replacement by agricultural fields with C_4 crops and agricultural weeds. Following the positive $\delta^{13}C_{OM}$ peak (-15.04‰) at 580 cal yr BP, there is a brief reversal (-24.67‰) at 560 cal yr BP, before the curve shifts positive again by 545 cal yr BP (-14.22‰). $\delta^{13}C_{OM}$ values then remain high until ~500 cal yr BP, before dropping to more negative values coincident with a large peak in charcoal influx. Near the top of the Laguna Danta record, a second shift (+10‰) in the $\delta^{13}C_{OM}$ occurs more gradually over the period 160–50 cal yr BP.

The Laguna Carse isotope record shows two major shifs in the $\delta^{13}C_{OM}$ curve at 200 cal yr BP and another at 160 cal yr BP. The major shift (+27‰) at 200 cal yr BP shows values that are considerably out of the expected range for organic matter, and could indicate a laboratory problem. Possibly, the fumigation technique we used left some residual carbonate in the samples. We discount this peak and will be reanalyzing samples from this portion of the core. However, the peak at 160 cal yr BP shows a pattern signaling the replacement of C3 by C4 vegetation that we interpret as evidence of forest clearance and increased agricultural activity. Shortly following the latter shift

in $\delta^{13}C_{OM}$ values, a decline occurs at ca. 150 cal yr BP suggesting decreased agricultural use and forest recovery. Minor shifts in the Laguna Carse $\delta^{13}C_{OM}$ curve occur following the LIA (~100 cal yr BP) and in historic times (~50 cal yr BP).

Sedimentary stable nitrogen isotope ratios ($\delta^{15}N_{OM}$) vary through the profiles by 5‰ at Laguna Danta and 3‰ at Laguna Carse, with a general trend of increasing $\delta^{15}N_{OM}$ values over time at both sites. A general lagging pattern of increases in $\delta^{15}N_{OM}$ values following large charcoal peaks is noticeable, with decreases in $\delta^{15}N_{OM}$ values at 50–70 years following the fire event.

4.6 Discussion

4.6.1 Late Holocene Fire History at Laguna Danta and Laguna Carse

The high-resolution records of fire history from Laguna Danta and Laguna Carse document repeated fires across the Little Ice Age in southern Pacific Costa Rica, with fires beginning shortly after lake formation at ca. 750 cal yr BP at Laguna Danta and extending to recent decades at Laguna Carse. We interpret the near continuous presence of charcoal across both profiles to primarily indicate burning associated with indigenous and modern agricultural practices, but with peaks in charcoal driven by intervals of drier climate that led to wildfires and increased areas burned.

The profile from Laguna Danta shows a cyclical pattern in charcoal influx that suggests major fire events at an interval of ca. 100 years until 300 cal yr BP. The broad

charcoal peak beginning ca. 350 cal yr BP that marks the most recent period of major fire activity at Laguna Danta matches a similarly broad peak beginning ca. 340 cal yr BP in the Laguna Carse record. This matching charcoal peak provides support for the Laguna Carse age model. We interpret this interval of high charcoal influx at both lakes to represent an extended period of drought in the region, which is supported by regional reconstructions of ITCZ position (Figure 4.11).

Based on a study of charcoal and nitrogen records from a lake in the Rocky Mountains, Dunnette et al. (2014) suggested that sedimentary stable nitrogen isotope ratios ($\delta^{15}N_{OM}$) should increase following major peaks in fire activity and then subsequently decline as forests recover and terrestrial N availability declines. Fires lead to nitrogen losses due to volatilization where ^{14}N is preferentially released to the atmosphere resulting in more positive sedimentary N stable isotope ratios ($\delta^{15}N_{OM}$) and percent N (Dunnette et al., 2014; Johnson et al., 1998; Nave et al., 2011; Saito et al., 2007; Turekian et al., 1998). Greater nitrogen shifts are expected from canopy fires in coniferous vegetation than from agricultural fires or surface fires as expected for most wildfires in a tropical moist forest. The Laguna Danta record shows some evidence of increases in $\delta^{15}N_{OM}$ following major peaks in fire activity with the values then declining ~50–70 years after the charcoal peak (Figure 4.12), following the pattern documented by Dunnette et al. (2014). Research has shown that the magnitude of shifts in nitrogen biochemistry in a watershed is directly related to the intensity of the fire event as reconstructed from soil and vegetation (Stephan et al., 2015), which suggests that lower-

intensity burns as evidenced from the Laguna Danta and Laguna Carse charcoal records may potentially produce less discernable shifts in our nitrogen lake sediment proxies. However, some peaks in $\delta^{15}N_{OM}$ are not associated with charcoal evidence of local fires, suggesting other factors have driven nitrogen input in the watersheds.

The fire history of the Laguna Danta watershed shows a marked decline in major fire events and charcoal influx at ~300 cal yr BP, with low charcoal influx extending to the present. At Laguna Carse, charcoal influx declines after ~275 cal yr BP, shows a brief resurgence from 225–200 cal yr BP, and then remains low until the twentieth century, when fire increases in association with modern anthropogenic actions in the watershed, perhaps representing new agricultural and land-management techniques.

Evidence of late Holocene fires in sediment records from lakes and wetlands in the Costa Rican lowlands is commonly attributed to fires set by people in connection with forest clearance and agricultural practices (Anchukaitis and Horn, 2005; Arford and Horn, 2004; Clement and Horn, 2001; Kennedy and Horn, 2008; Northrop and Horn, 1996). However, wildfires linked to multidecadal droughts are also a potential source of charcoal in lake sediment records in Costa Rica (Anchukaitis and Horn, 2005; Horn and Sanford, 1992). Distinguishing between natural wildfires and anthropogenic burning requires developing proxies for maize agriculture, such as pollen and stable carbon isotope ratios.

A sediment record from nearby Laguna Los Mangos (Chapter 3 of this dissertation) provides a ~4300-year record of pre-Columbian agriculture and fires,

including fires that preceded evidence of landscape modification for maize agriculture. From ~4200 to 3600 cal yr BP, there is minimal evidence for agriculture in the watershed, but microscopic charcoal concentrations indicate the occurrence of fires. This period predates the earliest maize agriculture in the region (Horn, 2006), and the fires recorded at Laguna Los Mangos at this time may have been hunting fires, or wildfires ignited accidentally by people, or by lightning or volcanism. The nearest volcanoes active during pre-Columbian time are Volcán Barú (8.8088° N, 82.5423° W) in western Panama and Volcán Turrialba (10.0163° N, 83.7649° W) in central Costa Rica, both located 90–100 km from the lake sites. Prior to the development of modern road networks, fires ignited by volcanic activity may have spread unimpeded over large distances.

Some of the charcoal peaks in the Laguna Danta and Laguna Carse records could be from wildfires ignited by natural sources during dry periods that facilitated fire spread. In other cases, peaks in charcoal may reflect the interplay of people and nature, with drier climate leading to greater burning by increasing the likelihood that agricultural fires will burn out of control and spread into adjacent intact or regenerating forests. In some cases, the fires recorded at the lakes are closely associated with increases in agricultural activity in the watersheds or related to social changes influenced by Spanish contact in the region.

4.6.2 Settlement, Agriculture, and Fire History at Laguna Danta and Laguna Carse

Stable carbon isotope ratios for Laguna Danta and Laguna Carse show wide swings that indicate two distinct periods of maize agriculture carried out by people living at or near the lakes. The strong positive shift in $\delta^{13}C_{OM}$ at ~600 cal yr BP in the Danta record follows a peak in fire activity in the watershed and signals forest clearance and the beginning of maize agriculture at the lake. Charcoal influx shows a second major peak (largest in the record) at ~500 cal yr BP, when agricultural activity declines. The peak in charcoal and agricultural decline at ~500 cal yr BP is temporally associated with the onset of the LIA and we infer that drought at this time reduced the extent of maize agriculture in the Danta watershed and led to widespread fires. These fires may have been set intentionally by people to clear more land to overcome poor agricultural yields, or may have been wildfires that burned adjacent forests that could support fire under drought conditions. The agricultural decline also occurs at the approximate time of initial Spanish contact in Central America (~450 cal yr BP or 1500 CE). Spanish presence in the Diquís subregion of southern Pacific Costa Rica likely did not occur until 400 cal yr BP (1550 CE), but diseases may have spread rapidly following initial contact.

Following the decline in agriculture, maize cultivation appears to have ceased in the watershed. However, fires continued to burn, showing patterns that appear to match regional climate trends. The strong fire activity at ~350–275 cal yr BP in both the Danta and Carse records is not associated with maize agriculture and likely reflects wildfires promoted by regional drought during a time of low human population density

in southern Pacific Costa Rica. These fires would have burned forests recovering after the post-Conquest population decline. Fire activity coinciding with intervals of drought is a large component of the fire history of the southern Pacific lowlands.

Our Laguna Danta and Laguna Carse records show a return of maize agriculture to the local region during the colonial period. Approximately 25 years after the Spanish relocated members of the Térraba indigenous community to the vicinity of Laguna Carse (1697 CE; Pittier 1941; Stone 1962), the sediments show evidence of fire. We interpret the evidence of fire beginning ca. 225 cal yr BP (1725 CE) to possibly signal fires associated with anthropogenic forest clearance and initial maize agriculture in the Carse watershed, although the aberrant values in the $\delta^{13}C_{OM}$ curve complicate our interpretation.

Paleoenvironmental analyses of other lakes in the southern Pacific region of Costa Rica have revealed evidence of near immediate anthropogenic activity in watersheds after lake formation, in the form of evidence of maize agriculture in both pollen and stable carbon isotope records (Anchukaitis and Horn, 2005; Clement and Horn, 2001; Kerr, 2014; Taylor et al., 2013b). Freshwater lakes are important microhabitats that add stability and diversity to the employed subsistence strategy when contrasted to the closed forests composing much of the vegetation surrounding the lake sites in Costa Rica (Gremillion et al., 2014). Settlement in the Laguna Danta and Laguna Carse watersheds, as inferred from maize agriculture, does not follow this trend of immediate exploitation of the lake resources but instead shows evidence of a delay of a

century or so at both sites. We hypothesize the delay in people using Laguna Carse to be unique to the recent age of the lake, which dates to the colonial period. At this time, populations in the immediate area were likely low, following the post-Conquest population decline. Our sediment analyses suggest that the area around Laguna Carse was sparsely populated until the relocation of indigenous communities, which occurred in the late 1700s, and which roughly coincides with an increase in fire, and is followed by agricultural activity in the watershed. In contrast, pre-Columbian peoples may have exploited the lacustrine resources at Laguna Danta for some time before beginning maize cultivation in the watershed. Laguna Danta formed during the Chiriquí archaeological period, when population levels were higher in southern Pacific Costa Rica.

More recent fire activity in the upper portion of the Carse profile corresponds to fire activity linked to the establishment or maintenance of agricultural fields and cattle pastures during the 20th century. Modern indigenous communities in Latin America have demonstrated growing interest in reinstating "traditional" land-use practices linked with sustainable-yield agriculture from before Spanish contact within indigenous communities (Bebbington and Carney, 1990; Doolittle, 1992; Lambert et al., 1984; Sluyter, 1994). While fire activity is nearly continuous across the records for Laguna Danta and Laguna Carse, the recent (last ~100 years), sustained high charcoal influx at Laguna Carse suggests differing land-management practices, involving more burning, than those that prevailed over the last ~800 years in the southern Pacific zone of Costa Rica.

4.6.3 Climate Trends and Fire History for Laguna Danta and Carse

Periods of burning and inferred agricultural decline in the Danta and Carse records show relationships with regional records of drought provided by the Cariaco Ti record of ITCZ position (Haug et al., 2001) (Figure 4.11). The large peak in fire activity and sharp decline in maize agriculture at Laguna Danta occurred ~50 years after the decline in Ti concentration in the Cariaco record that marks the onset of the LIA at ~550 cal yr BP. The decline in Ti concentration in the Cariaco record during the LIA is interpreted to indicate a southward migration of mean annual position of the ITCZ, resulting in drier and cooler conditions in southern Pacific Costa Rica. A local chironomid-based climate reconstruction at Laguna Zoncho (Wu et al., 2016) indicated a 1.3 °C lower than average mean annual air temperature (MAAT) associated with the LIA. The LIA in southern Pacific Costa Rica can be characterized as having cooler conditions, less productive for agriculture (Wu et al., 2016). The onset of the LIA, and of Spanish contact, coincide with agricultural decline in the Laguna Danta record. This decline is interpreted as the result of a population decline or of migration out of the lowland watersheds. Changes to the regional climate during the LIA likely produced extensive droughts driven by ITCZ dynamics and the weakening of the Central American Monsoon. The Danta record, which spans the LIA, shows high fire activity during the LIA independent of signals of agricultural activity.

ENSO activity has been linked to reduced precipitation from the Central American Monsoon for southern central America (Lachniet, 2004). In our records, we

see peaks in fire activity that roughly coincide with increases in El Niño events, or negative phase ENSO. During much of the LIA, when the population density was low in southern Pacific Costa Rica following Spanish contact, the relationship between our charcoal record and both ENSO activity and ITCZ position indicates that drought rather than anthropogenic activity on the landscape was the primary driver of fire.

4.6.4 Comparison of Fire Activity Across Southern Pacific Costa Rica and the Americas

Our high-resolution records of fire history at our low elevation sites (470 m and 366 m) in the northwestern portion of the Diquís archaeological subregion of southern Pacific Costa Rica shows some differences from records from two mid-elevation sites in the southeastern portion near the Panamanian border—Laguna Zoncho (1190 m) and Laguna Santa Elena (1100 m). At Laguna Santa Elena, Anchukaitis and Horn (2005) examined both microscopic and macroscopic charcoal, but at a lower temporal resolution than at Laguna Danta and Carse. Clement and Horn (2001) tallied microscopic charcoal on pollen slides from Laguna Zoncho, also at lower temporal resolution than the present study. The record from Laguna Santa Elena and Laguna Zoncho both show evidence of fires during the Aguas Buenas and Chiriquí archaeological periods, but fire activity at both sites declined markedly during the last ~750 years, while Laguna Danta and Laguna Carse show continued fire activity. The timing of the decline in fire activity differs between the two eastern mid-elevation sites (Santa Elena first at ~1300 cal yr BP and again at ~550 cal yr BP; Zoncho at ~500 cal yr

BP); however, both records do show declines in fire activity. Fire activity at Laguna Santa Elena appears less variable over time in comparison with our sites of Laguna Danta and Laguna Carse, with more consistent macroscopic charcoal influx values from level to level and a smoother overall trend. While some of this difference can be attributed to the lower sampling resolution at Laguna Santa Elena, the comparison suggests a different fire history at this mid-elevation site near the modern border with Panama than at our low elevation sites located to the north.

The timing of agricultural decline at Laguna Zoncho and Laguna Santa Elena differs from the timing at Laguna Danta and Carse. Based on high-resolution stable carbon isotope analyses of multiple cores recovered from Laguna Zoncho in 2007, Taylor et al. (2013a, 2013b, 2015) inferred two periods of agricultural decline, 1150–970 and 860–640 cal yr BP. This work followed initial isotope work by Lane et al. (2004) on the 1997 core examined by Clement and Horn (2001), which also showed evidence for agricultural decline prior to the Spanish Conquest. Despite the presence of maize pollen following these declines, carbon isotope ratios and organic matter concentrations suggest reduced agricultural practices in the watershed (Taylor et al., 2013a).

At Laguna Santa Elena, Anchukaitis and Horn (2005) noted pollen evidence for forest recovery and agricultural decline at ~700 cal yr BP, and inferred a further decline in agricultural activity and population at ~540 cal yr BP. Kerr (2014) examined stable carbon isotopes in the Santa Elena core and found a similar pattern of agricultural

decline at ~700 cal yr BP with $\delta^{13}C_{OM}$ ratios after that time indicating limited maize cultivation in the watershed until modern times.

Thus agricultural decline at Laguna Zoncho (Taylor et al., 2013a; 2015) and Laguna Santa Elena (Anchukaitis and Horn, 2005; Kerr, 2014) occurred ahead of Spanish contact and the LIA. In contrast, the northwestern lowland sites of Laguna Danta and Laguna Carse show agricultural decline coinciding with Spanish contact and the onset of the LIA.

At both Zoncho and Santa Elena, fire activity reconstructed from sedimentary charcoal coincided with agricultural activity and declined after forest recovery. At Santa Elena, macroscopic charcoal influx values were high during the Aguas Buenas and Chiriquí archaeological periods, but low through the post-Contact period, including the LIA (Anchukaitis and Horn, 2005). Here, climate conditions during the LIA do not appear to have promoted fires. This difference in fire history across a fairly small spatial area may indicate differential local effects of climate. Additionally, differences in social conditions potentially linked to location within the Diquís subregion and proximity to outside populations could have influenced the timing of declines in agriculture and fire. Decreased agricultural productivity because of cooler, drier climate during the LIA and increased morbidity related to Spanish contact likely increased social conflict in the region. The proximity to larger population centers in western Panama may have made people living in the southeastern Diquís archaeological subregion more vulnerable to conflict or warfare.

Across the Americas, fire activity declined at many sites after ~450 cal yr BP, coincident with Spanish contact but also closely following the onset of the LIA (Power et al., 2013). Based on their synthesis of charcoal records across the Americas and the world, Power et al. (2013) concluded that this reduction in biomass burning was driven more by climate than by indigenous population collapse. However, in Central America, southern Mexico, and the Caribbean, the idea of reduced fires during the LIA appears to contradict observations that fires are more common during periods of drier climate. Our new charcoal records for Laguna Danta and Laguna Carse emphasize that contradiction as they indeed show increased biomass burning during the first half of the Little Ice Age that appears to be driven by drought. Only in the later part of the Little Ice Age, after ~300 cal yr BP, does biomass burning show a decline at our sites. The very different pattern of fire activity over the Little Ice Age revealed by our high-resolution macroscopic charcoal analyses at Laguna Danta and Laguna Carse underscores the need for additional fire history records from the northern Neotropics, to support more detailed analyses of the relationships between fire history and climate in the northern Neotropics.

4.7 Conclusions

This study presents high-resolution charcoal records that show effects attributed to both the LIA and the Spanish Conquest. Close similarity between the Cariaco Ti curve and the macroscopic charcoal record at Laguna Danta suggest that drought was

an important driver of fire history in the lowlands of southern Pacific Costa Rica across the LIA. Indicators of agricultural activity in our records sharply declined following the onset of the LIA and Spanish contact in the region. But fires continued, indicating that local forest clearance and agricultural activity were not the only sources of fire at the study sites. We infer that wildfires set unintentionally by humans or ignited by lightning or volcanism spread across southern Pacific landscapes during the LIA in Costa Rica.

Our agricultural proxies from Laguna Danta show patterns of decline coinciding with the onset of the LIA and Spanish contact, while the southeastern, mid-elevation sites of Laguna Zoncho and Laguna Santa Elena show earlier agricultural decline. Fire histories also diverge, with Laguna Zoncho and Laguna Santa Elena showing sharp declines in charcoal following the onset of the LIA and Spanish contact. This difference in fire activity suggests the local effects of the LIA on fire history in southern Pacific Costa Rica were more pronounced at the northwestern, lowland sites. The continuation of fires across the LIA at Laguna Danta and Carse also contrasts with the global and regional synthesis of Power et al. (2013), from which we would expect a strong decline in fire coinciding with the LIA for Costa Rica.

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4.10 Appendix

Table 4.1. Radiocarbon determinations from the Laguna Danta 2014 and Laguna Carse 2014 cores.

Lab Number [a]	Core Site	Depth (cm)	Uncalibrated ^{14}C Age (^{14}C yr BP)	±2 σ Cal. Age Range [c] (cal yr BP)	Area Under Probability Curve	Material
DAMS-006456	Laguna Danta	136	143 ± 21	37–6	0.181	leaf
				118–65	0.217	
				152–124	0.120	
				231–170	0.315	
				281–243	0.168	
DAMS-014530	Laguna Danta	199	603 ± 28 [b]	573–544	0.250	reed
				652–577	0.750	
UGAMS-17834	Laguna Danta	265	370 ± 20	377–321	0.348	leaf
				499–428	0.652	
DAMS-014531	Laguna Danta	353	677 ± 25	592–563	0.363	leaf
				676–638	0.637	
DAMS-014527	Laguna Carse	312	206 ± 24	14–1	0.128	charcoal
				190–146	0.473	
				214–191	0.087	
				301–268	0.312	
UGAMS-19747	Laguna Carse	509	170 ± 20	31–1	0.193	leaf
				157–138	0.113	
				222–165	0.508	
				285–258	0.187	
DAMS-014528	Laguna Carse	608	306 ± 27	337–301	0.244	leaf
				459–348	0.756	
DAMS-014529	Laguna Carse	643	199 ± 24	19–1	0.153	leaf
				215–145	0.585	
				298–267	0.262	
UGAMS-19460	Laguna Carse	696	350 ± 20	399–316	0.552	wood
				405–405	0.002	
				487–422	0.446	

[a] Analyses were performed by Direct AMS (D-AMS) and by the Center for Applied Isotope Studies at UGA (UGAMS).

[b] Sample interpreted as redeposited plant material and not included in the age model.

[c] Calibrations were made using CALIB version 7.0.4 (Stuiver and Reimer, 1993) and the IntCal 13 dataset (Reimer et al., 2013).

Figure 4.1. Location of Laguna Danta and Laguna Carse in southern Pacific Costa Rica. Insert shows position of study in Costa Rica. Map also shows the location of the comparison site of Laguna Los Mangos. 90-m DEM Data from CGIAR-CSI. Aerial imagery modified from ESRI, DigitalGlobe and CGIAR-CSI.

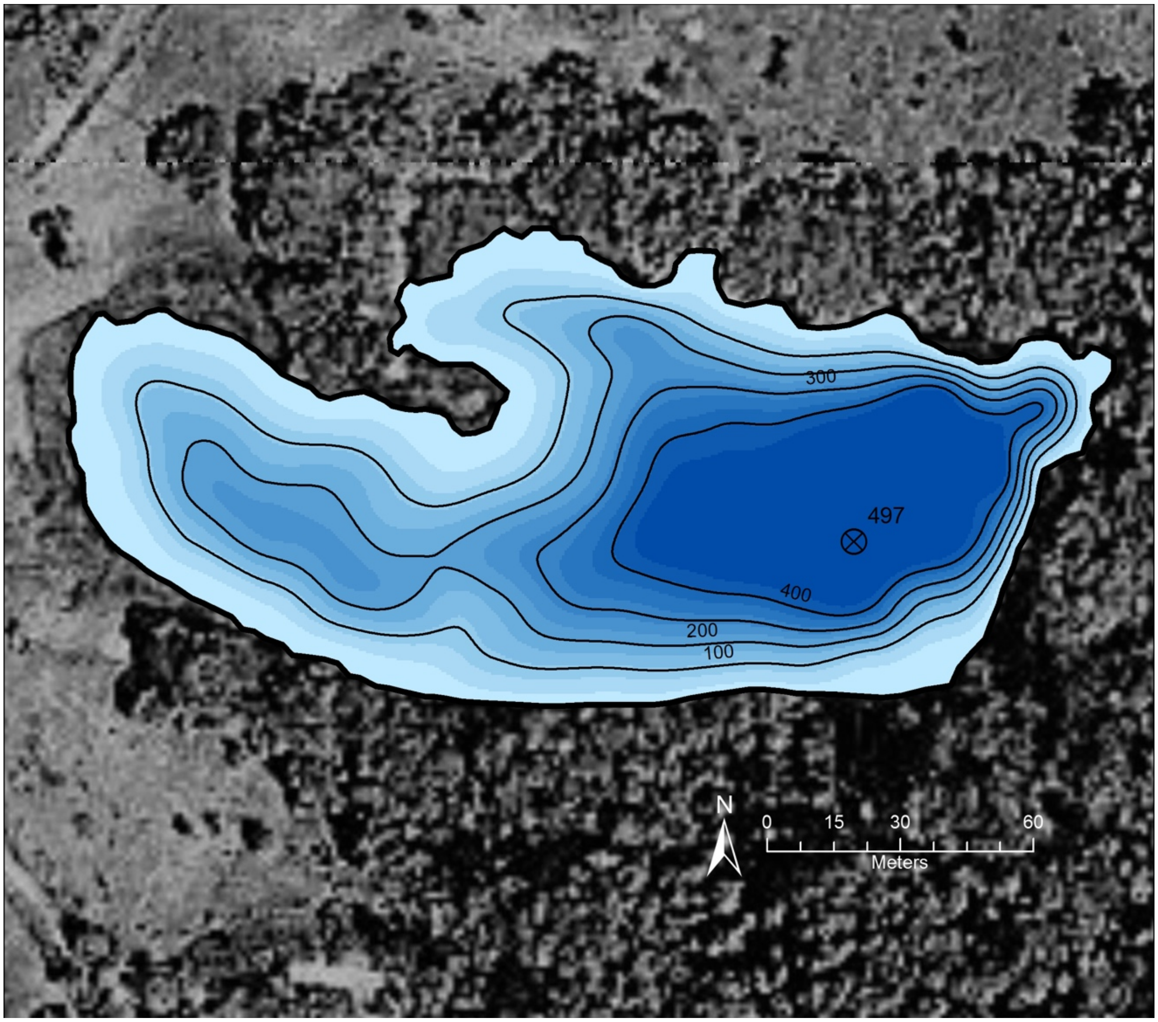

Figure 4.2. Bathymetry of Laguna Danta with coring location indicated. Lake depths (shown in cm) surveyed in March 2014 with bathymetry calculated using a spline function. Aerial Imagery modified from ESRI, DigitalGlobe.

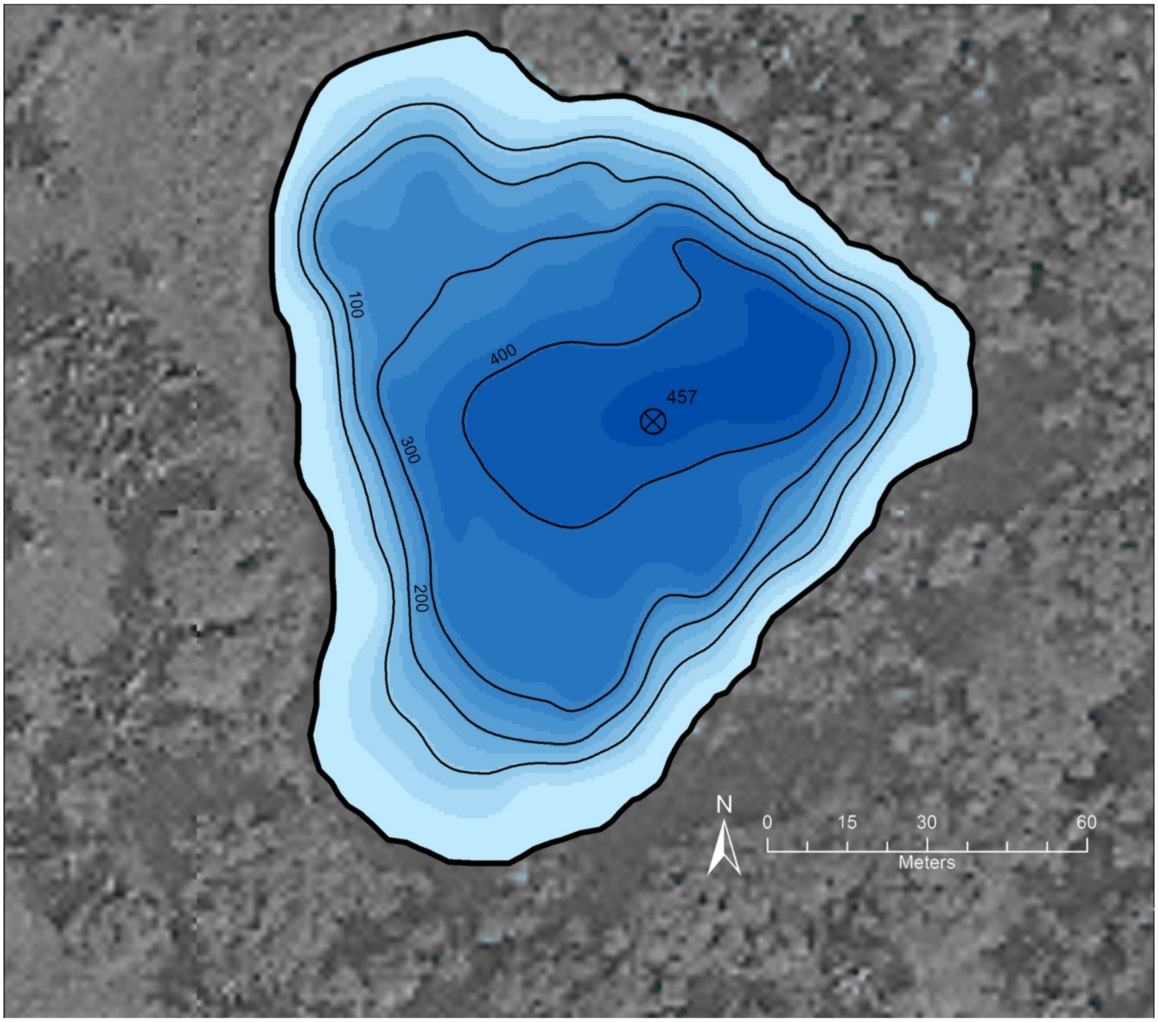

Figure 4.3. Bathymetry of Laguna Carse with coring location indicated. Lake depths (shown in cm) surveyed in July 2014 with bathymetry calculated using a spline function. Aerial Imagery modified from ESRI, DigitalGlobe.

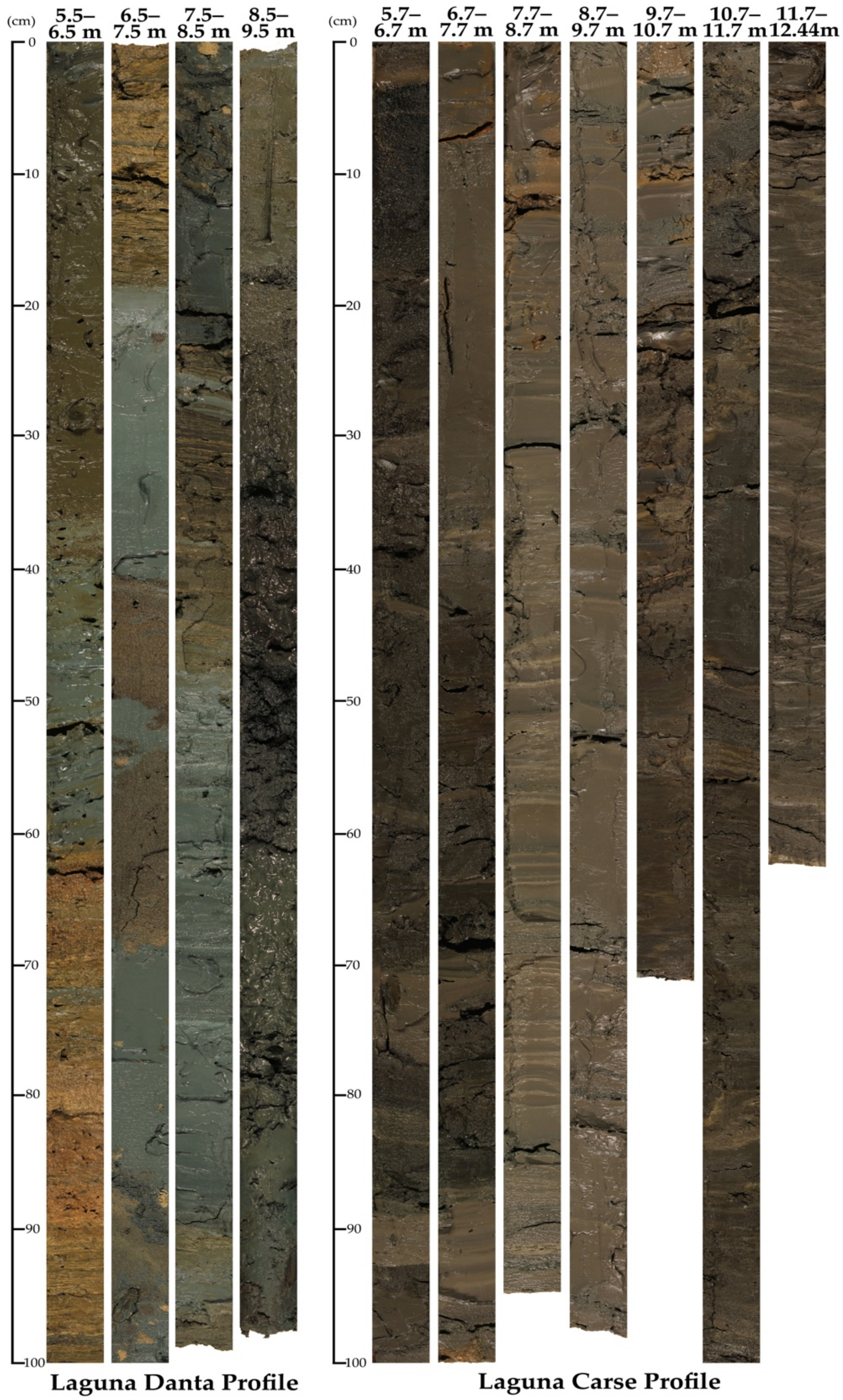

Figure 4.4. Sediment core sections from Laguna Danta and Laguna Carse. Depth ranges above photos are drive depths including water depth and height of platform.

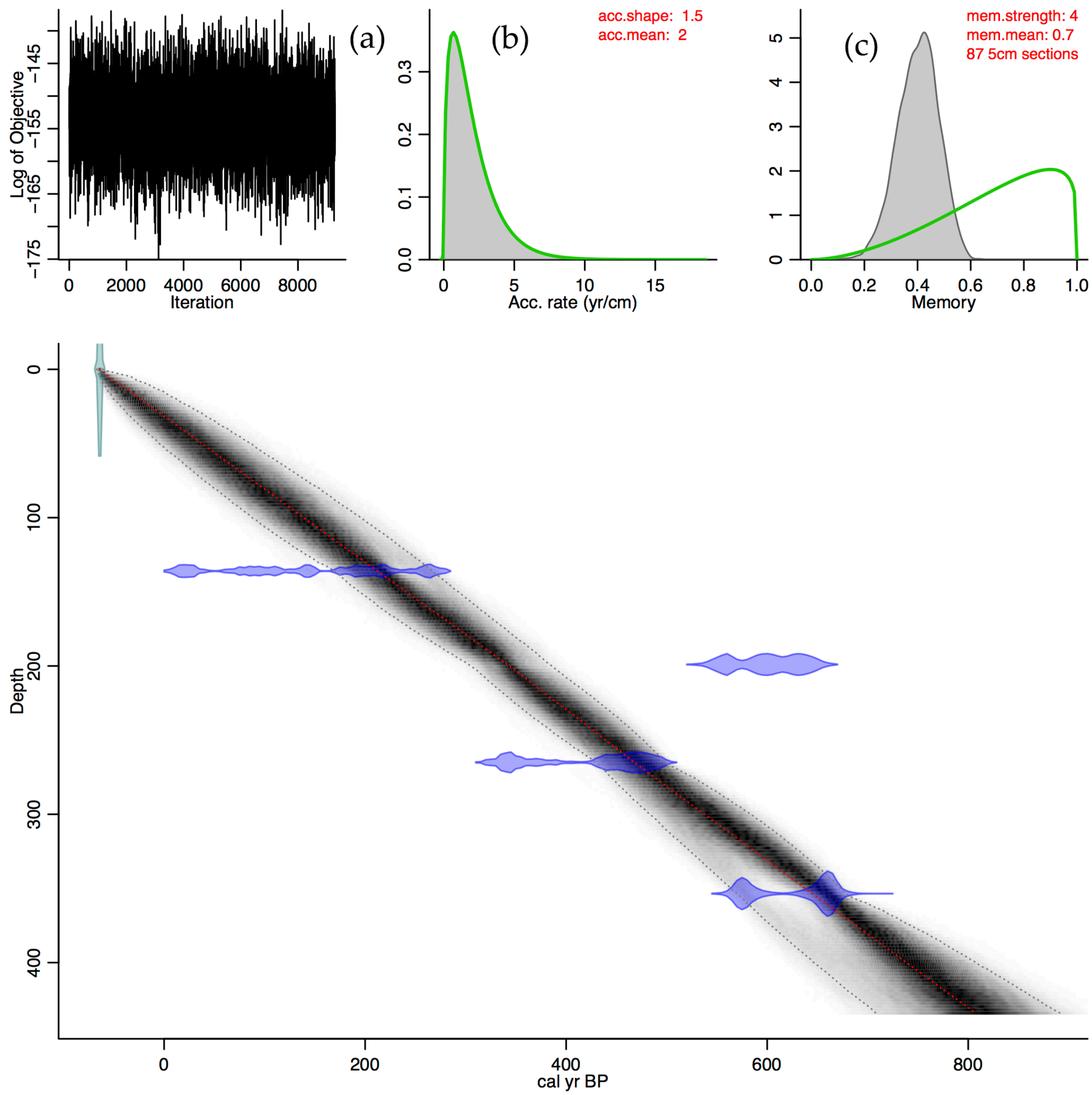

Figure 4.5. Age-depth model for Laguna Danta 2014 profile from southern Pacific Costa Rica. (a) MCMC iterations with stationary distributions ideal. (b) The accumulation rate consists of a gamma distribution with adjusted accumulation shape and mean values (Blaauw and Christen, 2011). (c) The memory value, or autocorrelation, defines how much the accumulation rate of a particular depth in a core depends on the depth above it. Assuming a low memory or autocorrelation, the accumulation rate would change greatly over time (highly variable environmental conditions), while a high memory implies a more constant accumulation (Blaauw and Christen, 2011).

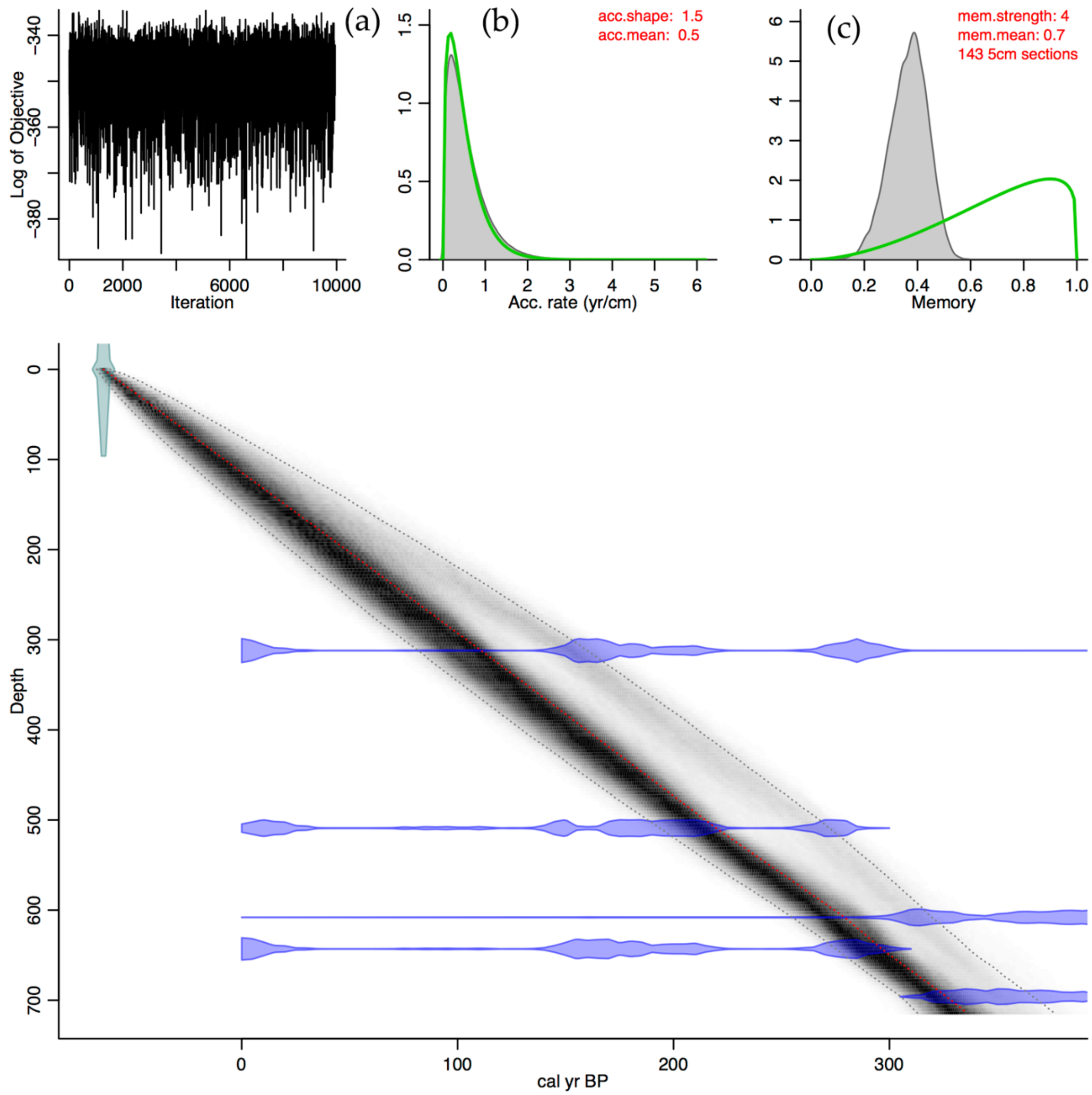

Figure 4.6. Age-depth model for Laguna Carse 2014 profile from southern Pacific Costa Rica. (a) MCMC iterations with stationary distributions ideal. (b) The accumulation rate consists of a gamma distribution with adjusted accumulation shape and mean values (Blaauw and Christen, 2011). (c) The memory value, or autocorrelation, defines how much the accumulation rate of a particular depth in a core depends on the depth above it. Assuming a low memory or autocorrelation, the accumulation rate would change greatly over time (highly variable environmental conditions), while a high memory implies a more constant accumulation (Blaauw and Christen, 2011).

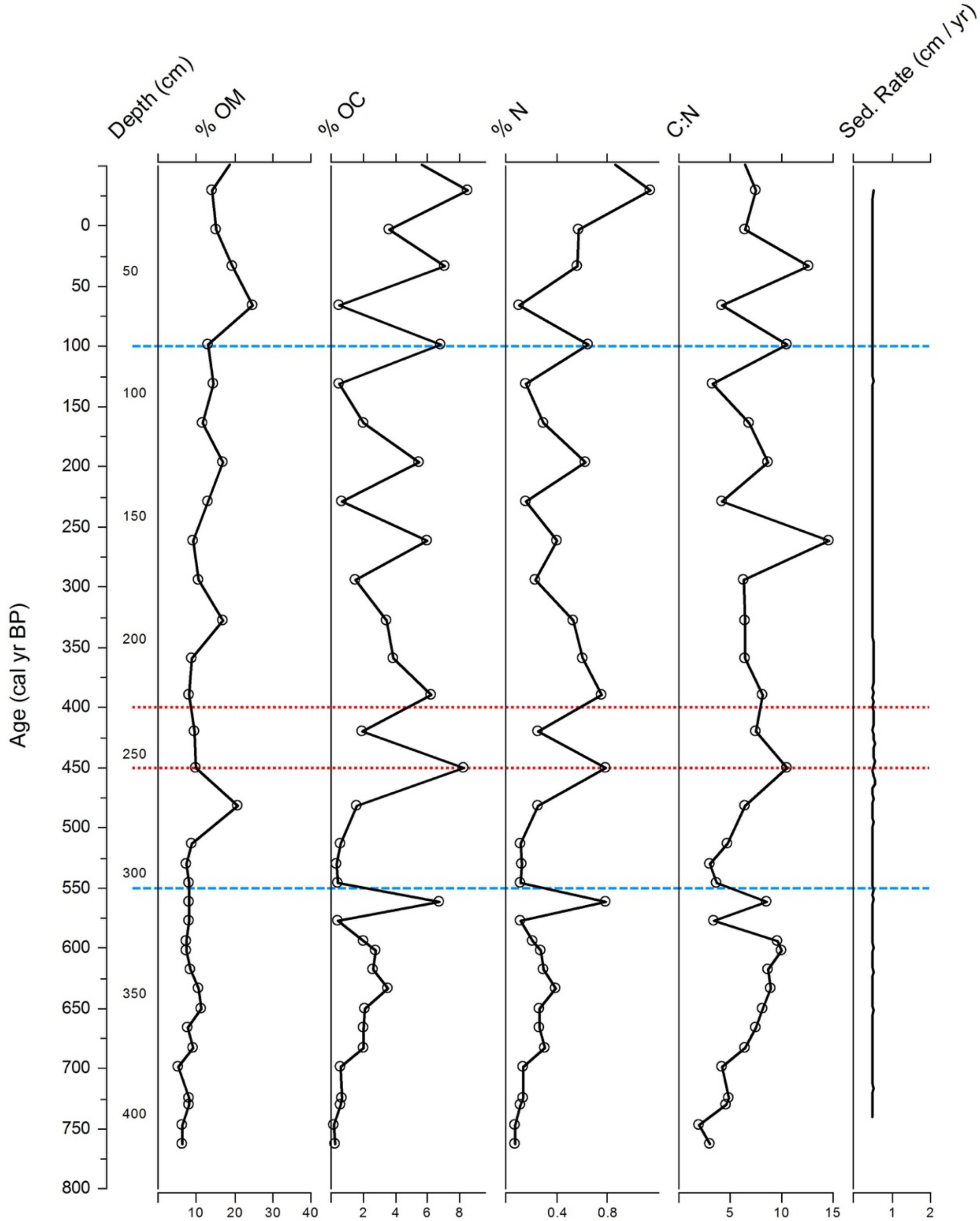

Figure 4.7. Laguna Danta sediment composition based on LOI and geochemical analyses, and sediment accumulation rate based on the Bacon age model. Red dotted lines bracket the timing of Spanish contact (~450–400 cal yr BP). Blue dashed lines delineate the LIA (~550–100 cal yr BP).

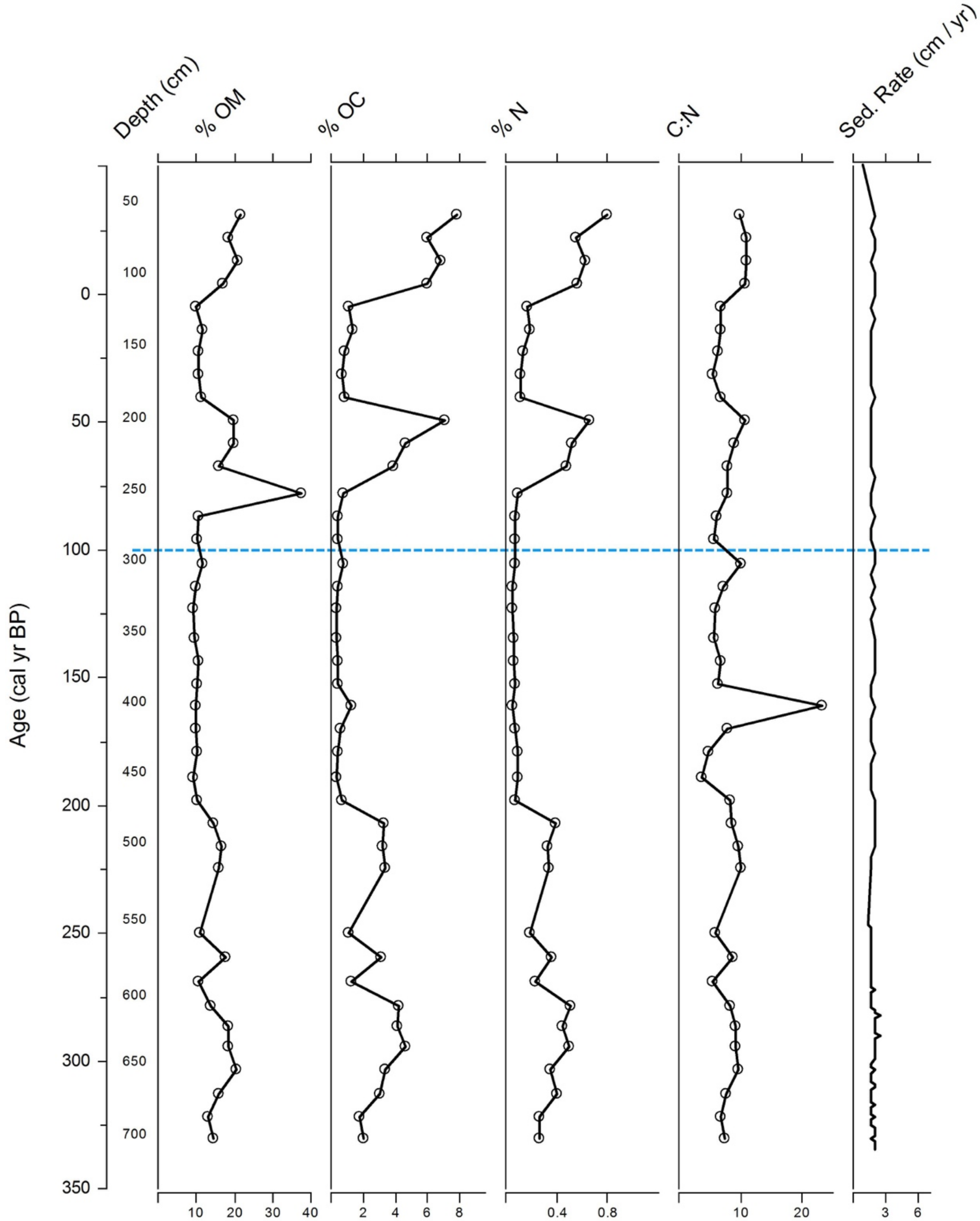

Figure 4.8. Laguna Carse sediment composition based on LOI and geochemical analyses, and sediment accumulation rate based on the Bacon age model. Blue dashed line represents the end of the LIA (~550–100 cal yr BP).

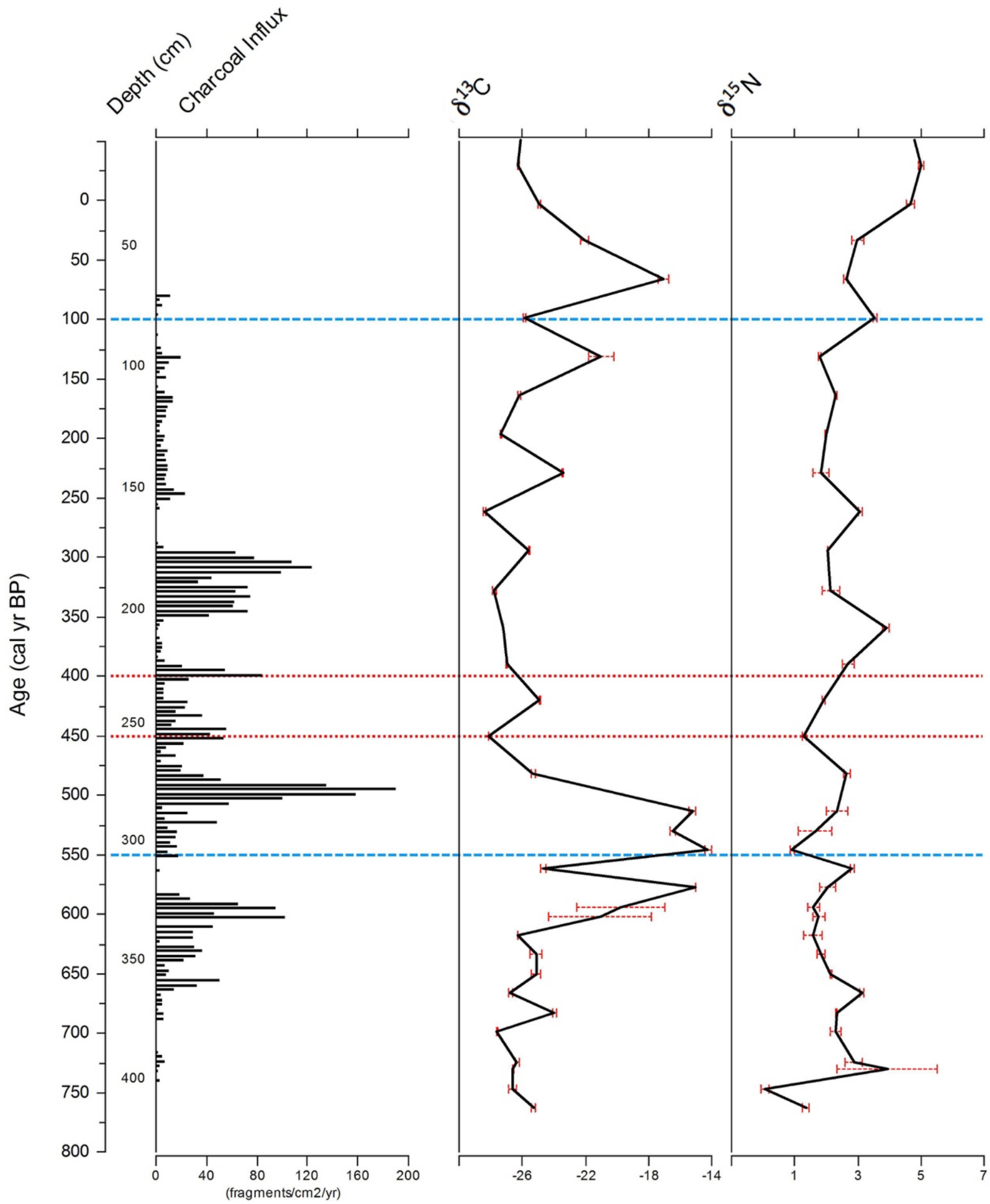

Figure 4.9. Laguna Danta charcoal influx and geochemical proxies. Red dotted line bracket the timing of Spanish contact (~450–400 cal yr BP). Blue dashed lines delineate the LIA (~550–100 cal yr BP). Charcoal influx values after 80 cal yr BP are too low to be visible in the graph; all samples contained some charcoal, but influx values were all < 2 fragments/cm2/yr.

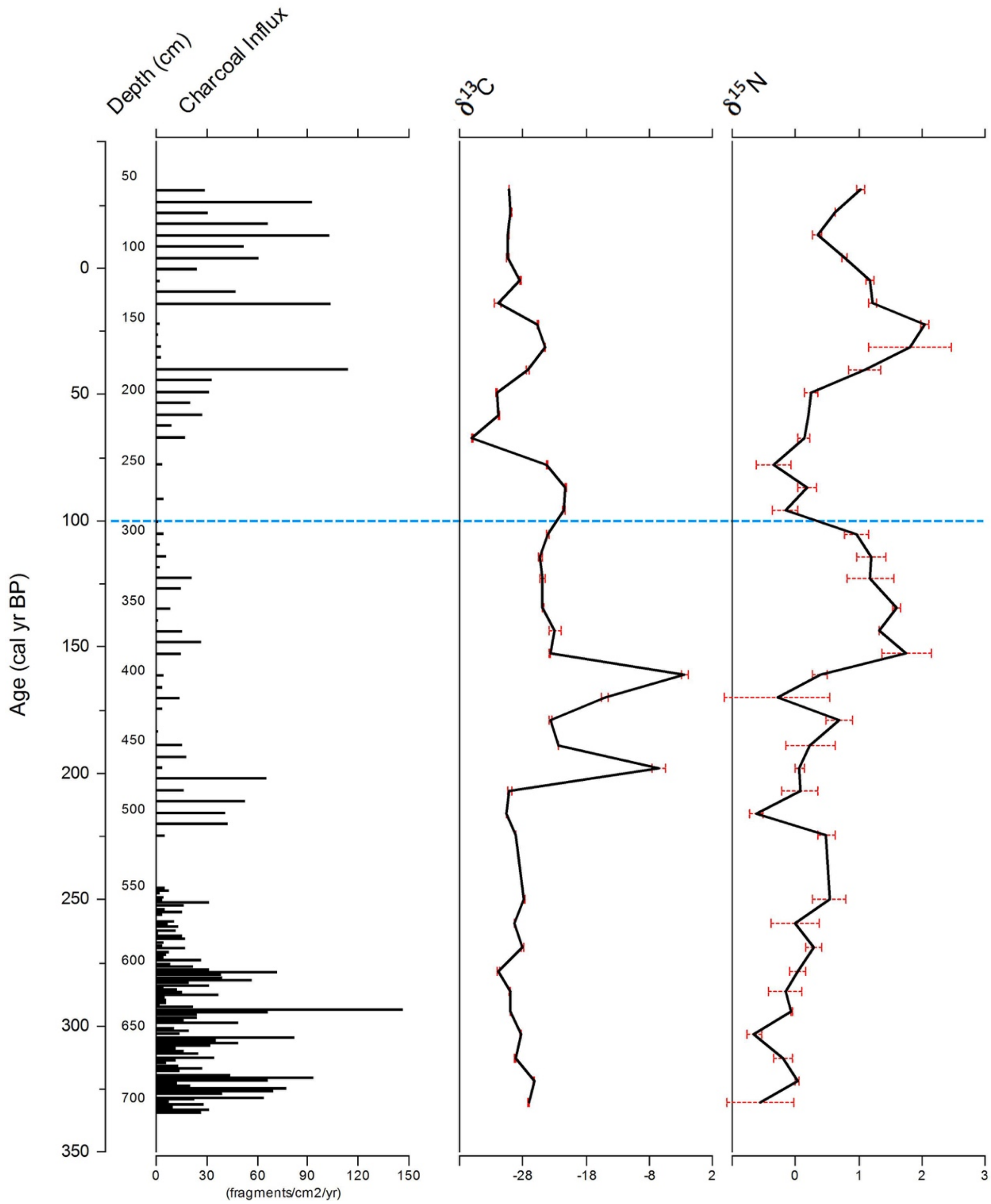

Figure 4.10. Laguna Carse charcoal influx and geochemical proxies. Blue dashed line represents the end of the LIA (~550–100 cal yr BP).

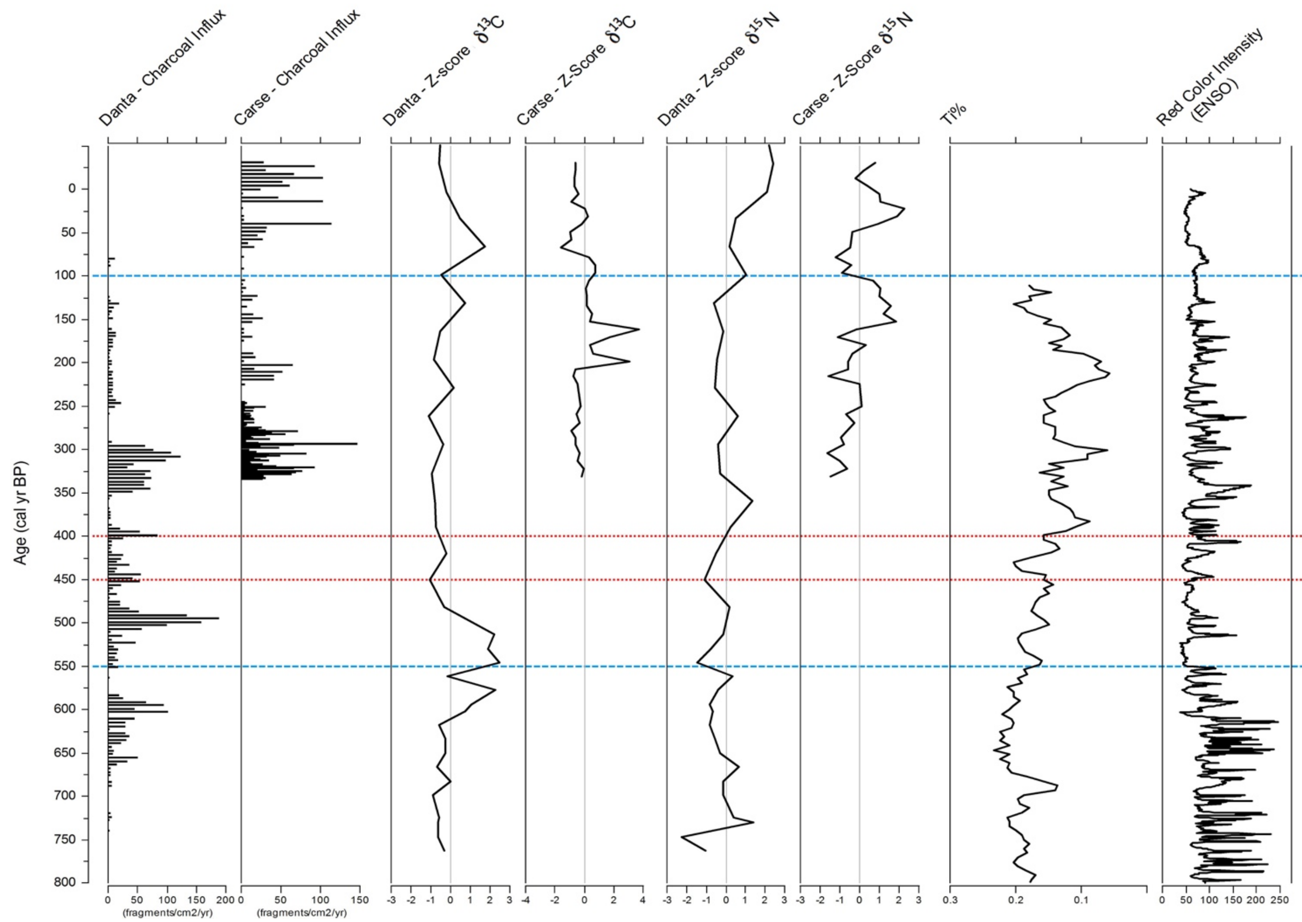

Figure 4.11. Laguna Danta and Laguna Carse fire and agricultural proxies compared to regional climate indices. Ti% record from the Cariaco Basin titanium record (Haug et al., 2001). The Red Color Intensity time series reconstructs warm ENSO events in the Laguna Pallcacocha sedimentary record with red quantifying the distribution and concentration of laminae in in the Laguna Pallcacocha sediment record (Moy et al., 2002). Red dotted line represents timing of Spanish contact (~400–450 cal yr BP). Blue dashed line represents duration of the LIA (~550–100 cal yr BP).

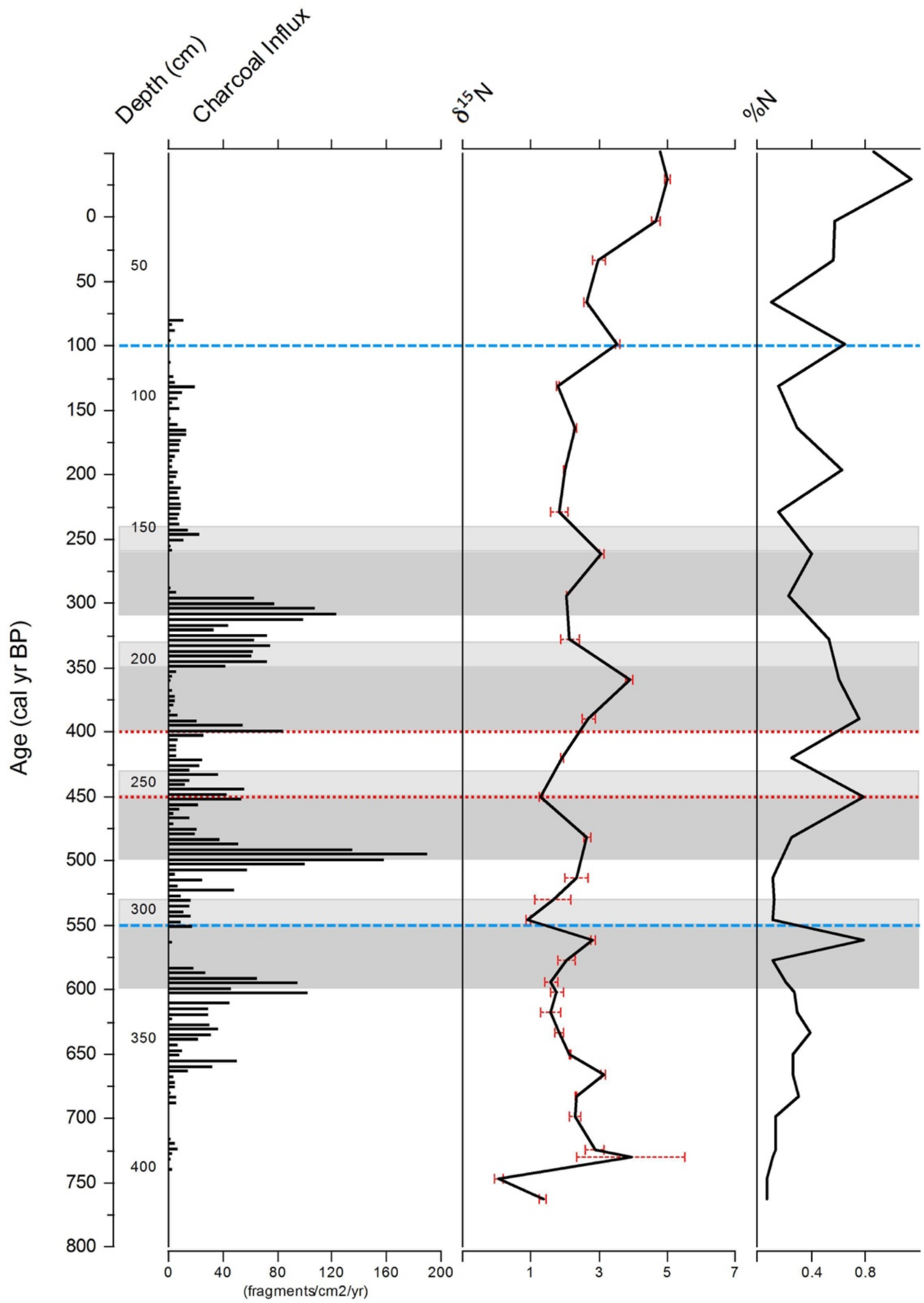

Figure 4.12. Fire and nitrogen response for the Laguna Danta record. Shaded interval corresponds to 50 years following a charcoal peak (dark grey) and 50–70 years following the charcoal peak (light grey). Charcoal influx values after 80 cal yr BP are too low to be visible in the graph; all samples contained some charcoal, but influx values were all < 2 fragments/cm2/yr.

CHAPTER 5

SUMMARY AND CONCLUSIONS

5.1 Summary of Research

The goal of this dissertation research was to use multiple proxies from sediment cores to identify periods of climate stress, specifically drought, during the late Holocene at sites within the circum-Caribbean region and to determine how fire activity and signals of pre-Columbian agriculture coincide with these arid periods. To do so, we evaluated evidence of aridity in a sediment record from a high-elevation site, and assessed the relationships between this evidence and regional proxy records linked to the migration dynamics of the Intertropical Convergence Zone (ITCZ) and to changes in the height of the Trade Wind Inversion (TWI). We used stable carbon isotopes and elemental composition analyses in a core from a highland bog in the Dominican Republic near the modern TWI elevation that was undisturbed by anthropogenic action until historic times. Our analyses were motivated by recent studies at other highland sites in the Caribbean (Crausbay et al., 2015; Kennedy et al., 2006; Lane and Horn, 2013) that explored relationships between sedimentary proxies and climate drivers including shifts in the mean latitudinal position of the ITCZ and TWI dynamics.

We also documented environmental conditions and fire history in southern Pacific Costa Rica prior to the arrival of maize agriculture, which added to regional evidence of the timing of the spread and later decline of maize agriculture in the region. Our 4300-year record of environmental change and fire activity at Laguna Los Mangos covered a ~1000 year interval that preceded the earliest evidence of maize agriculture in

the region at ca. 3200 cal yr BP (Horn, 2006). The Laguna Los Mangos record contained evidence of the transition to maize agriculture and its later decline.

Lastly, we compared the timing of agricultural decline at three new sites in the southern Pacific of Costa Rica to the onset of the Little Ice Age (LIA) and the arrival of Spanish in the New World. We also documented the influence of climate change on fire activity across the LIA and compared our findings with regional trends and climate interpretations derived from a recent global synthesis (Power et al., 2013), which revealed some contradictions and uncertainties for the northern Neotropics. Our two high-resolution records of fire history and signals of maize agriculture from Laguna Danta and Laguna Carse that together span the LIA showed fire history and signals of maize agriculture at a 4-year resolution, while our Laguna Los Mangos record spanned the LIA, but also extended the paleoenvironmental history of southern Pacific Costa Rica ~1000 years further in time to offer a longer-term perspective on environmental change in the region. We also considered spatial differences in fire activity and agricultural decline by comparing our three study lakes from the northwestern lowlands to lakes in the southeastern mid-elevation setting of the southern Pacific region.

Future research on paleoenvironments and paleoclimate in Costa Rica would benefit the development of more records of climate-specific proxies, such as compound-specific hydrogen isotope ratios (Lane and Horn, 2013) and chironomid assemblages (Wu et al., 2016). More high-resolution analyses of charcoal are needed to understand patterns across space and time as driven by climate and human activity. Developing

additional records of human-environment interaction and climate from sites distributed across the Diquís and other archaeological regions of Costa Rica are key to understanding early maize agriculture and how climate events and the Spanish Conquest affected past peoples at a local level.

5.2 Major Conclusions

5.1.1 Aridity in the Caribbean Highlands Detected from Multiple Sediment Proxies in a Bog in the Cordillera Central of the Dominican Republic

We examined the relationship between ITCZ position and TWI elevation and periods of aridity at Bao Bog in the Caribbean highlands. We compared results of sedimentary $\delta^{13}C_{TOC}$ and elemental composition analyses to Bao Bog proxies from prior research to evaluate and refine the timing of the Kennedy et al. (2006) interpretation of basal aridity in the Bao Bog record from 3700–1300 cal yr BP. Based on $\delta^{13}C_{TOC}$ values, elemental composition (Ti/Al, Fe/Al, Ca/Al, Zn/Al), organic content, and pollen and charcoal proxies, we identified an interval of aridity from 3600–2300 cal yr BP with a wetter period between 2300 cal yr BP and the Terminal Classic Drought (TCD).

We compared the $\delta^{13}C_{TOC}$ record with two regional paleoclimate records, the Cariaco Basin titanium concentration record and the Laguna Pallcacocha ENSO record, to evaluate the effects of ITCZ migrational dynamics and changing TWI elevations on the hydrology of Bao Bog. The two most prominent periods of aridity in the Bao Bog

record, the ~1300-year arid interval (3600 to 2300 cal yr BP) and the late phase of the TCD (1030 to 850 cal yr BP), correspond to intervals of a more southerly ITCZ position, which is expected to be associated with a lower TWI elevation. The Bao Bog record also showed some relationship between inferred aridity and the Laguna Pallcacocha ENSO record, suggesting reduced precipitation or lowered TWI elevation during some but not all intervals of enhanced El Niño activity.

5.1.2 Earliest Agriculture in Southern Pacific Costa Rica and Environmental Change

We presented a Late Holocene record of environmental change with the introduction of maize agriculture. From the Laguna Los Mangos record, we showed evidence of the timing of maize introduction in southern Pacific Costa Rica and the Gran Chiriquí archaeological region at ~3200 cal yr BP. The presence of maize pollen at the northwestern lowland site of Laguna Los Mangos and the southeastern mid-elevation site of Laguna Zoncho (Clement and Horn, 2001; Taylor et al., 2013a; 2013b) supported our interpretation of a rapid and widespread adoption of maize agriculture in the southern Pacific region following the initial introduction of this key cultigen.

The Laguna Los Mangos record also showed a pre-maize environment that changed with the introduction of maize agriculture. Proxies indicate a largely forested landscape surrounding Laguna Los Mangos, with some fire activity, during the 1000 years prior to the first pollen evidence of maize. Some land clearance for cultivation or horticulture may have taken place during this interval, but if so at small scale based on

the dominance of arboreal pollen types. At the time of maize establishment, the record showed evidence of forest clearance for agriculture and an increase in C_4 vegetation at the site. Charcoal evidence, large shifts in elemental composition of the lake sediments, and increases in grasses and herbs, some related to agricultural disturbance, also coincide at the approximate time of maize introduction.

Maize agriculture in the Laguna Los Mangos watershed decreased slightly following an initial peak shortly after introduction, based on stable carbon isotope ratios. Maize pollen presence from levels distributed across the profile suggests continued maize cultivation across the Late Holocene following introduction at 3200 cal yr BP. While paleoenvironmental analyses at Laguna Zoncho (Taylor et al., 2013a), a well-studied site ca. 65 km southeast of Laguna Los Mangos, revealed two periods of pronounced agricultural decline (from 1150–970 and 860–640 cal yr BP), our agricultural proxies at Laguna Los Mangos indicate only two, small declines, from 1400–1000 cal yr BP and from 480 cal yr BP to modern historic times. Both records show lowered agricultural signals during the TCD, but only the Laguna Los Mangos record indicates an increase in maize agriculture following the TCD and a subsequent decline coinciding with the LIA and Spanish contact.

5.1.3 Recent Fire and Agricultural History in Southern Pacific Costa Rica

We presented high-resolution charcoal records spanning the Little Ice Age (LIA) that show effects attributed to both the LIA and the Spanish Conquest. Close similarity

between the Cariaco Ti curve and the macroscopic charcoal record at Laguna Danta suggest that drought was an important driver of fire history in the lowlands of southern Pacific Costa Rica across the LIA. Indicators of agricultural activity in our records sharply declined following the onset of the LIA and Spanish contact in the region. But fires continued, indicating that local forest clearance and agricultural activity were not the only sources of fire at the study sites. We inferred that wildfires set unintentionally by humans or ignited by lightning or volcanism spread across southern Pacific landscapes during the LIA in Costa Rica.

Our agricultural proxies from Laguna Danta showed patterns of decline coinciding with the onset of the LIA and Spanish contact, while the southeastern, mid-elevation sites of Laguna Zoncho and Laguna Santa Elena show earlier agricultural decline. Fire histories also diverged, with Laguna Zoncho and Laguna Santa Elena showing sharp declines in charcoal following the onset of the LIA and Spanish contact. This difference in fire activity suggests the local effects of the LIA on fire history in southern Pacific Costa Rica were more pronounced at the northwestern, lowland sites. The continuation of fires across the LIA at Laguna Danta and Carse also contrasts with the global and regional synthesis of Power et al. (2013), from which we would expect a strong decline in fire coinciding with the LIA for Costa Rica.

5.3 References

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VITA

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