**A 4700-Year Record of Lake Evolution and Fire History for Laguna Limón, Dominican Republic**

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## Abstract

Fire is a primary driver of environmental change that can originate from natural or human ignition. Macroscopic charcoal (>125 µm) deposited into lake sediment is a record of a local fire event, whereas microscopic charcoal indicates fire activity on a broad landscape scale. Patterns of charcoal deposition may shed light on both human activities and climate history over long-time scales. Whether lowland Caribbean forests have experienced natural fire regimes over the long-term is unknown. Laguna Limón is a little-studied, large, freshwater lake on the northeastern coast of the Dominican Republic. We extracted four overlapping sediment cores totaling 315 cm in depth, and conducted analysis of macroscopic charcoal (2-cm), microscopic charcoal (16-cm), and loss-on-ignition (1-cm) to examine the long-term fire and environmental history of the area. Loss-on-ignition data established that the lake has only recently become organic rich, and was likely open to the sea as a low energy bay until 1400 Cal. Yr BP. The lake existed briefly as a wetland before transitioning to the modern freshwater lake 1200 Cal. Yr BP. Macroscopic charcoal was most abundant in the freshwater section of the core while microscopic charcoal peaked near the bottom of the core, and aligns well with other regional microscopic charcoal records. Overall the charcoal record reflects a combination of climatic and anthropogenic related charcoal deposition suggesting that fire has played an active role in the environmental history Laguna Limón.

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## Chapter 1: Introduction and Research Objectives

### 1.1 Introduction

Tropical islands like Hispaniola (19° N, 70° W) are dynamic systems sensitive to the interplay of various climatic, oceanic, and anthropogenic forces. Reconstructions of environmental changes in setting, vegetation, and fire through proxy data stored in lake sediments make possible the long-term analysis of how these systems respond to change (Last et al., 2001). Understanding long-term dynamics may aid modern conservation efforts in preparing for and mitigating future change.

Fire is regarded by researchers as an important disturbance component in many ecosystems (Whitlock, 2004). In addition to natural ignition, humans have used fire to alter landscapes to better suit their needs. Charcoal is a byproduct of fire that accumulates through primary or secondary deposition over time in the sediment profile of nearby lakes (Whitlock and Larson, 2002). Through sediment deposition, lakes act as time capsules cataloging proxy records of surrounding environments (Last et al., 2001). Charcoal is a primary method for examining fire history over the long-term (hundreds to thousands of years). Macroscopic charcoal (>125 μm) is a reliable indicator of a local fire event (Clark, 1988; Whitlock and Millspaugh, 1996; Gardner and Whitlock, 2001). Inversely, microscopic charcoal (<125 μm), typically assessed through the pollen slide technique, is indicative of regional fires due to the increased transportation properties of airborne microscopic charcoal particles (Patterson et al., 1998).

Because fires can occur both naturally and from anthropogenic sources, differentiating between the two can prove challenging. One method to distinguish between natural and human caused ignition is to look for charcoal sedimentation patterns indicative of one or the other. For example, Myers and van Lear (1998) hypothesized that an historical interaction has existed between hurricanes and fires in the coastal American Southeast. Liu et al., (2007) validated that

hypothesis with a core from coastal lakes in Alabama that identified charcoal peaks following hurricane overwash events. It is unknown if the hypothesized "hurricane-fire interaction" also exists in tropical regions of the world.

In general, coastal tropical forests of the Caribbean are not assumed to interact with fire (Santiago-Garcia et al., 2008), but long-term data regarding that assumption is lacking. In the Canadian boreal forest, climate, not vegetation type is the primary driver of fire regimes (Carcaillet et al., 2001). Macroscopic charcoal records have been used to link Holocene fire regimes to changes in climate in *Tsuga mertensiana* rainforests of British Columbia (Hallett et al., 2003). A 9000-year evolution of fire return intervals corresponded with changes in climate in the Oregon Coast Range and the modern fire regime there has only existed for the last 1000 years (Long et al., 1998). Charcoal deposition may indicate changing climatic patterns, even if existing vegetation is not fire adapted.

Charcoal records that do not correspond to climatic indicators may instead serve as archaeological evidence of humans on an island (Burney, 1997). For instance, Burney et al., (1994) interpreted a dramatic peak in microscopic charcoal that signified the arrival of paleo humans in Puerto Rico hundreds of years before the archaeological record. Kjellmark (1996) identified a peak in microscopic charcoal that coincided with archaeological evidence of the islands first inhabitants and a second peak with the arrival of the Spanish.

Tropical regions of the world have garnered more research attention in recent years, but remain understudied. The Dominican Republic is an ideal location for a paleo ecological fire history study due to its sensitivity to slight fluctuations in climate, frequency of hurricane strikes, and other natural disturbances (Pielke, 2003) and the relative scarcity of archaeological sites documenting the history of human inhabitants.

**1.2 Research Objectives**

This project examined the long-term environmental history of Laguna Limón, a coastal lake located in northern Dominican Republic (Figure 1), through analysis of proxy records contained within lake sediment. This research adds to the existing body of paleoenvironmental research on Caribbean islands and presents a long-term record of local and regional fire history in the Dominican Republic. Additionally, this research may be valuable to archaeologists in that the macroscopic charcoal record may indicate a human presence near Laguna Limón has existed for potentially thousands of years

This research had two major objectives: 1. document the origin and morphology of Laguna Limòn through the interpretation of sediment stratigraphy and loss-on-ignition analysis; 2. reconstruct a local and regional fire history by sampling sediment for macroscopic (>125 µm) and microscopic charcoal (<125 µm). We then compared this proxy information with the existing catalog of climate and anthropogenic data and explored any associations.

This thesis includes two additional chapters. Chapter 2 presents a review of relevant literature to this research including atmospheric regulators of the Caribbean, the hurricane-fire interaction, previous paleoenvironmental Caribbean research, paleo Caribbean people, properties of macroscopic charcoal and microscopic charcoal. Chapter 3 is a manuscript written for submission to The Holocene.

**Chapter 1 References**

Burney, D. A. (1997). Tropical islands as paleoecological laboratories: gauging the

consequences of human arrival. *Human Ecology, 25*(3), 437-457.

Burney, D. A., Burney, L. P., & MacPhee, R. D. E. (1994). Holocene charcoal stratigraphy from

Laguna Tortuguero, Puerto Rico, and the timing of human arrival on the island. *Journal

of Archaeological Science, 21*(2), 273-281.

Carcaillet, C., Bergeron, Y., Richard, P. J. H., Fréchette, B., Gauthier, S., & Prairie, Y. T. (2001).

Change of fire frequency in the eastern Canadian boreal forests during the Holocene:

does vegetation composition or climate trigger the fire regime? *Journal of Ecology,

89*(6), 930-946.

Clark, J. S. (1988). Particle motion and the theory of charcoal analysis: source area, transport,

deposition, and sampling. *Quarternary Research, 30*(1), 67-80.

Gardner, J. J., & Whitlock, C. (2001). Charcoal accumulation following a recent fire in the

Cascade Range, northwestern USA, and its relevance for fire-history studies. *The

Holocene, 11*(5), 541-549.

Hallett, D. J., Lepofsky, D. S., Mathewes, R. W., & Lertzman, K. P. (2003). 11,000 years of fire

history and climate in the mountain hemlock rain forests of southwestern British

Columbia based on sedimentary charcoal. *Canadian Journal of Forest Research*, *33*(2),

292-312.

Holdridge, L. R. (1967). Life zone ecology. Life zone ecology., (rev. ed.).

Kjellmark, E. (1996). Late Holocene climate change and human disturbance on Andros Island, Bahamas. *Journal of Paleolimnology, 15*(2), 133-145.

Last, W. M., Smol, J. P., & Birks, H. J. B. (2001). *Tracking environmental change using lake sediments* (Vol. 1-4). Boston: Kluwer Academic Publishers.

Long, C. J., Whitlock, C., Bartlein, P. J., & Millspaugh, S. H. (1998). A 9000-year fire history from the Oregon Coast Range, based on a high-resolution charcoal study. Canadian Journal of Forest Research, 28(5), 774-787.

Myers, R. K., & van Lear, D. H. (1998). Hurricane-fire interactions in coastal forests of the south: a review and hypothesis. *Forest ecology and management, 103*(2-3), 265-276.

Patterson, W. A., Edwards, K. J., & Maguire, D. J. (1988). Microscopic charcoal as a fossil indicator of fire. *Quaternary Science Reviews, 6*(1), 3-23.

Pielke, R. A., Rubiera, J., Landsea, C., Fernández, M. L., & Klein, R. (2003). Hurricane Vulnerability in Latin America and The Caribbean: Normalized Damage and Loss Potentials. *Natural Hazards Review, 4*(3), 101.

Santiago-García, R. J., Colón, S. M., Sollins, P., & Van Bloem, S. J. (2008). The role of nurse trees in mitigating fire effects on tropical dry forest restoration: a case study. *Ambio, 37*(7-8), 604-608.

Whitlock, C., & Larsen, C. (2002). Charcoal as a fire proxy. *Tracking environmental change using lake sediments*, 75-97.

Whitlock, C., & Millspaugh, S. H. (1996). Testing the assumptions of fire-history studies: an

    examination of modern charcoal accumulation in Yellowstone National Park, USA. *The*

    *Holocene, 6*(1), 7-15.

**Chapter 1 Figures**
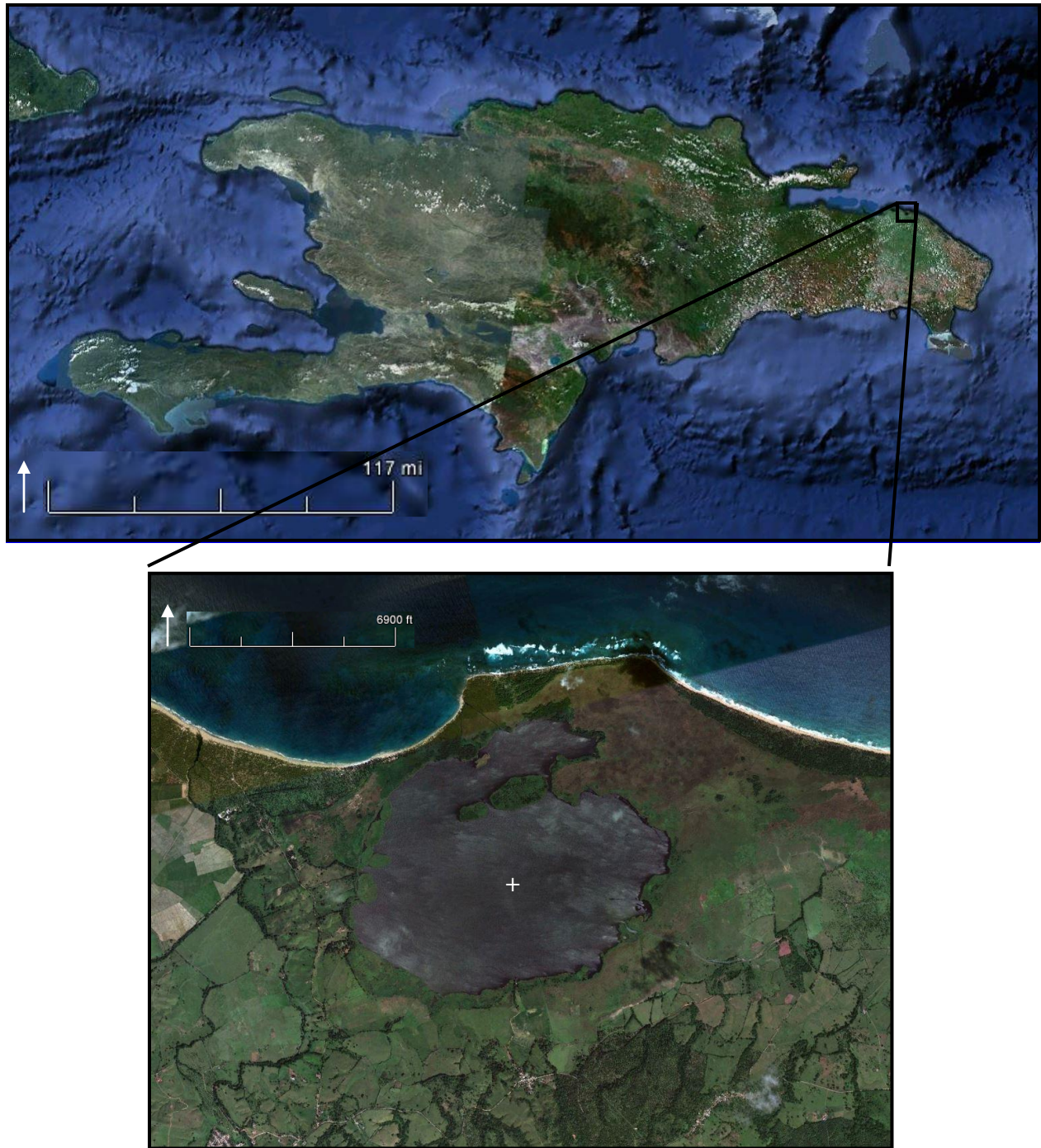


Figure 1

Map of Hispaniola (above) and Laguna Limón inset (below) with core location (18.9783° N, 68.8494° W) indicated by "+." Imagery from Google Earth, 2013.
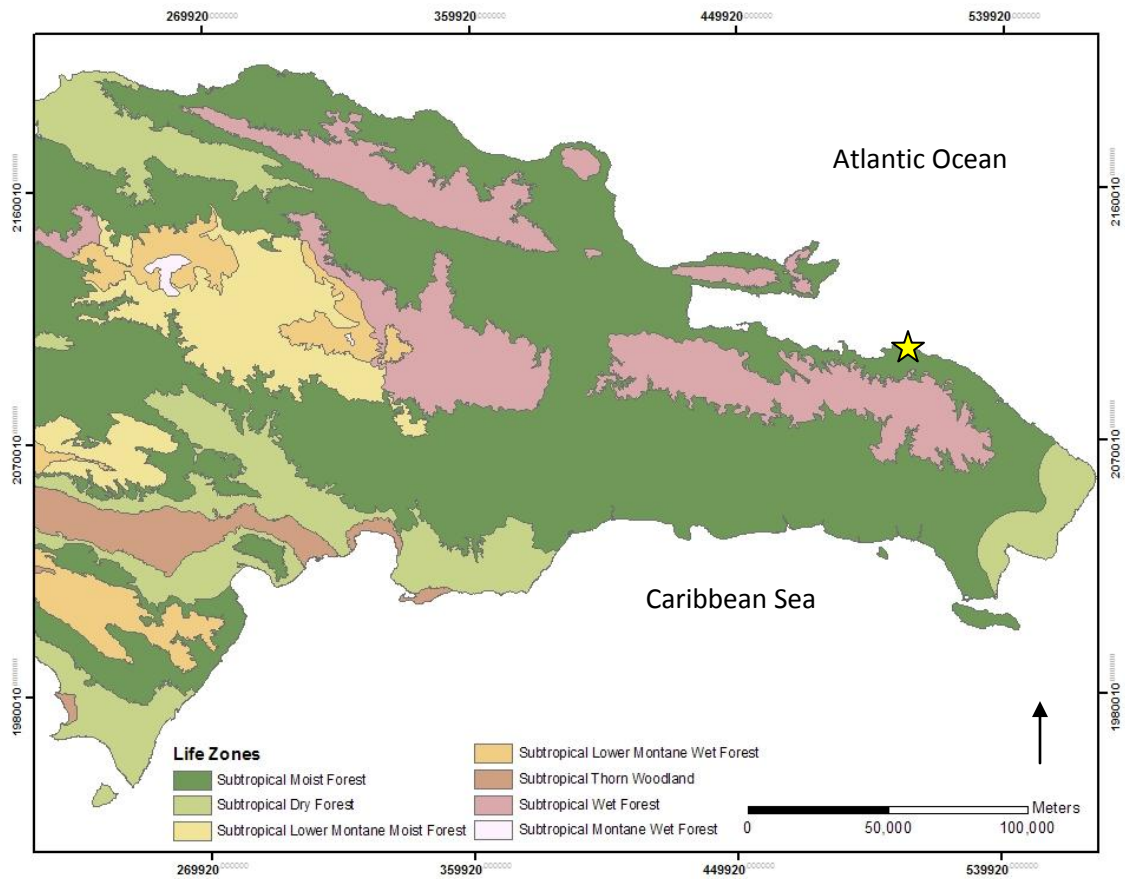
Figure 2

Vegetation life zones of the Dominican Republic with location of Laguna Limón indicated by star. Redrawn from Holdridge (1967).

## Chapter 2:  Literature Review

### 2.1 Caribbean Climate Drivers

Due to their isolation and sensitivity, islands present exceptional opportunities to study environmental changes associated with climate and anthropogenic influences. Caribbean islands are prone to periodic natural disasters like hurricanes, droughts, tsunamis, landslides, and earthquakes (Jury et al., 2007). The Dominican Republic and Haiti share the island of Hispaniola. Hispaniola is the second largest island in the Greater Antilles archipelago preceded in size and population only by Cuba. Eco-regions vary in the Dominican Republic from desert to rainforest (Bolay, 1997). Likewise, the Dominican Republic is a place of substantial elevation contrast, from below sea level in the Enriquillo Valley to the lofty volcanic peaks of the Cordillera Central. Caribbean climate is influenced by several oceanic and atmospheric processes including trade winds, subtropical high pressure, the Intertropical Convergence Zone (ITCZ), El Niño Southern Oscillation (ENSO), and the Northern Atlantic Oscillation (NAO).

The ITCZ is a low pressure convergence zone that is variably located between the northeastern and southeastern trade winds. Because the location is inconsistent, it impacts seasonal precipitation across the Caribbean. The further north the ITCZ is pushed during the northern hemisphere summer, the more precipitation falls on the Caribbean. Inversely, when the ITCZ falls to the south, Caribbean precipitation can decrease severely. The ITCZ has likely migrated southward over the course of the Holocene, influencing overall Caribbean precipitation and regional climate (Haug et al., 2001). Oxygen isotope records from sediment obtained by Lane et al., (2011) from a small mid-elevation lake in the Dominican Republic indicates that the climate era known as the Little Ice Age (LIA) during the 15th–19th centuries may strengthen the hypothesis that the ITCZ shifted southward during that period and points to the overall sensitivity of the Caribbean to the relative location of the ITCZ.

El Niño Southern Oscillation operates on rough half decade timescales and influences everything from precipitation, temperature, drought, and frequency and intensity of storm systems across a majority of the western hemisphere (Malmgren et al., 1998). ENSO is regulated by fluctuations in sea surface temperature (SST) of the eastern Pacific Ocean. As Pacific SSTs increase, atmospheric convectivity increases and slows convectivity over the neighboring Caribbean Sea. A warm ENSO event is known as an El Niño year. This decreases precipitation below the annual average over the Caribbean islands and can induce temporary periods of drought. A warm dry year is typically followed by an above average wet and cool year known as La Niña (Giannini et al., 2001).

The NAO is a fluctuation between two different atmospheric pressure systems at sea level. The relative position of the Azores High and the Icelandic Low result in a positive or negative NAO. Unlike the ENSO which is driven by changes in SST's, the NAO is strongly driven by atmospheric conditions. The position of the NAO Azores High has significant control over the direction of tropical storms leaving the African coast. When the Azores High is located further south, storms are more likely to take a tract over Caribbean islands and into the Gulf of Mexico. With a more northerly location of the Azores High, tropical storms will migrate up the Atlantic coast of the United States (Giannini et al., 2001).

These atmospheric and oceanic influences impact the manner in which sediment and the proxy data stored within accumulates in lakes. In that way, signals detailing the long-term interaction of climate and environment are retained in the sediment profile (Last et al., 2011).

**2.2 Hurricane-fire Interaction**

Hurricanes are important, frequent disturbance events that, despite their destructive potential, play a significant role in altering and shaping many ecosystems in the Caribbean (Lugo

et al., 1983; Boucher, 1990). Literature on various short-term impacts of hurricanes in the

Caribbean region is vast. However, the potential relationship between hurricanes and fire in the

Caribbean and elsewhere over the long-term is less understood.

The modern hurricane record for the North Atlantic only extends back to 1851 (Landsea

et al., 2008). Although some written records in the region do extend longer, they are generally

inconsistent, limited to populated areas of the time and not a reliable measure of hurricane

activity, size or strength (Donnelly et al., 2001). For example, the first recorded hurricane in the

Caribbean occurred in AD 1495, destroying the town of Isabella on Hispaniola (Rappaport and

Fernandez-Partagas, 1995).

Paleotempestology (the study of prehistoric hurricanes) implements the use of techniques

that make possible the reliable long-term documentation of past hurricane landfalls. By

combining radiometric dating and other proxy techniques such as pollen, charcoal, grain size,

loss on ignition, and isotopic signals of precipitation recorded in microfossils, a record of

hurricanes on a geologic timescale becomes possible (Liu et al., 2007). Overwash deposits

recorded in coastal lakes are one of the most reliable proxies for paleotempestological

interpretation (Donnely et al., 2001). When a coastal lake is cored, the sediment profile reveals

an historical record of hurricane induced overwash deposits that document both the frequency

and intensity of hurricanes over time (Donnely et al., 2001). Large, coarse white sand and shell

particles from coastal dunes and beaches are pushed beyond the shore and deposited into coastal

lakes by the storm surge created when a major hurricane (category 4-5) makes landfall. These

deposits appear as a distinct layer within the otherwise dark sediment made up of clay, silt, and

organic materials. Some deposits are visible to the naked eye, while others are identified through

laboratory processes such as loss-on-ignition and X-radiography. In that way, a chronology of

intense hurricanes is recorded in lake sediment with more recent storms near the surface and older storms at the bottom of the core.

Myers and van Lear (1998) hypothesized that despite nearly a century of natural fire suppression, there is a "hurricane-fire interaction" that has historically played a significant disturbance role in coastal forests of the Southeastern United States. Their review of literature and observations on the state of current forest communities led to the formation of a testable hypothesis. The implications for forest management practices in the Southeast and elsewhere are many, including the management and restoration opportunities of long leaf pine forests, an ecologically important but dwindling forest type that is dependent upon fire return intervals (Landers et al., 1995).

Fire potential increases following hurricanes (Webb, 1958; Whigham et al., 1991; Loope et al., 1994). As a hurricane topples branches, defoliates leaves, and creates gaps in tree canopies, fire potential on the ground increases due to the buildup of combustible materials. In a study of tropical dry forest response to a hurricane on the Lesser Antilles island of Guadeloupe, the accumulation of leaf litter from hurricane Hugo in 1988 was equivalent to the prior year's worth of leaf defoliation (Imbert and Portecop, 2008). When prolonged dry and windy conditions occur in areas following a hurricane, fire potential can increase even for mesic sites that are not typically fire prone (Webb, 1958).

Most structural damage to vegetation caused by hurricanes is due to high sustained wind speeds (Everham and Brokaw, 1996). Lewis and Bannar-Martin (2011) assessed the immediate structural damage to trees in Kirindy Mitea National Park, a coastal tropical dry forest in Madagascar, after a category three hurricane made landfall in 2009. Of the 1361 trees sampled, 95% suffered some kind of structural damage, but only 8.8% tree mortality was observed. Others

studies have recognized that not all tree mortality occurs immediately following a hurricane (Dittus, 1985). Whigham et al., (1991) found that only 21% of tree mortality occurred within the first four months of a two-year study following a hurricane.

Liu et al., (2007) produced the first empirical test of the Myers and van Lear (1998) hypothesized "hurricane-fire interaction" in the subtropical maritime forests of coastal Alabama. Three coastal lakes were cored and multiple proxy techniques were employed to identify overwash deposits. In one lake the authors discovered overwash deposits with evidence of two major hurricane strikes occurring in the last 1200 years. In each case, significant microscopic charcoal peaks followed overwash deposits. These data suggested major fires followed hurricanes and validated the Myers and van Lear (1998) hypothesis. Charcoal was present throughout the core, signifying that fire is ever-present in the ecosystem, peaks were highest following the overwash events. Major fires, fueled by downed woody debris from hurricane winds, occurred within 25 years following the hurricanes (Liu et al., 2007). It is unknown if similar results may exist for Caribbean tropical forests.

**2.3 Previous Caribbean Research**

Hurricane Joan, a category four storm, struck the Caribbean coast of Nicaragua in 1988. Damages from the storm were felt in over 500000 ha of tropical forest and 100000 ha of swamp forest lands (Boucher, 1990). During the dry season following the hurricane, fires from agricultural areas spread to the downed vegetation and burned extensively, killing a majority of the trees in the area (Vandermeer and Boucher et al., 1990).

The magnitude of these successional events inspired Urquhart (2009) to commence a paleotempestological investigation to calculate the return frequency of powerful hurricanes. Pollen, loss-on-ignition, macroscopic and microscopic charcoal processing were completed on a

core from a tropical lagoon nearly 15 km inland. A study area so far inland was justified by the author because it would have recorded storm surges from only extreme hurricane events like Joan. A hurricane similar to Joan and dated to 3340 Calibrated Years Before Present (Cal. Yr BP) was revealed in the sediment record that span roughly 8000 years (Urquhart, 2009). Also identified were two peaks of macroscopic and microscopic charcoal above the overwash deposit indicating major fires that burned following the prehistoric hurricane. Pollen data from the study indicated that it took roughly 500 years for the forest to return to pre-hurricane levels due to repeated fire events. Urquhart suggested that the similarities between that prehistoric storm and Hurricane Joan are many, and fire will play an important role in forest regeneration of the area. Furthermore, that study demonstrates the "hurricane-fire interaction" of Myers and van Lear (1998) and the shift in timescale necessary to view the ecological impacts of powerful hurricane events.

A core from Laguna Alejandro, located in the southwestern Dominican Republic by Desjardins (2007) revealed evidence of a major hurricane strike 1022 Cal. Yr BP. A follow-up study from a second core by LeBlanc (2011) used multiple proxy methods including loss on ignition, pollen, and charcoal to characterize the environment of Laguna Alejandro. Results detailed the vegetation history of the lake. LeBlanc (2011) also identified a rise in microscopic and macroscopic charcoal within the last 434 Cal. Yr BP that may be the result of fires that followed hurricanes or anthropogenic presence near the lake.

In addition to proxy information about paleo-hurricanes, examining the sediment from lakes and bogs can reveal patterns of past climate and thus information regarding paleoenvironmental conditions. In the Caribbean, one of the first high-resolution lake cores was produced by Curtis and Hodell (1993) from Lake Miragoâne in Haiti. The 7.6 m sediment core

was dated to 10300 $^{14}$C YBP making it one of the longest and containing some of the oldest sediment ever recovered from a Caribbean lake. The stable oxygen isotope of ostrocods and pollen records contained in the sediment has also produced one of the longest records of environmental response to Caribbean climate change. In the years before 10000 $^{14}$C YBP the lake was shallow and climate was relatively cool and dry. From 10000 to 7000 $^{14}$C YBP water level rose due to a slower evapotranspiration rate and increased precipitation. An increasingly moist characteristic continued until 3200 $^{14}$C YBP when conditions reverted back to aridity. The most recent 1000 years have continued the trend towards a drying environment. Pollen and charcoal data indicated that before human settlement the vegetation surrounding the lake was determined primarily by climate (Higuera-Gundy et al., 1999). Once populated, vegetation shifted and reflected the impact of the Taino inhabitants and later the arrival of the Spanish.

Laguna de la Leche is a large, shallow, coastal lake located on the north coast of Cuba. Peros et al., (2007) produced a 6000-year sediment record detailing paleoenvironmental change, sea level rise and the first long-term pollen record for the island of Cuba. The lake initially slowly filled a basin as a result of rise in sea level raising the aquifer below the lake. Changes in pollen data suggest that water level rise between 4800–4200 Cal. Yr BP was more likely a result of climatic changes in precipitation and not sea level rise. Sea level continued to rise slowly and from 4200–2000 Cal. Yr BP the lake may have been a lagoon at least partially open to the sea. The more recent history of the lake from 1700 Cal. Yr BP to present showed a slight decrease in sea level, evidence for decreased wave action and the establishment of mangroves that isolated the lake from the sea possibly due to a decreased rate of Relative Sea Level rise. Continued establishment of mangroves around the lake will likely allow for future infill (Peros et al., 2007).

Fire is an important function of many ecosystems and is a natural presence in upland pine forest regions of the Dominican Republic. In the pine forest uplands of the Dominican Republic sediments from a bog in the Cordillera Central and established a 4000-year cyclical history of fire from microscopic charcoal and pine pollen (Kennedy et al., 2006). That record indicated that repeated burning, likely of natural ignition sources, has been an important component of the ecosystem since bog formation. Evidence of fire in the pine uplands has been found in soil and sediment charcoal in the Cordillera Central dating back to the Pleistocene (Horn et al., 2000). Fire is the primary driver in shaping distinct boundaries in ecotones of the Cordillera Central. A combination of disturbances from intense hurricane winds and the resulting fires from accumulation of woody debris has created an ecotonal environment of fire adapted vegetation that thins out at the base of the cloud forest (Marin and Fahey, 2006). Dendrochronological investigations of *Pinus occidentalis* forest communities have established that historical fire activity prior to human occupation in the Cordillera Central increased during the extended dry seasons caused by El Niño Southern Oscillation (ENSO) years (Speer et al., 2004; Marin and Fahey, 2006).

Investigations into mid-elevation Cordillera Central locations in the Dominican Republic have revealed changes in paleoenvironmental characteristics to be a result of climatic and human alterations. Laguna Castilla and Laguna de Salvador, two lakes residing on the Caribbean slope of the Cordillera Central, contain sediment records detailing the previous 3000 Cal. Yr BP (Lane et al., 2009). The arrival of maize pollen and increased rates of microscopic charcoal indicate that human populations may have migrated to the lakes as a drought response mechanism due to the southward migration of the ITCZ during the late Holocene (Lane et al., 2009). Proxy records of pollen, charcoal, and stable isotopes indicated that the presence of humans near the lakes

drastically altered vegetation patterns in lake watersheds. The impacts of these disturbances were long lasting, possibly even extending hundreds of years after human abandonment.

**2.4 Paleo Caribbean People**

In addition to natural ignition, charcoal may also derive from anthropogenic sources (Burney, 1997). Archaeological evidence suggests that prior to the Spanish onset in the 15th century, the paleo people who lived on Caribbean islands arrived roughly 6000 YBP (Keegan, 1994). These first people, termed Casimiroids, set sail from the Yucatan Peninsula and arrived initially in Cuba and Hispaniola. Archaeological records suggest that these people did not practice conventional agriculture, instead they were coastal people who subsisted on marine resources and edible plants (Keegan, 2000). The Casimiroids existed until about 2500 YBP and likely harnessed the use of fire to assist with some sort of horticulture practice as they modified their surrounding environment to fit their needs (Siegel et al., 2005).

Later, a second wave of people known as Saladoid migrated from South America up through the Lesser Antilles Archipelago and spread westward across the islands to Puerto Rico 3200 YBP and Jamaica 1200 YBP (Rouse, 1993). The Saladoid people brought agricultural practices with them and moved slowly into the interior of Caribbean islands (Rouse, 1993).

The general scarcity of extensive archaeological sites in the Caribbean complicates more precisely timing the arrival of paleo people and the influence on their environment. One possibility for measuring the arrival of people to an island is to look for a dramatic peak in sedimentary charcoal deposits. In Puerto Rico, Burney et al., (1994) identified one such microscopic charcoal peak in Laguna Tortuguero. They interpreted that peak to be a sign of human arrival on the island nearly 2000 years before the existing archaeological record. The core, which documented 7000 years of lake sediment accumulation, contained a microscopic

charcoal peak at 5300 ^{14}C YBP which was inferred as the result of human-set fires upon their arrival to the island. Following that initial peak, charcoal numbers declined. The disparity between that result and the existing archaeological record of human arrival at 3200 YBP may be indicative of the lack of thorough archaeological work and the lack of evidence left behind by the first people to reach the island. Similar results have been interpreted to signal the arrival of humans on the Hawaiian Islands (Burney and Burney, 2003) and on Madagascar (Burney, 1987).

A charcoal record from Churches Blue Hole on Andros Island in the Bahamas likely contains both human and naturally ignited fires. Initial pollen and charcoal records from the bottom of the core indicated a dry climate before a transition to vegetation more typical of a mesic and tropical hardwood forest. Kjellmark (1996) interpreted a significant charcoal peak that coincided with a shift in vegetation as indicated by the pollen record as attributable to the arrival of humans to the island at 740 ^{14}C YBP. That proxy information aligns well with existing archaeological evidence of people which dates human arrival to 1200 YBP. The island was depopulated in 1530 AD when the Spanish captured and enslaved the majority of the inhabitants. The island sat empty and was subsequently repopulated 200 years later. Spikes in the charcoal record coincided with those dates and are likely attributed to a human source.

The arrival of the Spanish in the 15th century brought about a new age of human presence and forest disturbance in the Caribbean. Upon first contact, the native population is estimated to have been as high as 8 million people (Cook and Borah, 1971). By 1535 AD the native population was almost completely eliminated due to disease, enslavement, and violence (Binford and Leyden, 1981).

Most modern fires in the Dominican Republic are started intentionally for forest clearing purposes involving agriculture, grazing or wood charcoal production for fuel (Bolay 1997). The

existing notion is that fire is a serious threat to lowland forest vegetation because coastal Caribbean forests have never experienced naturally occurring fire regimes (Santiago-Garcia et al., 2008). In some places fire is a familiar occurrence such as highly disturbed areas near highways along the Guanica tropical dry forest of Puerto Rico. A 50-year study of undisturbed regions within the Guanica forest never documented natural ignition (Murphy and Lugo, 1986).

**2.5 Macroscopic Charcoal**

Charcoal is the result of organic matter that is not completely combusted during a fire event. Once charred, charcoal is resistant to oxidation and further breakdown by microbial bacteria and therefore preserved easily in sediment as a record of historical fire events (Herring, 1985). Natural processes that regulate charcoal production, transport, and deposition are essential to the interpretation of paleo fire studies. Of particular interest is the relationship between production and transport of macroscopic charcoal. Charcoal can be deposited into a water body and thus the sediment profile through primary and secondary sources. Generally, macroscopic charcoal particles (>125 μm) indicate a local fire event (Clark, 1988; Clark et al., 1998).

To measure the transportation properties of airborne macroscopic charcoal, Clark et al., (1998) compared macroscopic charcoal found in lake sediment with macroscopic charcoal produced during an experimental burn on Bor Island in the Siberian boreal forest. The researchers established a series of seven traps along three transects on 10 m intervals outside the burn area. The 21 total traps contained a pan of de-ionized water to simulate the surface of a lake. A lake core was also taken from the deepest part of Bor Lake in order to compare historical charcoal trends with the macroscopic charcoal produced by the experimental burn. Low winds at the time of the experimental burn prevented a fast moving crown fire and instead produced a high intensity surface fire that when combined with convection, created a crown fire during the

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final phase of the burn. Results from the burn revealed that traps closest to the burn edge contained the most macroscopic charcoal particles. Traps furthest from the burn edge contained the smallest class size particles and the least amount of charcoal. Pre- and post-burn fuel estimates indicated that roughly 2% of the burned material was preserved as charcoal in the traps. As an experimental burn, these results should not be taken as representative of all fires. The results of that experimental burn recognized the accepted notion of macroscopic charcoal as an indicator of local fire events (Clark et al., 1998). However, that was a controlled burn under a controlled situation and fire is a highly variable event. For a high intensity crown fire, traps located further than 60 m from the burn edge would be ideal (Clark et al., 1998).

Under certain scenarios such as a highly intense crown fire, long distance transport of macroscopic charcoal had been theorized (Garstang and Tyson, 1997), but not researched without systematic review until recently. Tinner et al., (2006) provided the first documented long distance transport of macroscopic charcoal from a high intensity crown fire in Switzerland. In total, 300 ha of forest and 10 ha of pasture area were burned before the fire was extinguished three weeks later. The authors had five litter traps and two litter nets in place since 2002 for a previously existing long-term eco-physiological study. The traps and nets were located 5.3 km from the forest fire edge. In total 2487 macroscopic charcoal particles were counted following the fire. The nets and traps were checked weekly with the highest accumulation occurring during the weeks of the fire. The traps continued to receive diminished amounts of charcoal for the next two weeks, probably due to the placement of the traps below the forest canopy. The largest charcoal piece measured 1.3 cm. Most of the charred particles in the nets in traps were charred pine needles, followed by pieces of charred wood.

The results of that study produced charcoal deposition numbers similar to two experimental burns (Clark et al., 1998; Lynch et al., 2004). However, in the case of Lynch et al., (2004) the most distant trap was set only 200 m from the burned edge. The results of the Tinner et al., (2006) study found macroscopic charcoal fragments more than 5 km from the burned edge. Tinner et al., (2006) suggest that the variation in the placement of the traps and nets over a 400 m plot suggest a relatively even distribution of charcoal throughout the area, not extreme outliers.

Intense crown fires are capable of transporting large unburned materials like branches or cones over long distances, so long distance transport of macroscopic charcoal is conceivably possible (Pisaric, 2002). The experimental burns of Clark et al., (1998) and Lynch et al., (2004) were 50 ha and 2.5 ha, respectively, compared with 310 ha from the Tinner et al., (2006) study. Charcoal production is related to vegetation and fire variables such as combustion efficiency and the rate of fuel consumption by the fire (Stocks and Kauffman, 1997). Tinner et al., (2006) concluded that macroscopic charcoal is still a reliable indicator of local fires, but future experimental burn studies should increase the distance of traps in order to replicate their results.

Research by Gardner and Whitlock (2001) built on the findings of the Clark et al., (1998) experimental burn and in interpreting macroscopic charcoal preserved in lake sediment. Their study examined the accumulation of macroscopic charcoal in 36 lakes after the Charlton fire of 1996 burned extensively in the Cascade Mountain Range of central Oregon. The Charlton fire was a crown fire with 95% tree mortality. Of the lakes sampled, 19 were within the burned area while the other 17 were in unburned watersheds. The researchers investigated whether or not wind conditions during a fire can distort recognition of its source area (Gardner and Whitlock, 2001). All lakes received charcoal from the fire, but charcoal peaks in lakes within the burned area were significantly stronger and higher than those outside the fire boundary. Downwind sites

contained more charcoal than upwind sites, indicating that prevailing winds can influence the amount of charcoal that is deposited in a lake. Results from that study were similar to those from eight lakes sampled five years after the 1988 Yellowstone National Park fires (Whitlock and Millspaugh, 1996). There, all lakes received charcoal deposition, but peaks were noticeably higher in the lakes within the burned area.

**2.6 Secondary Transport**

Like all sediment, charcoal is subject to transportation by secondary processes like surface runoff and sediment mixing years after a fire has occurred. Secondary deposition can blur the charcoal record and make estimating fire size, severity, and activity challenging. When Whitlock and Millspaugh (1996) measured charcoal accumulation in burned and unburned watersheds in Yellowstone after the 1988 fires, they noted that lakes continued to receive charcoal up to five years after the initial fire. Anderson et al., (1986) documented the secondary deposition of charcoal into a Maine lake for decades following a 1910 fire that burned the watershed of the lake. Charcoal can also be moved by seasonal lake currents that shift materials from shallow to deep water (Bradbury, 1996). Due to these processes, it is likely that charcoal peaks found in a sediment core are the result of both primary and secondary deposition processes within the watershed (Whitlock and Larsen, 2002).

**2.7 Charcoal Morphotypes**

Jensen et al., (2006) examined the largely unexplored possibility of determining plant source types from charcoal by comparing paleo-charcoal from lake sediment cored from Ferry Lake, Wisconsin with samples burned under laboratory conditions. Charred grass particles, thanks to their taxonomic resolution under a microscope have previously been identified on various pollen slide studies to family levels (Burney, 1987). The results of the Ferry Lake study

identified four distinct plant source classifications: grass, bordered pits, leaves, and resin. While

not all charcoal was possible to identify a source fuel, Jensen et al., (2006) found morphotype

assignment was possible for 20-30% of the samples in that study. Those results may be useful for

determining herbaceous community types in areas local to the depositional area.

**2.8 Microscopic Charcoal**

Whereas macroscopic charcoal is widely considered a reliable indicator of a local fire

event, microscopic charcoal is considered to be an indicator of more regional fire events

(Patterson et al., 1988; Clark and Royall, 1995). Microscopic charcoal fragments may be

transported over long distances because of their small size, generally less than 100 μm in

diameter (Odgaard, 1992; Patterson et al., 1988). Once microscopic charcoal is dispersed by the

smoke plume or wind into the atmosphere, it is then up to gravity to determine where that

charcoal will fall and ultimately be deposited (Patterson et al., 1988). Despite the increased

transportation properties of microscopic charcoal, exceptionally high peaks may still indicate a

local fire event (Carcaillet et al., 2001).

Differing preparation techniques may impact the results of microscopic charcoal

(Carcaillet et al., 2001).  Because many paleoecological studies often involve the analysis of

pollen in addition to charcoal, the pollen slide technique (Faegri and Iverson, 1964) is most

common for microscopic charcoal analysis (Swain et al., 1973; Patterson et al., 1988). Once

sieved and chemically processed, a researcher counts the opaque, jagged pieces under a

microscope to determine the number and area counts (Swain et al., 1973). Microscopic charcoal

may then be divided into size classes for interpretation. There is no size class standardization for

microscopic charcoal. Mehringer et al., (1977) proposed limiting to two size classes (<25 μm and

>25 μm). Recent literature suggests that given the amount of time for extra processing, size

classes are not necessary due to intense fragmentation during processing. Instead, researchers should keep a tally of 200 objects and record the ratio of controls to microscopic charcoal fragments larger than 10 μm (Finsinger and Tinner, 2005; Conedera et al., 2009).

**Chapter 2 References**

Anderson, R. S., Davis, R. B., Miller, N. G., & Stuckenrath, R. (1986). History of late-and post-glacial vegetation and disturbance around Upper South Branch Pond, northern Maine. *Canadian Journal of Botany, 64*(9), 1977-1986.

Binford, M. W., Brenner, M., Whitmore, T. J., Higuera-Gundy, A., Deevey, E. S., & Leyden, B. (1987). Ecosystems, paleoecology and human disturbance in subtropical and tropical America. *Quaternary Science Reviews, 6*(2), 115-128.

Bolay, E. (1997). *The Dominican Republic: A Country Between Rain Forest and Desert*: Margraf Verlag.

Boucher, D. H. (1990). Growing back after hurricanes. *Bioscience, 40*(3), 163-166.

Bradbury, J. P. (1996). Charcoal deposition and redeposition in Elk Lake, Minnesota, USA. *The Holocene, 6*(3), 339-344.

Burney, D. A. (1987). Late Quaternary stratigraphic charcoal records from Madagascar. *Quaternary Research, 28*(2), 274-280.

Burney, D. A. (1997). Tropical islands as paleoecological laboratories: gauging the consequences of human arrival. *Human Ecology, 25*(3), 437-457.

Burney, D. A., Burney, L. P., & MacPhee, R. D. E. (1994). Holocene charcoal stratigraphy from Laguna Tortuguero, Puerto Rico, and the timing of human arrival on the island. *Journal of Archaeological Science, 21*(2), 273-281.

Burney, L. P., & Burney, D. A. (2003). Charcoal stratigraphies for Kaua'i and the timing of human arrival. *Pacific Science, 57*(2), 211-226.

Carcaillet, C., Bouvier, M., Frechette, B., Larouche, A. C., & Richard, P. J. H. (2001). Comparison of pollen-slide and sieving methods in lacustrnie charcoal analyses for local and regional fire history. *The Holocene, 11*(4), 467-476.

Clark, J. (1988). Stratigraphic charcoal analysis on petrographic thin sections: Application to fire history in northwestern Minnesota. *Quaternary Research, 30*(1), 81-91.

Clark, J. S. (1988). Particle motion and the theory of charcoal analysis: source area, transport, deposition, and sampling. *Quaternary Research, 30*(1), 67-80.

Clark, J. S., & Royall, P. D. (1995). Particle-size evidence for source areas of charcoal accumulation in late holocene sediments of eastern north-american lakes. *Quaternary Research, 43*(1), 80-89.

Conedera, M., Tinner, W., Neff, C., Meurer, M., Dickens, A. F., & Krebs, P. (2009). Reconstructing past fire regimes: methods, applications, and relevance to fire management and conservation. *Quaternary Science Reviews, 28*(5–6), 555-576. doi: 10.1016/j.quascirev.2008.11.005

Cook, S. F., & Borah, W. W. (1971). *Essays in population history: Mexico and the Caribbean* (Vol. 1): Univ of California Pr.

Curtis, J. H., & Hodell, D. A. (1993). An isotopic and trace element study of ostracods from Lake Miragoâne, Haiti: A 10,500 year record of paleosalinity and paleotemperature changes in the Caribbean. *Geophysical Monograph Series, 78*, 135-152.

Desjardines, A. (2007). *Paleoenvironmental Reconstruction of a Coastal Lagoon in Southwestern Dominican Republic.* M.S., Virginia Polytechnic Institute and State University.

Dittus, W. P. J. (1985). The Influence of Leaf-Monkeys on their Feeding Trees in a Cyclone-Disturbed Environment. *Biotropica, 17*(2), 100-106.

Donnelly, J. P., Bryant, S. S., Butler, J., Dowling, J., Fan, L., Hausmann, N., Webb, T., III. (2001). 700 yr sedimentary record of intense hurricane landfalls in southern New England. *GSA Bulletin, 113*(6), 714-727.

Everham, E. M., & Brokaw, N. V. L. (1996). Forest damage and recovery from catastrophic wind. *Botanical Review, 62*(2), 113-185.

Faegri, K., & Iverson, J. (1964). Textbook of Pollen Analysis (2d ed.) Hafner. *New York*.

Finsinger, W., & Tinner, W. (2005). Minimum count sums for charcoal concentration estimates in pollen slides: accuracy and potential errors. *The Holocene, 15*(2), 293-297.

Gardner, J. J., & Whitlock, C. (2001). Charcoal accumulation following a recent fire in the Cascade Range, northwestern USA, and its relevance for fire-history studies. *The Holocene, 11*(5), 541-549.

Garstang, M., & Tyson, P. (1997). Atmospheric Transports of Participate and Gaseous Products by Fires. *Sediment records of biomass burning and global change, 51*, 207.

Giannini, A., Cane, M. A., & Kushnir, Y. (2001). Interdecadal Changes in the ENSO Teleconnection to the Caribbean Region and the North Atlantic Oscillation. *Journal Of Climate, 14*(13), 2867-2879.

Haug, G. H., Hughen, K. A., Sigman, D. M., Peterson, L. C., & Röhl, U. (2001). Southward

    migration of the Intertropical Convergence Zone through the Holocene. *Science,*

    *293*(5533), 1304-1308.

Higuera-Gundy, A., Brenner, M., Hodell, D. A., Curtis, J. H., Leyden, B. W., & Binford, M. W.

    (1999). A 10,300 14C yr record of climate and vegetation change from Haiti. *Quaternary*

    *Research, 52*(2), 159-170.

Horn, S. P., Orvis, K. H., Kennedy, L. M., & Clark, G. M. (2000). Prehistoric fires in the

    highlands of the Dominican Republic: Evidence from charcoal in soils and sediments.

    *Caribbean Journal of Science, 36*(1-2), 10-18.

Jensen, K., Lynch, E. A., Calcote, R., & Hotchkiss, S. C. (2007). Interpretation of charcoal

    morphotypes in sediments from Ferry Lake, Wisconsin, USA: do different plant fuel

    sources produce distinctive charcoal morphotypes. *The Holocene, 17*(7), 907-915.

Jury, M., Malmgren, B. A., & Winter, A. (2007). Subregional precipitation climate of the

    Caribbean and relationships with ENSO and NAO. *Journal of Geophysical Research,*

    *112*(D16), D16107.

Keegan, W. F. (1994). West Indian archaeology. 1. Overview and foragers. *Journal of*

    *Archaeological Research, 2*(3), 255-284.

Keegan, W. F. (2000). West Indian archaeology. 3. ceramic age. *Journal of Archaeological*

    *Research, 8*(2), 135-167.

Kennedy, L. M., Horn, S. P., & Orvis, K. H. (2005). A 4000-year record of fire and forest history from Valle de Bao, Cordillera Central, Dominican Republic. *Palaeogeography Palaeoclimatology Palaeoecology, 231*(3-4), 279-290.

Kjellmark, E. (1996). Late Holocene climate change and human disturbance on Andros Island, Bahamas. *Journal of Paleolimnology, 15*(2), 133-145.

Landers, J. L., Vanlear, D. H., & Boyer, W. D. (1995). The longleaf pine forests of the southeast - requiem or renaissance. *Journal of forestry, 93*(11), 39-44.

Landsea, C. W., Glenn, D. A., Bredemeyer, W., Chenoweth, M., Ellis, R., Gamache, J., Woolcock, L. (2008). A reanalysis of the 1911-20 Atlantic hurricane database. *Journal of Climate, 21*(10), 2138-2168.

Lane, C. S., Horn, S. P., Mora, C. I., & Orvis, K. H. (2009). Late-Holocene paleoenvironmental change at mid-elevation on the Caribbean slope of the Cordillera Central, Dominican Republic: a multi-site, multi-proxy analysis. *Quaternary Science Reviews, 28*(23), 2239-2260.

Lane, C. S., Horn, S. P., Orvis, K. H., & Thomason, J. M. (2011). Oxygen isotope evidence of Little Ice Age aridity on the Caribbean slope of the Cordillera Central, Dominican Republic. *Quaternary Research, 75*(3), 461-470.

Last, W. M., Smol, J. P., & Birks, H. J. B. (2001). *Tracking environmental change using lake sediments* (Vol. 1-4). Boston: Kluwer Academic Publishers.

LeBlanc, A. (2011). *A 1000-year sedimentary record of hurricane, fire, and vegetation history from a coastal lagoon in southwestern Dominican Republic.* M.S., Virginia Polytechnic Institute and State University.

Lewis, R. J., & Bannar-Martin, K. H. (2011). The Impact of Cyclone Fanele on a Tropical Dry Forest in Madagascar. [Online Journal article]. *Biotropica*. doi: 10.1111/j.1744-7429.2011.00799.x

Liu, K.-b., Lu, H., & Shen, C. (2007). A 1200-year proxy record of hurricanes and fires from the Gulf of Mexico coast: Testing the hypothesis of hurricane–fire interactions. *Quaternary Research, 69*(1), 29-41.

Loope, L., Duever, M., Herndon, A., Snyder, J., & Jansen, D. (1994). Hurricane impact on uplands and freshwater swamp forest. *Bioscience, 44*(4), 238-246.

Lugo, A. E., Applefield, M., Pool, D. J., & McDonald, R. B. (1983). The impact of Hurricane David on the forests of Dominica. *Canadian Journal of Forest Research, 13*(2), 201-211. doi: 10.1139/x83-029

Lynch, J. A., Clark, J. S., & Stocks, B. J. (2004). Charcoal production, dispersal, and deposition from the Fort Providence experimental fire: interpreting fire regimes from charcoal records in boreal forests. *Canadian Journal of Forest Research, 34*(8), 1642-1656.

Malmgren, B. A., Winter, A., & Chen, D. (1998). El Niño-southern oscillation and North Atlantic oscillation control of climate in Puerto Rico. *Journal Of Climate, 11*(10), 2713-2717.

Martin, P. H., Sherman, R. E., & Fahey, T. J. (2007). Tropical montane forest ecotones: climate gradients, natural disturbance, and vegetation zonation in the Cordillera Central, Dominican Republic. *Journal of Biogeography, 34*(10), 1792-1806.

Mehringer Jr, P. J., Arno, S. F., & Petersen, K. L. (1977). Postglacial history of lost trail pass bog, Bitterroot Mountains, Montana. *Arctic and Alpine Research*, 345-368.

Murphy, P. G., & Lugo, A. E. (1986). Ecology of Tropical Dry Forest. *Annual Review of Ecology and Systematics, 17*(1), 67-88.

Myers, R. K., & van Lear, D. H. (1998). Hurricane-fire interactions in coastal forests of the south: a review and hypothesis. *Forest ecology and management, 103*(2-3), 265-276.

Odgaard, B. V. (1992). The fire history of Danish heathland areas as reflected by pollen and charred particles in lake sediments. *The Holocene, 2*(3), 218-226.

Patterson, W. A., Edwards, K. J., & Maguire, D. J. (1988). Microscopic charcoal as a fossil indicator of fire. *Quaternary Science Reviews, 6*(1), 3-23.

Peros, M. C., Reinhardt, E. G., & Davis, A. M. (2007). A 6000-year record of ecological and hydrological changes from Laguna de la Leche, north coastal Cuba. *Quaternary Research, 67*(1), 69-82.

Pisaric, M. F. J. (2002). Long-distance transport of terrestrial plant material by convection resulting from forest fires. *Journal of Paleolimnology, 28*(3), 349-354.

Rappaport, E. N., Fernandez-Partagas, J., & Center, N. H. (1995). *The deadliest Atlantic tropical cyclones, 1492-1994*: National Oceanic and Atmospheric Administration.

Rouse, I. (1993). *The Tainos: Rise and decline of the people who greeted Columbus*: Yale Univ Pr.

Santiago-García, R. J., Colón, S. M., Sollins, P., & Van Bloem, S. J. (2008). The role of nurse trees in mitigating fire effects on tropical dry forest restoration: a case study. *Ambio, 37*(7-8), 604-608.

Siegel, P. E., Jones, J. G., Pearsall, D. M., & Wagner, D. P. (2005). Environmental and cultural correlates in the West Indies: A view from Puerto Rico. *Ancient Borinquen: Archaeology and Ethnohistory of Native Puerto Rico, edited by Peter E. Siegel*, 88-121.

Speer, J. H., Orvis, K. H., Grissino-Mayer, H. D., Kennedy, L. M., & Horn, S. P. (2004). Assessing the dendrochronological potential of Pinus occidentalis Swartz in the Cordillera Central of the Dominican Republic. *The Holocene, 14*(4), 563-569.

Stocks, B., & Kauffman, J. (1997). Biomass consumption and behavior of wildland fires in boreal, temperate, and tropical ecosystems: Parameters necessary to interpret historic fire regimes and future fire scenarios. *Sediment records of biomass burning and global change, 1*, 169-188.

Swain, A. M. (1973). A history of fire and vegetation in northeastern Minnesota as recorded in lake sediments. *Quaternary Research, 3*(3), 383-390.

Tinner, W., Hofstetter, S., Zeugin, F., Conedera, M., Wohlgemuth, T., Zimmermann, L., & Zweifel, R. (2006). Long-distance transport of macroscopic charcoal by an intensive crown fire in the Swiss Alps - implications for fire history reconstruction. *The Holocene, 16*(2), 287-292.

Urquhart, G. R. (2008). Paleoecological record of hurricane disturbance and forest regeneration in Nicaragua. *Quaternary International, 195*(1-2), 88-97.

Vandermeer, Boucher, Perfecto, Roth, Will, & Yih. (1990). El bosque devastado de Bluefields. [Journal Article]. *Wani, 8*, 60-73.

Webb, L. J. (1958). Cyclones as an ecological factor in tropical lowland rain-forest, North Queensland. *Australian Journal of Botany, 6*(3), 220-228.

Whigham, D. F., Olmsted, I., Cano, E. C., & Harmon, M. E. (1991). The impact of hurricane gilbert on trees, litterfall, and woody debris in a dry tropical forest in the northeastern yucatan peninsula. *Biotropica, 23*(4), 434-441.

Whitlock, C. (2004). Forests, fires and climate. *Nature, 432*(7013), 28.

Whitlock, C., & Larsen, C. (2002). Charcoal as a fire proxy. *Tracking environmental change using lake sediments*, 75-97.

Whitlock, C., & Millspaugh, S. H. (1996). Testing the assumptions of fire-history studies: an examination of modern charcoal accumulation in Yellowstone National Park, USA. *The Holocene, 6*(1), 7-15.

## Chapter 3:  Manuscript

## A 4700-Year Record of Lake Evolution and Fire History for Laguna Limón, Dominican Republic

## 3.1 Abstract

Fire is a primary driver of environmental change that can originate from natural or human ignition. Macroscopic charcoal (>125 µm) deposited into lake sediment is a record of a local fire event, whereas microscopic charcoal indicates fire activity on a broad landscape scale. Patterns of charcoal deposition may shed light on both human activities and climate history over long-time scales. Whether lowland Caribbean forests have experienced natural fire regimes over the long-term is unknown. Laguna Limón is a little-studied, large, freshwater lake on the northeastern coast of the Dominican Republic. We extracted four overlapping sediment cores totaling 315 cm in depth, and conducted analysis of macroscopic charcoal (2-cm), microscopic charcoal (16-cm), and loss-on-ignition (1-cm) to examine the long-term fire and environmental history of the area. Loss-on-ignition data established that the lake has only recently become organic rich, and was likely open to the sea as a low energy bay until 1400 Cal. Yr BP. The lake existed briefly as a wetland before transitioning to the modern freshwater lake 1200 Cal. Yr BP. Macroscopic charcoal was most abundant in the freshwater section of the core while microscopic charcoal peaked near the bottom of the core, and aligns well with other regional microscopic charcoal records. Overall the charcoal record reflects a combination of climatic and anthropogenic related charcoal deposition suggesting that fire has played an active role in the environmental history Laguna Limón.

**3.2 Introduction**

Tropical islands, like Hispaniola, are dynamic systems sensitive to the interplay of various climatic, oceanic, and anthropogenic forces. Reconstructions of environmental changes in setting, vegetation, and fire through proxy data stored in lake sediments make possible the long-term analysis of how these systems respond to change (Last et al., 2001). Understanding long-term dynamics of an environmental response may aid modern conservation efforts in preparing for and mitigating future change.

Fire is regarded by researchers as an important disturbance agent in many ecosystems (Whitlock, 2004). Numerous paleoenvironmental studies have established the vital role of fire in boreal ecosystems (Clark et al., 1998; Carcaillet et al., 2001), but less is known about the long-term fire record of coastal tropical Caribbean ecosystems. Paleoecological studies of tropical Caribbean ecosystems have increased in recent decades, but most of these studies have only included regional fire history reconstruction through microscopic charcoal analysis, often as a byproduct of pollen analysis (Burney and Burney, 1994; Higuera-Gundy et al., 1999; Kennedy et al., 2005; Kjellmark, 1996; Lane et al., 2009). Microscopic charcoal is an established indicator of regional fires due to the increased transportation properties of airborne particles (Patterson et al., 1988). Caribbean paleoecological studies that analyze macroscopic charcoal, an indicator of local fire events (Clark, 1988; Clark et al., 1998; Whitlock and Larsen, 2002), are rare.

Charcoal is a byproduct of fire that accumulates through primary or secondary deposition over time in the sediment profile of lakes (Anderson et al., 1986; Whitlock and Larson, 2002). In addition to natural ignition by lightning, humans have used fire to alter landscapes to better suit their needs. Lakes, through sediment deposition, act as time capsules cataloging proxy records of surrounding environments (Last et al., 2001). Charcoal analysis is the primary method for examining fire history over the long term (hundreds to thousands of years).

Because fires can occur both naturally and from anthropogenic sources, differentiating between the two can be challenging. One method for distinguish between natural and human caused ignition is to look for charcoal sedimentation patterns indicative of one or the other. For example, Myers and van Lear (1998) hypothesized that an historical interaction has existed between hurricanes and fires in the coastal American Southeast due to the increased ground fuel buildup as a result of high winds. Liu et al., (2007) validated that hypothesis through sediment analysis of two coastal lakes in Alabama that identified microscopic charcoal peaks following hurricane overwash events.

Coastal tropical forests of the Caribbean are not assumed to interact with fire (Santiago-Garcia et al., 2008), but long-term data regarding that assumption is lacking. In the Canadian boreal forest, climate, not vegetation type is the primary driver of fire regimes (Carcaillet et al., 2001). Macroscopic charcoal records have been used to link Holocene fire regimes to changes in climate in *Tsuga mertensiana* rainforests of British Columbia (Hallett et al., 2003). A 9000-year evolution of fire return intervals corresponded with changes in climate in the Oregon Coast Range and the modern fire regime there has only existed for the last 1000 years (Long et al., 1998). Charcoal deposition may indicate changing climatic patterns, even if existing vegetation is not fire adapted.

Fire is an important disturbance in many ecosystems and a natural presence in upland pine forest regions of the Dominican Republic. Sediments from Valle de Bao in the Cordillera Central contained records of a 4000-year cyclical history of fire from microscopic charcoal and pine pollen (Kennedy et al., 2006). That record indicated that repeated burning, likely of natural ignitions, has been an important component of the ecosystem since the bog formation. Soil and sediment charcoal in the Cordillera Central revealed evidence of fire in the pine uplands dating

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back to the Pleistocene (Horn et al., 2000). Natural fires are the primary driver in shaping distinct boundaries in ecotones of the Cordillera Central (Martin and Fahey, 2006). A combination of disturbance from intense hurricane winds and the resulting fires from accumulation of woody debris created an ecotonal environment of fire adapted vegetation that thinned out at the base of the cloud forest (Martin and Fahey, 2006). Dendrochronological investigations have established that historical fire activity prior to human occupation in the Cordillera Central increased during the extended dry seasons caused by El Niño Southern Oscillation (ENSO) years (Speer et al., 2004; Martin and Fahey, 2006).

Charcoal records that do not correspond to climatic indicators may instead serve as archaeological evidence of human activity (Burney, 1997). For instance, Burney and Burney (1994) interpreted a dramatic peak in microscopic charcoal that signified the arrival of paleo-humans in Puerto Rico almost 2000 years before the archaeological record. Kjellmark (1996) identified a peak in microscopic charcoal from Churches Blue Hole in the Bahamas that coincided with archaeological evidence of the islands first inhabitants and a second peak with the arrival of the Spanish.

Most Caribbean lowland paleoenvironmental studies have focused on reconstructions of vegetation through pollen analysis, paleo hurricane records, or reconstructions of climate from isotopic signals recorded by macro invertebrates (Burney and Burney, 1994; Curtis et al., 1993; Curtis et al., 1996; Desjardines, 2007; Donnelly and Woodruff, 2007; Higuera-Gundy et al., Holmes et al., 1995; 1999; LeBlanc, 2011; Peros et al., 2007; Urquhart, 2008). This study of Laguna Limón, a freshwater lake in coastal northeastern Dominican Republic, documented changes in lake morphology and provided a 4700-year record of local and regional fires from

macroscopic and microscopic charcoal (respectively) that can be compared with past and future sediment records in the circum-Caribbean region.

     This research had two major objectives: 1. document the origin and morphology of Laguna Limòn through the interpretation of sediment stratigraphy and loss-on-ignition analysis; 2. reconstruct a local and regional fire history by sampling sediment for macroscopic (>125 µm) and microscopic charcoal (<125 µm). We then compared this proxy information with the existing catalog of climate and anthropogenic data and explored any associations.

**3.3 Methods**

*Environmental Setting*

The Dominican Republic and Haiti share the island of Hispaniola (19° N, 70° W) in the central Caribbean. Hispaniola is the second largest island in the Greater Antilles archipelago preceded in size and population only by Cuba. Eco-regions vary in the Dominican Republic from desert to rainforest (Bolay, 1997) (Figure 1). Likewise, the Dominican Republic exhibits substantial elevation contrast, from 46 m below sea level in the Enriquillo Valley to 3098 m atop Pico Duarte in the Cordillera Central (Figure 2). Caribbean climate is influenced by several oceanic and atmospheric processes including subtropical high pressure, trade winds, ENSO, Northern Atlantic Oscillation, and the Intertropical Convergence Zone (ITCZ).

Hispaniola is located at the northern periphery of the tropical zone. Therefore, the climate near Laguna Limón (18.9783° N, 68.8494° W) is largely reflective of other tropical regions. Annual temperatures average a high of 30° C and a low of 21° C (Miches) with little annual variation due to its tropical location and proximity to the ocean. Trade winds blow from the northeast and bring seasonal rainfall. Due to the shifting position of the ITCZ and subtropical high pressure, a dry season occurs between December and March. Rainfall for the region surrounding Laguna Limón ranges between 1600–2000 mm annually and a majority of the rainfall can come during the hurricane season (June–October) (Bolay, 1997).

The island arc of the Greater Antilles formed as a result of a collision between the Caribbean and North American tectonic plates (Mann et al., 1991). The geologic origins of the area around Laguna Limón are classified as a bed of Cretaceous alluvium (French and Schenk, 1997). The Septentrional Fault Zone (SFZ) and Enriquillo-Plantain Garden are two active fault zones that run roughly parallel through Hispaniola. The SFZ, located near Laguna Limón may

have had an historical influence in the accumulation of sediment into the lake. Fault zones are known to uplift and alter land, impact hydrology, raise or lower the water table, and cause earthquakes and trigger tsunamis. Any or all of these processes could have impacted the sediment profile of Laguna Limón.

The Cordillera Orientál is an east-west running chain of mountains located approximately four km south of Laguna Limón. The mountains were formed by volcanic intrusion during the Eocene (Mann et al., 1991) and reach a maximum height of 244 m. Vegetation throughout the range is classified as subtropical wet forest. Two rivers flow north into Laguna Limón from the Atlantic slope of the Cordillera Orientál.

*Study Site*

Laguna Limón is a 5.1 km$^2$ freshwater lake located on the Atlantic coast of the northern Dominican Republic (Figure 3, 4). The lake is 3 km at its widest point and separated from the Atlantic Ocean at its narrowest point by 200 m. A small, seasonal inlet approximately 400 m long leads to Playa Limón on the eastern coastal edge of the lake. The inlet is open temporarily to the sea during the rainy season and closed during the dry season. Water depth ranges 3–4 m near the center of the lake. According to local sources, water depth can vary annually 1–2 m depending upon precipitation. A salinity reading near the center of the lake registered 0 parts per trillion (ppt) and 5 ppt nearer the ocean suggesting that some degree of subterranean flow exists between the lake and the Atlantic Ocean. Two small islands are located near the coastal edge of the lake, and a floating island consisting of various species of interlocking vegetation is regularly pushed from side to side of the lake depending on wind speed and direction. Vegetation surrounding the lake is classified as subtropical moist forest (Figure 1) and includes *Ipomea* sp.,

*Typha* sp., palm trees, and red, white, and black mangroves. The combination fresh water, islands and marshes make Laguna Limón exceptional bird habitat.

Laguna Limón is the centerpiece of the Ecological Preserve. A small marina specializing in fishing and a kayaking and boating based tourism operation exists at the southern edge of the lake. The village of Los Guineos is located 1 km from the lake. Agriculture and small livestock operations are the primary land use activities in the immediate vicinity of the Laguna Limón.

*Field Methods*

In January 2012, we used a Livingstone drive rod piston corer to extract one complete sediment profile composed of four overlapping cores, including the mud-water interface, from near the center of Laguna Limón (18.9783° N, 68.8494° W) (Table 1). The first three cores were recovered in succession from the near the original hole. The final core was taken at a slightly different location (1–2 m) when the anchors of the boat were readjusted. Coring ended at 315 cm due to a thick layer of impenetrable sand. The cores were retained in PVC tubes and capped on location. Water depth at the site of the core was 335 cm. The cores were stored at 6°C in the Paleoenvironments Laboratory at Virginia Tech.

*Laboratory Methods*

*Stratigraphy, Chronology, and Loss on Ignition*

We described the core using the Munsell soil color chart (Charts, 1975) taking note of sediment color changes, texture, stratigraphy, and the presence or absence of shells. We photographed and obtained X-radiograph images of the core sections.

We isolated five organic samples for radiocarbon dating. Four of these samples were macroscopic charcoal fragments and one plant fragment. The samples were processed by Woods Hole Oceanographic Institute National Ocean Sciences Accelerator Mass Spectrometry Facility.

We conducted loss-on-ignition analysis at 1-cm intervals for the entire length of the core. This process measured water, organic, carbonate, and silicate content in each sample. Weighed samples were dried for 24 hours at 100 °C then re-weighed to determine water loss. Samples were then burned at 500 °C for 2 hours to measure organic content and then at 1000 °C for 1 hour. The samples were reweighed after each burn in order to determine carbonate and residual silicate content (Dean, 1973).

*Macroscopic charcoal*

We defined macroscopic charcoal as any charcoal fragment larger than 125 μm in any dimension. We sampled sediment at 2-cm intervals throughout the entire length of the sediment profile using the wet sieve sampling method. Sediment samples of 1-cm³ were taken from the center of the core and placed into a pre-weighed tube and reweighed to measure sediment mass. Hot de-ionized water was added to each sample to break apart sediment. We soaked samples in tubes overnight then washed gently with hot de-ionized water through a 125 μm mesh sieve. All material on top of the sieve was transferred to a zoned petri-dish and examined under a microscope at 30X magnification. Each zone was searched for charcoal. Charcoal fragments were isolated, counted, and transferred to a pre-weighed vial for drying and weighing.

*Microscopic charcoal*

We conducted microscopic charcoal sampling via the pollen slide technique at 16-cm intervals, occasionally finer, for a total of 24 samples. We processed microscopic charcoal following the standard pollen slide preparation technique (Faegri and Iverson, 1989). Lycopodium spore tablets containing a known number of spores were added to the samples at the beginning of processing to provide control. We suspended pollen residues in silicone oil and mounted them on glass microscope slides. Lycopodium control spores and charcoal fragments—

defined as any jagged, opaque and angular object larger than 10 μm—were counted until we

reached a total of 200 objects following a standard outlined by Tinner et al., (1998).

**3.4 Results**

*Core Description and Zonation*

We divided the environmental history of Laguna Limón into three distinct zones based on sediment stratigraphy, color, and loss-on-ignition analysis (Figure 5). Zone I represented the oldest section of the core and contained sediment from 126–315 cm. From 226–315 cm the sediment was distinctly coarse and dry. Sediment was mostly light gray in color and contained abundant colorful shell, fragmented coral, and coarse sand. Sediment became less coarse and transitioned to fine clay from 126–226 cm. Large shells and shell fragments were visible in the sediment and in X-radiographs throughout Zone I.

Zone II contained sediment from 111–126 cm. Sediment in this section distinctly transitioned from fine gray clay to black organic material. This was the clearest stratigraphy change within the core. Large, mostly intact shells were present here, but not as densely as in Zone I.

Zone III represented the most recent time period and contained sediment from the surface to111 cm. At 94 cm the sediment transitioned to dark gray and returned to a finely textured silt and clay mix. Shells were no longer present and organic content almost completely replaced carbonate content.

*Chronology*

We captured radiocarbon dates using Accelerated Mass Spectrometry (AMS) on five samples from Laguna Limón (Table 2). All dates were returned in chronological order suggesting an accurate record of continuous and regular sediment deposition. We used the Calib 6.0.1 software (Stuiver and Reimer, 1993) to calibrate the radiocarbon dates. We graphed the mean year calculated from the 2 sigma age range which represented a 95% confidence interval.

All dates are graphed as Calibrated Years Before Present (Cal. Yr BP) where present equals the

year 1950 AD. Plant material from 313 cm returned a radiocarbon date of 4697 ± 131 Cal. Yr BP,

indicating the approximate age of the lake.

Chronologically ordered samples allow for the calculation of an Age Depth graph (Figure

6) and thus an estimation of sedimentation rates (Table 3). The sedimentation rate was fairly

even throughout with the fastest rate of 1.7 mm$^2$ yr$^{-1}$ occurring between 272 and 313 cm. The

average sediment accumulation rate for Laguna Limón was 0.7 mm$^2$ yr$^{-1}$ and represented 15.01

yr$^1$ cm$^{-2}$.

*Loss on Ignition*

Loss-on-ignition documented a steady decline in carbonate content as it was replaced

primarily with organic content (Figure 7, 8). Carbonate content began at 35% at 315 cm and

steadily decreased toward the top of the sediment profile. Organic content remained below 10%

until a major shift in stratigraphy at 126 cm, where it experienced a sudden and prolonged peak

until 111 cm. At 94 cm organic content decreased considerably to 10% and then slowly increased

to levels between 30–40% in the uppermost 30 cm of the core.

*Macroscopic Charcoal*

Out of 151 depths sampled, we found macroscopic charcoal to be present in 93 samples

for a total of 477 fragments. We graphed charcoal fragments by number of fragments found per

sample interval (Figure 9) and by Charcoal Accumulation Rate (CHAR) using the sedimentation

rate from the Age Depth graph (Figure 10). Macroscopic CHAR represents number of fragments

cm$^2$ yr$^{-1}$ (Ali et al., 2009). Calculation of CHAR is essential for cross comparison with other

regional sedimentary charcoal studies. We found macroscopic charcoal fragments to be most

numerous in Zone III where organic content was also high. The highest CHAR value occurred at

54 cm where 29 fragments reached an index of 2.54 fragments cm$^2$ yr$^{-1}$. An AMS radiocarbon date from that sample revealed a sample age of 616 ± 36 Cal. Yr BP.

*Microscopic Charcoal*

Microscopic charcoal was present in all sample depths. We graphed an estimation of the microscopic charcoal area concentration using the following regression equation (Tinner et al., 1998):

ln $(A)$ = −7.418 + 0.936 ln $(N)$

Where $A$ is the area concentration (mm$^2$ cm³) and $N$ is the charcoal particle number concentration (cm³) of all charcoal particles longer than 10 μm up to 200 objects (Figure 11). Microscopic charcoal area concentration was fairly evenly distributed throughout the core. We then used the sedimentation rates from the Age Depth graph to graph CHAR (mm$^2$ cm$^2$ yr$^{-1}$) by dividing the charcoal area concentration by the number of years represented by 1 cm$^3$ of sediment (CHARa) (Figure 12).

We also expressed microscopic charcoal CHAR as fragments cm$^2$ yr$^{-1}$ (CHARf) (Figure 13). The largest CHAR peaks were located in the bottom section of the core from the four samples below 286 cm. Above 286 cm, CHAR values were moderate and steady with the exception of one peak at 82 cm.

**3.5 Discussion**

*Reconstruction of Lake Evolution and Morphology*

*Zone I (4700–1400 Cal. Yr BP)*

We interpret the moderate carbonate and low organic levels in Zone I as evidence that Laguna Limón was open to the sea as a low energy bay for the earliest portion of its history. An open system may explain the low organic content in Zone I. In an open system, organic content would likely have been swept away by the tide. The high concentration of shells in this zone observed visually and in X-radiographs support the interpretation of an open connection to the sea. Crushed coral fragments observed in the lowest section of the core add to the evidence of a connection to the sea. The initial formation of the lake basin is roughly equivalent to the time period described by Peros et al., (2007) as an era of slow regional sea level rise that continued until roughly 2000 Cal. Yr BP as well as increasingly wet climatic conditions of the mid Holocene indicative of a northerly position of the ITCZ (Curtis and Hodell, 1993). Periodic high rainfall events may explain the peaks in silicate and water content at 284 cm, 298 cm, and 305 cm, respectively. These peaks may represent flood events from a river that replaced oceanic-borne carbonate content with land-borne silicate and mud content.

*Zone II (1400 –1200 Cal. Yr BP)*

The proxy data within Zone II suggest a transition from an open, low energy bay connected to the ocean to a closed wetland system. We interpret the sudden change in stratigraphy, the dark sediment color, and loss-on-ignition results that show prolonged high organic content as an indication of a wetland environment. Shells were present, but larger and not fragmented in Zone II, suggesting that those shells completed their life cycle in that environment.

There are at least two possible explanations for this transition. First, an increase in the sedimentation rate near the end of Zone I may have allowed for infill due to the presence of a barrier reef located just offshore. This would have permitted material to accumulate and ultimately blocked the connection to the sea. A test core near the modern coastal edge of Laguna Limón revealed sediment composed primarily of mangrove peat. The establishment of mangroves and the resulting peat accumulation in Laguna de Leche, Cuba were a contributing factor in the separation of that lake from the sea (Peros et al., 2007). At Laguna Limón, a similar establishment of mangroves near the coastal edge of the bay may have accelerated peat production and thus increased the sedimentation rate, ultimately closing off the connection to the sea.

A second possibility for this transition is tectonic activity. The SFZ is an active strike-slip and dip-slip zone located just offshore to the north of Laguna Limón. Historic earthquakes in the Cibao Valley directly to the west of Laguna Limón have been attributed to this fault zone. The most recent ground rupturing earthquake was estimated to have occurred roughly 800 Cal. Yr BP with an estimated recurrence interval of 800–1200 years (Prentice et al., 2003). A ground rupturing tectonic event may have disconnected the bay from the sea and created a low depression that was colonized by wetland vegetation such as mangroves and *Typha* sp. that exist today. Alternatively, a tectonic event could have altered the flow of one or both of the rivers that currently drain into Laguna Limón. The transition of Laguna Saladilla in coastal northern Dominican Republic from a salt water system to a closed fresh water system due to the migration of a river into the local hydrological cycle may have been due to tectonic activity owed to the SFZ (Caffrey, 2011).

The loss-on-ignition data and visual observations of abrupt stratigraphy and color change suggest that an abrupt increase in the sedimentation rate was unlikely. AMS Radiocarbon dates from depths of 96 cm and 196 cm allow for the calculation of a sedimentation rate equaling 0.5 mm/year, the slowest section of the core. Due to our AMS radiocarbon sample spacing, this is also the longest period in the sediment record between radiocarbon dates, representing an estimated 2000 years, so an increase in the sedimentation rate near the transition between Zone I and Zone II may be blurred. Given the sharp contrast in sediment color, texture and the dramatic rise in organic content as revealed by loss-on-ignition, combined with the presence of the SFZ located just offshore to the North, tectonic activity was a more likely cause for the disconnection from the Atlantic Ocean. If the core location existed at the time in a shallow bay, even slight uplift could have caused complete separation from the sea. This uplift, combined with mangrove establishment and thus peat accumulation, may have contributed to further separate Laguna Limón from the sea.

*Zone III (1200-present)*

Zone III represents the most recent history of the lake and what we have interpreted to be the origin of the modern freshwater lake that exists today. Organic content initially decreased from the high levels in Zone II and stayed relatively stable with exceptions toward the most recent portion of the sediment profile. Carbonate content continued to trend downward and shells are completely absent in Zone III. This depression, created by an event at the transition of Zone I and Zone II, likely filled slowly over the course of the 200-year span of Zone II by the two rivers that flow from the nearby Cordillera Orientál to the South, ultimately leading to lake formation 1200 YBP.

*Reconstruction of Local and Regional Fire History*

*Zone I (4700–1400 Cal. Yr BP)*

Low macroscopic CHAR, particularly the depths below 196 cm, are juxtaposed with the highest values of microscopic CHAR in Zone I. It is important to note that macroscopic CHAR values in the upper half of Zone I were not all 0, indicating that there were local fires of some kind at this time. The open, low energy bay system that characterized Laguna Limón in Zone I may help explain these low macroscopic CHAR values. Large macroscopic charcoal fragments, like organic content, may have been swept away by the ocean and not retained in the sediment profile. Alternatively, a relatively moist climate may have decreased naturally ignited local fires. Curtis and Hodell (1993) analyzed stable isotopes contained in sediment from Lake Miragoâne in Haiti and described this period as an era of increased moisture and precipitation up to 3200 $^{14}$C YBP (196 cm). Increased moisture would not have been conducive to natural ignition thus making naturally ignited local fire events rare.

The presence of charcoal may be attributed to anthropogenic disturbances within the watershed. The Casimiroids were the first people known to arrive on Hispaniola (Keegan, 1994). They originated from the Yucatan peninsula and migrated east across the Greater Antilles arriving in Hispaniola roughly 6000 YBP (Keegan, 1994). These people relied on marine life and to a lesser extent edible plants near the coast (Rouse, 1993). A low energy bay would have provided an ideal and safe fishing location. People living and fishing around the location of Laguna Limón undoubtedly kept small fires for cooking and fuel production. These actions could explain the presence of macroscopic charcoal in Zone I.

In an investigation of Laguna Tortuguero in Puerto Rico, Burney and Burney (1994) cited Curtis and Hodell's (1993) climate data from Lake Miragoâne in Haiti in their argument for a

dramatic microscopic charcoal peak signaling the arrival of humans to Puerto Rico nearly 2000 years earlier than indicated by the existing archaeological record. Burney and Burney (1994) argued that vegetation would be less likely to burn naturally if climate conditions were moist, despite the increased lightning from storms. The alternative explanation would be human arrival and forest clearance by fire. Burney and Burney (1994) suggested that humans would be more likely to conduct burning during moist conditions because fires would be easier to control. Burney and Burney (1994) reported a high microscopic charcoal influx in a time period similar to the results from the four lowest samples of our study. Sediment from a follow up study by Schoen (2011) in another section of Lake Tortuguero found similar evidence of a microscopic charcoal peak like that found by Burney and Burney (1994).

An alternative explanation involving increased winter insolation in the circum-Caribbean may clarify high microscopic charcoal values in Lake Tortuguero and in Laguna Limòn. Caffrey (2011) examined Burney and Burney's (1994) claim in conjunction with microscopic charcoal values reported by Higuera-Gundy et al., (1999) from Lake Miragoâne, Haiti and microscopic charcoal from Laguna Saladilla in northern Dominican Republic. Caffrey's (2011) results showed that high microscopic charcoal influx during this period may have been linked regionally to increased mid-Holocene winter insolation which drove increases in fire activity and charcoal deposition. The onset of exceptionally dry winters would have allowed more time for fuel to accumulate and dry on the ground. An increase in regional fire activity may help explain the high microscopic CHAR values found in the lowest section of Laguna Limón.

Macroscopic CHAR values were similar but more frequent from 196 cm to the upper end of Zone I at 126 cm (3100–1400 Cal. Yr BP). This section was characterized by a lower but level rate of microscopic CHAR deposition. Climatically the time period from 2500–1500 YBP has

been described as regionally moist from isotopic records from the Yucatan by Hodell et al., (1995, 2000) and in mid-elevation regions of the Cordillera Central, Dominican Republic by Lane et al., (2009). High moisture delivery at this time was likely indicative of a relatively northern position of the ITCZ (Haug et al., 2001). Kennedy et al., (2005) documented the emergence of broad leaf taxa pollen in Valle de Bao during this time period, also indicating increased precipitation in the uplands of the Cordillera Central.

From 2500–1500 Cal. Yr BP Lane et al. (2009), identified an increase in microscopic charcoal at two mid-elevation lakes in the Cordillera Central while a decline in lake levels at Lake Miragoâne in Haiti (Curtis and Hodell, 1993) suggested extremely dry lowland conditions persisted. Lane et al., (2009) postulated that the increase in microscopic charcoal may be explained by drought conditions ripe for natural ignition, or the arrival of the Saladoid People around 2000 YBP (Rouse, 1992). These people migrated north from South America across the Lesser Antilles and practiced slash and burn agriculture while moving into the interior of Hispaniola. A regionally moist climate could explain the decrease in microscopic CHAR, while seasonally dry lowland conditions combined with the arrival of the Saladoid People and thus agriculture may account for the increased frequency in macroscopic CHAR recorded in upper section of Zone III.

*Zone II (1400–1200 Cal. Yr BP)*

Lane et al. (2009), described the time period from 1500–1200 Cal. Yr BP as one of increasing aridity and documented decreases in lake water levels from both sites in the mid-elevation Cordillera Central. That finding coincides with the wetland era at Laguna Limón as the site slowly filled with fresh water during the course of Zone II. Macroscopic CHAR values in Zone II were very low with the exception of one peak near the transition to Zone III. The lone

macroscopic CHAR peak in Zone II was composed of 30 fragments that were all noted as grass charcoal. This result may indicate low intensity surface fires, possibly of natural ignition. Alternatively, this result could signal human set fires intended for agricultural land clearance purposes. Due to the short duration of Zone II and broad sampling interval of microscopic charcoal, only one sample represents Zone II. This sample returned the lowest CHAR value of the entire core, an indication that regional fire activity may have been very low at this time.

*Zone III (1200 Cal. Yr BP–present)*

Zone III marked the transition of Laguna Limón from a wetland to a freshwater lake. That time period also coincided with the Terminal Classic Drought (TCD), a series of wet and dry events that lasted from 1200–900 $^{14}$C YBP (Hodell et al., 1995). The TCD may have been at least partially responsible for the collapse of the Mayan civilization in Central America (Hodell et al., 1995). Horn and Sanford (1992) documented a period of increased biomass burning in the microscopic charcoal record from a lake in Costa Rica during the same time period. Lane et al., (2009) noted the arrival of maize pollen and a rise in microscopic charcoal that likely signaled the arrival of people to the mid-elevation lakes of the Cordillera Central. Lane et al., (2009) postulated that people likely migrated up from the lowlands due to drought stress and settled around available fresh water sources.

Macroscopic charcoal was most abundant in Zone III. One explanation is that the closed system of a freshwater lake allowed for higher retention of macroscopic charcoal fragments. Indeed, macroscopic CHAR values were particularly high at depths between 111–50 cm which represents the time period of the TCD. Likewise, a microscopic CHAR peak occurred at 82 cm. An AMS radiocarbon date of 616 ± 36 Cal. Yr BP from 54 cm infers that these high values were prior to Spanish arrival. Dry periods during the TCD may have been responsible for increasing

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the fire fuel potential in moist forests like those found around Laguna Limón. Alternatively, these high macroscopic CHAR values may reflect an increased human population around Laguna Limón. A freshwater lake would have been an appealing place to settle near during times of drought stress. Microscopic charcoal also increased around this time at Lake Miragoâne in Haiti. There, the rise in charcoal was attributed to the arrival of agriculturalists in the region (Higuera-Gundy et al., 1999). A similar transition to agriculture may have taken place at Laguna Limòn.

The TCD was followed by a climatic era known as the Medieval Warm Period (MWP). Although the exact dates are debated, the MWP lasted from approximately 900–350 Cal. Yr BP (Lane et al., 2011). That time period showed an increase in regional precipitation and temperatures. Climate records from the Cariaco Basin in Venezuela (Haug, 2001), the Florida Everglades (Winkler, 2001), Guadeloupe (Beets, 2006), coastal Puerto Rico (Nyberg, 2001), and mid-elevations in the Cordillera Central of the Dominican Republic (Lane, 2011) all indicate increased precipitation typical of a more northerly position of the ITCZ. The MWP also saw the arrival of the Spanish to the Caribbean region roughly 500 YBP. Despite this increase in regional precipitation, microscopic CHAR values remained high in the sediment record for Laguna Limón. Our charcoal data point toward continued burning in the region, likely by people as clearing for agriculture increased at least in part due to Spanish occupation of the region after 500 YBP. A peak in microscopic charcoal concentration during this time period at Church's Blue Hole in the Bahamas was attributed to human-ignited fires by natives and Spanish occupation (Kjellmark, 1996). Charcoal concentration declined after human removal from South Andros Island despite an increasingly dry climate after 400 YBP, supporting the role of human generated fires and charcoal.

Similar to microscopic CHAR, macroscopic CHAR values from Laguna Limòn trended higher in Zone III than in earlier zones. We interpreted these high macroscopic CHAR values during a period of documented high moisture and a northerly location of the ITCZ as indicative of human burning directly within the watershed of Laguna Limón.

The MWP was followed by the Little Ice Age (LIA), a climatic era that greatly affected temperature and precipitation in more northerly latitudes of the northern hemisphere but its effect on tropical regions has been debated. Isotope records from Laguna Felipè in the Cordillera Central of the Dominican Republic suggest that the LIA did have a minor impact as conditions trended towards aridity and the ITCZ migrated southward (Lane et al., 2011). Curtis and Hodell (1993) also suggest that climate conditions of the late Holocene point to steady increases in aridity and the southward migration of the ITCZ. Sediment accumulated during the LIA to present is likely contained in the uppermost 25-cm of the Laguna Limòn core. In that section macroscopic CHAR values do show a slight increase when compared to the previous 20 cm (25–45 cm). Human disturbances within the watershed were likely the main source of charcoal deposited during this era. Modern vegetation surrounding Laguna Limón is primarily moist deciduous and local sources have no record of natural ignition nor do they consider natural ignition a plausible source of fire events.

*Regional Implications*

The charcoal record from Laguna Limón likely indicates both climatically driven as well as human set fire events. The macroscopic charcoal record, which represents local fires within the catchment of the watershed, is particularly indicative of human activities near Laguna Limón considering the archaeologically recognized tendencies of the Casimiroid people (Keegan, 1994).

The microscopic charcoal record tended to follow established trends of fire activity within the

circum-Caribbean region (Caffrey, 2011).

## 3.6 Conclusion

This research documented the morphology of Laguna Limón from open to the sea to closed freshwater lake. We also identified patterns of local and regional fire history as evidenced by the macroscopic and microscopic charcoal record. Chronologically ordered AMS radiocarbon samples indicated an accurate record of continuous sediment deposition.

We identified tectonic activity attributed to the SFZ as a possible cause for the evolution of Laguna Limón from open to the sea to a closed lake system. That change may explain comparatively low organic content and macroscopic charcoal concentrations in in the oldest section of the core. Despite the possible loss of macroscopic charcoal fragments to the tide, low numbers of macroscopic charcoal may be better served to view in a presence/absence manner. The presence of macroscopic charcoal in a large lake indicated local fires, likely of anthropogenic origin. Conversely, high microscopic charcoal peaks near the bottom may be climatically driven as they align with other regionally high records of microscopic charcoal, possibly indicative of higher than usual winter insolation during the mid-Holocene.

Our charcoal data adds to the existing catalog of other circum-Caribbean climate and archaeological research. Local fires identified in the sediment record likely originated from a combination of anthropogenic and climatic influences. As indicated by other studies, the ITCZ has migrated south over the course of the late Holocene, trending towards increasingly arid conditions over the Caribbean region. Human populations and activities have also increased, complicating the assessment of macroscopic charcoal fragments.

**Chapter 3 References**

Ali, A. A., Higuera, P. E., Bergeron, Y., & Carcaillet, C. (2009). Comparing fire-history interpretations based on area, number and estimated volume of macroscopic charcoal in lake sediments. *Quaternary Research, 72*(3), 462-468.

Anderson, R. S., Davis, R. B., Miller, N. G., & Stuckenrath, R. (1986). History of late-and post-glacial vegetation and disturbance around Upper South Branch Pond, northern Maine. *Canadian Journal of Botany, 64*(9), 1977-1986.

Beets, C. J., Troelstra, S. R., Grootes, P. M., Nadeau, M. J., Borg, K. v., Jong, A. d., . . . Hoogland, M. L. (2006). Climate and pre-Columbian settlement at Anse à la Gourde, Guadeloupe, Northeastern Caribbean. *Geoarchaeology, 21*(3), 271-280.

Bolay, E. (1997). *The Dominican Republic: A Country Between Rain Forest and Desert*: Margraf Verlag.

Burney, D. A. (1997). Tropical islands as paleoecological laboratories: gauging the consequences of human arrival. *Human Ecology, 25*(3), 437-457.

Burney, D. A., Burney, L. P., & MacPhee, R. D. E. (1994). Holocene charcoal stratigraphy from Laguna Tortuguero, Puerto Rico, and the timing of human arrival on the island. *Journal of Archaeological Science, 21*(2), 273-281.

Caffrey, M. A. (2011). Holocene Climate and Environmental History of Laguna Saladilla, Dominican Republic. PhD diss., University of Tennessee. http://trace.tennessee.edu/utk_graddiss/955

Carcaillet, C., Bergeron, Y., Richard, P. J. H., Fréchette, B., Gauthier, S., & Prairie, Y. T. (2001). Change of fire frequency in the eastern Canadian boreal forests during the Holocene: does vegetation composition or climate trigger the fire regime? *Journal of Ecology, 89*(6), 930-946.

Charts, M. S. C. (1975). Munsell color. *Macbeth Division of Kollmorgen Corporation, Baltimore*.

Clark, J. S. (1988). Particle motion and the theory of charcoal analysis: source area, transport, deposition, and sampling. *Quaternary Research, 30*(1), 67-80.

Clark, J. S., Lynch, J., Goldammer, J. G., & Stocks, B. J. (1998). Relationships between charcoal particles in air and sediments in west-central Siberia. *The Holocene, 8*(1), 19-29.

Curtis, J. H., & Hodell, D. A. (1993). An isotopic and trace element study of ostracods from Lake Miragoâne, Haiti: A 10,500 year record of paleosalinity and paleotemperature changes in the Caribbean. *Geophysical Monograph Series, 78*, 135-152.

Curtis, J. H., Hodell, D. A., & Brenner, M. (1996). Climate variability on the Yucatan Peninsula (Mexico) during the past 3500 years, and implications for Maya cultural evolution. *Quaternary Research, 46*(1), 37-47.

Dean, W. E. (1974). Determination of carbonate and organic matter in calcareous sediments and sedimentary rocks by loss on ignition; comparison with other methods. *Journal of Sedimentary Research, 44*(1), 242-248.

Desjardines, A. (2007). *Paleoenvironmental Reconstruction of a Coastal Lagoon in Southwestern Dominican Republic.* M.S., Virginia Polytechnic Institute and State University.

Donnelly, J. P., & Woodruff, J. D. (2007). Intense hurricane activity over the past 5,000 years controlled by El Niño and the West African monsoon. *Nature, 447*(7143), 465-468.

Faegri, K., & Iverson, J. (1964). Textbook of Pollen Analysis (2d ed.) Hafner. *New York*.

French, C. D. & Schenk, C. J. (1997). Open file report 97-470-K: Map showing geology, oil and gas fields, and geologic provinces of the Caribbean region. *In:* U.S. Geological Survey (ed.). Denver, Colorado: Department of the Interior.

Haug, G. H., Hughen, K. A., Sigman, D. M., Peterson, L. C., & Röhl, U. (2001). Southward migration of the Intertropical Convergence Zone through the Holocene. *Science, 293*(5533), 1304-1308.

Hallett, D. J., Lepofsky, D. S., Mathewes, R. W., & Lertzman, K. P. (2003). 11,000 years of fire history and climate in the mountain hemlock rain forests of southwestern British Columbia based on sedimentary charcoal. *Canadian Journal of Forest Research*, *33*(2), 292-312.

Higuera-Gundy, A., Brenner, M., Hodell, D. A., Curtis, J. H., Leyden, B. W., & Binford, M. W. (1999). A 10,300 14C yr record of climate and vegetation change from Haiti. *Quaternary Research, 52*(2), 159-170.

Hodell, D. A., Brenner, M., & Curtis, J. H. (2000). Climate change in the northern American tropics and subtropics since the last ice age. *Landscape transformations in the pre-Columbian Americas*, 13-38.

Hodell, D. A., Curtis, J. H., & Brenner, M. (1995). Possible role of climate in the collapse of Classic Maya civilization. *Nature*, *375*, 391-394.

Holdridge, L. R. (1967). Life zone ecology. Life zone ecology., (rev. ed.).

Holmes, J. A., Street-Peffott, F. A., Ivanovich, M., & Peffott, R. A. (1995). A late Quaternary palaeolimnological record from Jamaica based on trace-element chemistry of ostracod shells. *Chemical Geology, 124*(1), 143-160.

Horn, S. P., Orvis, K. H., Kennedy, L. M., & Clark, G. M. (2000). Prehistoric fires in the highlands of the Dominican Republic: Evidence from charcoal in soils and sediments. *Caribbean Journal of Science, 36*(1-2), 10-18.

Horn, S. P., & Sanford Jr, R. L. (1992). Holocene fires in Costa Rica. *Biotropica*, 354-361.

Keegan, W. F. (1994). West Indian archaeology. 1. Overview and foragers. *Journal of Archaeological Research, 2*(3), 255-284.

Kennedy, L. M., Horn, S. P., & Orvis, K. H. (2005). A 4000-year record of fire and forest history from Valle de Bao, Cordillera Central, Dominican Republic. *Palaeogeography Palaeoclimatology Palaeoecology, 231*(3-4), 279-290.

Kjellmark, E. (1996). Late Holocene climate change and human disturbance on Andros Island, Bahamas. *Journal of Paleolimnology, 15*(2), 133-145.

Lane, C. S., Horn, S. P., Mora, C. I., & Orvis, K. H. (2009). Late-Holocene paleoenvironmental change at mid-elevation on the Caribbean slope of the Cordillera Central, Dominican Republic: a multi-site, multi-proxy analysis. *Quaternary Science Reviews, 28*(23), 2239-2260.

Lane, C. S., Horn, S. P., Orvis, K. H., & Thomason, J. M. (2011). Oxygen isotope evidence of Little Ice Age aridity on the Caribbean slope of the Cordillera Central, Dominican Republic. *Quaternary Research, 75*(3), 461-470.

Last, W. M., Smol, J. P., & Birks, H. J. B. (2001). *Tracking environmental change using lake sediments* (Vol. 1-4). Boston: Kluwer Academic Publishers.

LeBlanc, A. (2011). A 1000-year sedimentary record of hurricane, fire, and vegetation history from a coastal lagoon in southwestern Dominican Republic. M.S., Virginia Polytechnic Institute and State University.

Liu, K.-b., Lu, H., & Shen, C. (2007). A 1200-year proxy record of hurricanes and fires from the Gulf of Mexico coast: Testing the hypothesis of hurricane–fire interactions. Quaternary Research, 69(1), 29-41.

Long, C. J., Whitlock, C., Bartlein, P. J., & Millspaugh, S. H. (1998). A 9000-year fire history from the Oregon Coast Range, based on a high-resolution charcoal study. Canadian Journal of Forest Research, 28(5), 774-787.

Mann, P., Draper, G., & Lewis, J. F. (1991). An overview of the geologic and tectonic development of Hispaniola.

Martin, P. H., Sherman, R. E., & Fahey, T. J. (2007). Tropical montane forest ecotones: climate gradients, natural disturbance, and vegetation zonation in the Cordillera Central, Dominican Republic. *Journal of Biogeography, 34*(10), 1792-1806.

Myers, R. K., & van Lear, D. H. (1998). Hurricane-fire interactions in coastal forests of the south: a review and hypothesis. *Forest ecology and management, 103*(2-3), 265-276.

Nyberg, J., Kuijpers, A., Malmgren, B. A., & Kunzendorf, H. (2001). Late Holocene changes in precipitation and hydrography recorded in marine sediments from the northeastern Caribbean Sea. *Quaternary Research, 56*(1), 87-102.

Patterson, W. A., Edwards, K. J., & Maguire, D. J. (1988). Microscopic charcoal as a fossil indicator of fire. *Quaternary Science Reviews, 6*(1), 3-23.

Peros, M. C., Reinhardt, E. G., & Davis, A. M. (2007). A 6000-year record of ecological and hydrological changes from Laguna de la Leche, north coastal Cuba. *Quaternary Research, 67*(1), 69-82.

Prentice, C. S., Mann, P., Peña, L. R., & Burr, G. (2003). Slip rate and earthquake recurrence along the central Septentrional fault, North American–Caribbean plate boundary, Dominican Republic. *Journal of Geophysical Research, 108*(B3), 2149.

Rouse, I. (1993). *The Tainos: Rise and decline of the people who greeted Columbus*: Yale Univ Pr.

Santiago-García, R. J., Colón, S. M., Sollins, P., & Van Bloem, S. J. (2008). The role of nurse trees in mitigating fire effects on tropical dry forest restoration: a case study. *Ambio, 37*(7-8), 604-608.

Schoen, Alice Renee, (2011). *A 7600-year Record of Environmental History from the Sediments of Laguna Tortuguero, Puerto Rico*. MS., University of Tennessee.

Speer, J. H., Orvis, K. H., Grissino-Mayer, H. D., Kennedy, L. M., & Horn, S. P. (2004). Assessing the dendrochronological potential of Pinus occidentalis Swartz in the Cordillera Central of the Dominican Republic. *The Holocene, 14*(4), 563-569.

Stuiver, M., and Reimer, P.J. (1993). Radiocarbon, 35, 215-230.

Tinner, W., Conedera, M., Ammann, B., Gaggeler, H. W., Gedye, S., Jones, R., & Sagesser, B. (1998). Pollen and charcoal in lake sediments compared with historically documented forest fires in southern Switzerland since AD 1920. *The Holocene, 8*(1), 31-42.

Urquhart, G. R. (2008). Paleoecological record of hurricane disturbance and forest regeneration in Nicaragua. *Quaternary International, 195*(1-2), 88-97.

Whitlock, C. (2004). Forests, fires and climate. *Nature, 432*(7013), 28.

Whitlock, C., & Larsen, C. (2002). Charcoal as a fire proxy. *Tracking environmental change using lake sediments*, 75-97.

Winkler, M., Sanford, P., & Kaplan, S. (2001). Hydrology, vegetation, and climate change in the southern Everglades during the Holocene. *Bulletins of American Paleontology*, 57-100.

**Chapter 3 Figures**
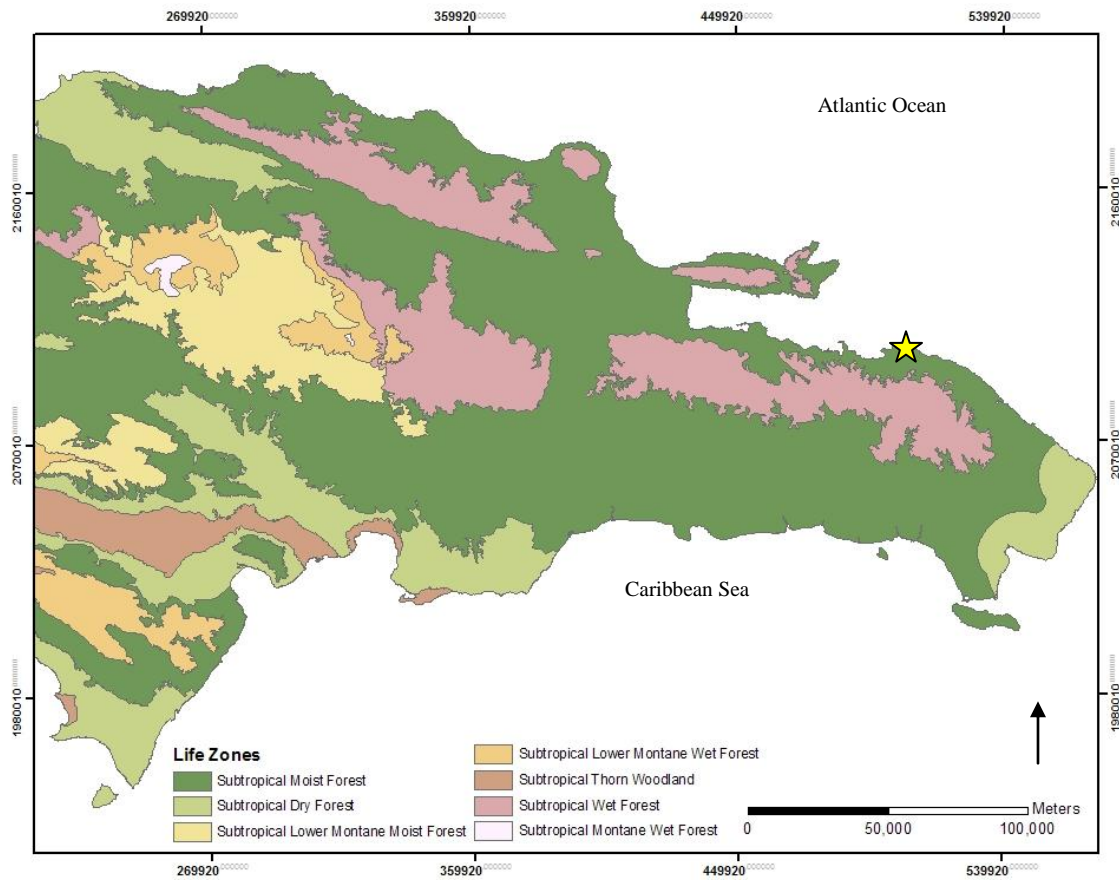


Figure 1

Map of vegetation life zones in the Dominican Republic. The location of Laguna Limón is indicated by the star and located in the Subtropical Moist Forest zone. Redrawn from Holdridge (1967).
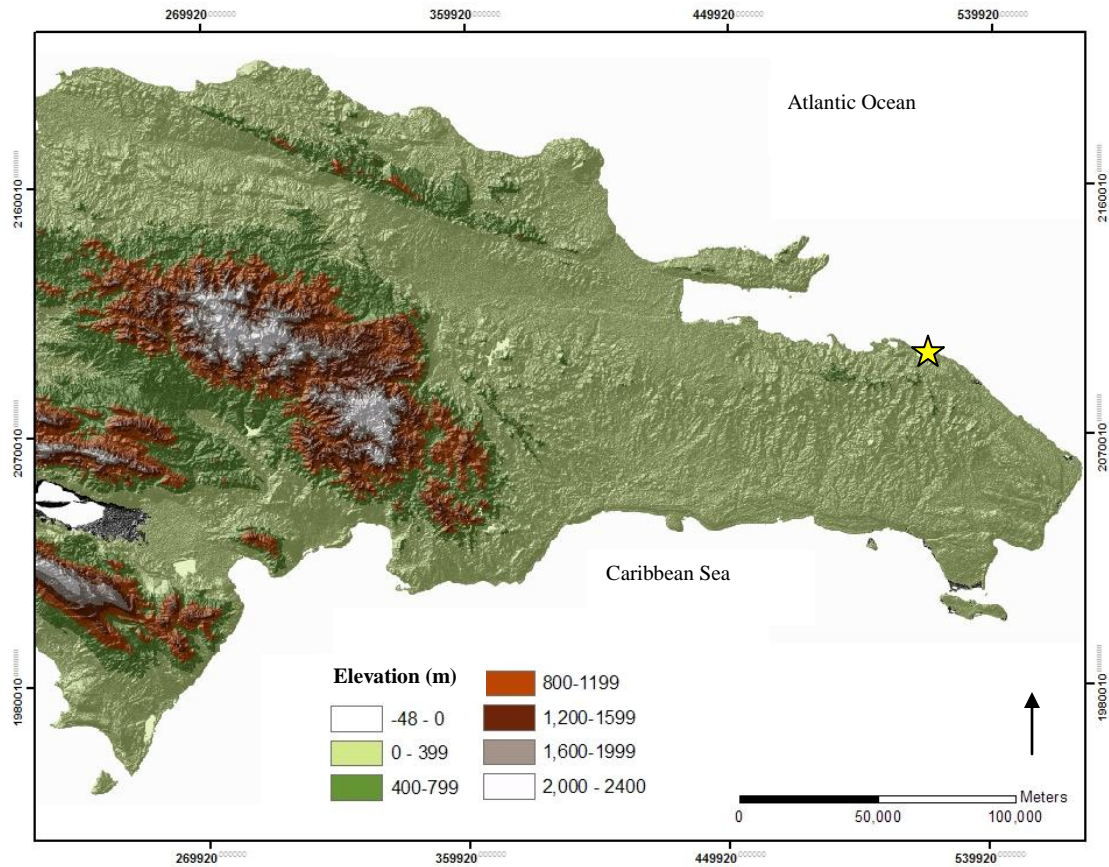
Figure 2

Elevation relief map of Dominican Republic. Location of Laguna Limón is indicated by the star.
Redrawn from Holdridge (1967).
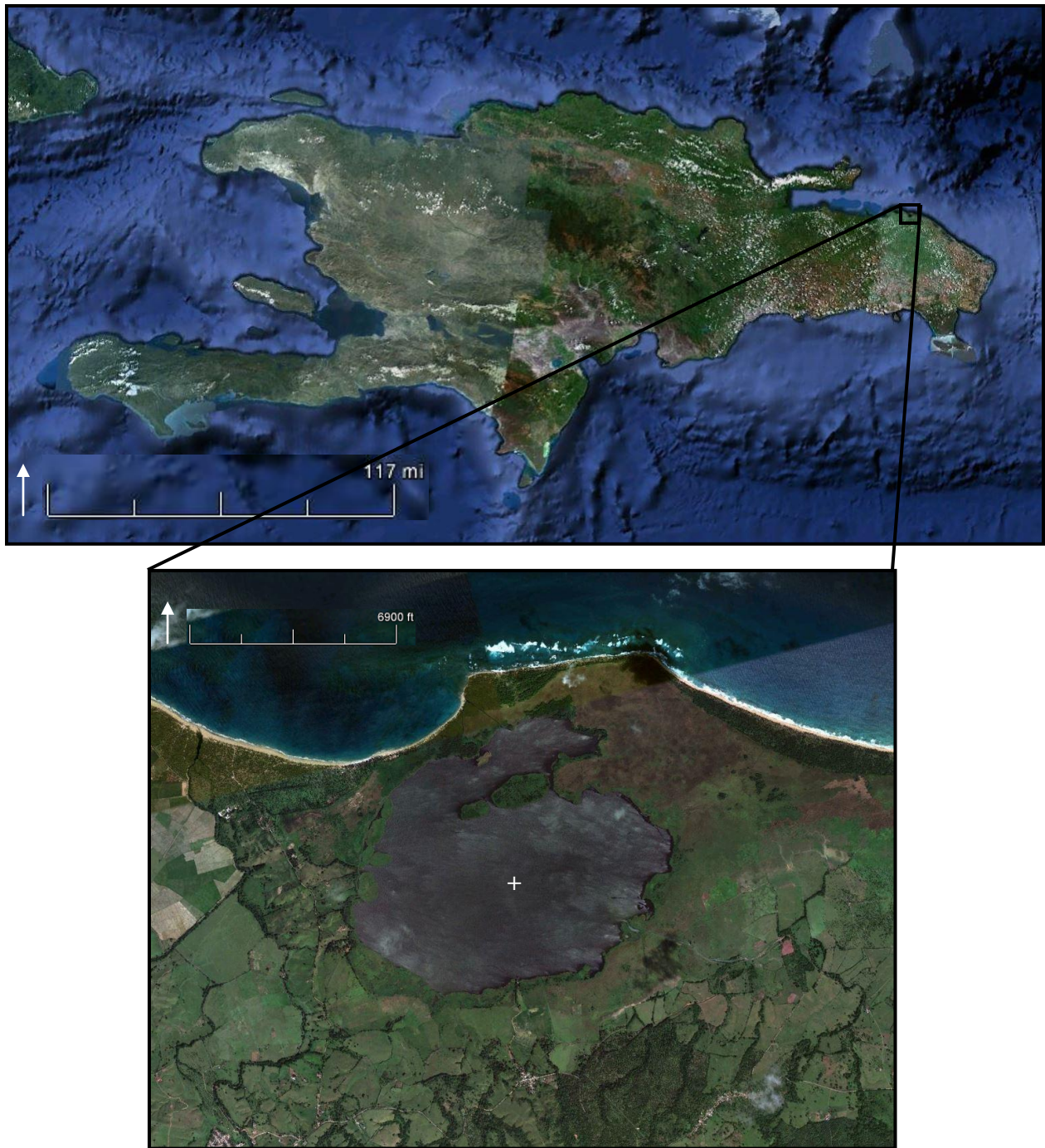
Figure 3

Regional Map of Hispaniola (above) and Laguna Limón study site inset (below) with coring location (18.9783° N, 68.8494° W) indicated by "+." Imagery from Google Earth, 2013.

Figure 4

Above:  The Las Lisas River entering Laguna Limón from the east and Cordillera Orientál visible in the background to the south.

Below: Laguna Limón from the northern shore looking south toward the Cordillera Orientál.
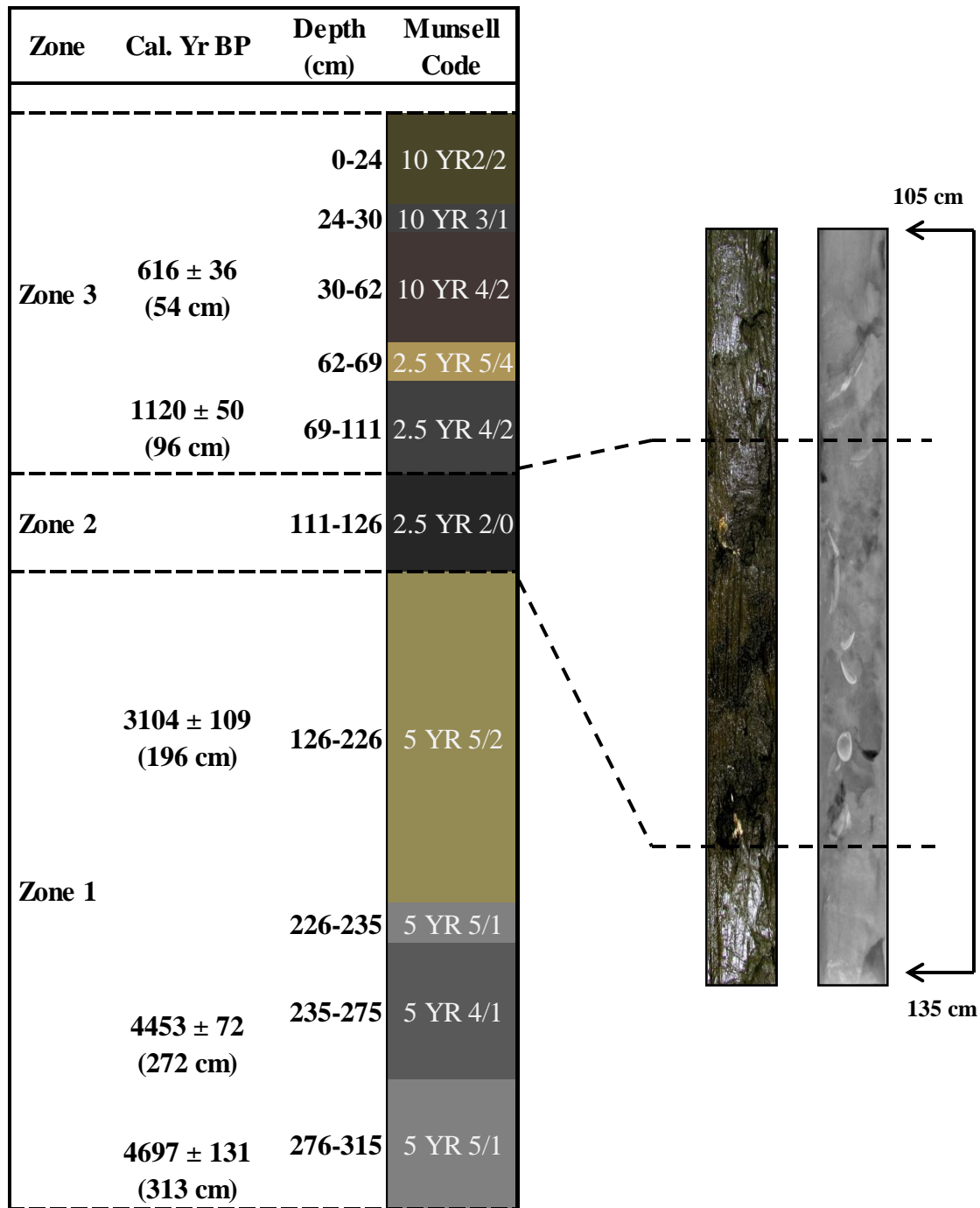
Figure 5

Munsell color code description indicating changes in sediment color for entire Laguna Limòn core. Subsection of Laguna Limón sediment core showing natural color photograph (left) and x-radiograph (right) 105–135 cm of 0–315 cm of core. Whole shells are visible in the x-radiograph and color photograph in Zone II. Sediment color change is evident in the color photograph. Dark sediment in Zone II is also where organic content is highest. AMS radiocarbon dates with the

mean age 2 sigma range corresponding to depth. Dashed lines equal zone delineation. Munsell Key: 10 YR 2/2 = Very dark brown. 10 YR 3/1 = Very dark gray. 10 YR 4/2 = Dark grayish brown. 2.5 YR 5/4 = Light olive brown. 2.5 YR 2/0 = Black. 5 YR 5/2 = Olive Gray. 5 YR 5/1 = Gray. 5 YR 4/1 = Dark Gray.
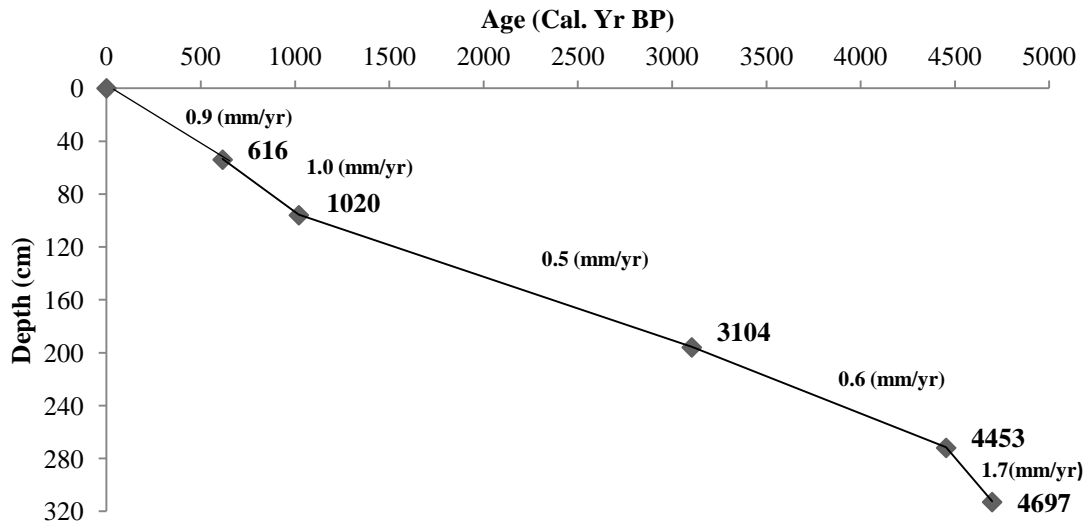
Figure 6

AMS radiocarbon sample depth fit to the median age (points) of the 2 sigma AMS radiocarbon range with sediment accumulation rate between points. Cal. Yr BP where present = 1950
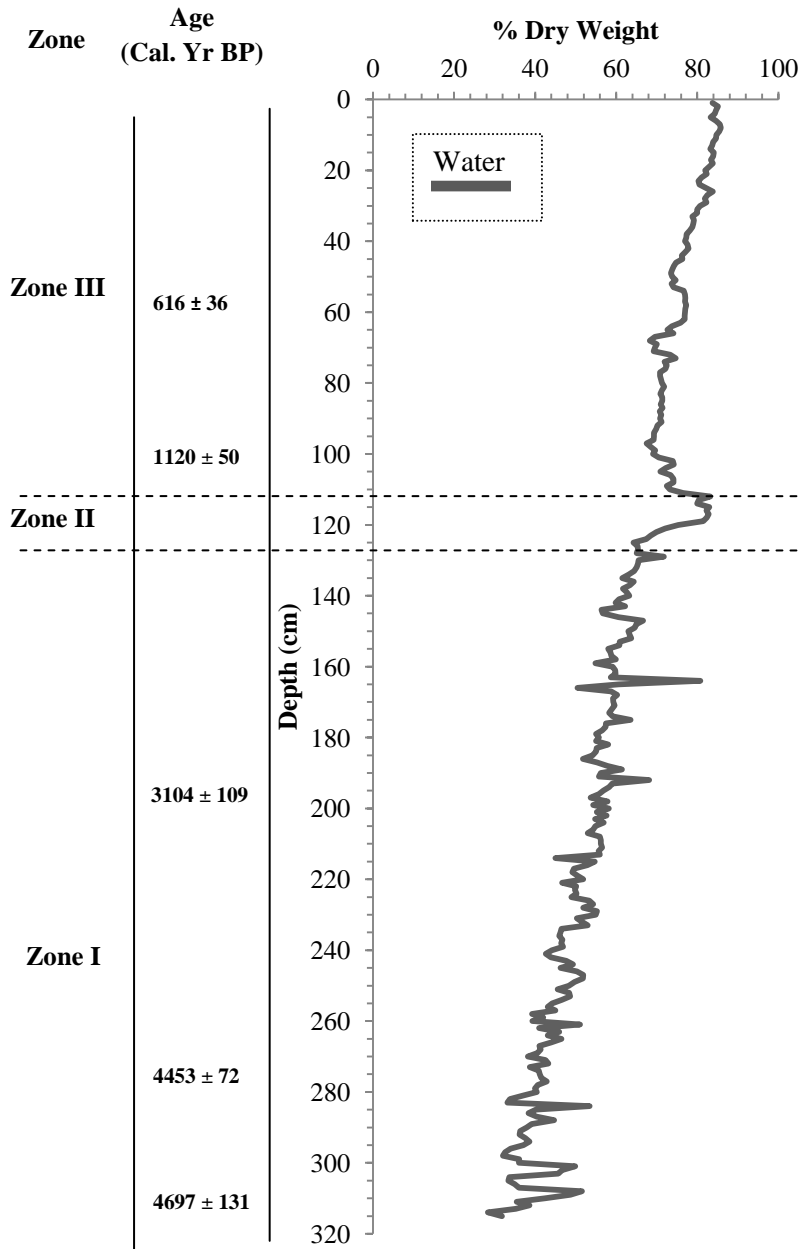
Figure 7

Loss-on-ignition (1-cm resolution) graph documenting % water content weight per 1-cm$^3$ sample. AMS radiocarbon dates with the mean age 2 sigma range corresponding to depth. Dashed lines equal zone delineation.
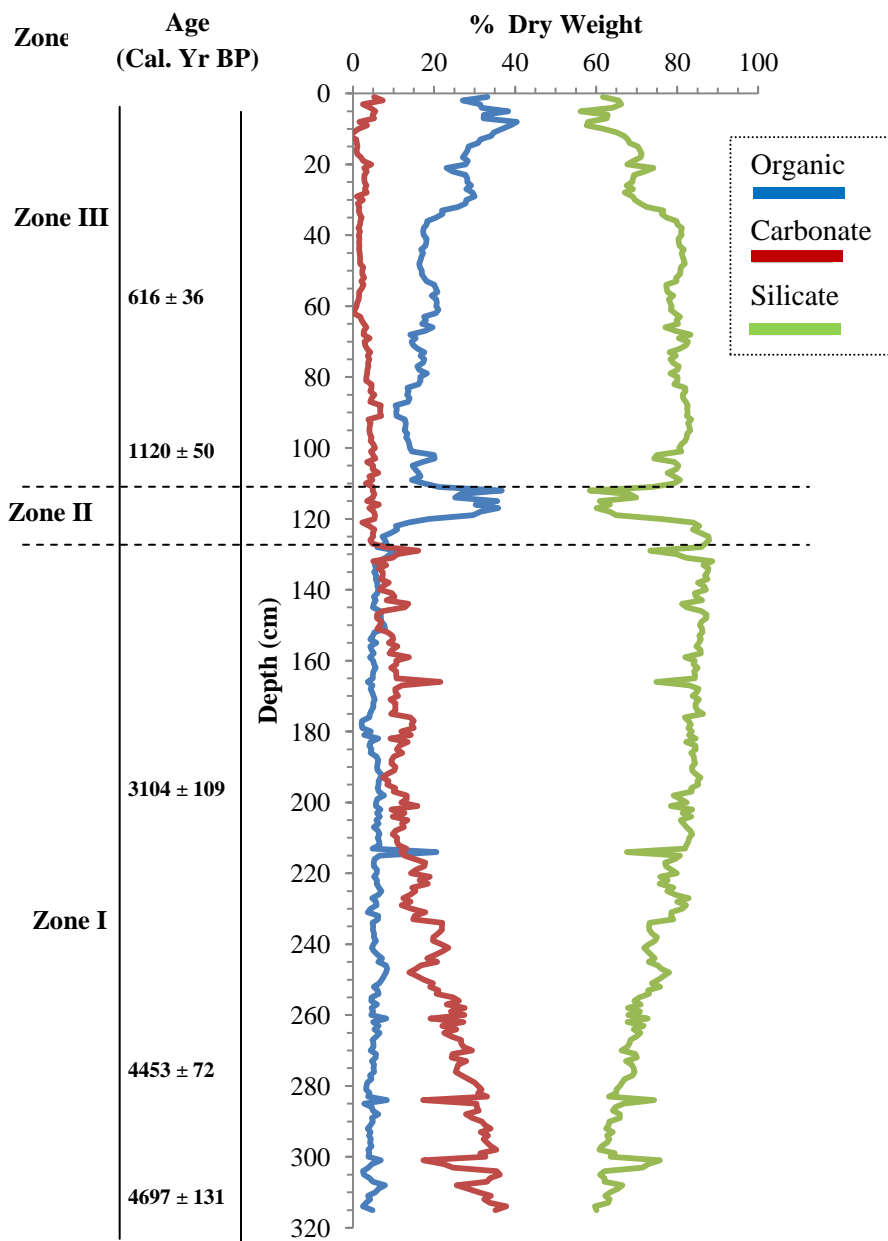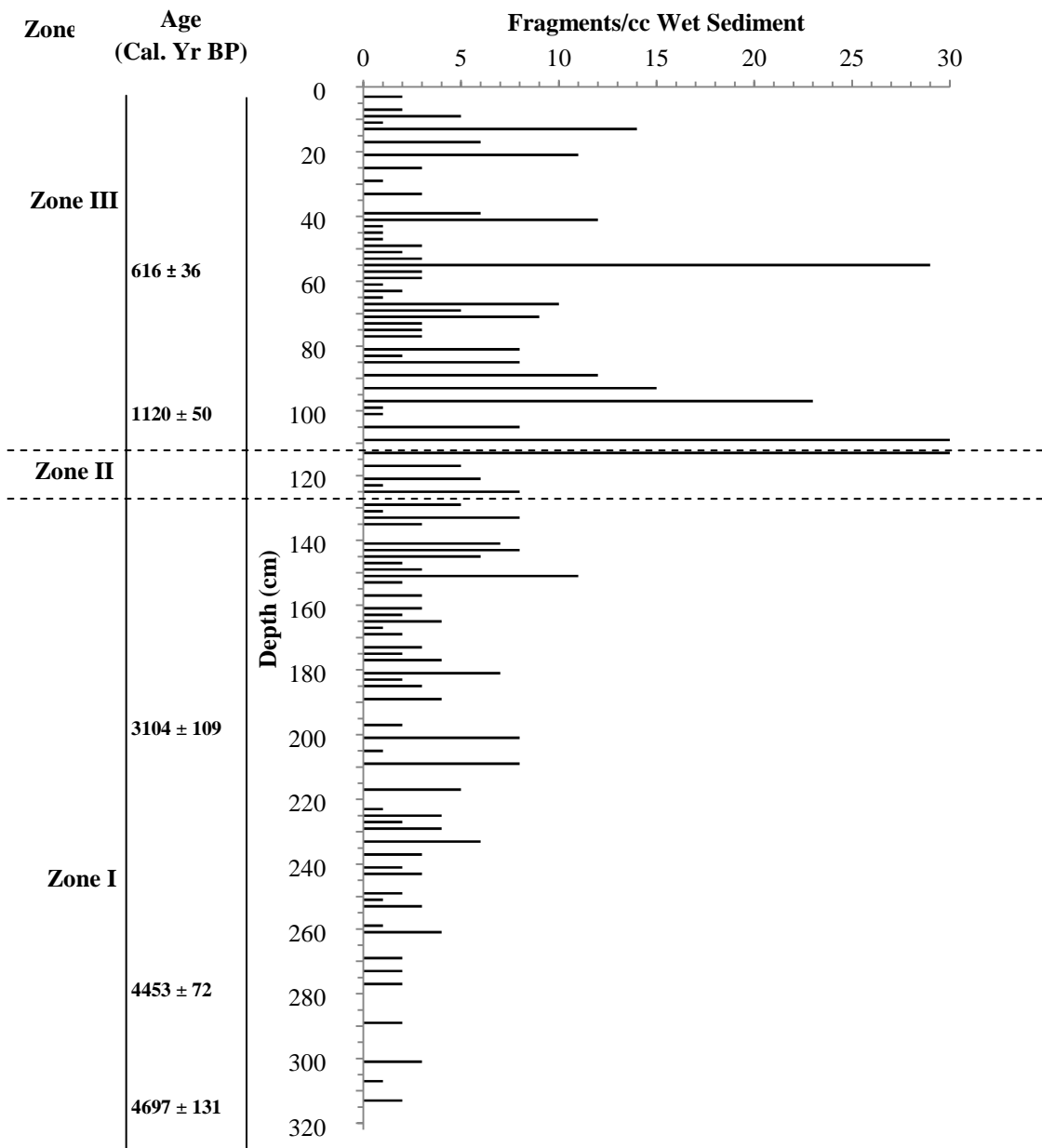
Figure 8

Loss-on-ignition (1-cm resolution) graph showing % organic, carbonate, and silicate content per 1-cm$^3$ sample. AMS radiocarbon dates with the mean age and 2 sigma range corresponding to depth. Dashed lines equal zone delineation.

Figure 9

Number of macroscopic charcoal fragments larger than 125 μm identified per 1-cm$^3$ sample (2-cm resolution). AMS radiocarbon dates with the mean age and 2 sigma range corresponding to depth. Dashed lines equal zone delineation.
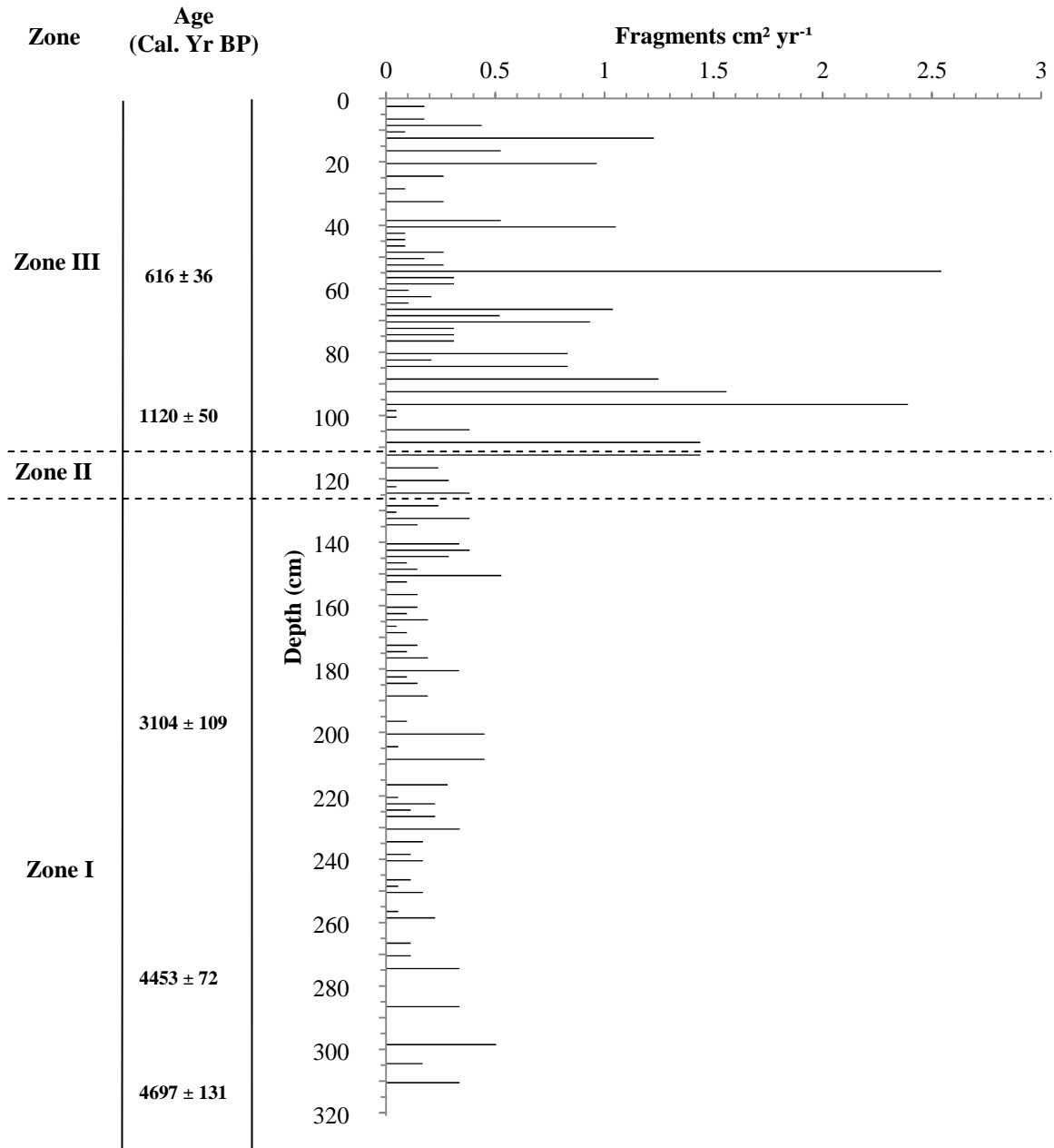
Figure 10

Macroscopic Charcoal Accumulation Rate (CHAR). Macroscopic charcoal fragments larger than 125 μm by year per 1-cm$^3$ sample as indicated by the sediment accumulation rate (2-cm resolution). AMS radiocarbon dates with the mean age and 2 sigma range corresponding to depth. Dashed lines equal zone delineation.
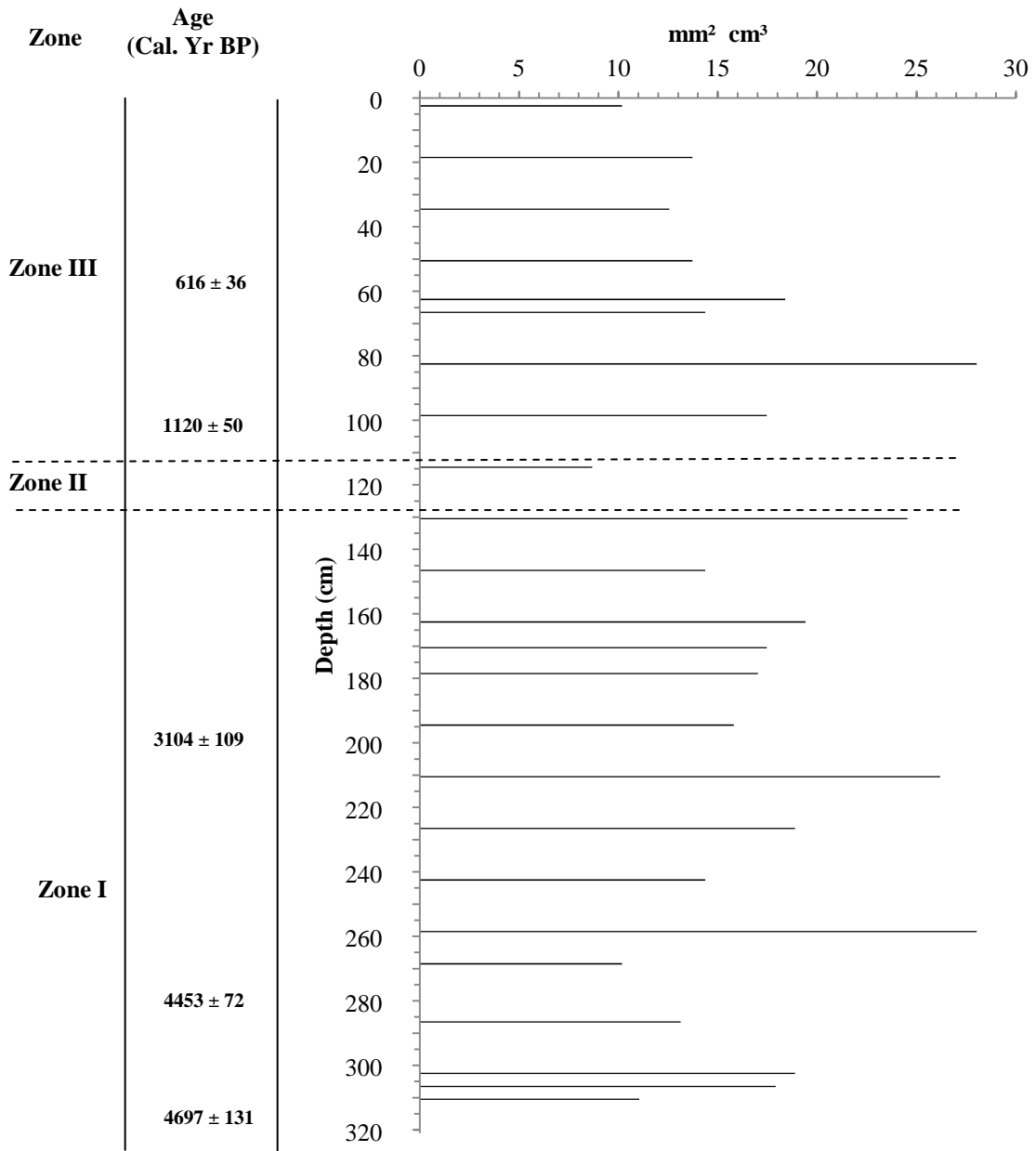
Figure 11

Microscopic charcoal (<125 µm) area concentration estimate per 1-cm$^3$ sample. Produced by the regression equation:  ln $(A) = -7.418 + 0.936$ ln $(N)$  Where $A$ is the area concentration (mm² cm³) and $N$ is the charcoal particle number concentration (cm³) of all charcoal particles longer than 10 µm up to 200 objects including control spores (16-cm resolution, occasionally finer). AMS radiocarbon dates with the mean age and 2 sigma range corresponding to depth. Dashed lines equal zone delineation.
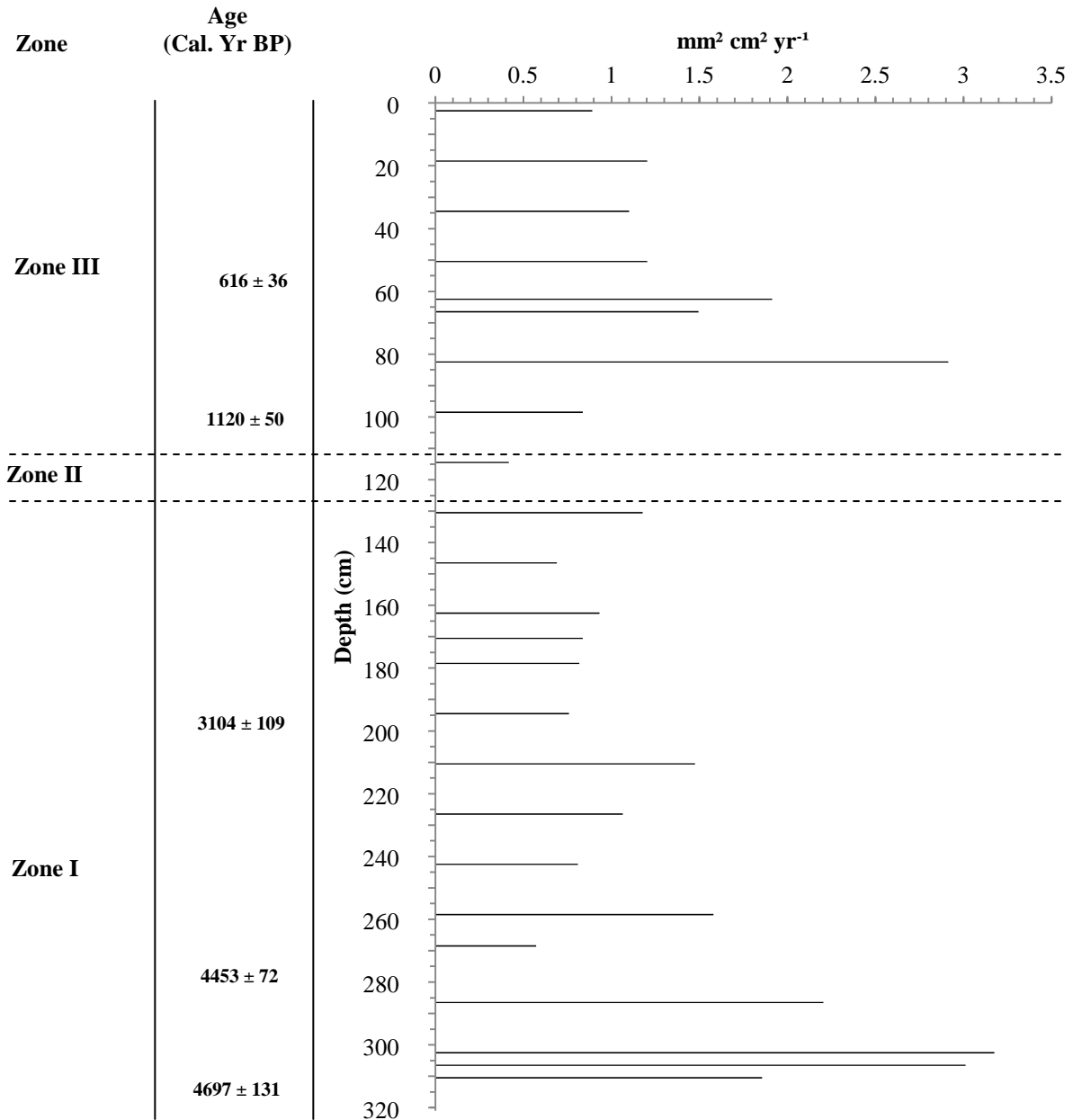
Figure 12

Microscopic Charcoal Accumulation Rate by Area (CHARa). Microscopic charcoal (<125 μm) by year sample as indicated by the sediment accumulation rate, graphed as estimated area concentration per 1-cm$^3$ sample (16-cm resolution, occasionally finer). AMS radiocarbon dates with the mean age and 2 sigma range corresponding to depth. Dashed lines equal zone delineation. Charcoal area concentration divided by the number of years represented by one cm of sediment from age/depth graph.
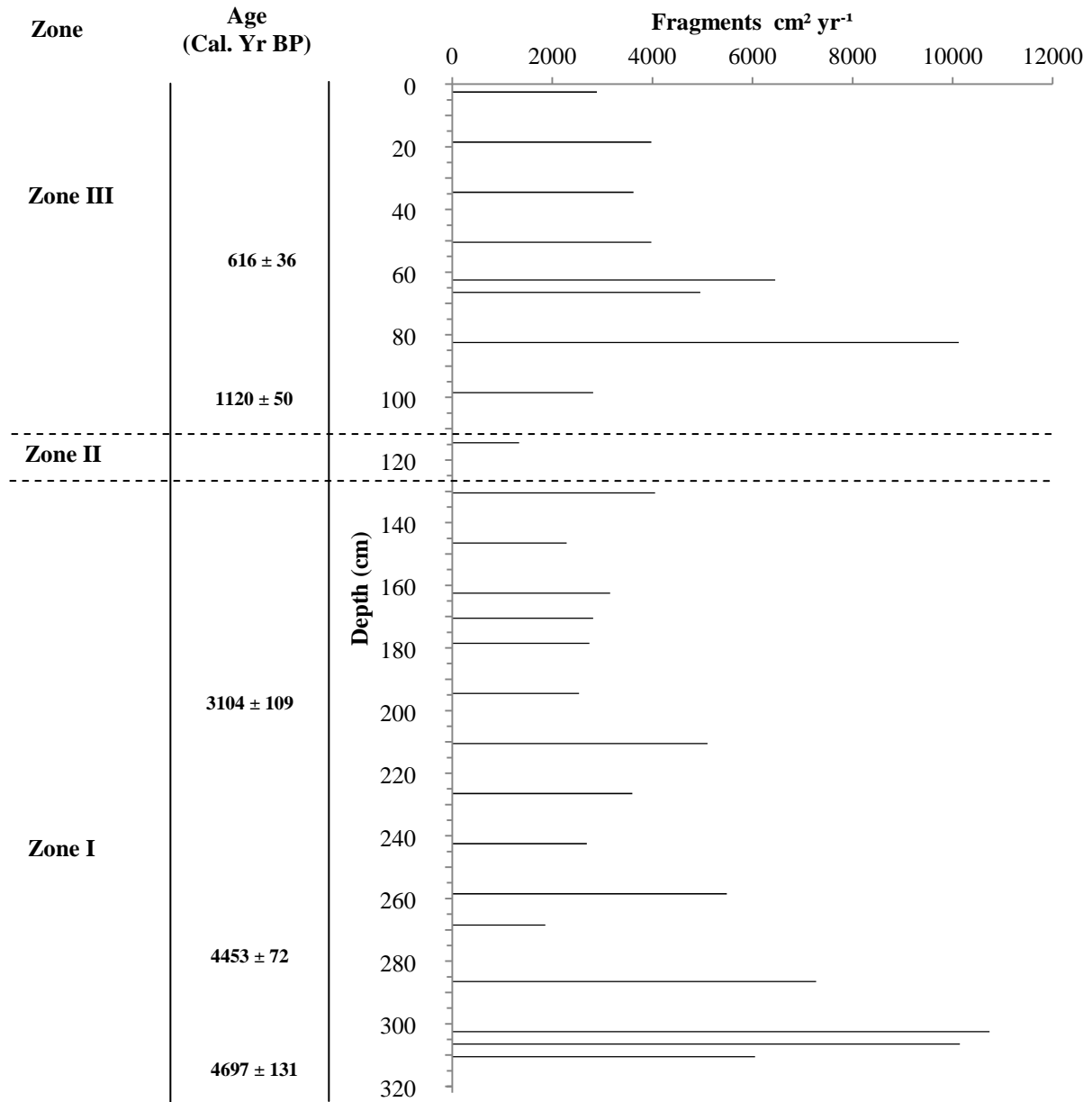
Figure 13

Microscopic Charcoal Accumulation Rate by Fragment (CHARf). Microscopic charcoal (<125 μm) by year sample as indicated by the sediment accumulation rate, graphed as estimated total fragment concentration per 1-cm$^3$ sample (16-cm resolution, occasionally finer). AMS radiocarbon dates with the mean age and 2 sigma range corresponding to depth. Dashed lines equal zone delineation.

**Chapter 3 Tables**

Table 1

Core measurements taken in the field for Laguna Limón. Coring ended at 315 cm.

| Core ID | Depth (cm) |
| --- | --- |
| LIMO A | 0-80 |
| LIMO B | 62-200 |
| LIMO C | 177-288 |
| LIMO D | 282-315 |
| Total | 0-315 |

Table 2

AMS radiocarbon samples and calibrated dates. Calibrated using Calib 6.0.1 (Stuiver and Reimer, 1993). Before Present (BP) = 1950. We graphed the mean year of the Cal. Yr BP 2 sigma which represents a 95% confidence level. C = Charcoal. W = Wood.

| Depth (cm) | Type | $^{14}$C yr BP | Cal Yr BP 1 sigma | Cal Yr BP 2 sigma | Cal Yr AD/ BC 1 sigma | Cal Yr AD/BC 2 sigma |
| --- | --- | --- | --- | --- | --- | --- |
| 54 | C | 580 ± 35 | 595–635 | 580–652 | AD 1315–1355 | AD 1298–1370 |
| 96 | C | 1130 ± 20 | 986–1032 | 969–1070 | AD 918–964 | AD 880–981 |
| 196 | C | 2940 ± 30 | 3062–3163 | 2995–3212 | BC 1214–1113 | BC 1263–1046 |
| 272 | C | 3970 ± 35 | 4473–4515 | 4382–4525 | BC 2566–2524 | BC 2576–2433 |
| 313 | W | 4150 ± 40 | 4615–4728 | 4569–4828 | BC 2779–2666 | BC 2879–2620 |

Table 3

Accumulation Rates presented by mm/yr and yr/cm. Age is the mean year of the Cal. YrBP 2 sigma between AMS radiocarbon dates. Cm gaps represents the number of cm between mean year AMS radiocarbon dates. Years represents the years between mean year AMS radiocarbon dates.

| Depth Range | Cal. Yr BP | cm gaps | Cal. Yr BP Range | Years | (mm/yr) | (yr/cm) |
|---|---|---|---|---|---|---|
| 0-54 | 616 | 54 | 0-616 | 616 | 0.9 | 11.41 |
| 54-96 | 1020 | 42 | 616-1020 | 404 | 1.0 | 9.62 |
| 96-196 | 3104 | 100 | 1020-3104 | 2084 | 0.5 | 20.84 |
| 196-272 | 4453 | 76 | 3104-4453 | 1349 | 0.6 | 17.75 |
| 272-313 | 4697 | 41 | 4453-4697 | 244 | 1.7 | 5.95 |
| 0-313 | | 313 | 0-4697 | 4697 | 0.7 | 15.01 |