A 1000-year sedimentary record of hurricane, fire, and vegetation history from a coastal lagoon in southwestern Dominican Republic

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Abstract

Our knowledge of whether hurricanes cause lasting changes in forest composition and the patterns and role of fire in Caribbean dry forests are lacking. This project combines paleoecological and paleotempestological methods to document the disturbance and environmental history of the last 1000 yrs at Laguna Alejandro, situated in the lowland dry forests of arid SW Dominican Republic. I analyzed multiple proxy data sources of a 160 cm coastal lagoon sediment profile. High-resolution (1 cm) sampling for loss-on-ignition and magnetic susceptibility indicated multiple erosion and hurricane events, including a hurricane ~996 cal YBP, and several erosion events and hurricanes between ~321 cal YBP and present day. Pollen analysis documented 32 plant families with most levels dominated by pollen of Fabaceae (legumes), the Urticales order, and Cyperaceae (sedges), though families of upland and montane vegetation are also present ~510–996 cal YBP. All pollen slides contained microscopic charcoal indicating the occurrence of regional or extra-local fires over the last ~1000 yrs. Local fires, as indicated by macroscopic charcoal, occurred before ~434 cal YBP and may be tied to hurricanes, increased moisture in the region (thereby increased fuel and ignition chances), or prehistoric human activities. Pollen spectra representing periods before and after disturbance events were similar and may support the idea of forest resilience, but more samples are needed. Multiple erosion events between ~294 cal YBP and present may be tied to hurricanes or tropical storms and increasing late-Holocene aridity in the region as documented by several studies from the Caribbean.

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I would like to thank my advisor and committee chair Dr. Lisa M. Kennedy for her guidance and encouragement throughout the entirety of this project. Her knowledge of paleoenvironmental reconstruction, paleotempestology, tropical biogeography, and field and laboratory methods was instrumental to the completion of this project. I also thank my committee members Drs. James B. Campbell and Carolyn A. Copenheaver for their helpful comments throughout my thesis work. I greatly appreciate the help of Dr. Kam-biu Liu of Louisiana State University, and field assistance from his students, Terry McCloskey and Devyani Karr. This work was funded in part by Virginia Tech's Graduate Student Assembly Graduate Research Development Program, the Sidman P. Poole's Endowment in Geography (Department of Geography, Virginia Tech), and a grant to my advisor (L. M. Kennedy) and her collaborator K.b. Liu from the National Science Foundation (BCS-0964138). I am grateful for laboratory assistance from Chardy Staton, Alyssa Durden, Stewart Scales, Anthony Phillips, and Karlie Tucker. I would also like to thank my family and friends for their advice, encouragement, and understanding throughout the completion of my thesis.

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CHAPTER 1: INTRODUCTION AND RESEARCH OBJECTIVES

1.1 INTRODUCTION

Hurricanes are complex disturbance events that pose a threat to life and property and may be tied to other disturbance events such as fire and erosion events (Urquhart 2009, Liu et al. 2008, Tanner et al. 1991). The short-term ecological impacts of hurricanes, i.e., those occurring within a decade, on tropical vegetation in the Caribbean region are well documented (Imbert et al. 2008, Metcalfe et al. 2008), but whether hurricanes have lasting impacts on vegetation composition is still debated. Several studies from the Caribbean have suggested that while hurricanes could have long-lasting effects on the basic characteristics of forest structure and function they only have shorter-term impacts on species richness (Tanner et al. 1991). However, this conclusion is based on short-term studies. Some researchers (Tanner et al. 1991) have pointed out that the lack of information on longer-term hurricane impacts is related to a deficiency of long-term analysis of sites impacted by hurricanes.

In addition to long-term hurricane impacts on vegetation, there is a question of whether hurricanes affect fire regimes in tropical ecosystems. In the subtropical maritime forests of the southeastern U.S., Myers and Van Lear (1998) hypothesized that hurricanes would increase fuel on the ground and thereby increase the risk of fire post-hurricane. The findings of recent paleoecological studies (Urquhart 2009, Liu et al. 2008) supported that hypothesis, at least for tropical swamp forests in Nicaragua and subtropical pine forests of the southeast U.S., respectively. Increases in microscopic (>10 μm) charcoal occurring after hurricane deposited sediments was interpreted by Liu et al. (2008) as major fires occurring after hurricane landfall events while Urquhart (2009) found this same relationship in occurring in his microscopic (>5 µm) and macroscopic (> 250 µm) charcoal samples. However, the question of whether hurricanes have long-term impacts on vegetation and fire regimes in tropical regions is still unanswered.

Another knowledge gap exists as to the role of fire in tropical dry forests. Numerous studies (Otterstrom and Schwartz 2006, Kennard and Gholz 2001, Pinnard and Huffman 1997, Murphy and Lugo 1986) have examined the role and short-term impacts of fire in tropical dry forests to determine if these forest types are resistant or show resilience to disturbance by fire. These studies indicated that major fires have not played a role in determining the species composition and structure of tropical dry forests though the role of low-intensity, more frequent fires is still debated.

Methodologies from paleoecology and paleotempestology (the study of prehistoric storms) can be used to study the long-term impacts of hurricanes on vegetation composition and fire patterns through the analysis of sediment cores containing hurricane deposits and other microfossils (e.g., pollen and charcoal). The underlying assumption of paleotempestology is that as intense (category 3–5) hurricanes approach shore, wave and wind action will push sediment from the ocean and coastal barrier of lakes further inland, documenting the storm in the geologic record which can then be analyzed through sediment cores (Figure 1.1). Local changes in vegetation species composition before and after hurricanes can be identified through the high-resolution sampling of pollen and spores, and the effect of hurricanes on regional and local fire regimes can be determined through the analysis of microscopic (>10 µm) and macroscopic (>125 µm) charcoal, respectively (Liu 2008, Carcaillet 2007, Gavin et al. 2007, Whitlock and Anderson

2003, Whitlock and Larson 2001, Patterson et al. 1987). Materials in the sediment cores above and below the storm deposits can then be radiocarbon dated so that the age and frequency of storms can be calculated for a specific location.

The Dominican Republic lies within the path of numerous intense (category 3-5) historical hurricane tracks (Fig 1.2). Laguna Alejandro, located in the southwestern Dominican Republic is an excellent study site from which to examine the long-term impacts of hurricanes on tropical dry forests, and whether a link exists between hurricanes and fire in this region. Results from a previous study (Desjardins 2007) indicate that Alejandro has probably been struck by several hurricanes over the past 1200 cal YBP. Also, tropical dry forests currently grow around the lagoon at lower elevations (Bolay 1997, Figure 1.3). Thus, Laguna Alejandro provides an ideal study site to fill several knowledge gaps regarding the relationship between hurricanes, vegetation, and fires in the Dominican Republic (Murphy and Lugo 1986).

1.2 RESEARCH OBJECTIVES

This project investigated the long-term environmental history of a tropical dry forest site in the southwestern Dominican Republic using proxy data sources contained in sediment cores collected from a coastal lagoon. I have four main research objectives: 1. to reconstruct late-Holocene hurricane landfalls that are recorded in the lagoon as sand overwash deposits; 2. to document the long-term (decadal to century scale) effects of hurricanes on Laguna Alejandro and surrounding area through the study of pollen grains in samples above and below the storm deposits; 3. to examine the relationship between fires and hurricane events through the analysis of macroscopic charcoal in the sediment cores; 4. to reconstruct other aspects of the paleoenvironmental history of the study site and surrounding area through the analysis of microfossils archived in lake sediments.

This thesis has two additional chapters. Chapter 2 provides a review of literature on methods used in paleotempestology and paleoenvironmental science, the ecology of tropical dry forests, and the impacts of hurricanes on mangroves, Caribbean forests, and fire regimes. Chapter 3 is a manuscript written in preparation for submission to Quaternary International.

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Chapter 1 Figures

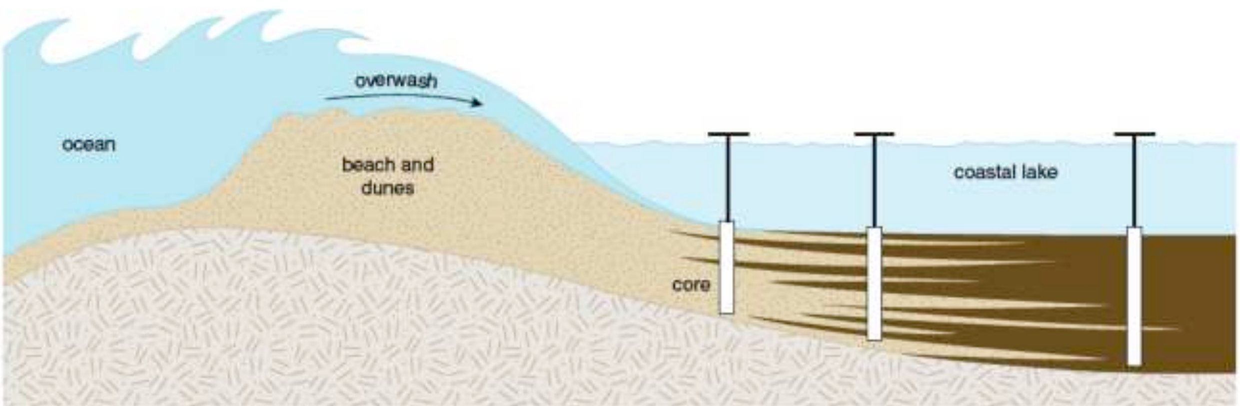

Figure 1.1. Basic premise of paleotempestology: as hurricanes make landfall, storm surge and wave action push sediment from the ocean and coastal barriers further inland, forming overwash fans that record the storm and that can be analyzed through sediment cores. Source: Liu 2007. Used with permission of the author.

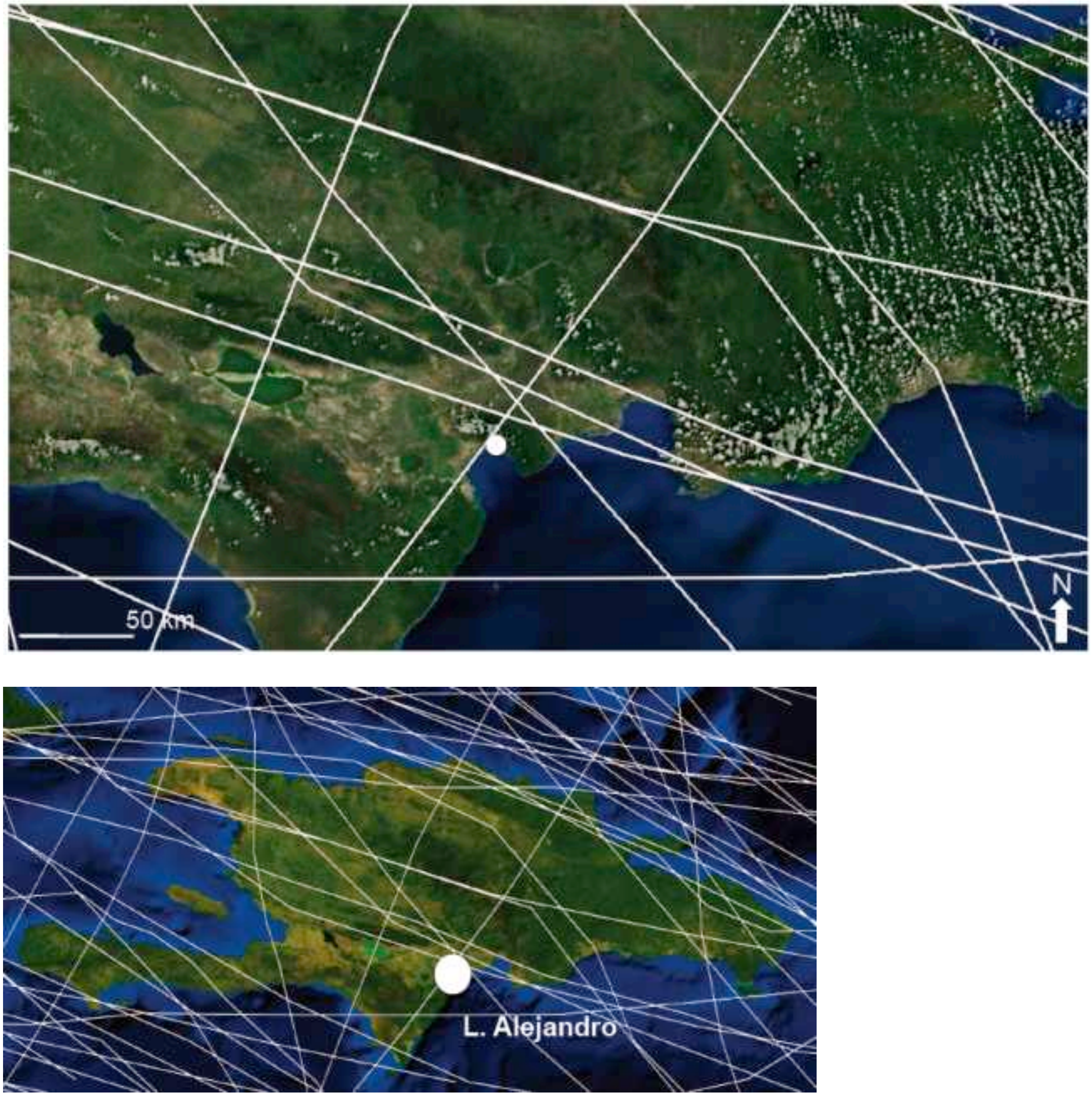

Figure 1.2. Intense (category 3, 4, or 5) historical (1851–2008) hurricane tracks for Laguna Alejandro (upper map; lake indicated by filled circle) and Hispaniola (lower map). Constructed using the International Best Track Archive for Climate Stewardship (IBTrACS); data by Knapp et al. 2010.

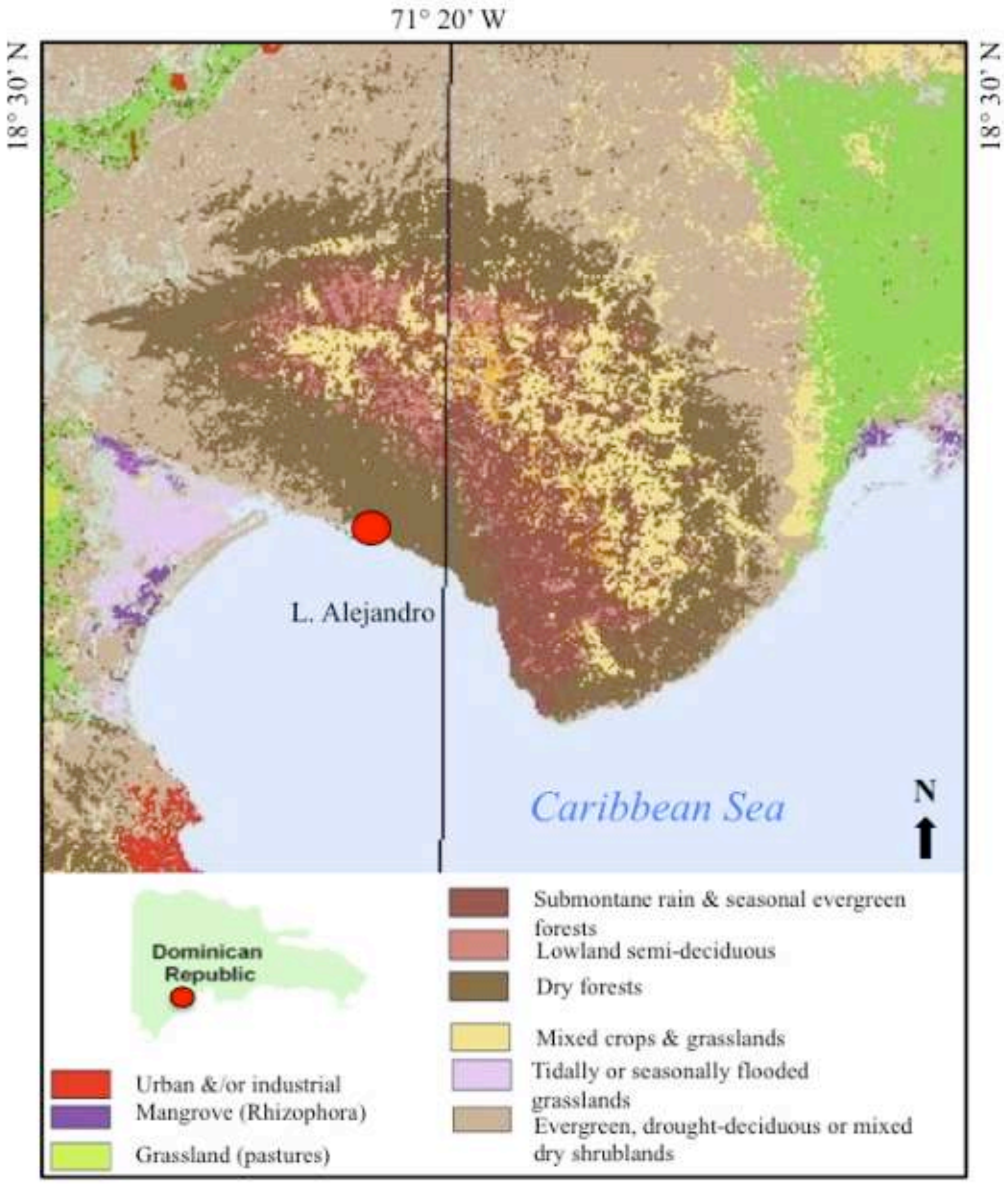

Figure 1.3. Landcover map of the area surrounding Laguna Alejandro in the southwestern Dominican Republic. At lower elevations, dry forests are the predominant vegetation around Laguna Alejandro. Modified from "Dominican Republic: Vegetation Map" produced by The Nature Conservancy.

CHAPTER 2: LITERATURE REVIEW

2.1 INTRODUCTION

The multi-disciplinary nature of this project requires that the literature review be divided into three sections: Part 1 involves an introduction to the field of paleotempestology. Here I address the basic principles, methodologies, and applications of the discipline, the links between regional and global climate mechanisms and hurricanes, the variability of hurricane activity through time, and the processes involved in formation of geologic records of hurricanes and tsunamis in coastal lakes and wetlands. A discussion then follows as to the utility of studying coastal bodies of water in paleoenvironmental studies, the identification of hurricane-deposited sediment within sediment cores, and the various ways in which paleotempestological studies are validated. An introduction to pollen analysis, including the basic principles and validation of pollen studies as well as a discussion of sediment core logging and the analyses conducted in this study are also presented here. Part 1 concludes with a discussion of the GEOTEK sediment core logger analyses and their applications in paleoenvironmental reconstruction. Part 2 of the literature review presents a discussion of dry tropical forest ecology, including the structure, function, species richness and role of fire in tropical dry forests. Part 3, the final section of this literature review, examines the impacts of hurricanes on mangrove forests, Caribbean tropical forests, and fire regimes.

2.2 PALEOTEMPESTOLOGY: BASIC PRINCIPLES, METHODOLOGIES, AND APPLICATIONS

Paleotempestology, the study of prehistoric storms, can be used to study prehistoric tropical cyclones or hurricanes. The basic assumption underlying the discipline is that as storms make landfall, storm surge and wave action driven by strong onshore flowing winds will push sediment from the ocean and coastal areas further inland, documenting the storm in the geologic record which can then be analyzed through sediment cores (Figure 2.1). Materials in the sediment cores above and below the storm deposits can then be radiocarbon dated so that the age and frequency of storms can be calculated for a specific location.

Much of the initial research in paleotempestology has focused on coastal lakes and the study of inorganic bands of sediments sandwiched between more organic layers that accumulate through time between major storms. The idea behind using coastal lakes is that only intense category 3, 4, or 5 (often called "major") hurricanes would have storm surge and wave action strong enough to wash over the margin of land separating these coastal lakes from the ocean (Liu et al. 2008, Liu 2007, Donnelly et al. 2001, Liu et al. 2000). Studying recent hurricanes captured in the historic record provides a modern day analog and validity to this scenario (Figure 2.2) (Liu et al. 2008, Liu et al. 2000). Paleotempestologists are also able to distinguish the marine origin of the sediment through the presence of microfossils such as phytoliths (plant remains), diatoms, foraminifera, and dinoflagellates, which are unique to specific types of marine environments (Liu 2007, Lu et al. 2005, Nott 2004). Multi-proxy techniques, such as combining sediment cores and tree ring analysis, as well as regional synchronicity of proxy records, increases the accuracy of interpretations of hurricane events based upon paleotempestology studies (Nott 2004). The study of isotope ratios in speleothems (cave deposits), corals, and tree rings can also add to the validity of paleotempestology studies (Liu 2007, Miller et al. 2006, Nott 2004).

In addition to the study of storm deposits in sediment cores, other proxy information can be extracted from the cores so environmental changes related to hurricanes can be reconstructed.

For instance, local changes in vegetation species composition before and after hurricanes can be identified through the high-resolution sampling of pollen and spores, and the effect of hurricanes on regional, extra-local, and local fire regimes can be determined through the analysis of microscopic and macroscopic charcoal (Urquhart 2009, Liu 2008).

Long-term Hurricane Frequencies

In North America, the written historical record of hurricane events is limited to the past 130 years (Liu et al. 2000). Sedimentary records of hurricane activity from coastal lakes, though restricted to the last 6000 years when sea levels stabilized, can provide a much more accurate record of changes in hurricane frequency through time. These longer records have shown that hurricane frequencies have changed over time at centennial and millennial scales. For instance, researchers have found that hurricane activity was lower in the Gulf of Mexico between 5000–3800 years ago but higher from 3800–1000 years ago (Liu 2007, Liu et al. 2000). Increasingly, research has shown that hurricane frequency is linked to regional and global climate oscillations. Shifts in the Bermuda High, a permanent high-pressure cell over the subtropical Atlantic Ocean, can steer more hurricanes off the coast of West Africa toward the Gulf Coast region or more northwards, along the New England seaboard depending on its location, which changes through time. The frequency and intensity of hurricanes in the Gulf Coast have also been linked to climate patterns such as El Nino-Southern Oscillation and the West African monsoon (Liu et al. 2008, Liu 2007, Donnelly 2007, Liu et al. 2000).

Hurricane Deposits in the Geological Record

There are a variety of sediment depositional types that indicate strong storms in the geological record, including ridges of coral fragments, pumice, shell, or sand and shell; splays or sheets of sand incorporating other materials such as shells, coral fragments; lithic clasts; overwash layers of sand between muddy and/or organic sediments in back barrier lagoons; and shell layers in otherwise fine-grained sediments in other shallow marine environments (Liu 2007, Nott 2004). Sand splays and overwash layers are the most often studied deposits (Liu et al. 2008, Donnelly 2005, Nott 2004, Liu et al. 2000)

Sand splays are deposits of sand carried inland, exhibiting a distance decay relationship in which the sheet of sand is thickest towards the shore and thinning with increased distance inland. Grain size of splay sediment exhibits a similar distance decay relationship, with the larger grain sizes settling closer to the shore and finer and more porous material carried further inland (Woodruff et al. 2008). A disadvantage of the study of sand splay deposits is that tsunami inundation can also form this type of deposit. In areas affected by both hurricane and tsunami activity, it can be difficult to tell which disturbance caused the deposition (Donnelly 2005, Nott 2004). However, some researchers have been able to separate tsunami- versus hurricane-deposited sediment due to an erosional lower contact and the entrainment of rip-up clasts in contrast to the sharp contact of the storm deposit (Goff et al. 2004).

There is also disagreement within the field of paleotempestology as to the occurrence of tsunamis in the Caribbean Sea. Liu et al. (2008) note that there are no historical (post-Columbian) records of tsunamis in the Caribbean and Gulf of Mexico and thus sand splays in this region are accurate indicators of hurricanes. Donnelly (2005) notes that one well-documented tsunami struck eastern Puerto Rico in 1867.

Overwash deposits in the form of sand layers up to tens of centimeters thick interbedded with muddy, organic, or fine-grained layers can be caused by storm surge and waves overtopping a sand dune barrier and depositing sand in an environment where it is not usually found, such as back barrier lagoons and swamps (Urquhart 2009, Liu et al. 2008, Nott 2004, Liu et al. 2000). The long-term stability of overwashed barrier dunes has been questioned. According to Nott (2004), dunes are likely to be entirely eroded away when they are completely inundated by storm surge and wave action. However, if the dune is simply overtopped by wave action, dunes will simply erode vertically, but not disappear (Nott 2004).

Site Suitability for Paleotempestological Studies

Paleotempestological studies have focused on coastal bodies of water and the study of inorganic bands of sediments sandwiched between organic layers deposited as sand splays or washover deposits (Urquhart 2009, Liu et al. 2008, Donnelly 2005, Donnelly et al. 2001). Coastal lakes and lagoons in the Caribbean provide ideal sites for paleotempestological studies as hurricanes are common in the Caribbean, with most islands being struck by at least one hurricane every 15 to 22 years (Tanner et al. 1991). In addition, sediments in water bodies in the Caribbean are less likely to be contaminated by other disturbance events such as tsunamis and earthquakes than other regions of the world (Donnelly 2005).

Coastal lakes and lagoons in the Caribbean also provide ideal sites for paleoenvironmental studies as the material (i.e. pollen, charcoal) is usually preserved once it is deposited into the body of water, especially if the body of water does not experience a lowering of the water level. Pollen is best preserved in oxygen poor environments such as in water, thus water bodies such as lakes and wetlands, are common study sites for pollen analysis (Delcourt 2004). Even if the water-level stability of a lake or pond is unknown, the depositional environment may still preserve pollen, especially if the water is saline. An experiment by

Campbell and Campbell (1994) examined the impact of repeated wetting and drying on a natural pollen assemblage in saline and desalinated water. Their experiment showed that while pollen in both saline and desalinated sediment is damaged by repeated wet-dry cycles, there is greater damage to the pollen found in the desalinated sediment. The authors hypothesized that pollen grains in saline water are mechanically stabilized by the growth of the salt crystals encasing them, which may thus help to preserve them, particularly the larger-grained taxa. Further, in the saline sediment they found no clear trend in loss of pollen, while there was a large net loss of pollen in the desalinated sediment; after the first wet-dry cycle nearly half of the pollen was lost. This study supports the idea that saline bodies of water, such as coastal lagoons, can provide ideal sites for paleoenvironmental studies. In addition, if the pollen is found in undisturbed sediment, it should be indicative of the species of vegetation in the location at the time of the disturbance event (Ruddiman 2001).

Criticisms regarding the validity of paleotempestological research (Liu 2007) also arises from knowledge of sea level changes over the last several millennia and its affects on coastal lakes and other shallow marine environments. However, Liu (2007) has shown in his studies of the southeastern United States that sea level changes over the past 2000 to 3000 have not affected coastal lakes where sediment cores have been taken. Donnelly (2005) asserts that the eastern Caribbean is highly suitable for paleotempestological study because of a large number of coastal lakes positioned to record hurricane events, the relatively low chance of occurrence of tsunamis in the region, and the existence of a historical record of hurricane landfalls dating back to the 16th Century, which can be used to validate some storm deposits identified in the geological record. Liu (2007) does not recognize tsunamis as a possible disturbance in the southeastern United States through his examination of the historical record and Donnelly notes only one well-documented tsunami in the Caribbean, which struck Puerto Rico in 1867 (Liu et al. 2008, Donnelly 2005). Additionally, hypersaline salt ponds decrease the amount of bioturbation and thus preserve the stratigraphy of the sedimentary record (Donnelly 2005). In his study of Laguna Alejandro, the study location of my research, Desjardins (2007) showed that the lagoon experienced generally higher levels of salinity over time, thus bioturbation should not have strongly affected the sediment stratigraphy of the lake.

Records of strong storms can be derived from many types of depositional environments but inorganic overwash deposits in coastal lakes is one of the most common and well-proven methods used in the North Atlantic and Caribbean regions as indicated by the a number of studies (Urquhart 2009, Liu et al. 2008, Donnelly 2005, Donnelly et al. 2001). Other depositional environments have also been successfully used for paleotempestological studies, such as Donnelly et al. (2001) who reconstructed 700 years of hurricane landfalls in New England from back-barrier salt marsh sediments.

Identification of Hurricane-Deposited Sediments

In coastal bodies of water, hurricane-deposited sediments, such as sand, show as distinct layers of poorly laminated, moderately well sorted units with sharp boundaries, sandwiched between organic layers; such deposits indicate that they were formed by discrete events and not daily fluctuations in tide or wind. Both thicker deposits of coarse sand and thinner deposits of fine sand and/or silt have been interpreted as storm deposits in paleotempestological studies (Urquhart 2009, Liu et al. 2008, Donnelly et al. 2001). The sediment units can be further linked to hurricanes through sediment color and stratigraphy (Woodruff et al. 2008, Donnelly et al.

2001), with hurricane-deposited sediments exhibiting a distinct color change from layers above and below the storm deposit. Hurricane-deposited sediments can be differentiated from tsunami deposits by areal extent and thickness of the deposit, as well as grain-size characteristics. In addition, tsunami deposits exhibit an erosional lower contact and entrainment rip-up clasts in contrast to the sharp contact of the storm deposit (Goff et al. 2004).

Paleotempestologists are also able to distinguish the marine origin of the sediment through the presence of microfossils such as phytoliths (plant remains), diatoms, foraminifera, and dinoflagellates, which are unique to specific types of environments (e.g., freshwater versus saltwater, littoral versus benthic). Phytolith assemblages are useful not only in determining the marine origin of sediment but also in determining if prehistoric sand layers are from other coastal or fluvial environments versus sand dunes and beach ridges of the coastal margin, further validating the source material in the geologic record (Liu 2007, Lu et al. 2005, Nott 2004).

Validation of Paleoenvironmental Studies

Regional synchronicity of proxy records can increase the validity of paleotempestology studies (Nott 2004). In his paleoecological study from coastal Alabama, Liu et al. (2008) reconstructed the local hurricane history as well as changes in vegetation and fire regimes resulting from the hurricane events. By the comparison of two sediment cores obtained from three different coastal lakes kilometers apart, Liu et al. (2008) increased the validity of their study through determination of regional synchronicity hurricanes. Through the visual comparison of the cores, including sediment stratigraphy and relative matching of hurricane deposits between the cores, in combination with similar radiocarbon dates, Liu et al. (2008) was able to support their hypothesis that the same hurricanes that deposited sediment in one lake also deposited sediment into the neighboring lakes kilometers to the west. Donnelly et al. (2001) was able to correlate overwash sand deposits across cores taken in transects through sediment characteristics and radiocarbon dating in their paleotempestological study of Succotash Marsh located on the southern coast of Rhode Island. While few paleoecological reconstructions include the regional synchronicity of proxy records, sometimes due to lack of available sites, they are valuable in that they decrease the chance that sediments assumed to be deposited by hurricanes are actually the result of some other meteorological or weathering event.

Multi-proxy techniques, such as combining sediment cores with tree rings, are another means of validating paleoecological reconstructions. For example, the study of isotope ratios in tree rings can validate whether disturbance events recorded in the geologic record are hurricanes or some other event. The essence of the isotope ratio technique is that rainwater associated with hurricanes is strongly depleted in oxygen-18 that makes it distinct from other forms of precipitation or groundwater. Thus, the trees would be absorbing the lighter oxygen-16 isotopes into their growth bands. Therefore, if a hurricane event is identified in the geologic record, the validity of this conclusion is increased if the event is also associated with an increase in oxygen-16 isotope ratios in trees of the area. This tree-ring technique is only in its early development and its use is dependent on the availability of coastal trees with annual rings and of an age sufficient to contain a record of interest; in the tropical areas such trees are rare and may not be feasible for paleotempestology. Isotope ratios can also be extracted from speleothem (cave deposit) and coral annual growth rings (Nott 2004, Miller et al. 2006, Liu 2007).

Further validation of paleotempestological studies can be found through combining sediment cores with historical data, such as long meteorological records, repeat aerial photography, and historical accounts to reconstruct the history of storms for a specific location. Liu (2007), for example, was able to use historical records to reconstruct the last 4000 years of hurricane activity for Guangdong Province in southeastern China. Donnelly et al. (2001) combined hurricane deposits within sediment cores with historical accounts of hurricanes and aerial photographs taken after hurricanes in New England.

Pollen Analysis

The analysis of pollen in combination with the identification of hurricane deposits in the geological record allows reconstruction of the past vegetation, climate, and ecosystem dynamics of a location. The development of paleotempestology over the past two decades has brought forth a new opportunity to link hurricanes to other aspects of ecosystem dynamics, such as fire and vegetation change, through multi-proxy analysis that includes pollen and microscopic charcoal. In the first example of such work, Liu et al. (2008) reconstructed hurricane strikes over the past 1200 years in the southeastern United States and consequent changes in the vegetation composition, fire frequency, and fire-vegetation dynamics.

Pollen analysis is based on the ideas that pollen grains are: 1. morphologically unique at the level of genus or species; 2. produced in vast quantities by wind-pollinated plants and dispersed from their source; 3. extremely resistant to physical and chemical decay in certain sedimentary environments; 4. reflect the natural vegetation at the time of pollen deposition (Bradley 1999).

Spatial Scale of Pollen Analyses

A critique of pollen studies has been determining whether a pollen assemblage represents a local or regional vegetation signal. Several studies have shown that the catchment size (i.e., depositional environment) determines the spatial resolution of the pollen analysis. In order to reconstruct vegetation history at the regional versus the local level Bradley (1999) suggested using larger lakes (> 1 km^2) so that the analysis is not unduly influenced by vegetation immediately surrounding the study site.

Another complication in the interpretation of pollen assemblages is the source of fossil pollen. Pollen dispersal exhibits a distance decay relationship with the dispersal distance of the grain from the plant inversely related to the number of grains. However, this relationship is complicated by grain size, with larger grains dropping out of the air column and being deposited more quickly than smaller grain sizes. In general, most wind-pollinated species' pollen will not be carried farther than half a kilometer from their source (Lowe and Walker 1997).

Validation of Pollen Analysis

Previous studies have validated the results of pollen analysis, showing that the technique is able to capture vegetation composition, abundance, and general spatial patterns on the landscape. In one of the most extensive validation studies, Webb (1974) collected surface pollen from 64 sample sites in Michigan and compared the results of his pollen analysis to 1500 samples collected from the most recent forest inventory. Webb (1974) then constructed maps with isopolls to compare the geographic distribution and amount of vegetation and pollen. His study showed that the pollen abundance and distribution was very similar to the vegetation abundance and distribution. Further, major patterns within the vegetation, such as the latitudinal division of major forest types, were also reflected in the pollen. Webb's (1974) study thus indicated that the broad geographical patterns of vegetation are closely mirrored by the composition and amount of pollen rain and pollen analysis is then an appropriate method of reconstructing vegetation composition and abundance.

GEOTEK Core Logger

Multi-sensor sediment core loggers, such as the GEOTEK core logger utilized by Lamont Doherty Earth Observatory (LDEO) for core ALEJ08-5 examined in this study, provide several advantages to traditional methods of measuring physical parameters of cores such as water content and magnetic susceptibility. Traditionally, physical parameters of sediment cores had to be obtained through time consuming, discontinuous sampling and consequent destruction of, the sediment. However, relatively recent advances in sediment core logging instruments and techniques provide a means of computer controlled and non-destructive continuous sampling of the sediment in either unopened or split casing. Sediment core logging techniques can now provide calibrated, sub-centimeter measurements of gamma-ray attenuation, p-wave travel time, and magnetic susceptibility for several meters of core in a matter of hours in addition to digital spectral photographs of the sediment. Results using a multi-sensor core logger have shown good correlations to results from discrete samples and are also valid for sediments from varying geologic settings and chemical compositions (Zolitschka et al. 2001, Weber et al. 1997).

While originally used in marine studies, many of the physical parameters measured using core logger technology are now being incorporated into paleoenvironmental studies, especially concerning the study of lake sediments. Yu et al. (1990) used magnetic measurements (including magnetic susceptibility), loss on ignition, and pollen analysis to reconstruct changes in climate and lake development in a subtropical region in China. Through AMS C14 dating and magnetic susceptibility records of a sedimentary sequence from Lake Tritrivakely, Madagascar, Williamson et al. (1998) were able to correlate cores and reconstruct the general depositional environment and climate for the last 46000 years.

The multi-sensor core logger is a unique tool encapsulating the multi-proxy methodology practiced in paleoenvironmental studies. Hodell et al. (2005) used density measurements from gamma ray attenuation and spectral photographs of sediment cores taken from Lake Chichancanab, Mexico to identify a series of alternating gypsum and organic rich bands of sediment deposited during a series of dry events with intervening more moist periods. Results from that study disprove earlier ideas of a two-century long megadrought associated with the collapse of Maya civilization (i.e. Terminal Classic Drought). Wahl et al. (2007) utilized pollen analysis, loss on ignition, and magnetic susceptibility to study temporal patterns of Mayan settlement, anthropogenic landscape disturbance and consequent land abandonment, and climate change in the Mirador Basin near Peten, Guatemala.

2.3 ECOLOGY OF TROPICAL DRY FORESTS

Tropical dry forests occur in frost-free areas where mean annual temperature does not fall below 17˚ C, where mean annual rainfall is between 250 and 2000 mm, and where the annual potential evapotranspiration (PET) exceeds precipitation (P). Within this classification are a variety of woodland and forest ecosystems with tropical dry forests transitional along a spectrum between semi desert/savanna and moist forests (Murphy and Lugo 1986).

Seasonality

While these climatic parameters are used to define tropical dry forests, there is a seasonal aspect with respect to rainfall in most tropical forests, with the timing, frequency, and duration of dry periods dependent upon latitudinal position, proximity to ocean currents, and monsoon air mass movements. The seasonality of annual rainfall distribution in addition to the mean annual amount of precipitation is important in determining the type of tropical dry forest. Both the seasonal and annual variability in rainfall can impact the ecosystem structure and function of tropical dry forests, especially with regards to the timing of biological activity such as growth or reproduction, and for ecosystems that include flora and fauna near their ecological margins of tolerance to moisture stress. Therefore, while tropical dry forests are defined according to mean annual climatic parameters, the more extreme years may have a greater impact in determining the structural, compositional, and functional properties of dry forest ecosystems.

Some researchers assert that disturbance and not moisture stress may play the primary role in determining the structure of particular tropical dry forests. For instance, Van Bloem et al. (2007) attributed the low and dense structure of Caribbean tropical dry forests to repeated impacts by hurricanes. They also found that Caribbean tropical dry forests have higher stem densities and lower basal areas versus other tropical dry forests.

Vegetation Structure

Structurally, dry forests generally exhibit overall lower canopy heights, basal area, and number of strata in comparison to tropical moist and rain forests. According to Murphy and Lugo (1986), tropical dry forest canopy heights average 50% of wet forests, while basal area average is 30–75% that of wet forests. While wet forests have three to five canopy strata, many dry forests have only one or two. Similar to the overall smaller and simpler structure of the tropical dry forests is the low biomass in comparison to wet forests (Murphy and Lugo, 1986).

Biodiversity

The deficiency of studies in tropical dry forests in addition to differences in sampling in previous studies have made comparisons of species diversity among various tropical forests difficult (Gillespie et al. 2000). However, Gillespie et al. (2000) note that measures of diversity are dependent upon standardization and if standardized to diversity per unit number of stems, the Central American tropical dry forest fragments would contain a higher diversity compared to other forest types. In general, dry tropical forests are structurally and biologically less diverse than their moist counterparts (Murphy and Lugo 1986).

When comparing several tropical dry forests in Central America, Gillespie et al. (2000) found that floristic diversity and structure differed significantly. The relative close proximity of the study sites to each other led the researchers to determine that the unique disturbance history of each site accounted for the most variation in biological diversity, rather than precipitation patterns. In the study, a total of seven dry forest sites in Costa Rica and Nicaragua were compared to twenty-one other neotropical dry forests, using Spearman's rank correlation to identify ecological and environmental variables associated with species richness and abundance. Gillespie et al. (2000) also ranked the sites according to current frequency and intensity of anthropogenic disturbance. They analyzed data on human disturbance information along with the environmental data to compare the seven sites in this study to the twenty-one other neotropical dry forest sites examined in previous studies and found no significant difference in family richness, total number of plant species, total number of liana species, and number of tree and shrub species amongst the sites. There was also no significant correlation between forest cover or seasonality of annual precipitation and species richness (Gillespie et al. 2000), findings that are in agreement with Murphy and Lugo (1986) who assert that extreme years of precipitation may be the most important to the composition of tropical dry forests.

Gillespie et al. (2000) did find anthropogenic disturbance to be significantly correlated with plant species diversity in Central American dry tropical forests. They also found that Central American dry tropical forests have decreased density in comparison to the neotropical dry tropical forests, which they attributed to historical disturbance, primarily fire, and further, hypothesized that undisturbed or mature tropical dry forests may not exist in Central America, except in fragments that persist because edaphic conditions limit agriculture.

Succession

With increasing tropical dry forest fragmentation due to human disturbances such as clearance and fire (Pinnard and Huffman 1997, Murphy and Lugo 1986), a clearer understanding of tropical dry forest successional pathways will become increasing important to conservation efforts. Interestingly, while tropical dry forests may be more vulnerable to disturbance versus wet forests due to moisture stress, tropical dry forests tend to be more resilient to disturbance than their moist counterparts, though successional processes occur over a longer time period (Murphy and Lugo, 1986). The resilience of tropical dry forests is hypothesized to be due to their structural simplicity, small stature, and the predominance of resprouting as the primary regeneration strategy (Murphy and Lugo, 1986). Resprouting from live stems allows dry forests the potential to return to a mature state more quickly than wet forests and thus, they may be considered more resilient. Van Bloem et al. (2007, 2006, 2005) assert that the small structure and predominance of resprouting as a successional pathway of Caribbean dry forests results from repeated impacts of hurricanes over time. Wet forest's recovery times are estimated to be almost seven times as long as dry forests (1000 years versus 150 years) (Murphy and Lugo 1986). However, the lack of study of long-disturbed sites leaves many questions related to the successional traits of tropical dry forests unanswered, including the impacts of root systems, seed pools, and seed dispersal on succession and thus, resilience (Murphy and Lugo 1986).

The Role of Fire

The role of fire in tropical dry forest dynamics, including the frequency and intensity of fires, and the impacts of fire on succession and species diversity is also understudied. According to Murphy and Lugo (1986), the effects of fire on tropical dry forest are not well understood though they contend that under "normal conditions," major fires do not appear to be a frequent occurrence in even the drier tropical forest types. Some studies (Pinard and Huffman 1997, Murphy and Lugo 1986) assert the lack of major fires occurring within the interiors of tropical dry forests due to the lack of combustible materials on the forest floor. However, Pinard and Huffman (1997) asserted that with the continued fragmentation of tropical dry forests and the intentional burning of dry forests and the savannas adjoining them, fires penetrating tropical dry forest interiors are likely to increase. While several studies assert that major fires are infrequent in tropical dry forests, the frequency and role of low-intensity fires in these ecosystems are still poorly understood.

Several studies have investigated the impacts of low-intensity fires on tropical dry forest trees and soil. Otterstrom and Schwartz (2006) conducted a prescribed burn in an upland tropical dry forest in Nicaragua and found that their particular study site was dominated by species that exhibited fire tolerance through survivorship or a combination of adaptations to fire, suggesting that the common species at their site had adapted to fire through time. The results from this study suggest that this tropical dry forest site is dominated by species able to survive infrequent, low-intensity fires of small spatial extent. The results also suggest that tropical dry forests may even benefit from infrequent, low-intensity fires in terms of increased biodiversity as the Nicaragua site exhibited increased post-fire recruitment of rare plant species. The Otterstrom and Schwartz (2006) study was a short-term (three year) survey, thus longer-term (decadal to century scale) study would help to validate their results. Spatial differences in tropical dry forest ecology should also be considered before extrapolating these results.

A study by Kennard and Gholz (2001) also found that infrequent, low-intensity fires may be beneficial to tropical dry forests in lowland Bolivia in terms of plant species diversity or increased soil organic content. The authors compared the short-term (18 months) effects of both high- and low-intensity prescribed burns to plant-removal and control plots on soil properties and plant growth. Both low- and high-intensity fires increased the nutrient content and pH of the upper few centimeters of soil with the more intense fires increasing the nutrient content and pH more than the less intense fires. The plant-removal treatments and control plots experienced no changes in nutrient content or pH. The more intense fires also significantly changed the soil chemistry and physical properties by increasing available nutrients, decreasing soil organic content (SOC), decreasing soil nitrogen, and altering the soil structure. Notably, total vegetation at sites with more intense burns also recovered more slowly than in the other treatments, findings in agreement with Gillespie et al. (2000). However, the low intensity fires actually increased SOC in comparison to adjacent forest soils and had no impact on soil physical properties. Seedling heights of the dominant commercial timber species, *Anadenanthera colubrina*, increased after more intense fires, a result the authors attributed to the decreased initial soil strength, which impeded root growth of early colonizers, decreased competition, and increased nutrients through ash. However, the more intense prescribed burns also altered soil structure, which may take years to decades to recover. Therefore, low- to medium-intensity fires may be beneficial to tropical dry forests over the long-term as these types of fires can increase nutrient availability to seedlings without damaging the soil. However, there is still little knowledge of historical or prehistorical fire regimes in tropical dry forests and the longer-term (decadal to century scale) impacts of fires on them (Otterstrom 2006, Kennard and Gholz 2001).

Other studies in Costa Rica and Nicaragua indicated that fires in their tropical dry forest sites lowered species diversity by selecting for fire resistant species or early successional plants, and destroying the understory, which makes up a significant portion of woody plants in tropical dry forests. Higher plant species diversity at one of the study locations was attributed to an active fire suppression program that maintained lower intensity and frequency fires, compared to another that experienced major fires annually (Gillespie et al. 2000).

Pinard and Huffman (1997) aimed to increase their understanding of the role of fire in tropical dry forests by examining the bark properties of sixteen common tree species in a tropical dry forest in eastern Bolivia to characterize tree fire-resistance. In this study, Pinard and Huffman related maximum cambial temperature during prescribed fires to bark characteristics in an effort to measure the insulating quality of the bark. During their experiment, the researchers found that bark thickness explained most of the variation in peak cambial temperature and the time to peak cambial temperatures, with thicker-barked trees taking longer to reach peak cambial temperatures, experiencing lower peak temperatures in comparison to thinner barked trees, and taking longer to return to ambient temperatures. The authors proposed that bark thickness is a useful indicator for predicting a species' susceptibility to cambial injury during low intensity fires. They found that the majority of species in their sites had relatively low fire tolerances due to the predominance of thin-barked species. The authors believe that this characteristic is indicative of a long-fire free interval and that the species composition of this particular site will be changed by increasing fire frequency or intensity. They also postulated an alternative hypothesis in which frequent fires do not select for thicker barked species due to the heterogeneous spatial extent and intensities of fire in addition to the predominance of resprouting as a regeneration pathway for many tropical dry forest species. In this scenario, frequent low-intensity fires would actually select against shade-intolerant thicker-barked species.

2.4 IMPACTS OF HURRICANES ON ECOSYSTEMS

Vulnerability to Fire

Ecosystems impacted by hurricanes are thought to have an elevated vulnerability to fire (Laurance et al. 2008, Brokaw and Walker 1991) primarily due to the increase in fuel load deposited to the forest floor. This relationship can be examined over long time scales through analysis of microscopic and macroscopic charcoal above and below hurricane deposits in lake sediments. Liu et al. (2008), in a paleoenvironmental study of coastal Alabama, showed that in the past, major fires followed within years to decades of more intense category 3, 4, and 5 hurricanes as indicated by charcoal fragments on top of hurricane-deposited lake sediments . They hypothesized that the outbreak of fires following a hurricane was due to the removal of biomass from forest canopy to the floor, which increased fuel load on the ground, drying of the ground fuel due to hurricane winds, and further drying of the forest floor due to the canopy gaps created by the destruction of vegetation. Modern and paleoenvironmental studies have shown that recovery of vegetation is slower in areas that have burned after being struck by hurricanes (Urquhart 2009, Liu et al. 2008, Brokaw and Walker 1991) with the more intense burns increasing the recovery time (Kennard and Gholz 2001).

Vegetation Type

Mangroves

Mangrove forests occur along many tropical coastlines and are thus frequently and severely damaged by hurricanes. Often mangrove forests experience greater damage than inland tropical maritime forests as they bare the brunt of wind and storm surge action (Baldwin et al. 2001, Brokaw and Walker 1991) as well as sediment deposition (Smith III et al. 2009). Researchers have examined the impact of hurricanes on mangroves by mangrove forest type/geomorphic setting and species-specific effects (Smith III et al 2009), as well as community level impacts including changes in forest structure and composition (Baldwin et al. 2001).

Smith III et al. (2009) studied the impacts of four storms occurring between 1935 and 2005 on three types of mangroves, *Rhizophora mangle* (red), *Laguncularia racemosa* (yellow or white), and *Avicennia germinans* (black) in Florida. Their study revealed that at the plot and species level stem mortality and basal area lost were highly variable (0–100%) and that damage was not significantly correlated with the amount of sediment deposited, distance from open water, or height of the storm surge. Rather, patterns of hurricane damage were revealed by examining mangrove forests damage by hydro-geomorphic setting; basin, riverine, or overwash island. Storms had differential impacts on the forest types located in different hydro-geomorphic settings, with the basin mangrove forests the most susceptible to damage. Smith III et al. (2009) hypothesized that basin mangrove forests are more susceptible to disturbance versus other types due to floodwater inundation and edaphic conditions specific to this type of setting. The researchers also hypothesized that mangroves that are severely impacted by hurricanes could be transformed into completely different ecosystems, such as mudflats.

Baldwin et al. (2001) examined regeneration in fringe mangrove forests by relating species regeneration pathways to severity of damage from Hurricane Andrew at two study locations in southern Florida. Similar to the Smith II et al. (2009) study, mangrove forests in the Baldwin et al. (2001) study were dominated primarily by *Rhizophora mangle, Laguncularia racemosa,* and *Avicennia germinans.*

Smith III et al. (2009) found that the regeneration pathways following hurricanes in fringe mangrove forests depended largely upon the density of *Rhizophora* seedlings or advance recruits that survived the hurricane while both *Laguncularia racemosa* and *Avicennia germinans* survived by resprouting. The density of *Rhizophora* seedlings surviving the hurricane depended on the damage to the mangrove forest with less severe damage allowing the survival of dense patches of *Rhizophora* seedlings. If the *Rhizophora* seedlings survived in large densities, these seedlings repressed the seedlings of other species, which led to the creation of monospecific patches of small *Rhizophora mangles* interspersed with larger *Laguncularia racemosa* and *Avicennia germinans* that had survived the storm as stems. If no dense patches of *Rhizophora* seedlings survived the storm then no single species of mangrove would dominant colonization. In this case, released and colonizing seedlings of all three species of mangroves grew rapidly while, herbaceous vegetation suppressed woody plant colonization in patches to form a multi-species stand of small mangroves that are interspersed with patches of herbaceous vegetation and scattered large *Laguncularia racemosa* and *Avicennia germinans* trees. Smith III et al. (2009)

postulated that in the event of the more common and less severe damage to fringe mangrove forests by storm events, low diversity or even mono-specific stands will persist while more severe damage to fringe mangrove forests can significantly alter community structure and biodiversity.

Caribbean Tropical Forests

The long-term effects of hurricanes on vegetation are the result of the short-term damage to individuals and subsequent recovery. However, there are few long-term studies of the impacts of hurricanes on tropical and subtropical ecosystems. Most studies have focused on shorter-term impacts of hurricanes on vegetation such as those impacts occurring within ten years or less of the event. While these studies are important to understanding of hurricane effects on different ecosystems, longer-term studies are needed to determine how hurricanes influence forest structure, function, and species composition over long temporal scales.

A paleoecological study by Liu et al. (2008) demonstrated that the saltwater intrusions into ecosystems in the southeastern US caused by hurricanes, and the destruction of vegetation itself, impacts the composition of successional species. They found that in general halophytic and heliophytic plants moved into hurricane-impacted areas. At the same time, pine regeneration was inhibited by outbreaks of fire that occurred in the years to decades following the hurricanes. Another paleoecological study in Nicaragua (Urquhart 2009) also found increases in disturbance-type vegetation and increases in fire post-hurricane. In his literature review of the impacts of hurricanes on forests in the Caribbean, Tanner et al. (1991) also discussed hurricane impacts on succession, noting that the pioneer and shade intolerant species were replaced by successional and more shade tolerant trees over time.

Lugo (2000) summarized some of the impacts of hurricanes on Caribbean vegetation from long-term ecological research sites in Puerto Rico ("long-term" was not defined in the study), including sudden and delayed tree mortality, alternative methods of forest regeneration and successional direction, convergence of community structure and organization, etc. A study by Sherman et al. (2001) conducted seven and 18 months following a hurricane event in Dominican Republic also notes that hurricanes can have major effects on forest structure and function such as age and size distribution of trees, forest composition, forest biomass, species diversity, canopy structure, and changes in species composition.

Other studies (Lugo 2005) of hurricane impacts on Caribbean forests have focused on the frequency of intense hurricanes. In their study of a Caribbean dry forest, Imbert et al. (2008) found that while the impact of hurricanes on forest ecosystems depends on the intensity of the disturbance, forest ecosystem functioning can recover within years of the disturbance due to resprouting from remaining living stumps or trunks. However, they postulated that forest structure would depart from its initial state prior to the disturbance over a much longer time period. The authors also note that Caribbean dry forest recovery will differ from other forest ecosystems and may be delayed due to other disturbances that may have a cumulative impact on this ecosystem specifically, such as drought. Van Bloem et al. (2005) also noted the cumulative impacts of disturbances such as drought in Caribbean dry forests.

Other studies of hurricane disturbance to tropical ecosystems have focused on varying impacts according to a wide range of site-specific conditions including species-specific effects (Imbert et al. 2008, Sherman et al. 2001, Brokaw and Walker 1991), land use history (Uriarte et al. 2004), and the complex interactions of topographic, biotic, and meteorological factors

(Metcalfe et al. 2008, Sherman et al. 2001). Uriarte et al. (2004) posed the idea that anthropogenic disturbances can either aid or hinder forest recovery from a natural disturbance depending on prior land use and the amount of basal area present before the hurricane. The authors found that the land use history of their study locations in the Dominican Republic left an impact upon the structure and composition of plant communities that persisted even after disturbance by a hurricane.

As in other forest types, the interactions of topographic (ridge versus valley, aspect), meteorlogic (strong local wind gusts and differences in rainfall), and biotic factors can influence the damage incurred by tropical forests from hurricane strikes (Lugo 2000, Sherman et al. 2001). Also, site conditions (Sherman et al. 2001, Imbert et al. 2008, Metcalfe et al. 2008) such as species-specific effects, forest structure, tree age, tree height, tree health, rooting characteristics, and soil conditions can all affect damage incurred from hurricane winds. For instance, uneven-aged stands with vertically differentiated canopies are more susceptible to wind damage than smooth canopies. Canopy roughness or smoothness can also be related to the species composition (Sherman et al. 2001). According to a study by Laurance et al. (2008), the damage incurred to tropical forests by winds can be especially severe if the forest is fragmented. The researchers also found that wind disturbances can lead to altered forest structure, shifts in plant species composition, exotic-plant invasions, reduced carbon storage, and elevated vulnerability to fire.

Some researchers assert that disturbances have played a major role in the structure of Caribbean ecosystems and that these ecosystems need disturbance by hurricanes to maintain their natural growth patterns (Van Bloem et al. 2007, Sherman et al. 2001). Van Bloem et al. (2007, 2006, 2005) state that it is hurricane damage over time that maintains the low and dense structure of Caribbean dry forests. According to their studies, hurricanes damage larger stems without causing mortality, leading to basal sprouting and thus multi-stemmed trees of the same size cohort. In that scenario, species composition and structure of the forest is reinforced. Interestingly, Van Bloem et al. (2007) found that even stems not directly affected by hurricanes (i.e., they suffered no apparent damage) developed basal sprouts. Van Bloem et al. contend that cases of basal sprouting without stem damage are threshold responses to wind speeds between a category 1 and 3 storm (119–178 km/h). The 2007 study by Van Bloem et al. disagrees with an earlier study by the same authors (2005) that postulates that differences in the structure of dry forests have been attributed to various climatic factors such as low annual rainfall in addition to the effects of disturbances such as hurricanes. The results of the 2007 study led the researchers to attribute the low, dense structures of Caribbean tropical dry forests directly to the impact of hurricanes over time.

Clearly, there are several ideas on the impacts of hurricanes to Caribbean tropical forests. However, whether hurricanes can cause long-lasting changes in Caribbean forest structure, function, and species composition is still largely unknown due to a lack of long-term analysis (decadal to century scale) (Imbert et al. 2008, Tanner et al. 1991).

2.5 CONCLUSION

Mounting paleoenvironmental studies, such as those by Hodell et al. (2000) in the Caribbean and Higuera-Gundy et al. (1999) in Haiti, indicate the variability of climate and vegetation through time. While these studies have focused on general, broad-scale trends in climate and vegetation, there are few long-term studies examining changes in disturbance regimes through time or the long-term impacts of disturbance regimes on vegetation.

At present, most studies of changes in hurricane activity have been based upon the historic written and observational record, limited in temporal resolution to the past few centuries in many regions of the world. Many studies of the short-term impacts of hurricanes upon tropical ecosystems have been conducted and assert that hurricanes can affect tropical forest's structure and functioning but disagree on the impact of hurricanes on species composition over time. However, long-term impacts of hurricanes upon forest ecosystems are poorly understood and a paleoenvironmental study of the impacts of hurricanes on tropical ecosystems is needed.

Paleotempestology, through studies in the southeastern United States and insular Caribbean (e.g., Liu et al. 2008, Desjardins 2007, Donnelly 2005) has proven its utility in providing a methodology for studying the frequency of past intense hurricanes and their impact on vegetation through time. Through the study of sedimentary pollen and charcoal, changes in vegetation and other disturbance regimes, such as fire, in response to hurricane disturbance can also be analyzed. Past research has hypothesized that hurricane strikes can increase the occurrence of fire within ecosystems. However, until recently, this relationship had not been examined. With a study by Liu et al. (2008) in the southeastern United States and Urquhart (2009) in Nicaragua showing a link between increased fire activity occurring after hurricane events, this relationship needs to be further examined in other ecosystems, specifically tropical dry forests where a knowledge gap exists as to the role of fire in these forest types.

Laguna Alejandro, located in the southwestern Dominican Republic, is an appropriate study site to examine the long-term impacts of hurricanes on tropical dry forests, the fire ecology of these forests, and possible hurricane impacts on fire activity in tropical dry forests. Results from a previous study (Desjardins 2007) indicate that Alejandro has probably been struck by several hurricanes over the past 1200 YBP. Also, tropical dry forests currently grow around the lagoon at lower elevations. Therefore, Laguna Alejandro provides an ideal study site to fill several knowledge gaps regarding the relationship between hurricane and fires in the Dominican Republic, as well as the role of fire in today's increasingly fragmented tropical dry forests.

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Chapter 2 Figures

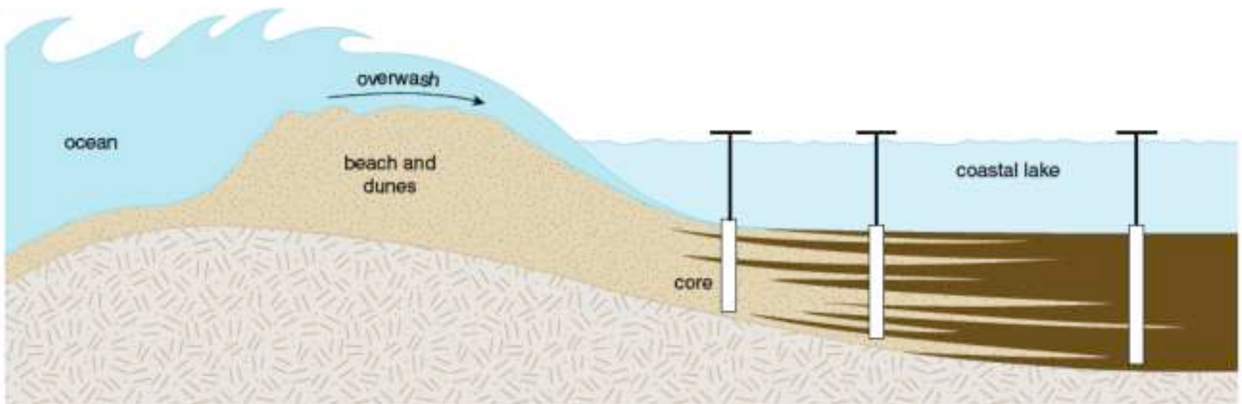

Figure 2.1. Basic premise of paleotempestology: as hurricanes make landfall, storm surge and wave action push sediment from the ocean and coastal barriers further inland forming overwash fans that record the storm and that can be analyzed through sediment cores. Source: Liu 2007. Used with permission of the author.

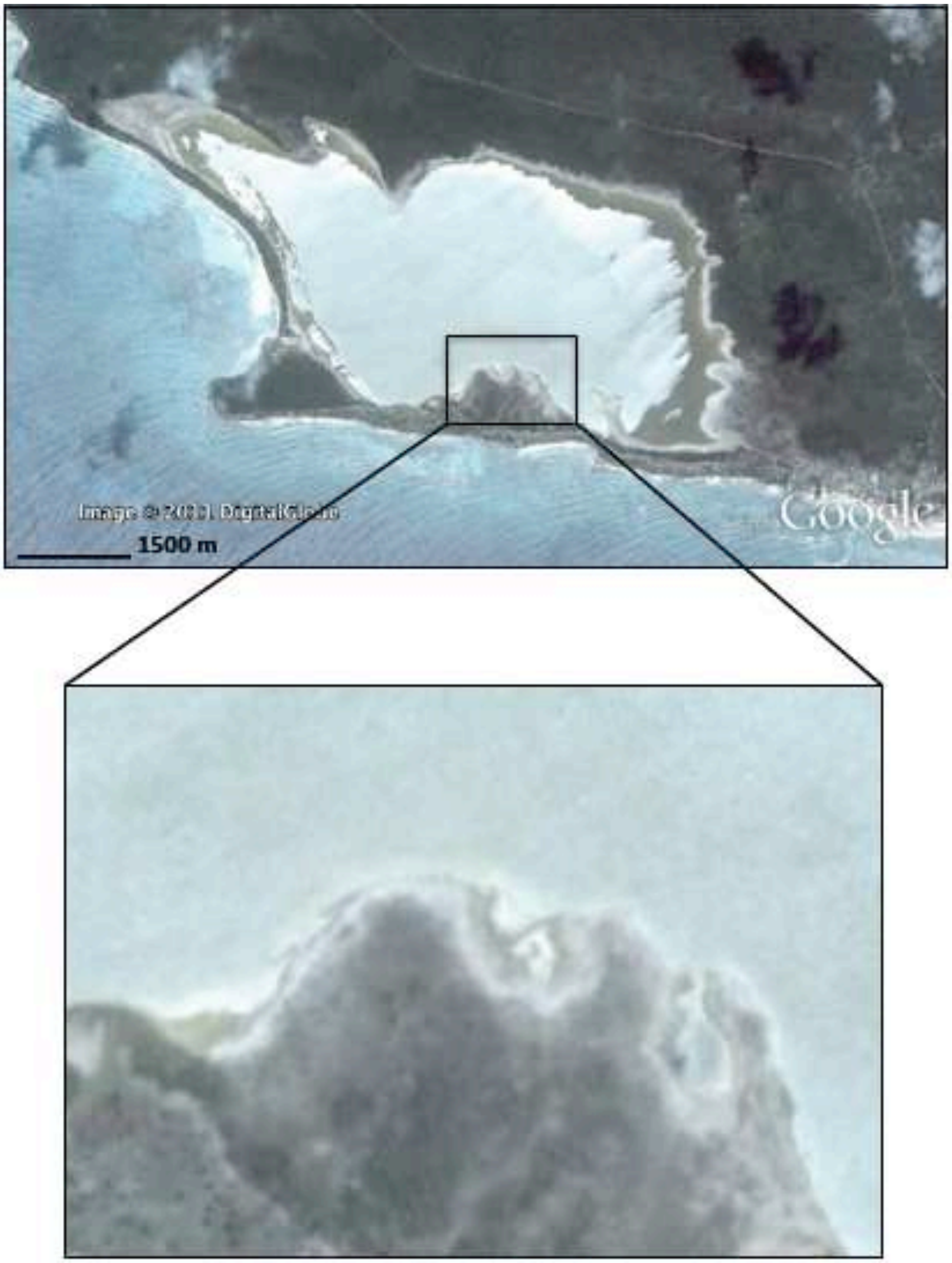

Figure 2.2. Hurricane-generated sand overwash fan (inset) on shoreline and in Isla Saona, DR visible in a July 2003 satellite image (Google Earth). Overwash fans from recent (historical) hurricanes validate prehistoric storm deposits in the geological record

CHAPTER 3: MANUSCRIPT

3.1 INTRODUCTION

Hurricanes are complex disturbance events that threaten life and property and may be tied to other disturbance types such as fire and erosion events (Urquhart 2009, Liu et al. 2008, Tanner et al. 1991). The short-term ecological impacts, those occurring within a decade, of hurricanes on tropical vegetation in the Caribbean region are well documented (Imbert et al. 2008, Metcalfe et al. 2008), but whether hurricanes have lasting impacts on vegetation composition is still in question. Some studies from the Caribbean have suggested that while hurricanes could have long-lasting effects on basic forest structure and function, they only have shorter-term impacts on species richness and actually reinforce species composition (Van Bloem et al. 2007, Tanner et al. 1991). However, this conclusion is based on short-term studies. Tanner et al. (1991) pointed out that the lack of information on longer-term hurricane impacts is related to a deficiency of long-term analysis of sites impacted by hurricanes.

In addition to long-term hurricane impacts on vegetation, there is a question of whether hurricanes affect tropical fire regimes. In the subtropical maritime forests of the southeastern United States, Myers and Van Lear (1998) hypothesized that hurricanes would increase fuel on the ground and thereby raise the risks of post-hurricane fires. The findings of a recent paleoecological study by Liu et al. (2008) supported that hypothesis; their study showed increases in microscopic (>10 μm) charcoal deposited on top of hurricane-deposited sediments during the late Holocene in Little Lake, Alabama, suggesting that major fires occurred after hurricane landfall events. However, a gap exists in our understanding of long-term hurricane impacts on vegetation and fire regimes in tropical ecosystems.

Another gap exists regarding the role of fire in tropical dry forests. Several studies (Otterstrom and Schwartz 2006, Kennard and Gholz 2001, Pinnard and Huffman 1997, Murphy and Lugo 1986) have examined the roles and short-term impacts of fire in tropical dry forests to determine whether these forests are resistant or show resilience to disturbance by fire. These studies generally surmised that major fires have not impacted species composition and structure of tropical dry forests although the effects of low-intensity, more frequent fires are still debated.

In North America, the written historical record of hurricane events is limited to the past 130 years (Liu et al. 2000). Sedimentary records of hurricane activity from coastal lakes can provide much more accurate records of changes in hurricane frequency through time. Methodologies from paleoecology and paleotempestology (the study of prehistoric storms) can be used to study the long-term impacts of hurricanes on vegetation composition and fire patterns through identification of hurricane deposits and analysis of microfossils (e.g., pollen, charcoal). Local changes in vegetation composition before and after hurricanes can be identified through the high-resolution sampling of pollen and spores and effects of hurricanes on regional and local fire regimes can be determined through analysis of microscopic (>10 µm) and macroscopic (>125 µm) charcoal, respectively (Urquhart 2009, Liu 2008, Carcaillet 2007, Gavin et al. 2007, Whitlock and Anderson 2003, Whitlock and Larson 2001, Patterson et al. 1987). Organic materials in the samples above and below storm deposits can then be radiocarbon dated so that the age and frequency of storms can be calculated for specific locations.

Major storms may leave a variety of sediment deposits on the landscape though much paleotempestology has focused on coastal lakes and the study of sand splays and overwash layers sandwiched between more organic layers that accumulate through time between major storms.

Many studies analyze coastal lake sediments (Figure 3.1) assuming that only intense category 3, 4, or 5 (often called “major”) hurricanes would have storm surge and wave action strong enough to wash over the margin of land separating these coastal lakes from the ocean (Liu et al. 2008, Liu 2007, Nott 2004, Donnelly et al. 2001, Liu et al. 2000).

Many paleotempestological reconstructions have been conducted on coastal lakes in the northeastern and southeastern United States. Donnelly et al. (2001) reconstructed hurricane events in transects of sediment cores from Succotash March, Rhode Island through description of sediment characteristics, radiocarbon dating and relative dating of storm deposits, and historical photography. Through sediment stratigraphy, loss on ignition, and radiocarbon dating of multiple sediment cores from Lake Shelby, Middle Lake, and Little Lake in coastal Alabama, Liu et al. (2008) were able to identify and date hurricane deposits and determine that the same hurricanes deposited sediments in all three lakes though they are located several kilometers apart. Liu and Fearn (2000) were able to reconstruct prehistoric hurricane landfalls from sediment stratigraphies of 16 cores obtained from Western Lake, Florida.

Coastal lakes in the Caribbean provide ideal sites for paleotempestological studies as hurricanes are common, with most islands experiencing a landfall at least once every 15 to 22 years (Tanner et al. 1991). Donnelly (2005) used sediment characteristics, stratigraphy, radiocarbon dating, and grain size analysis of three cores and beach samples from Big Culebrita Salt Pond, Puerto Rico to identify and correlate hurricane events in the geologic record. Sediments of Laguna Alejandro, located in the tropical dry forests of southwestern Dominican Republic (Bolay 1997), have recorded evidence of past hurricane and drought events from multi-proxy analysis including loss on ignition, magnetic susceptibility, and stable isotope analysis (Desjardins and Kennedy, unpublished data).

The Dominican Republic and the study site, Laguna Alejandro, located within the southwestern region of the country, lie within the path of numerous intense (category 3, 4, or 5) historical hurricane tracks (Figure 3.2). This site provides an ideal study site to contribute to our knowledge of the long-term fire history of tropical dry forests, long-term impacts to tropical vegetation from disturbance by hurricanes, and the relationship between hurricanes and other disturbance types (e.g. fire, erosion events) at the study site.

This study combines paleoecological and paleotempestological methods to document the disturbance and environmental history at a coastal lagoon in the southwestern Dominican Republic. We used multiple proxies including pollen, microscopic and macroscopic charcoal, radiocarbon dating, loss on ignition (LOI), and magnetic susceptibility to analyze a 160 cm sedimentary profile obtained near the dune barrier of a coastal lagoon in the arid Enriquillo Valley. Here we present information on hurricane strikes, erosion events, and their links to fire and vegetation history over the past millennium at Laguna Alejandro.

3.2 METHODS

Site Description

Our study site (Figure 3.3), the ~25 ha Laguna Alejandro (informally named by researchers), lies along the arid southwest coast of the Dominican Republic at the northern edge of the Lago Enriquillo basin, once a sea channel before the Miocene and now a semi-desertic to desertic depression (Bolay 1997). Laguna Alejandro is located in limestone bedrock and is separated from the Caribbean Sea by a limestone barrier 75–100 m wide and 3–5 m in height.

The bathymetry of the lagoon is shallow and homogenous, with an average depth of 200 cm (Desjardins 2007), though seasonal changes are evident from our observations on several visits.

The limestone ridge that separates the lagoon from the Caribbean Sea is vegetated by dense thorny scrubs. The vegetation of the study area (and pollen source area) consists of tropical dry forest and scrub near the lake and tropical moist forests containing evergreen broadleaf trees and pines at higher elevations in the nearby Sierra Martín García that reach about 1300 m elevation (Bolay 1997, The Nature Conservancy). Two ephemeral freshwater streams flow seasonally from the mountains and enter the lagoon at its northeastern edge.

According to Bolay's (1997) descriptions of the phytogeography of the Dominican Republic, the study area vegetation consists of subxerophytic forests, mangroves, and vegetation of coastal lagoons. This classification defines subxerophytic forests as semi-open forests with 750–1000 mm annual precipitation and slightly alkaline soils. Most trees are from the *Leguminosae* family with the bush layer often dense and composed of various species of *Acacia, Prospis, Cassia*, and *Caesalpinia*. A relatively small grove of *Laguncularia racemosa* (white mangrove) exists on the inland western edge of Laguna Alejandro.

Developed archaeological sites are relatively rare in the Dominican Republic due to a dearth of research, but a pre-ceramic, pre-agricultural site, El Curro, dating to about 1450 B.C. (3400 YBP) is located near the lake. Current anthropogenic influence on the lagoon is mainly via a small saltpan operation at its eastern edge. However, due to the distance of the operation from the location of the core analyzed in this study and preserved strata near the top of the sediment core, we believe the sedimentary record of the core was not disturbed.

Earlier work on sediments of Laguna Alejandro has recorded evidence of past hurricane and drought events using multiple proxies (Desjardins and Kennedy, unpublished data). Radiocarbon dates show the lake to be older than 1163 ± 85 cal YBP. Low stable isotope values below a layer of organics dated at 1158 ± 85 cal YBP and high stable isotope values above the organic layer indicate a moister period followed by drier conditions, increased lake salinity levels, and dieback of vegetation. A shell layer at 181.5–188 cm depth (1130 ± 40 cal YBP) indicates either an intense hurricane event or increased salinity within the lagoon. Analysis of foraminifera, determined that the lake became separate from the sea at around 1000 YBP. Stable isotope analysis indicated that the salinity levels of the lagoon were increasing during this time period. The core contained hurricane overwash layers at 150.5–152.5 cm dating to 1022 ± 60 cal YBP, 168 cm dating to 1097 ± 73 cal YBP, and at 181 cm dating to 1131±79 cal YBP. A gypsum layer dating to 620 ± 60 cal YBP was evidence of an intense drought in the area.

Field Methods

We collected two overlapping cores, ALEJ 08 5A (132 cm total length) and 5B (42 cm total length) representing a sediment profile from 0–160.5 cm in depth using a Colinvaux-Vohnout piston corer in February 2008. We collected the cores from about 260 cm of water approximately 35 m from the shoreline of the sand barrier (Figure 3.3). The cores were collected in clear PVC tubes, capped, and returned to Virginia Tech, where they were stored at 6 °C.

Laboratory Methods

Objective 1: Reconstruct late-Holocene hurricane landfalls recorded in the lagoon sediments as overwash deposits.

The cores were split at Lamont Doherty Earth Observatory (LDEO) and run through a GEOTEK core logger that spectrally photographed and analyzed the cores for density and magnetic susceptibility. Core sections were described on core logs, noting sediment stratigraphy, texture, and Munsell colors (Figure 3.4). X-radiographs (x-rays) were taken at the Virginia-Maryland Regional College of Veterinary Medicine at Virginia Tech to provide additional insights on stratigraphy not always visible to the eye.

We conducted loss-on-ignition analysis (Dean 1974) at 1 cm intervals throughout the profile to determine the fractions of water, organic matter, and carbonates in each level. We dried weighed samples overnight at 100 °C to determine water content; burned weighed 1 cc samples at 550 °C for two hours, reweighing the samples once they had completely cooled in a dessicator to determine carbon loss; we burned them again at 1000 °C for one hour, and reweighed after cooling to determine the carbonate fraction. Following Liu et al. (2008), we used LOI, along with visual examination, to help document past hurricane overwash events. Liu et al. (2008) found that overwash layers had increased water content, relatively high mineral content, increased carbonate content, and decreased organic matter.

In order to provide chronological control for the profile, and approximate dates for hurricane events, we removed organic materials from four depths in the profile and sent them for Accelerator Mass Spectrometry (AMS) radiocarbon dating through the facilities at Arizona University and University of Georgia (Table 3.2). The organic material we removed for dating consisted of charcoal, leaves, or woody material lying horizontally, and thus appearing to be deposited within the sediment matrix. Calibrated samples age was determined by the online calibration program CALIB v. 6.0 (available as of July 2010) and calibrated by the Intcal09 dataset (Reimer et al. 2009, Stuiver and Reimer 1993).

Following the work of Wahl et al. (2007), we identified deposition of terrigenous material into the lake (i.e. erosion events) based upon simultaneous increases in the magnetic susceptibility and silicates (from loss on ignition) (Figure 3.7).

Objective 2: Document the long-term (decadal to century scale) effects of hurricanes on Laguna Alejandro and the surrounding area through the study of pollen grains in samples above and below the storm deposits.

After identification of hurricane overwash deposits within the sediment core, we conducted high-resolution pollen sampling (1 cc intervals) for sections above and below the storm deposit. We sampled twelve intervals to represent before and after the hurricane events. Examining individual hurricane events and pollen samples allowed us to document immediate and short-term impacts of hurricanes on vegetation composition. Comparing pollen samples related to hurricane deposits at several locations along the core allowed us to document whether disturbance by hurricanes to the area has caused long-term changes to vegetation composition at the study site.

We processed sediment samples to isolate pollen and spores using standard pollen preparation techniques (HF, HCl, KOH, acetolysis, safranin stain; Faegri and Iverson 1989) and added *Lycopodium* spore tablets as controls. Due to the low pollen concentration and the poor preservation of pollen, especially near erosion and/or hurricane events, the minimum pollen sum for each depth was 200 grains. Indeterminate grains were tallied and classified as either damaged (i.e. folded, crumpled, corroded, etc.) or obscured. We then made slides of pollen residue and identified and counted a minimum of 200 pollen grains and spores per slide at 400x magnification using a Leica compound light microscope. Identifications were aided by pollen/spore reference slides, published references (Colinvaux et al. 1999, Roubik and Moreno 1991, Hooghiemstra, 1984), and online pollen databases with photographs and descriptions (Davis 2001). Pollen/spore data were graphed and analyzed using the specialized pollen plotting software TILIA v. 1.49, available upon request from Eric C. Grimm (grimm@museum.state.il.us). Pollen/spore/charcoal data were compared with core stratigraphy and other proxy data such as from loss-on-ignition, density, and magnetic susceptibility.

Objective 3: Examine the relationship between fires and hurricane events through the analysis of microscopic and macroscopic charcoal in the sediment cores.

Thirty depth levels (Table 3.3) were analyzed for microscopic (pollen slide charcoal) and macroscopic charcoal; identified as black, opaque, angular fragments, classified by size (10–25 μm and >25 μm) in the longest dimension, and counted on slides along with pollen and spores. We compared abundance of microscopic charcoal in the pre- and post-hurricane samples to determine whether fires increased after hurricanes and, if so, for how long. We also analyzed macroscopic samples: 2 ml samples of sediment were wet-sieved, using 125 μm screens, from the same depths analyzed for microscopic charcoal and pollen in order to determine the presence or absence of macroscopic charcoal. Microscopic charcoal abundance was graphed with the pollen results in Tilia while the presence/absence of macroscopic charcoal was noted with an asterisk (Figure 3.9).

Objective 4: Reconstruct the paleoenvironmental history of the study site and surrounding area through the analysis of pollen archived in lake sediments.

In addition to the high-resolution samples analyzed to study vegetation composition before and after hurricanes, we processed pollen/spores/microcharcoal from 18 well-distributed depth intervals throughout the profile with sample locations focused on stratigraphic changes. These samples provided insights on past vegetation and environmental change throughout the time period represented by the profile.

In total, 30 samples from 28 depths were processed for pollen. Slides from all depths were initially scanned for pollen concentration and preservation. Due to low concentrations of identifiable pollen we limited our pollen analyses to depths with higher pollen concentrations, better preservation, and proximity to stratigraphic changes, possible hurricane deposited sediments (Table 3.1.), and samples removed for radiocarbon dating (Table 3.2).

Pollen taxa of cosmopolitan families (such as Solanaceae) and those pollen taxa comprising less than 3% of samples (except rare types of known ecological importance) from individual depths were excluded from the Tilia pollen diagrams to aid interpretation. In Tilia, pollen types (excluding spores and indeterminates) were organized into five groups: 1.Upland/montane trees/shrubs/lianas, 2. Mid-elevation trees/shrubs/lianas, 3. Lowland trees/shrubs/lianas, 4. Coastal, 5. Grasses and herbs based upon Bolay (1997), Gentry (1993), Watson and Dallwitz (1992).

3.3 RESULTS

Radiocarbon Dates

Four AMS radiocarbon dates provided chronological control of the sediment profile (Table 3.2). The basal sediments dated to ~1030 ^{14}C YBP (through interpolation).

Loss on Ignition

In general, water and organic percentages were high and relatively stable from 160–46 cm except for decreases in both water and organic fractions at 146 and 58 cm (Figure 3.5).

Signals become highly variable above 46 cm. From 46 to the top of the core, water and organic content share similar patterns of peaks and troughs with synchronous peaks at 46, 41, 33, 25, and 22 cm. Water and organic content are consistently lower in depths above 46 cm than in the lower core (160–43 cm). Overall, the water and organic component of the sediment decreases upcore, with water content decreasing from a maximum of ~74% to a minimum of ~35% and the organic content from ~33% (maximum) to ~6% (minimum).

In contrast to the pattern of water and organic composition, carbonate content remains high in the core from 160–79 cm, comprising ~50% of the sediment. From 79–0 cm, carbonate content generally decreased to range from ~40–6%. Several spikes in carbonate content appear between 46 and 22 cm, as with the water and organic curves. The variability of the carbonate signal in relation to the water and organic content of the lake is also notable. The carbonate curve consists of a series of alternating peaks and troughs that contrast with the much smoother water and organic content curves.

The silicate component presents a pattern that is the inverse of the carbonate content. The silicate content remains relatively low and variable from 160–79 cm, where it constitutes approximately 42% of the sediment. From 79–0 cm, the silicate content increases to its maximum values at the top of the core at 90%.

GEOTEK Core Logger

Magnetic Susceptibility

We obtained 1 cm resolution data on magnetic susceptibility (Figure 3.7) from a Geotek Core Logger (SI units) at Lamont Doherty Earth Observatory. The magnetic susceptibility curve from L. Alejandro sediment profile is reminiscent of the carbonate/silicate curves (Figure3.5) in that the bottom of the core (160–135 cm) show relatively little change in magnetic susceptibility values with increasing variability towards the top of the core (90–0 cm) with peaks occurring at depths of 88, 76, 54, 37, 33, 20, 13, 8, and 1 cm. Several of the peaks in the magnetic susceptibility values correspond to peaks in silicate fractions (Figure 3.7) determined by LOI. A series of four peaks in the magnetic susceptibility values at 20, 13, 8, and 1 cm correlate to the high silicate values that occur from approximately 20 to 0 cm. In addition, a series of peaks in both the magnetic susceptibility and silicate values occurs between 45 and 30 cm (Figure 3.7).

Density

The signal from the Geotek Core Logger, 1 cm resolution data on density (Figure 3.5) shows increasing density from 160 to 0 cm, with steadily increasing density from 125–54 cm. Two areas of interest in the density signal occur at the bottom and top of the sediment core. From 160–125 cm, the density is slighter higher and more varied than the middle section (125–54 cm) of the core, with peaks in density at 147 and 138 cm. Also, at the top of the core, from 54–0 cm, the data show the density of the sediment to continue increasing although the signal is again more variable than the middle section of the core, with peaks in density at 39 and 9 cm and a trough at a depth of 12 cm.

The higher density of the top of the sediment core corresponds to patterns seen in the magnetic susceptibility and loss on ignition data with the higher density values at the top of the core (54–0 cm) matching with a series of peaks in the magnetic susceptibility values, high silicate fractions and low carbonate and organic components from loss on ignition.

X-radiography

X-radiographs of ALEJ08-5 were digitally merged using Adobe Illustrator to create a single image. The x-rays showed layers of higher-density sediment at 24, 33, and 109 cm that were not detected by visual inspection of the cores (Figure 3.6). Magnetic susceptibility and/or loss-on-ignition analyses confirmed these higher-density layers.

Identification of Hurricane Deposits

Liu et al. (2008) were able to identify hurricane overwash layers through loss on ignition as layers with relatively high mineral content, relatively high carbonate content along with increases in water content and decreases in organic matter. Sediments from Little Lake in the southeastern United States (Liu et al. 2008), had much higher organic content (up to ~60%) and lower carbonate component (<10%) compared with sediments of Laguna Alejandro, where carbonate content ranges from ~6–50%. Thus we identified potential hurricane-deposited sediments through simultaneous increases in the water and carbonate content of sediments and matching increases or decreases in organic content, along with other data sources.

Higher-density layers revealed in the x-radiographs, peaks in magnetic susceptibility and density, and visual inspection of the cores and digital photographs to examine color and grain-size, were combined with loss on ignition to identify hurricane overwash layers in L. Alejandro. We defined hurricane deposits as consisting of discrete layers of inorganic (sand, shells, etc) materials that possessed distinctive color (usually lighter), higher sand content, and/or higher density than over- and under-lying sediments.

From these multiple proxies, at least three overwash deposits, and thus hurricane events, were identified between 25 and 43 cm. This section of the core represents the most active time period in terms of hurricane activity. Loss on ignition (Figure 3.5) reveals several probable storm events by simultaneous and discrete increases in water, carbonate, and organic content of the sediment at 25, 33, and 41 cm. These events are also recorded in the x-rays (Figure 3.6) and

GEOTEK corelogger density data (Figure 3.5) as discrete bands of higher density material than the over and under lying sediment. Other hurricane deposits are found at 85 cm and 142–150 cm, where loss on ignition reveals simultaneous increases in the organic and carbonate content of the sediment (142–150 cm), and simultaneous increases in the water, organic, and carbonate content of the sediment at 85 cm. Visual inspection of the core also found thin layers of shells and organics at 85 cm though evidence from the other proxy sources in this study are missing; changes in the density at these layers are subtle as revealed by the Geotek core logger and x-radiographs of these core sections. However, it is important to note that the high carbonate component of the sediment from 79–160 cm would obscure the hurricane signal in the carbonate loss on ignition results. In addition, the density and x-rays do not reveal any more discrete deposits in the sediment after 43 cm though the event at 142–150 cm is indicated by a thin layer of shells at 149 cm and a sharp contact at 142 cm, with the sediment changing from high organics (peat) to more inorganic.

Identification of Erosion Events

We identified erosion events at 37, 33, 20, 13, and 8 cm. Several hurricane and erosion events occur in the same areas of the core, especially between 25 and 43 cm, where loss on ignition, magnetic susceptibility, and x-ray evidence indicates alternating hurricane and erosion events.

Pollen

Pollen was sparse in the L. Alejandro sediments across all depths processed and scanned (8930–80800 grains/cc) for pollen concentration (Figure 3.8). Preservation of pollen varied by depth with indeterminate pollen grains accounting for 18–38% of samples. Most of the indeterminate grains were obscured by clays in the samples. Pollen samples contained high levels of clay (mineral grains of similar size to pollen, so not sieved out during the process) that led to the problem of large, dense, and dark colored "clumps" of material covering pollen grains and making identification impossible in some cases.

We identified pollen from 32 families, with dominant taxa including the Urticales order and the families within (particularly Urticaceae (nettles), Fabaceae (subfamily Mimosoideae) (legumes), and Cyperaceae (sedges). Less commonly found pollen taxa include *Pinus* (pine), Poaceae (grass), Araceae (herbaceous climbers), Melastomataceae, Piperaceae, *Celtis, Bursera*, and Arecaceae (palms) (Figure 3.9). Most pollen grains were from lowland dry (Mimosoideae) and mid-elevation (Urticales) forest taxa and sedges. Pollen of the Urticales order had the most stable presence throughout the sampled depths, accounting for 15.3– 51.2% percent of the pollen sums for each depth. While also present for all counted levels, Mimosoideae varied considerably, accounting for as little as 4.5% up to 50.2% of the pollen counted. More rare upland and montane wet forest taxa (e.g. Melastomataceae, *Weinmannia*) and pine were present and more abundant in the middle of the core (118–83 cm). Of the rare upland and montane taxa, Melastomataceae and pine were the most abundant and accounted for 3.4 and 8.7% of the pollen sum, respectively.

Lowland and coastal taxa, and grasses and herbs were more abundant at the bottom and top of the core. Pollen of *Bursera* (insect-pollinated deciduous tree common in tropical dry or seasonal forest), *Celtis* (one species is a common tropical dry forest tree), Poaceae (grasses), Piperaceae (small trees/shrubs/herbs), Arecaceae (terrestrial or swamp herbs), *Cecropia* (a pioneer tree species occurring in moist forests) all exhibit a similar bimodal distribution in the core; with greater abundances in the bottom and top of the core and very low to no presence in the middle of the core.

Microscopic and Macroscopic Charcoal

Microscopic charcoal fragments (>10 µm in the longest dimension) were present in all thirty levels examined and are presented as fragments/cc (Figure 3.9). Charcoal abundance was variable but sparse in most levels with a greater abundance at the bottom (159–127 cm, except at levels 151 and 147 cm) and the top of the core (38–16 cm).

While not tallied, several slides contained charcoal fragments with a least one dimension measuring over 125 µm, a size class often attributed to local fires as large charcoal does not travel far from its source (Whitlock and Larson 2001). Therefore, while overall concentration of charcoal was low this does not exclude the importance of prehistoric fires at our study site, further evidenced by the presence of macroscopic charcoal (Table 3.3) in 6 (67.5, 83, 112, 118, 127, and 136 cm) of the 30 levels examined. The presence of macroscopic charcoal indicates local fires occurred in the older, more organic section of the core.

3.4 DISCUSSION

Emerging from this multi-proxy study is a story of repeated disturbance to the tropical dry forests around Laguna Alejandro by hurricanes, erosion events, and fire over the last millennium. The oldest hurricane recorded by our Laguna Alejandro core occurs ~ 996 ^{14}C YBP (149 cm). The hurricane deposit is represented by a thin layer of freshwater-type (Dr. Michael Burn, personal communication) gastropod shells (149 cm), occurring within a thick layer of mangrove peat (peat dominating older, more organic section of core to 142 cm). The discrete layer of shells could indicate a sudden die-off due to saltwater intrusion into the lagoon from the storm. There is a sharp contact above this peat layer, indicating a die-off of mangroves near the barrier at L. Alejandro (possibly suddenly) after the hurricane. This peat layer represents the only peat in this sediment profile from L. Alejandro, and thus the permanent disappearance of mangroves from this particular area of the lake. Discrete deposits of mangrove peat overtopped by more mineral layers are found in other sediment cores from L. Alejandro obtained further inland (unpublished data). The mangrove die-off may be due to changes to the lagoon from regional climate shifts or hurricane disturbance. Smith III et al. (2009) found that intense hurricanes can cause die offs to mangroves and change ecosystems types entirely, such as from mangrove forest to mudflat. In sediments deposited after the hurricane (147 cm) Urticales dominates the record and Fabaceae percentages are lower, suggesting damage to the dry tropical forests surrounding the lagoon. This same hurricane was also possibly recorded by Desjardins (2007) study of a sediment core from L. Alejandro; he noted an overwash deposit characterized by fine sand in a matrix of more organic sediments ~1022 ± 60 cal YBP (152–150 cm).

After the hurricane event ~ 996 ^{14}C YBP, local and regional fire events in tropical dry forests at lower elevations or pines in the nearby mountains increased for a period of several decades (Figure 3.9) as evidenced by an increase in microscopic charcoal ~1003–959 ^{14}C YBP (151–137 cm) and the presence of macroscopic charcoal at ~990 cal YBP (147 cm). This increase in fire events post-hurricane is in agreement with Urquhart's (2009) and Liu et al.'s (2008) study, in which increased microscopic charcoal fragments were interpreted as increased post-hurricane fire events in swamp forests of Nicaragua and coastal forests of the southeastern United States, respectively. The increased microscopic charcoal and presence of macroscopic charcoal following the hurricane event could be due to increased fire events as the result of increased fuel availability or secondary transport of charcoal due to precipitation associated with the hurricane. Alternatively, increased fuel availability could be due to changes in regional climate; more moist conditions could increase fuel availability and lightning ignited fires. In a paleoecological study at nearby Lake Miragoane, Haiti by Higuera-Gundy et al. (1999), researchers found that "natural" fires remained low until ~5945 ^{14}C yr BP when moist conditions allowed the accumulation of fuels.

Moister conditions may also explain the increase in more rare upland vegetation types. Upland pollen types (e.g., Ericaceae, *Weinmannia*, etc.) were only present in the core for a period of ~480 years (~996–510 ± 30 ^{14}C YBP). Alternatively, increases in upland pollen types post-hurricane may be due to the destruction and mortality of dry tropical forest vegetation at lower elevations. The pollen from the dry forest taxa may not have been incorporated into the lake sediments or too damaged to identify once incorporated.

The pollen concentration (for all taxa combined) after the hurricane at ~996 ^{14}C YBP to ~742 ^{14}C YBP (107.5 cm) remains low to moderate (250–1000 grains/cc sediment) though organic content is highest (~33%) in that section. The moderate pollen concentration during a more organic period may be in part explained by hurricane destruction and die-off of vegetation and thus lower pollen production.

After the hurricane at ~996 ^{14}C YBP, there is no evidence in the sediment profile of storm or erosion events until ~ 321 ^{14}C YBP (~43 cm). It is important to note, however, that a single core would not record all the storms that have affected this lake. Following the storm event ~996 ^{14}C YBP the period of increased regional fire continues for approximately a century, becoming increasingly rare ~842 ^{14}C YBP (118 cm) though local fires occurred ~927–434 ^{14}C

YBP as indicated by macroscopic charcoal at 127, 118, 112.5, 83, and 67.5 cm. Presence of macroscopic charcoal and freshwater-type gastropods during a more organic period of the site's history (as indicated by loss on ignition) all indicate a more moist environment. A paleoecological study from mid-elevation lagoons in the Dominican Republic found increasing aridity in the region after ~1520 cal YBP though the period from ~700–350 cal YBP was relatively wet (Lane et al. 2009).

From ~927–434 ^{14}C YBP, the vegetation surrounding the lagoon is dominated by woody vegetation, particularly legumes and Urticales. Pollen of the upland and montane tree, shrub, and liana taxa, though generally rare throughout the sedimentary record, also reach their highest abundances in the middle of the core, particularly ~842– ~790 ^{14}C YBP (118 and 112.5 cm). Melastomataceae, a cloud-forest vegetation type, in particular exhibits this pattern. *Weinmannia*, another cloud forest taxon, is only found at 118 and 112.5 cm. Moister conditions that allow the expansion of wet forest types during dry forest recover and the accumulation of fuels may explain the dominance of Urticales and legumes, increases in rare forest pollen types, and local fires. Regional fire events are rare for this time period but local fires occurred as evidenced by the presence of macropscopic charcoal; indicating local fires are out of sync with regional fire events. Increased pollen concentrations (Figure 3.8), which reach their highest levels during this time period, may also be evidence of post-hurricane vegetation recovery and wet forest expansion.

At ~529 ^{14}C YBP (85 cm) there is an increase in carbonates, organics, and water content of the core, indicating a possible storm event though no storm deposit is evident in the x-rays or digital photographs of the core. However, a hurricane event could help explain the decline in legumes, increase in pines, and the occurrence of local fires occurring after hurricane at ~510 ± 30. Alternatively, local fires may be tied to moister climate conditions and not the hurricane event as the presence of freshwater-type gastropods and high organic LOI results indicate overall more moist conditions at the study site. As previously discussed, the high carbonate content of the core during this time could obscure a pulse of carbonates into the lagoon from a storm event. After approximately 85 cm, the carbonate content of the sediment begins a steady decline to 43 cm ~ 321 ^{14}C YBP, while silicates begin a steady increase and organics decline slightly. Regional fire remain relatively rare from ~586 to ~327 ^{14}C YBP (91–44 cm), except for the moderate increase ~411 ^{14}C YBP (72.5 cm).

Poor pollen preservation from 510 ± 30 to 336 ± 50 YBP (83–46 cm) makes reconstruction of vegetation changes during this time period impossible. This portion of the core also appeared disturbed and was thus not a priority for pollen analysis. In addition, x-rays and loss-on-ignition organic results do not reveal changes in stratigraphy or organic content. The decreasing carbonate content evident from the loss on ignition could indicate the increasing autonomy Laguna Alejandro from the Caribbean Sea or simply result from the lack of hurricane deposited carbonates and the greater influence of terrigenous inputs (silicates) into the lagoon. Desjardins's (2007) results indicated that Laguna Alejandro was becoming autonomous from the Caribbean Sea ~1097 ± 73–1131 ± 79 cal YPB. The core analyzed in this study was from a location closer to the coastal barrier separating the lagoon from the Caribbean Sea than the 2007 study and thus may be more greatly influenced by coastal barrier morphology.

Of particular interest are the past ~321 ^{14}C YBP years at Laguna Alejandro, during which the study site has experienced several hurricane and erosion events as evidenced by a complex stratigraphy between 43–0 cm. Magnetic susceptibility results in particular indicate the high number of erosion events occurring in the Sierra Martin Garcia during this time period.

Magnetic susceptibility (MS) of lake sediments has been used in limnological applications since 1975, when Thompson et al. noted that changes in MS values were positively correlated with changes in the amount of inwashed inorganic allocthonous material present in sediment cores. Essentially, increases in MS values are due to increases in mineral yield from the catchment to the lake (Oldfield et al. 1983). Magnetic susceptibility of lake sediments has relatively recently transitioned into the toolkit of paleoecologists and paleoclimatologists as several studies have noted that shifts in sediment core stratigraphy based on MS values are coincident with pollen assemblage zones; thus changes in MS values at a study site may indicate not only terrigenous inputs to the lake but changes in climate (Wahl et al., 1997, Yu et al., 1990). Therefore, the erosion events may due to disturbance events or regional shifts in climate. The erosion deposits may be tied to hurricane events, with hurricanes possibly damaging vegetation and leading to forest canopy gaps, and the exposed soil either eroding into Laguna Alejandro or precipitation from the storm events leading to landslides consisting of the exposed soil and downed vegetation. At the same time multiple hurricane events are recorded for the study site, the climate of the Caribbean was becoming increasingly arid as noted by mid-elevation sites in the Dominican Republic, particularly after ~350 cal YBP (Lane et al. 2009). Desjardins and Kennedy (unpublished data) found evidence of an intense drought at ~620 ± 60 cal YBP as evidenced by a 2.5 cm gypsum layer (identified by x-ray diffraction (XRD). We did not find any substantial gypsum layers in this core, but other sediment cores from L. Alejandro do contain gypsum (unpublished data).

The hurricane and erosion events occurring from 43–0 cm also coincide with changes in other macro- and micro-fossil evidence. During the period of increasing aridity and multiple disturbance events ~321 ^{14}C YBP to present day, no freshwater-type gastropods are found, the organic content of the core is variable though low, and local fires did not occur as indicated by the absence of macroscopic charcoal after ~434 ^{14}C YBP (67.5 cm). Pollen concentrations for this section of the core are low and lowland dry forest Fabaceae and upland Melastomataceae decrease during this time period, Urticales remains steady, and Cyperaceae (sedges) and *Pinus* increase. Fabaceae (*Acacia*) currently dominates the dry tropical forest at lower elevations of the study site and would like be directly impacted by both onshore winds from hurricane events and associated precipitation events that produced landslides. Pine is generally limited to the tops of the nearby mountains as they cannot compete with evergreen and broadleaf vegetation found at lower elevations with more favorable soil conditions (Bolay 1997).

On large-scale vegetation maps, pines are not located at L. Alejandro but pure stands occur in the Cordillera Central to the east and Sierra de Baoruco to the west of the study site (The Nature Conservancy). A single or series of hurricane events followed by erosion events could explain the decrease in lowland and upland taxa through direct vegetation destruction. With hurricane and landslides increasing fuel availability, fires would increase and pines might expand at the expense of more fire sensitive wet forest species. Alternatively, extended drought could cause wet forest mortality; thus increasing fuel availability and lightning ignited fire events. In this alternative scenario, the increase in pines is again explained as pines would outcompete more fire sensitive wet forest types.

Decreases to dry forest taxa and erosion events may also be due to anthropogenic forest clearance and subsequent soil erosion. There is no evidence of prehistoric anthropogenic activity at the study site from published cultural sites or microfossils in the sediment core, such as the presence of pollen from cultivated taxa such as *Zea mays* (corn). Though microscopic charcoal abundances increased from ~321 ^{14}C YBP to modern day, Kjellmark (1996), in dry shrublands in the Bahamas, found charcoal abundances to increase abruptly and dramatically (i.e., ~5000–~50000 fragments) post-human arrival. From ~321 ^{14}C YBP to modern day at L. Alejandro, the increased microscopic charcoal abundance does not reach previous amounts recorded in the more organic bottom section of the core. Also, no macroscopic charcoal was found in the top of the sediment core, indicating the absence of local fires.

3.5 CONCLUSION

This research documents repeated disturbance events and regional climate change around Laguna Alejandro over the last ~1000 years. We identified five hurricanes corresponding to interpolated dates of ~996, 529, 313, 276, and 237 ^{14}C YBP in a recent time period, ~ 321 ^{14}C YBP to modern day (sediment interval 43–0 cm). We also identified several erosion events from 37–0 cm representing ~294 ^{14}C YBP to present, likely associated with heavy precipitation events (tropical storms) or hurricanes not recorded as overwash deposits in the sedimentary record. Increasing aridity of the Caribbean during this time period (Lane et al. 2009) could have caused reduced vegetation cover, making slopes around L. Alejandro even more susceptible to erosion and landslides. Microscopic charcoal is present in all depths examined (30 intervals) and indicated the occurrence of regional or extralocal fires during the last 1000 years. Following the ~996, 313, and 237 ^{14}C YBP hurricane events, the abundance of microscopic charcoal fragments increased, especially after the storm around ~996 ^{14}C YBP (deposit from 150–142.5 cm); the same hurricane probably recognized in another core from L. Alejandro by Desjardins (2007).

Following the event at ~996 ^{14}C YBP 150–142.5 cm event, legumes, an important tree in dry tropical forests, decline but recover with time. Between 927 ± 45 ^{14}C YBP and 510 ± 30 ^{14}C YBP, lowland, mid-elevation, and upland forests recover and expand, and the climate is more moist as evidenced by wet-and cloud-forest taxa expansion in the pollen record, high organic content from loss on ignition, and freshwater-type gastropods. The presence of macroscopic charcoal during this time of wet forest expansion indicates local fire events, perhaps due to increased availability of fuel. The sedimentary record revealed a possible hurricane event at 85 cm ~529 ^{14}C YBP that could explain the decline in legumes at this depth though no overwash deposit was revealed in the x-radiographs. From ~510 ± 30 ^{14}C YBP to present, the organic and carbonate content of the sediment core declined while the silicate content increases. This trend indicated the increased autonomy of L. Alejandro from the sea and increased influence from inland sediment sources such as the nearby Sierra Martin Garcia, while also reflecting the lack of carbonate pulses to the lagoon from hurricane overwash events. After ~510 ± 30 ^{14}C YBP, the more rare wet forest types are absent from the core. The hurricane events found at the top of the core between ~313 ^{14}C YBP–237 ^{14}C YBP (41 and 25 cm) are followed by declines in legumes and increases in microscopic charcoal fragments, similar to the ~996 ^{14}C YBP.

This multi-proxy analysis of a sediment profile from Laguna Alejandro suggests that the dry tropical forests in the L. Alejandro pollen source area have not experienced major or permanent changes associated with hurricanes or fires over the past millennium as the pollen record has been continuously dominated by Urticales, Fabaceae-Mimosoideae, and Cyperaceae for the depths examined. While pollen spectra representing periods before and after disturbance events were similar and may support the idea of forest resilience, manyt more samples are needed before generalizations can be made. Conversely, it appears that *Rhizophora* mangroves near the core site were destroyed by a hurricane and never recovered. Mangroves are often thought to be resilient to hurricane damage, but especially intense events may result in state changes in these seaside plant communities.

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Chapter 3 Figures

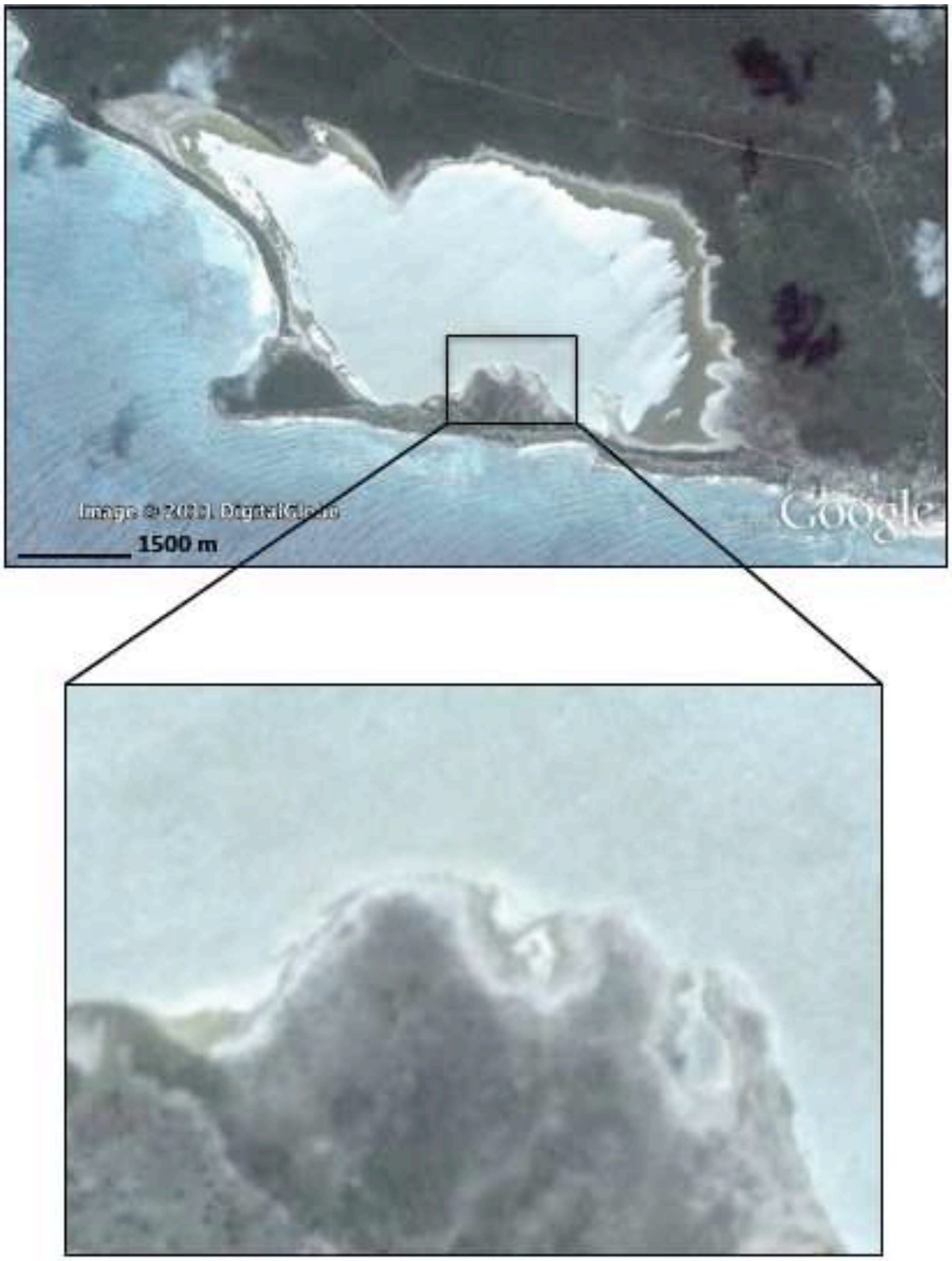

Figure 3.1. Hurricane-generated sand overwash fan (inset) on shoreline and in Isla Saona, DR visible in a July 2003 satellite image (Google Earth). Overwash fans from recent (historical) hurricanes validate prehistoric storm deposits in the geological record.

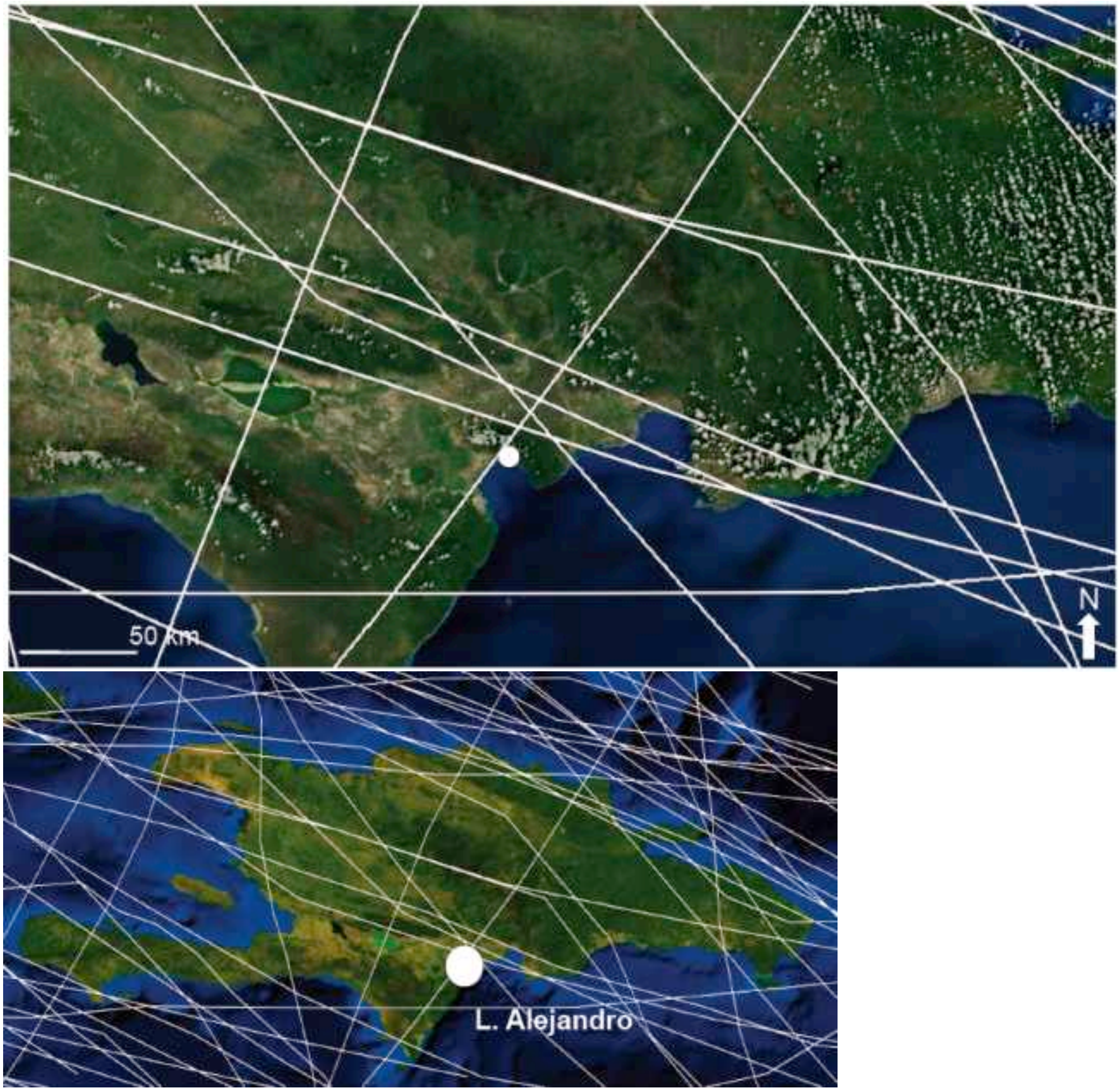

Figure 3.2. Intense (category 3, 4, or 5) historical (1851–2008) hurricane tracks for Laguna Alejandro (upper map; lake indicated by filled circle) and Hispaniola (lower map). Constructed using the International Best Track Archive for Climate Stewardship (IBTrACS); data by Knapp et al. 2010.

Figure 3.3. Location of sediment core ALEJ08 used in this study within Laguna Alejandro and in relation to Sierra Martin Garcia, a source of sediment to the study site.

Depth (cm)	Munsell color
0–4	2.5 Y 5/3
4–14	2.5 Y 5/3 grades to 2.5 Y 7/1
14–17.5	2.5 Y 6/3
17.5–24	7.5 Y 6/6, contact at 17.5 (10 YR 3/4)
24–27	2.5 Y 8/2, laminae 2.5 Y 3/1 to 2.5 Y 3/3
27–32	2.5 Y 8/2, vaguely laminated
	10 YR 3/4
34–38.5	2.5 Y 6/3, organics
38.5–44	5 YR 6/4
44–47	7.5 YR 5/3, organics
47–58	7.5 YR 5/3 to 7.5 YR 8/3, organics
58–72	10 YR 2/1 to 10 YR 4/3 to 10 YR 8/4, organics
72–94	10 YR 2/1 to 10 YR 4/2, organics and gastropods
	2.5 YR 4/3
95–100	2.5 YR 4/3, gastropods
	10 YR 5/3, gastropods
102–110	10 YR 3/1, organics and gastropods
110–116	5 YR 6/4 to 5 YR 5/3, organics and gastropods
116–123	10 YR 4/2, thin lines of organics
123–129	10 YR 6/2 to 10 YR 5/2, organics and gastropods
129–132	7.5 YR 3/2
129–133.5	10 YR 5/2, organics and gastropods
133.5–137.5	10 YR 4/2 to 10 YR 6/3, organics
137.5–142	7.5 YR 3/2, gastropods
	10 YR 6/3
142–149	10 YR 2/2, organics and gastropods
149–154.5	10 YR 4/2, organics
154.5–160.5	10 YR 6/3 to 10 YR 4/3, organics
	10 YR 3/1

Figure 3.4. Sediment stratigraphy of the ALEJ08 core (0–160.5 cm). Left column is a photo of the core; right column indicates description. Blue section indicates missing photo. White space between core photos indicates the change from ALEJ08-A section (0–132 cm) to ALEJ08-B (129–160.5 cm).

Table 3.1. Sediment depths analyzed for pollen. Gray bars indicate intervals of hurricane-deposited sediment.

Core	Depth (cm)
5A	25.0—26.0
5A	33.0—34.0
5A	34.5
5A	41.0—42.0
5A	46.0
5A	83.0
5A	85.0—86.0
5A	91.0
5A	107.5
5A	112.5
5A	118.0
5B	130.75
5B	133.0
5B	147.0
5B	149.0—150.0
5B	150.75

Table 3.2. Accelerator Mass Spectrometry (AMS) radiocarbon dating results. Samples with an X lab number were dated by the NSF Arizona AMS Facility; one sample was dated by the University of Georgia Center for Applied Isotope Studies. Dates were calibrated using the CALIB 6.0 calibration program (Stuiver and Reimer, 1993) and the datasets of Reimer et al. (2009). Errors estimate 68% (1-sigma) and 95% (2-sigma) probability.

Lab no.	Depth (cm)	Sample Type	14C Yr BP	Cal Yr BP 1 sigma	Cal Yr AD 1 sigma	Cal Yr BP 2 sigma	Cal Yr AD 2 sigma
X15115A	46.0-46.5	Leaf fragments	336± 50	407-346	1543-1604	496-304	1454-1646
ALEJ08D	83.0-83.5	Piece of charcoal	510±30	540-515	1410-1435	555-505	1395-1445
X15116	127.0-127.5	Leaf fragments	927±45	909-841	1041-1109	927-757	1023-1193
X15117A	158.5-159.0	Woody/ fibrous materials, leaves, bark (?)	1027±55	986-906	964-1044	1058-892	892-1058

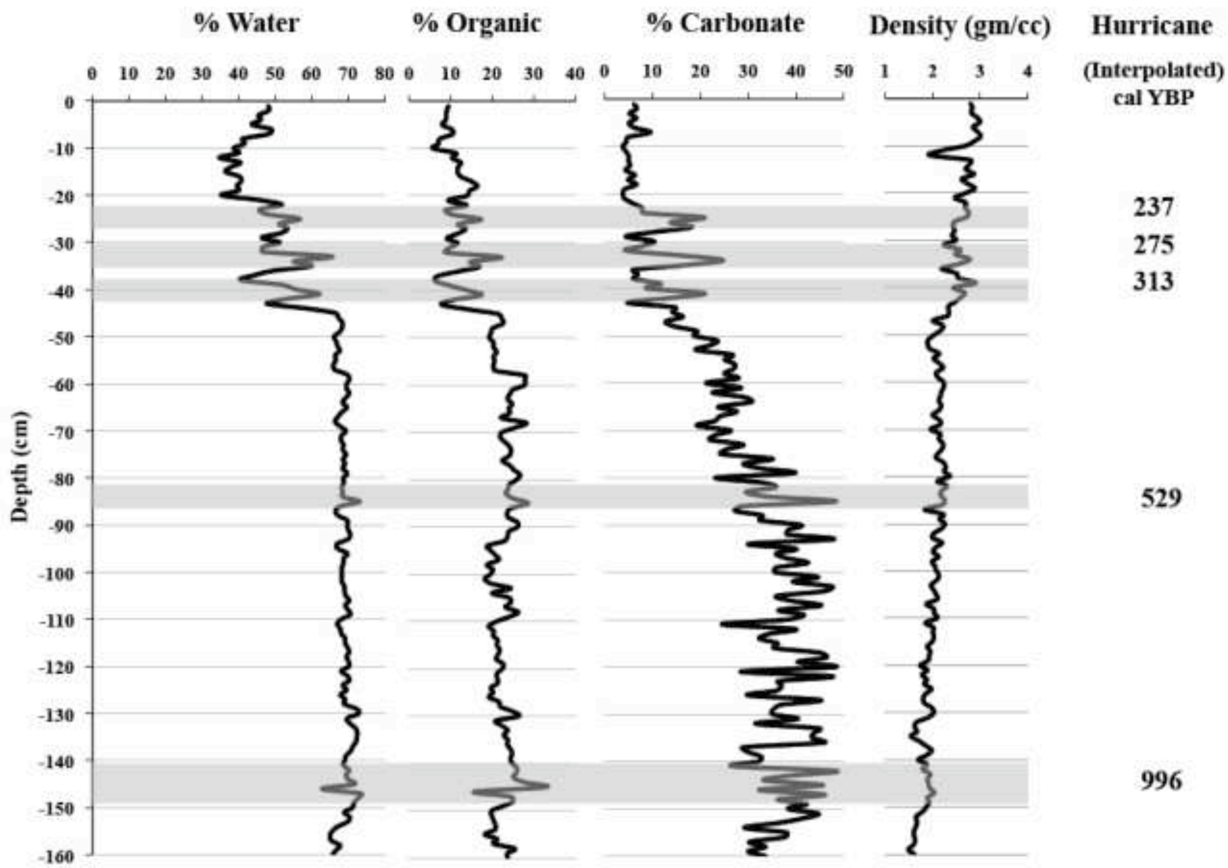

Figure 3.5. Loss-on-ignition (silicates shown in figure 3.7.) and density results (1 cm resolution) for ALEJ08 5A and 5B 0–160.5 cm. Hurricane deposits (gray bars) are indicated by layers with relatively low organic values along with simultaneous increases in carbonate and water content.

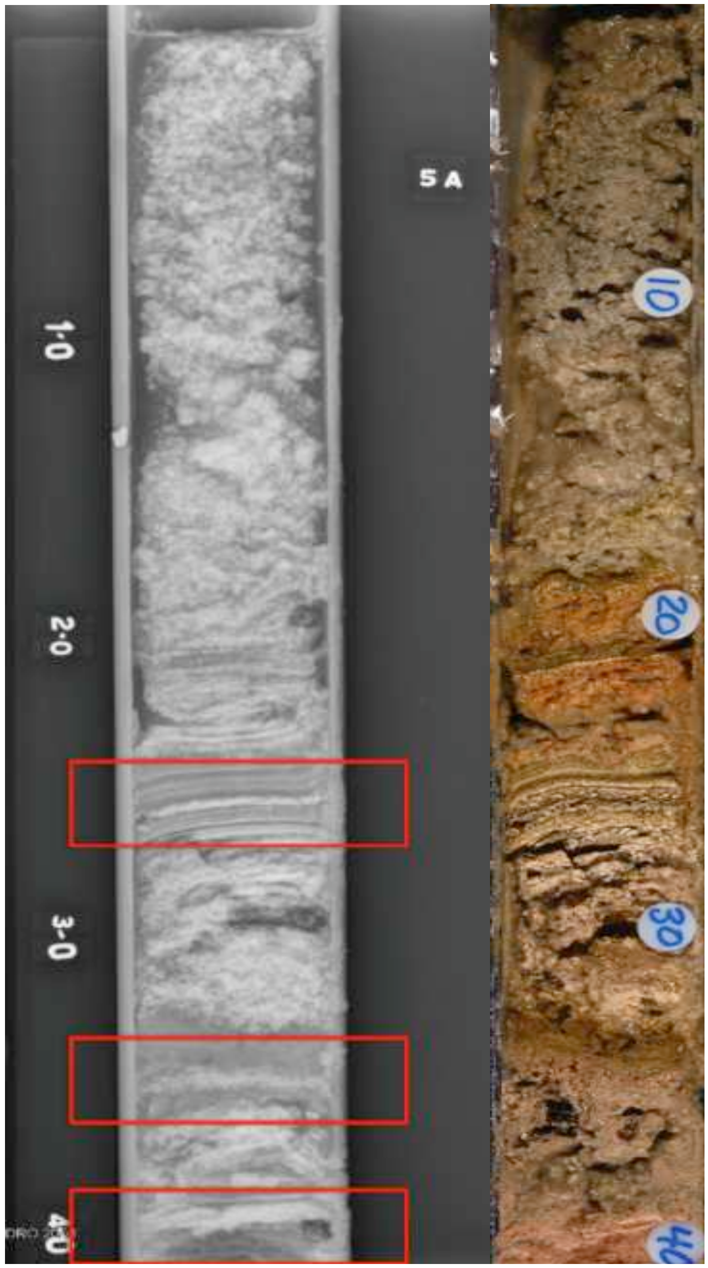

Figure 3.6. X-radiograph and digital photograph of 5A 0.0-40.0 cm with more dense sediments indicated by red boxes (x-ray only). Identification of discrete layers of more dense sediments between less dense sediments is used in conjunction with loss on ignition results to identify hurricane and erosion events.

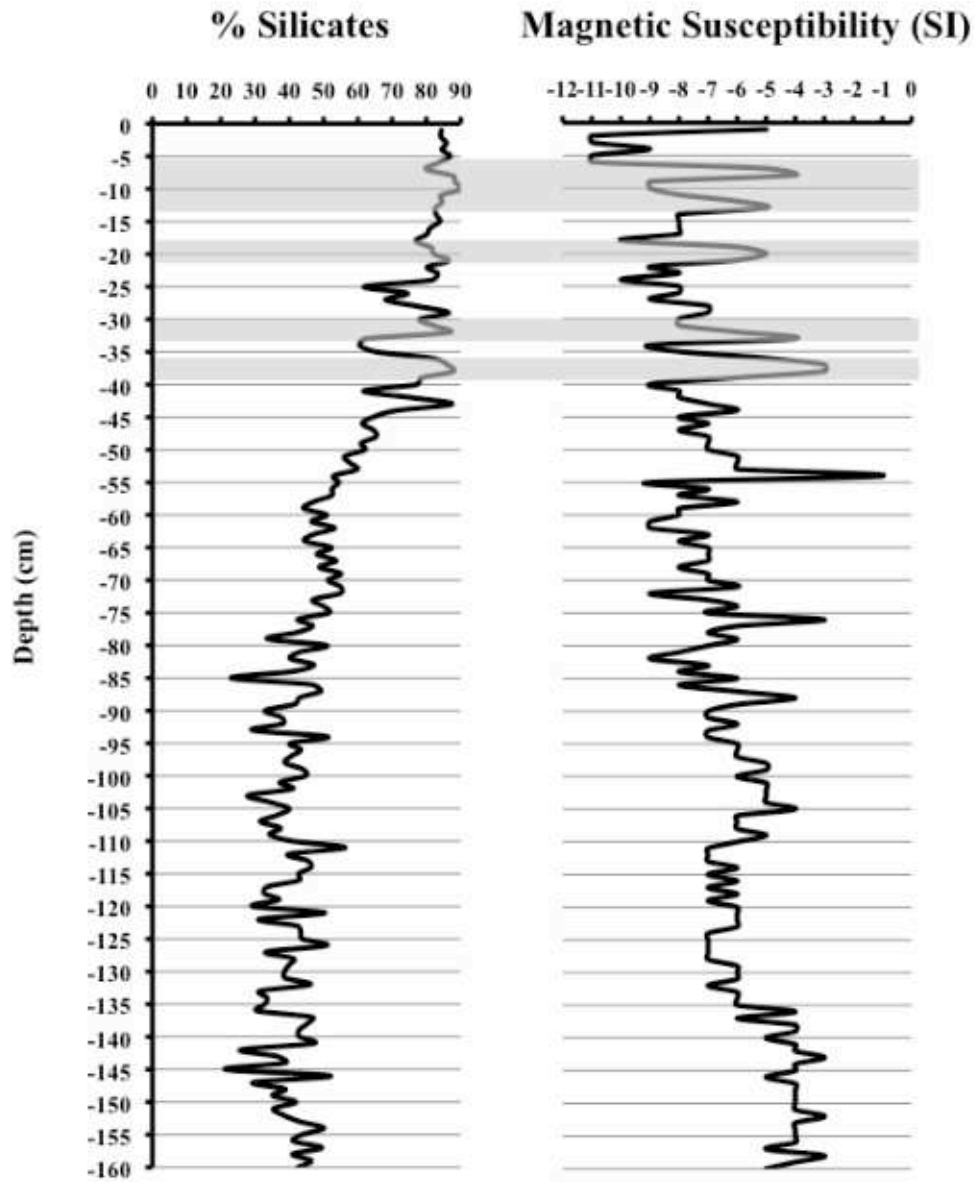

Figure 3.7. Identification of erosion events (gray bars) from loss on ignition silicate component (% Silicates) and magnetic susceptibility (MS). Based upon Wahl et al. (2007), we interpreted the deposition of terrigenous material into the lake (i.e. erosion events) upon simultaneous increases in the magnetic susceptibility and silicates.

Table 3.3. Sediment samples analyzed for microscopic pollen slide charcoal (>10 µm) and macroscopic charcoal (>125 µm; wet sieved). All depth levels contained microscopic charcoal while macroscopic charcoal was present in six levels (highlighted in gray)

Sample #	Core	Depth (cm)
1	5A	16.50
2	5A	19.00
3	5A	22.00
4	5A	31.50
5	5A	34.50
6	5A	38.00
7	5A	44.00
8	5A	46.00
9	5A	65.50
10	5A	67.50
11	5A	72.50
12	5A	83.00 (0.63 cc)
13	5A	83.00
14	5A	91.00
15	5A	94.50
16	5A	101.75
17	5A	107.50
18	5A	112.50
19	5A	118.00
20	5A	124.00
21	5A	127.00
22	5B	127.00
23	5B	130.75
24	5B	133.00
25	5B	137.00
26	5B	141.00
27	5B	147.00
28	5B	150.75
29	5B	154.50
30	5B	159.00

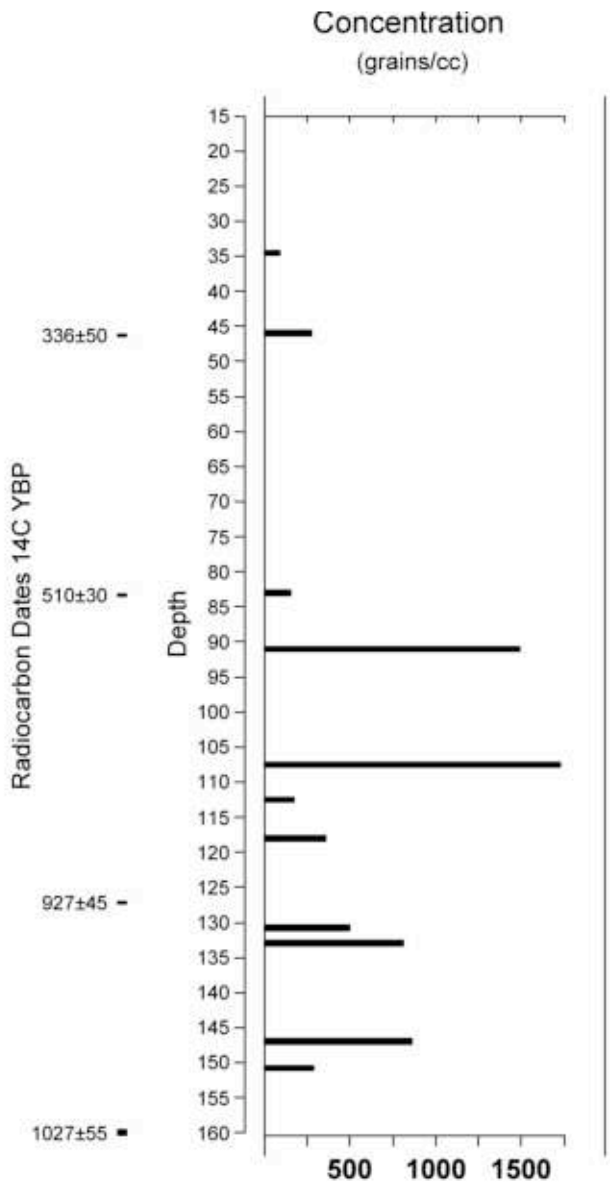

Figure 3.8. Pollen concentration (grains/cc of wet sediment) in samples analyzed for pollen (Table 3.1)

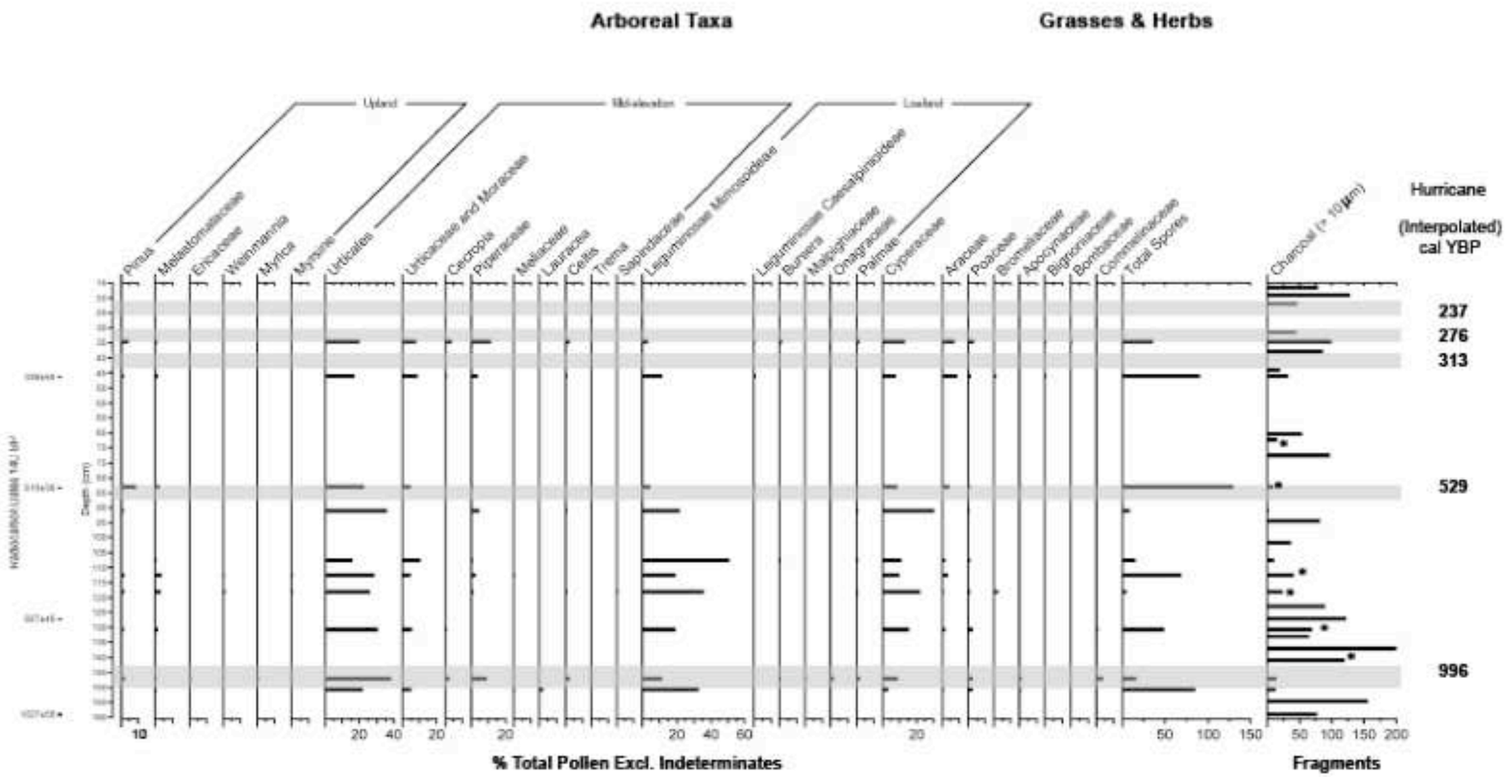

Figure 3.9. Pollen, microscopic (> 10 µm), and macroscopic charcoal (> 125 µm) results with hurricane events indicated by gray bars. Macroscopic charcoal presence indicated by asterisk.