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Holocene Fire History at Laguna Martínez, Costa Rica, Based on High-Resolution Macroscopic Charcoal Analysis of an 8400 cal yr BP Sediment Record

Jason Elliott Graham
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To the Graduate Council:

I am submitting herewith a thesis written by Jason Elliott Graham entitled "Holocene Fire History at Laguna Martínez, Costa Rica, Based on High-Resolution Macroscopic Charcoal Analysis of an 8400 cal yr BP Sediment Record." I have examined the final electronic copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Geography.

Sally P. Horn, Major Professor

We have read this thesis and recommend its acceptance:

Henri D. Grissino-Mayer, Kenneth H. Orvis

Accepted for the Council:
Carolyn R. Hodges

Vice Provost and Dean of the Graduate School

(Original signatures are on file with official student records.)

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A Thesis

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Degree

The University of Tennessee

Jason Elliott Graham

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Abstract

Macroscopic charcoal proxy records from sediment profiles from lakes and swamps provide valuable information on the role of fire in the world's varied ecosystems. Macroscopic charcoal is not normally transported long distances, making it a good indicator of local fire history. This study focused on the macroscopic charcoal in an 8400 cal yr BP sediment record from Laguna Martínez, located in northwestern Costa Rica on the Pacific slope of the Miravalles volcano. Prior study of pollen assemblages in the Martínez sediment core revealed the earliest evidence of maize agriculture in Costa Rica at about 5500 cal yr BP. I sampled the core for high-resolution macroscopic charcoal analysis using a 4 cc sampler at contiguous 1 cm intervals, and quantified charcoal fragments in two size classes (250–500 μm and >500 μm) by sieving following treatment with 3% hydrogen peroxide. Charcoal concentration and influx were very high in the deepest portion of the sediment record, prior to about 7500 cal yr BP, when fires were likely associated with volcanic activity. Charcoal values were moderate at the time of the earliest evidence of maize agriculture, but increased in the later Holocene, with charcoal influx indicating elevated fire activity from about 3200–2600 cal yr BP, near 2000 cal yr BP, and near 1200 cal yr BP. Experimental use of the charcoal analysis program CHAPS revealed some trends and events not apparent in the raw charcoal influx data, including evidence of a fire event about 260 years prior to the first evidence of maize agriculture at Laguna Martínez.

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Chapter 1

Introduction

Various proxy records can be used to reconstruct past fire history and the role fire plays in the ecosystem under study. The development of these proxy records involves dendrochronological techniques that examine fire-scarred trees, and paleoecological analyses of charcoal fragments found in stratified lake or swamp sediments or in soils. These techniques are beneficial for reconstructing past fire history, but they each have advantages and disadvantages (Whitlock and Millspaugh, 1996).

Sedimentary charcoal profiles from lakes and swamps and charcoal data from soils complement evidence of fire history from dendrochronological studies. Dendrochronological techniques that use fire-scarred trees provide very high resolution data on past fires. The exact year of a fire event can be determined by examining a fire scar on a tree that produces an annual growth ring. The presence of trees or logs with fire scars proves that fires have occurred at the site. Dendrochronological studies are, however, restricted by the ages of the trees and preserved dead wood at the site (Whitlock and Millspaugh, 1996). While dendrochronological data may span millennia where trees are long lived and wood decay is slow, in many areas such data may span only a few centuries. Opportunities for dendrochronological reconstruction of past fires are also limited geographically, with fewer options available in tropical areas where many trees may not form distinct annual rings.

Sedimentary charcoal analysis is a particularly important proxy for reconstructing fire events many thousands of years ago, both in temperate (Brunelle and Anderson, 2003) and tropical (Sanford and Horn, 2000) environments. Two main types of charcoal analysis can be distinguished, based on the sizes of particles examined and the methods used to examine them. Microscopic or "pollen-slide" charcoal analysis generally focuses on particles <125 µm in maximum dimension that are present in samples prepared for pollen analysis and are examined at high magnification using light microscopy (Clark, 1982; Patterson et al., 1987; Mensing et al., 1999; Tinner and Hu, 2003). Microscopic charcoal is often interpreted as a signal for regional fires (Gardner and Whitlock, 2001). Macroscopic charcoal analysis generally focuses on particles >125 µm in maximum dimension that are separated from sediments by sieving and tallied using a dissecting microscope at low power magnification. The size and mass of macroscopic charcoal particles limit the distance they are transported from the fire source, making these sized charcoal particles good evidence for local fires within the watershed (Clark, 1988a, 1988b; Clark and Hussey, 1996; Whitlock and Millspaugh, 1996; Horn et al., 2000; Laird and Campbell, 2000; Millspaugh et al., 2000; Whitlock and Larsen, 2001; Schlachter, 2005).

Macroscopic charcoal is also studied in soil profiles (Horn and Sanford, 1992; Sanford and Horn, 2000; Whitlock and Larsen, 2001; Hammond, 2006; Titiz and Sanford, 2007). An advantage of soil charcoal studies is that the large size of the particles investigated (often >2 mm) ensures that they were produced by local fires. Sanford and Horn (2000) noted that soil charcoal analyses are useful for determining if fire has occurred in the past, and for inferring the fire recurrence interval at a study site.

Coarse fire history records can be created by studying spatial patterns and ages of soil charcoal. Gavin et al. (2007) described the importance of soil charcoal as a proxy for past fire in locations without lakes, and the ability of soil charcoal to remain in soils for thousands of years. However, unlike lake and swamp sediments, soils are often not stratified, due to bioturbation, soil slippage, and other factors. Also, soils do not build up overtime in the manner that lake sediments do. They develop from regolith material below the soil profile, while they erode at the surface. One cannot assume that deeper charcoal is always older than charcoal higher in the soil profile. Sanford and Horn (2000) and Gavin et al. (2007) noted that fire history records created using soil charcoal are of coarse resolution because of these factors as well as the high cost of obtaining radiocarbon dates. Hammond (2006) described some of the other drawbacks associated with soil charcoal analysis. He noted that vertical infiltration within soils can be altered by biological factors such as animals burrowing, treefall, and decomposition. For these reasons, when lakes or wetlands are available in study areas, charcoal records from sediment profiles are generally believed to provide better evidence of past fire.

For the world as a whole, there are many more records of fire history based on microscopic charcoal on pollen slides than on macroscopic charcoal sieved from sediments. However, some limitations exist for using microscopic charcoal on pollen slides to interpret fire history. Whitlock and Larsen (2001) noted three factors that limit the usefulness of such records. First, they noted that samples are usually taken from sediment cores at intervals of a few centimeters to tens of centimeters, leaving gaps of unsampled material and the chance that fire events will be missed. Second, charcoal particles can become fragmented during the pollen slide processing procedure, inflating

microscopic charcoal counts. Third, microscopic charcoal is much lighter than macroscopic charcoal. It can be transported much farther from its source than macroscopic charcoal. For this reason, microscopic charcoal particles may signal regional fires rather than local fires. However, some microscopic charcoal may be from local fires. Much of the research on the dispersal of charcoal following fires has been based on crown fires. Charcoal transport in surface fires may not result in as much long-distance dispersal of small charcoal. In some situations, the amount of macroscopic charcoal in lake sediment samples may be insufficient to characterize fire history. Schlachter and Horn (in review) have questioned the replicability of macroscopic charcoal analysis of small volumes of lake sediment.

Leaving aside the question of whether microscopic charcoal might serve as a proxy for local fire in some situations, this thesis focuses on macroscopic charcoal in lake sediments from Laguna Martínez in northwestern Costa Rica to produce a record of fires of certain local origin during the past ca. 7610 ^{14}C years (8420 calibrated years). This fire record provides context for evidence of the earliest maize agriculture in Costa Rica, dated to 4760 ^{14}C yr BP (ca. 5500 cal yr BP) in the Laguna Martínez sediment core (Arford and Horn, 2004; Horn, 2006). It should reveal, for example, the extent to which fire was used to clear forests and to create and maintain maize fields. Comparing the macroscopic charcoal record to the pollen record from Laguna Martínez (Arford, 2007) may reveal possible signals of crop cultivation prior to the first evidence of maize in the watershed. I will also compare my results to a microscopic charcoal record from Laguna Martínez (Arford, 2007), and to a macroscopic charcoal record from nearby Laguna Estero Blanco (Schlachter, 2005), thereby contributing to an improved understanding of

the relationship between microscopic and macroscopic charcoal records in the seasonally dry tropics. Finally, because climate can drive fire regimes even when fires are human set, my work will contribute to knowledge of tropical paleoclimate.

By constructing and analyzing a high resolution macroscopic charcoal record from Laguna Martinez, I sought to answer these questions:

- What are the general trends in the fire history of the Laguna Martínez watershed over the past ca. 8400 years?
- How do patterns of macroscopic charcoal abundance relate to pollen evidence of local maize cultivation, and how does this differ between the time of early maize cultivation and later?
- How does the macroscopic charcoal record compare to the microscopic charcoal and pollen record from Laguna Martínez developed by Arford (2007)?
- How does the Martínez macroscopic charcoal record compare to the macroscopic charcoal record developed by Schlachter (2005) from nearby Laguna Estero Blanco?
- What are possible constraints or difficulties in using the charcoal analysis program developed by P. Bartlein (CHAPS; Long et al., 1998) to reconstruct local fire history in tropical dry forest environments, and what do the results from CHAPS reveal about fire history?

This thesis is divided into seven chapters. The second chapter reviews past studies that used sedimentary charcoal to reconstruct past fire history. The environmental

setting of Laguna Martínez is described in Chapter Three. Chapter Four describes the methods I used in my study. Chapters Five and Six present and discuss the high-resolution local fire history of Laguna Martínez, and the thesis is concluded in Chapter Seven.

Chapter 2

Literature Review

Charcoal is created when combustion of organic material such as plant tissue is incomplete (Patterson et al., 1987; MacDonald et al., 1991; Whitlock and Larsen, 2001; Orvis et al. 2005). Charcoal particles can be identified visually by their planar, angular, black, and opaque properties (Whitlock and Larsen, 2001). The production of charcoal particles occurs at temperatures of 280 to 500 ºC (Chandler et al., 1983; Whitlock and Larsen, 2001). Patterson et al. (1987) noted that different materials and the properties of these materials, such as the hardness of the woody tissues, affect the amount of charcoal produced during a fire. Charcoal preserves well when sequestered under both dry and humid conditions, lasting for many thousands of years in a range of soils and sediments. Charcoal can also withstand laboratory procedures such as chemical processing for pollen slide preparation. These characteristics make charcoal a proxy that can be used to reconstruct fire events over millennial time spans (Brunelle and Anderson, 2003).

Charcoal particles can be transported away from the fire source to distances determined by factors that include the fire size, intensity, and severity (Whitlock and Larsen, 2001). Charcoal particles can be displaced from the fire source either during or after the fire. Primary-deposition charcoal is transported during the fire event by wind. Secondary charcoal particles are those that are transported after primary deposition has occurred, by wind or water.

Research on fire history focuses on two broad size classes. One class or type of charcoal is microscopic charcoal. These charcoal particles are identified and counted on microscope slides at high magnification, often together with pollen grains in preparations made using standard pollen processing techniques. The second type of charcoal is termed "macroscopic charcoal," which describes charcoal large enough to be seen with the unaided eye. There is no set size that is considered to be macroscopic in charcoal studies. Individual paleoecological studies have defined macroscopic charcoal in different ways. Often 125 μm is the minimum size that researchers consider to be macroscopic (Schlachter, 2005). Researchers commonly will examine several size classes of macroscopic charcoal, for example, particles 125–250 μm in size and those 250–500 μm in size. Macroscopic charcoal is generally studied by sieving core samples and counting particles retained on sieves of different mesh size (Whitlock and Larsen, 2001).

Many studies have used macroscopic charcoal in sediments as an indicator of a fire that has occurred locally or within the watershed (Clark, 1988a, 1988b; Clark and Royall, 1995; Whitlock and Millspaugh, 1996; Clark et al., 1998; Laird and Campbell, 2000; League and Horn, 2000; Ohlson and Tryterud, 2000; Gardner and Whitlock, 2001; Whitlock and Larsen, 2001; Brunelle and Anderson, 2003; Tinner and Hu, 2003; Schlachter, 2005). The basis for these studies is the idea that the macroscopic charcoal particles, because of their size, do not travel long distances from the fire event source.

Whitlock and Millspaugh (1996) examined the accumulation of charcoal in lake sediments in Yellowstone National Park after the 1988 fires. They investigated modern charcoal deposition because of the potential for this proxy to extend the fire history back thousands of years. Comparison of pollen data from a sediment core with macroscopic

charcoal data could determine the role that fire played in vegetational and climatic changes through this period. They found that significant amounts of charcoal were introduced into the Yellowstone lake sediments from primary deposition in the 1988 fires. Secondary deposition processes resulted in some particles produced in the 1988 fire taking up to 5 years to reach the lake bottom. After this secondary charcoal had settled, the charcoal abundance in the surface sediments of different lakes contrasted enough to distinguish areas that had burned in the 1988 fire from those that had not burned.

Millspaugh and Whitlock (1995) developed a 750-year history of fire from several lakes in Yellowstone National Park and found that charcoal particles >125 µm in size correlated well with local fires within the watershed, as reconstructed from dendrochronological studies of fire-scarred trees. They found that runoff from the surface of the burned watersheds that fed into their study lakes transported secondary charcoal.

Clark (1988b) studied macroscopic charcoal in sediments using a thin-sectioning technique to extend the fire history record created from using fire-scar chronologies. He found that the record of thin section charcoal particles >60 µm in size in a lake in northwestern Minnesota correlated well with fire history as recorded by fire scars. Clark and Royall (1995) investigated a series of sediment cores from eastern North American lakes. They found that thin-section charcoal declined because of the lack of local fire during the 20th century, while pollen-slide charcoal amounts increased during the same period. The study also showed that periods without local fire resulted in the deposition of very few macroscopic charcoal particles in the sediment. Their study determined that

when the thin-section and pollen-slide methods are compared, they complement each other. An increase in pollen-slide charcoal and a decrease in thin-section charcoal suggests that the two proxies are recording combustion at different spatial scales (Clark and Royall 1995). There is some chance for error, however, when studying thin-section charcoal particles. These particles are not perfectly round nor do they have the same dimensions on all sides, and because of this the particles might be counted in the wrong size class, depending on particle orientation.

Gardner and Whitlock (2001) examined charcoal accumulation in lakes after a fire event, and the effects charcoal accumulation rates have on fire history reconstructions. Their study showed that macroscopic charcoal was indeed found in their study lake when the watershed had burned. Their research also confirmed that abundant amounts of charcoal found in a layer of sediment were related to a fire event. Charcoal peaks within lake sediment profiles were from the primary charcoal that was transported during or very shortly after the fire event. They determined that secondary charcoal that was deposited into the lake did not create extra peaks and should not be a problem for charcoal analyses. This study also further corroborated the findings of Millspaugh and Whitlock (1995) that lakes downwind from fire events receive more charcoal than lakes upwind from fire events. This suggests that lakes upwind from fire events will not contain charcoal peaks from those fires, while lakes outside of the watershed downwind from the fire might contain charcoal peaks even if fires do not reach them. Gardner and Whitlock found that peaks in macroscopic charcoal abundance in palaeoecological records could represent either a fire that had occurred at the edge of the lake or events

that took place as far as a few kilometers away from the lake, depending on the fire and weather conditions during the events.

Schlachter (2005) created an 8,000 year record of fire history from sediment extracted from Laguna Estero Blanco in northwestern Costa Rica. He chose to use hydrogen peroxide to disaggregate the samples instead of sodium hexametaphosphate as used by Whitlock and Millspaugh (1996). The hydrogen peroxide produced better samples from the Estero Blanco sediments because it bleached the non-charcoal organic matter. Rhodes (1998) had experimented with the use of hydrogen peroxide in preparing microscopic charcoal samples and Schlachter (2005) built on the results of his work and that of other researchers. He found that it was much easier to identify charcoal particles in samples that were treated using 3% U.S.P. cosmetic grade hydrogen peroxide than in those treated with 5% sodium hexametaphosphate.

Schlachter (2005) and many other researchers examined downcore changes in charcoal abundance using CHAPS, a set of charcoal analysis programs developed by P. Bartlein at the University of Oregon. These programs are used to distinguish charcoal peaks from background charcoal. This program first creates a pseudo-annual interval from the raw influx data because ages are not consistent throughout the core. The user selects the desired pseudo-annual interpolation value to get the influx values returned at the consistent time throughout the entire core. For example, if the user selects a pseudo-annual interpolation value of 10, then interpolations will be made at 10 year intervals. A second program determines the statistics of the sediment core and breaks the raw influx data into peaks and background charcoal. The background and peak charcoal are determined by selecting a background-window width and a peak threshold value. The

user must select the desired background-window width to smooth the time series as appropriate. The background component represents charcoal that has been introduced into the lake through secondary transport rather than a single fire event. The peak threshold value is selected to determine single fire events throughout the sediment core. If the influx values are higher then the peak threshold value, then a fire peak is assigned. For example, if the user selects a peak threshold value of 1.3, then the influx value must be 1.3 times higher than the peak threshold to be recorded as a fire event (Long et al., 1998).

Chapter 3

Research Setting

My study is part of a much larger project being carried out in the Laboratory of Paleoenvironmental Research at the University of Tennessee. The project involves analyses of multiple proxies in sediment cores from six lakes in northwestern Costa Rica. The lakes are located on the southwestern slope of Volcán Miravalles, in the Cordillera de Guanacaste (Figure 3.1). The volcanoes of the Cordillera de Guanacaste are classified as stratovolcanoes. Four primary volcanoes are arranged in a NW-SE orientation; starting near the Nicaraguan border they are Orosí-Cacao, Rincón de la Vieja, Miravalles, and Tenorio. Gaps between the stratovolcanoes in the Cordillera de Guanacaste allow the trade winds from the Caribbean ocean to blow through with ease to the Pacific Ocean. These winds warm as they descend, creating a drier environment in the western portion of the Guanacaste cordillera near the Pacific coast (Marshall, 2007).

Laguna Martínez

Laguna Martínez (10.6419 ºN, 85.1969 ºW) (Figure 3.2) is located at an elevation of 340 m above sea level. The lake is the larger of the two lakes identified as "Lagunas Huerton" on the 1:50,000 topographic map of the Tierras Morenas quadrangle, but residents of the area call the lake "Laguna Martínez" (Arford, 2007). The other lakes studied in the larger paleoecological research project are Laguna San Pablo, Laguna Los Juncos Near, Laguna Las Brisas, Laguna Sorpresa, and Laguna Estero Blanco.

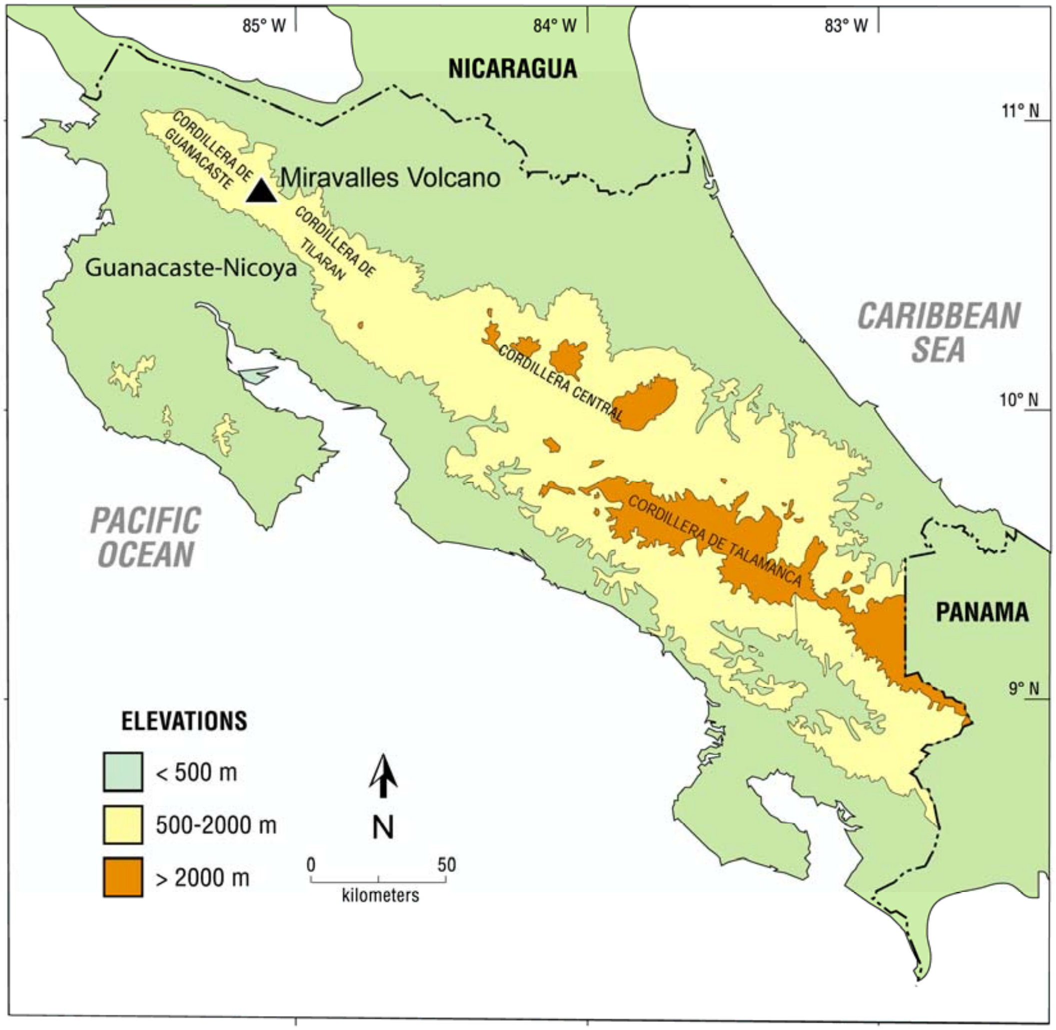

Figure 3.1. Location of the Miravalles volcano in northwestern Costa Rica. Source: Arford (2007); modified by from a map produced by the Cartographic Services Laboratory at the University of Tennessee.

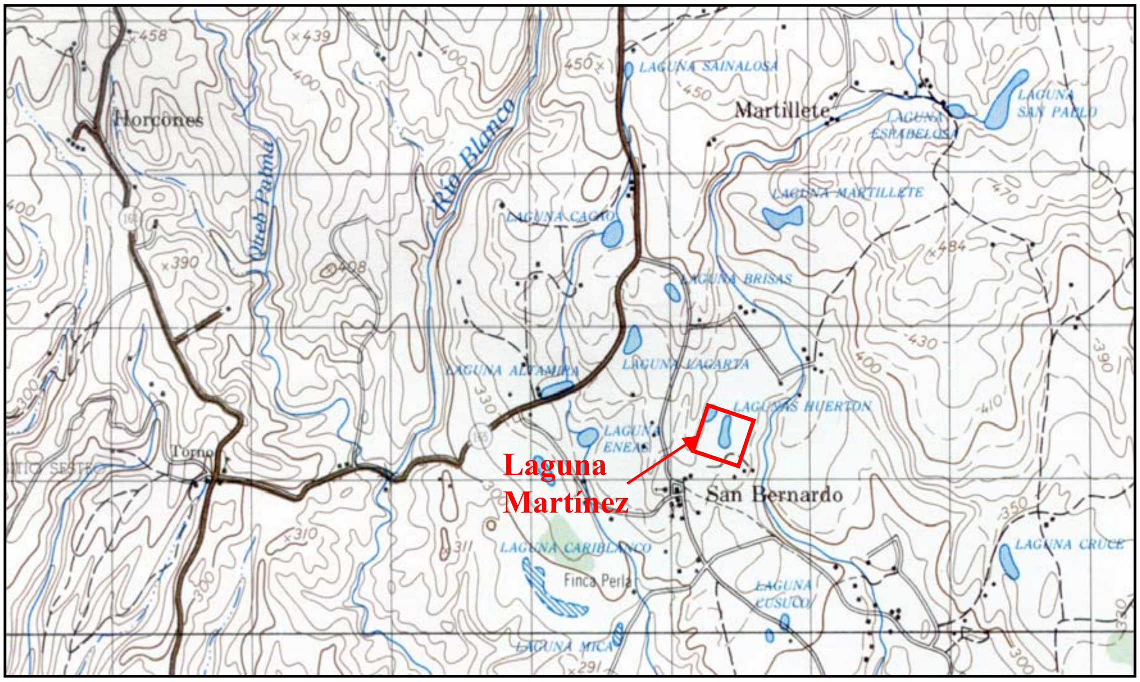

Figure 3.2. Location of Laguna Martínez relative to other lakes in the Miravalles region. Source: from Arford (unpublished), modified from the 1:50,000 scale Tierras Morenas topographic quadrangle produced by the Instituto Geográfico Nacional.

Laguna Martínez has a surface area of 1.5 ha, and a dry season water depth of at least 3.6 m (Arford and Horn, 2004). Laguna Martínez and other lakes of the region occupy depressions in the undulating surface of a volcanic debris avalanche from Miravalles volcano that Siebert et al. (2006) dated to approximately 8300 calibrated years BP. Remnant patches of lowland deciduous dry forest can be found near the Miravalles lakes, although the lakes are mostly surrounded by pasture lands presently. Laguna Martínez is very important for paleoenvironmental research because it is filled with water throughout the year, limiting disturbance to the sediments and providing an environment for long-term preservation of pollen grains and other organic proxies (Haberyan et al., 2003).

Climate and Vegetation

The close proximity of Costa Rica to the equator keeps the average temperature of the warmest month within 5 °C of the average temperature of the coolest month. Elevation increases the difference between the mean daily maximum and minimum temperatures (Coen, 1983). The largest difference between the mean maximum and minimum temperatures occurs along the Pacific side of the Cordillera de Guanacaste and Cordillera Central. During the dry season from November to April, the Pacific slope is mostly cloud free and the deciduous vegetation loses its foliage. This allows more incoming solar radiation to reach the surface. The cloud-free nights allow longwave radiation to emit from the surface, causing cooler temperatures. On the Pacific slope of Costa Rica, the coolest months are November through January, and the warmest months

are February through April. The mean temperature at sea level on the Pacific coast of Costa Rica is about 32.6 °C (Coen, 1983).

The area around Laguna Martínez is classified as Subhumid-humid, with a very long dry season, in the climate classification of Herrera (1985). Based on Bergoeing (1998), as cited by Arford (2007), annual precipitation is between 1500 and 2000 mm per year and mean annual temperatures are 22.5–25.0 °C. The five-month dry season in the study area between November and April results from the rainshadow effect caused by the passage of trade winds over the Cordillera de Talamanca, which become warmer and drier as they descend toward the Pacific (Coen, 1983).

Laguna Martínez is located within the Northern Pacific Lowland Deciduous Dry Forest ecosystem in the classification of Kappelle and Gómez (in preparation). However, the dominant vegetation at the site today is cattle pasture with coyol palms (*Acrocomia aculeata*). Pastures that appear to have been abandoned for a few years are overgrown with thick vegetation, including thorny shrubs such as *Mimosa pigra* (Arford, 2007). A small area of gallery forest is located near one side of Laguna Martínez. The gallery forest contains tall trees, including *Ficus*, *Coccoloba,* and several species of Fabaceae (Arford, 2007).

Arford (2007) noted that the size of the lake diminished between 2001 and 2003 due to the encroachment of aquatic vegetation that has covered most of the lake's surface. This made coring difficult, because the vegetation had to be cleared to position the coring platform. The aquatic vegetation that covers Laguna Martínez includes grasses, ferns, and water hyacinth.

Historical and Cultural Context

During the Pliocene, the Central American isthmus developed and created a landbridge that facilitated the exchange of plants and animals between North and South America (Marshall, 2007). The isthmus connects the Nearctic and Neotropic biogeographical realms (Rich and Rich, 1983). Humans migrated south through the isthmus, with the earliest humans thought to have arrived in Costa Rica around 12,000 years ago (10,000 BC; Snarskis, 1979). These Paleo-Indians gathered fruits, nuts, and seeds, and hunted megafauna as well as smaller animals. A few Clovis-like arrowheads document the presence of these early hunters and gatherers in Costa Rica, but little other evidence of their presence has been found (Snarskis, 1979; 1984).

How and when Central America was populated has in fact led to much debate. Archaeologists have argued over different models of the peopling of the Americas and the spread of technology. Fishtail-shaped arrowheads in the southern portion of South America as early as 11,000 ^{14}C yr BP (Bryan and Gruhn, 2003) indicate that people had by this time already migrated through Central America. But research by Dillehay (1989) at the Monte Verde archaeological site in south-central Chile suggests that the migration through Central America may have occurred much earlier. The site contained bones from extinct animals, diverse wood and stone artifacts, and plant remains. The excavation revealed artifacts including arrow points and bifacially chipped stone dated to 13,000 years ago. Two radiocarbon determinations on charcoal found at the Monte Verde site yielded ages of 33,000 years BP. This is significant because it shows that humans might have migrated through Central America before 33,000 years BP (Dillehay, 1989).

Several archaeological studies have been carried out in northwestern Costa Rica. Sheets et al. (1991) studied the area near Arenal volcano, about 40 km southeast of Miravalles volcano. They found that the village lifestyle in the region around 4000 yr BP was very resilient despite repeated site devastation by at least nine prehistoric volcanic explosions. Five phases of inhabitants occupied the Arenal volcano area from the local Archaic period (prior to 4950 yr BP) to the Tilarán phase (around 450 yr BP or AD 1500), prior to the Spanish conquest (Sheets et al., 1991).

Two archaeological studies were conducted by Norr (1982–1983) and by Ryder (1982–1983) near the Miravalles lakes. Both studies revealed evidence of pre-Columbian occupation and cultural practices. Ryder (1982–1983) noted burial mound looting as being a problem in his study, but plenty of evidence of aboriginal cultural practices still existed.

Norr (1982–1983) and her work crew conducted a site survey and excavation of burial mounds in the Rio Naranjo-Bijagua valley near the Cordillera de Guanacaste. The study area was located between the Miravalles and Tenorio volcanoes and included both the Pacific and Atlantic sides of the saddle. The team found that most of their sample sites had one or more low stone burial mounds 20–40 m in diameter and 0.5–2 m in height. They discovered that the sites on the Pacific slope were initiated and abandoned earlier than sites on the Atlantic slope. The earliest radiocarbon date obtained (3500 ± 60 ^{14}C yr BP) was from wood charcoal found underneath a burial mound. Examining ceramics found in the burial mounds led Norr to conclude that the region was occupied in the southern portion of the study area first. The ceramic material excavated from sites in the southern portions of the valley was from the Zoned Bichrome Period (2750–1450 yr

BP). The northern portions of the valley were occupied later (1850–850 yr BP) and the ceramics were from two later phases of the Zoned Bichrome Period (Norr, 1982–1983).

Ryder (1982–1983) in collaboration with the Museo Nacional de Costa Rica conducted an archaeological study at the Guayabo de Bagaces site, along the southwest flank of the Miravalles volcano. Prior to the study, surveys on the land were being conducted to determine the environmental impact of building a dam near the site. During the survey, petroglyphs were found, leading the head geologist from the team conducting the survey to organize an archaeological team from the Museo Nacional de Costa Rica to investigate. Ryder (1982–1983) noted that the site was mostly pasture land at the time of the survey, but had been forested during pre-Columbian time. Aboriginal people cleared some of the land for crop cultivation, but he believed that modern populations did the majority of the deforestation. The study found 23 sites of pre-Columbian activity in the Guayabo de Bagaces study area, including 17 cemeteries, 2 cemeteries with signs of habitation, 2 habitation sites, and 2 petroglyphs. The largest burial mound found in the Guayabo de Bagaces site was 50 m in diameter and rose 6 m above the surface, indicating the energy the aboriginals devoted to creating their cemeteries.

Ceramics in the burial mounds were from the Zoned Bichrome Period (2750–1450 yr BP). Ceramics from the Middle Polychrome Period (1150–750 yr BP) were also found eroding from a slope. Ryder (1982–1983) interpreted these ceramics as having been left during a short period of human occupancy. Human remains were also found beneath each of the rock burial mounds. The human remains, ceramic material, and the burial mounds all provide evidence of pre-Columbian occupation near the Miravalles volcano (Ryder, 1982–1983).

In the early 1500s, Spanish conquistadors first came through the Cordillera de Guanacaste along a route similar to that of the present Pan-American Highway. They transmitted new diseases, brought on war, enslaved indigenous populations, and destroyed local vegetation including cultivated crops (Allen, 2001). In the mid-1500s, the Spanish government began giving out land grants to local governments formed in the Guanacaste region and to soldiers who had fought in the conquest. The land grant boundaries were rather ambiguous, which led to many future disputes. The land grants were passed on through families. The establishment of cattle ranches led to the demise of much of the forest cover in the region. The land had to be deforested for the cattle to have room to roam and graze (Allen, 2001).

Chapter 4

The Martínez Core and Methods of Charcoal Analysis

A sediment core approximately 5.8 m long was recovered from Laguna Martínez by M. Arford and student assistants in 2001 using a Colinvaux-Vohnout (C-V) locking piston corer (Colinvaux *et al*., 1999). The core was retrieved in six sections using successive 1-m drives, from a site near the middle of the lake. A plastic pipe fitted with a rubber piston was used to recover the mud-water interface. This material was extruded and bagged in 2 cm intervals in the field. The C-V core sections were returned to the lab in the original aluminum coring tubes and stored at 6 ºC.

The aluminum core tubes were opened in the Laboratory of Paleoenvironmental Research by M. Arford, S. Horn, and others. The tubes were sliced into two equal sections longitudinally using a modified table router. The sediment inside the core tube was also sliced longitudinally using a wire. Each section was then photographed and described on core logs that noted sediment texture and Munsell colors (Table 4.1). Arford (2007) took samples from one half of each core section for pollen and microscopic charcoal analysis. The same core half was also sampled by Horn for diatom analysis. The lowest meter of the core consists of mineral sediments deposited before the lake formed and was not sampled in previous studies or this study.

Nine radiocarbon dates were obtained on charcoal fragments and dicotyledonous leaves extracted from the Laguna Martínez core by M. Arford and S. Horn. The macrofossils were rinsed with distilled water, oven dried, and submitted to Beta Analytic Laboratory in Miami, Florida and to the Accelerator Mass Spectrometry (AMS)

Table 4.1. Stratigraphy of the Laguna Martínez Core (from Arford, 2007)

Depth (cm)	Munsell Color	Description
0–10	10YR 3/1	watery
11–23	10YR 3/1	firm, mineral matrix, organic fragments
24–51	10YR 3/2	Mineral matrix, but organic-rich
52–75	10YR 3/1	very firm, mineral-rich
76–94	7.5YR 2/0	fibrous organic-rich, mottling of 10YR 3/1
94–99	10YR 2/1	clay-rich dense inorganics
100–117	--	gap in sediment recovery
118–143	10YR 3/2 & 2/1	peaty/fibrous but mineral-rich
144–155	10YR 2/1	very dense, tightly packed layers of organics & minerals, diatoms, charcoal; compressed
156–180	10YR 3/2	dense, gritty, mineral-rich, mottling
181–205	10YR 2/1	gritty mineral-rich
206–217	--	gap in sediment recovery
218–306	10YR 2/1	firm, smooth
307–316	--	gap in sediment recovery
317–398	10YR 3/1	smooth mineral-rich mud
399–402	10YR 2/1	firmer, darker, finer grained
403–409	--	gap in sediment recovery
410–440	10YR 2/1 & 3/1	slightly banded fine grained mud
441		thin tephra layer
442–471	10YR 3/1& 2/1,	discrete banded sediments, fine-grained
	5Y 2.5/1 & 3/1	occasional thin diatomaceous layers
	GLEY 3/10Y, 2.5/N, & 4/10Y	
472–477	5Y 4/1 &	Clay
	10YR 4/1	
478–482		coarse sand and gravel-sized clastics
483–488	10YR 4/1	Clay
489–498		coarse sand and gravel-sized clastics
499–507		gap in sediment recovery
508–582	10YR 4/1, 5Y 4/1	silty-clay, very dense

laboratory at the University of Arizona for AMS radiocarbon dating. The earliest radiocarbon date obtained, at the base of the lacustrine sediments of the core, was 7610 ± 50 ^{14}C yr BP (ca. 8400 cal yr BP; Table 4.2). Additional AMS radiocarbon dates on charcoal fragments and dicotyledonous leaves indicate that sediment accumulated rapidly in the earliest period of the lake's history but slowed after 6060 ± 40 ^{14}C yr BP (ca. 6900 cal yr BP; Figure 4.1). Pollen evidence indicates that this reduction in sedimentation rate was associated with an interval of drier climate (Arford and Horn, 2004). The first appearance of maize pollen occurred after the dry period, and was associated with a decrease in the percentage of tree pollen, an increase in grass pollen, and increased microscopic charcoal (Arford and Horn, 2004). The maize pollen in the Martínez sediment core presently constitutes the earliest botanical evidence of maize anywhere in Costa Rica (Horn, 2006).

Charcoal Analysis

I sampled the Martínez sediment core sections for macroscopic charcoal analysis with a 4 cc sampler (Figure 4.2), taking contiguous samples of 1 cm thickness from each core section. I used the archive half of each core section that had not been previously sampled for pollen or other analyses. The brass sampler was designed and fabricated by R. Horn, and is similar to the 2 cc sampler R. Horn built following a design by S. Horn and K. Schlachter, used in Schlachter's (2005) study of macroscopic charcoal in the Estero Blanco core. Use of this sampler creates a trough along the length of each sediment core section, visually indicating the continuous nature of the sampling (Figure 4.3). I sampled the mud-water interface samples using a small spoon.

Table 4.2. AMS Radiocarbon Dates for Laguna Martínez[1] (from Arford, 2007)

Lab Number	Depth (cm)	Material Dated	Radiocarbon Date	Weighted Mean cal yr BP	Calibrated 2 Sigma Range cal yr BP	Calibrated 2 Sigma Range yrs AD/BC
ß-167804	30	Charcoal	190 ± 40	170	306–248	AD 1644–1702
		(single piece)			228–135	AD 1722–1815
					120–69	AD 1830–1881
					36–0	AD 1914–1950
AA-60654	37	Dicot leaf	301 ± 38	380	463–293	AD 1487–1657
AA-60655	63	Charcoal fragments	1572 ± 39	1460	1363–1353	AD 587–597
					1382–1369	AD 568–581
					1537–1385	AD413–565
ß-184799	78	Charcoal	2410 ± 40	2490	2710–2630	760–680 BC
		fragments			2617–2582	667–632 BC
					2541–2527	591–577 BC
					2509–2346	559–396 BC
ß-179844	127	Charcoal fragments	4410 ± 40	5000	5276–5270	3326–3320 BC
					5264–5182	3314–3232 BC
					5123–5110	3173–3160 BC
					5068–5058	3118–3108 BC
					5054–4864	3104–2914 BC
ß-176224	133	Charcoal fragments	4760 ± 40	5500	5592–5453	3642–3503 BC
					5379–5330	3429–3380 BC
ß-172357	154	Dicot leaves	6060 ± 40	6900	7136–7135	5186–5185 BC
					7008–6790	5058–4840 BC
					6770–6757	4820–4807 BC
ß-188888	238	Charcoal fragments	6750 ± 50	7610	7679–7563	5729–5613 BC
					7537–7510	5587–5560 BC
ß-157205	477	Charcoal fragments	7610 ± 50	8400	8538–8530	6588–6580 BC
					8520–8493	6570–6543 BC
					8481–8332	6531–6382 BC
					8231–8221	6281–6271 BC

[1] Radiocarbon determinations were made by Beta Analytic Laboratory, Miami Florida (ß-numbers), or the University of Arizona AMS Laboratory (AA-numbers). Radiocarbon dates were calibrated by Arford (2007) using the program CALIB v4.4.2. (Stuiver and Reimer, 1993) and the INTCAL98 dataset (Stuiver et al., 1998). The weighted mean of the calibration probability distribution was used to assign a single calendar age to each radiocarbon-dated sample (Telford et al., 2004). Sedimentation rates and estimated ages for each sediment interval were calculated using linear interpolation between the weighted means of the calibrated dates, assuming a constant sedimentation rate between dated intervals (Arford, 2007). [2] This table corrects typographical errors in Arford's original dates table.

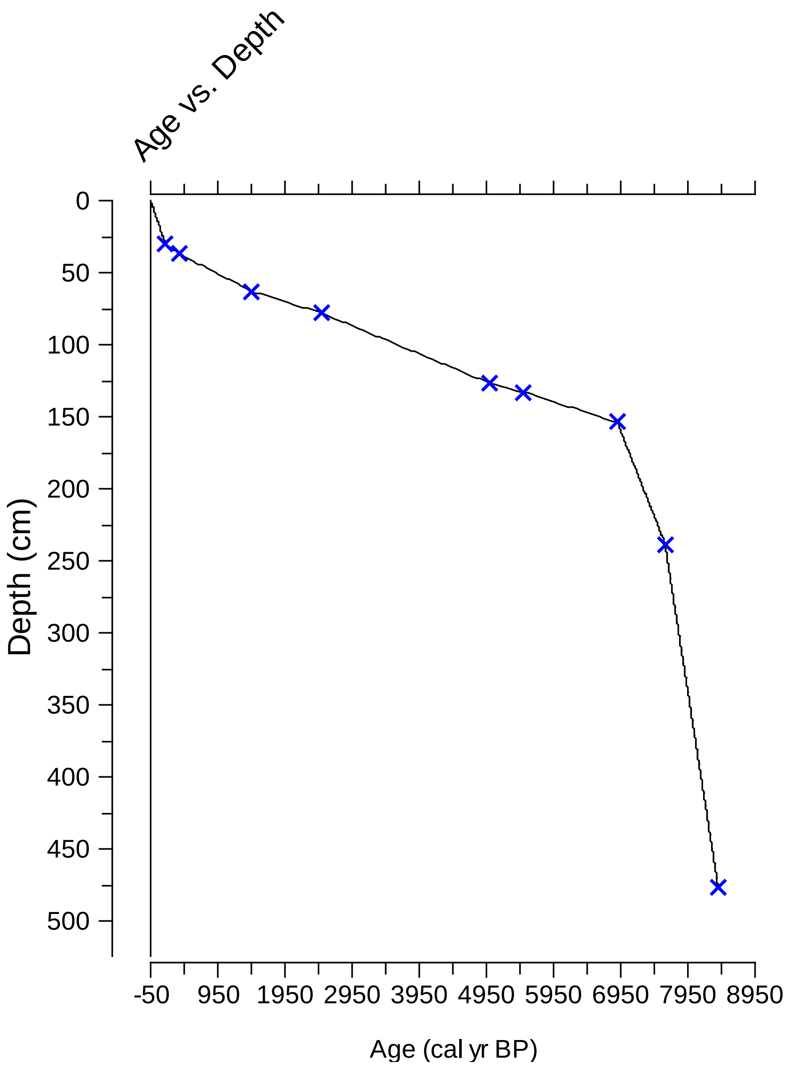

Figure 4.1. Age-Depth diagram for the Laguna Martínez sediment core. Ages plotted are the weighted means of the calibration probability distributions, from Arford (2007).

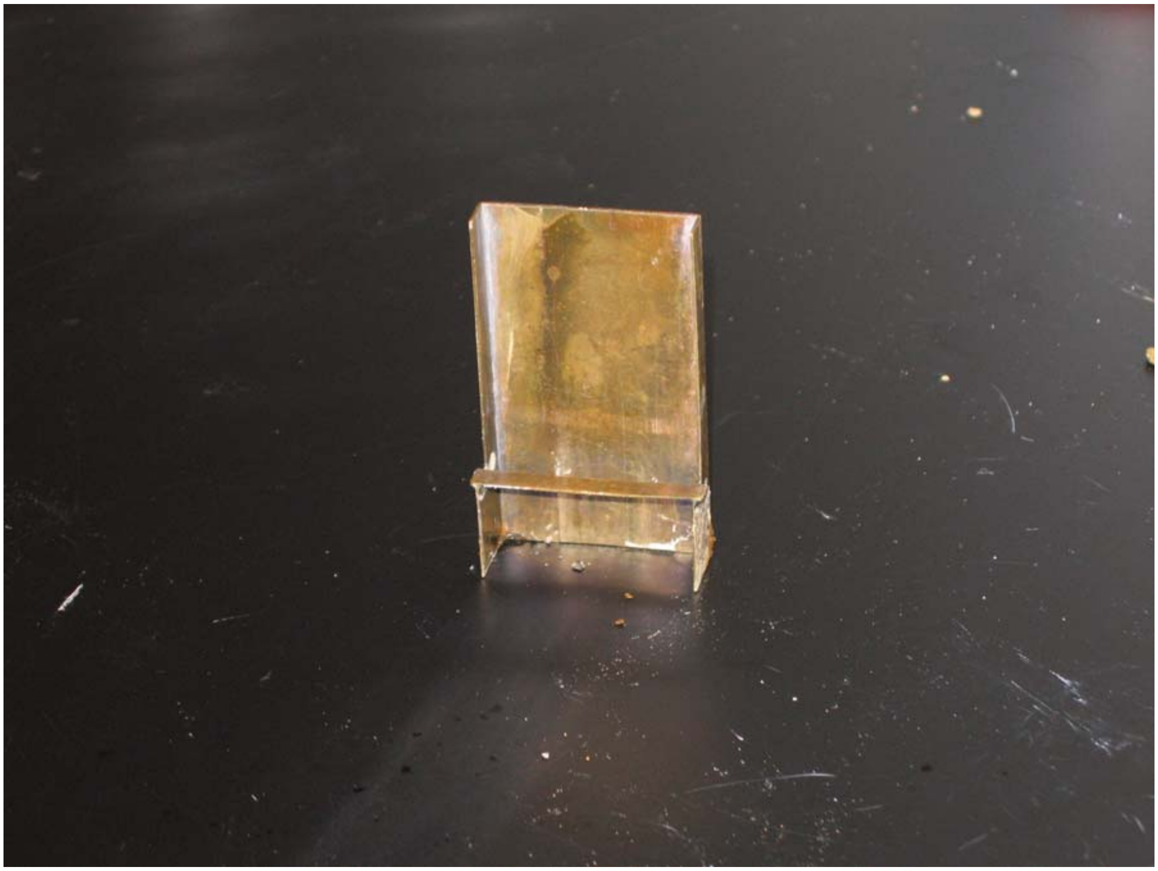

Figure 4.2. The 4 cc brass sampler designed and fabricated by R. Horn for this study.

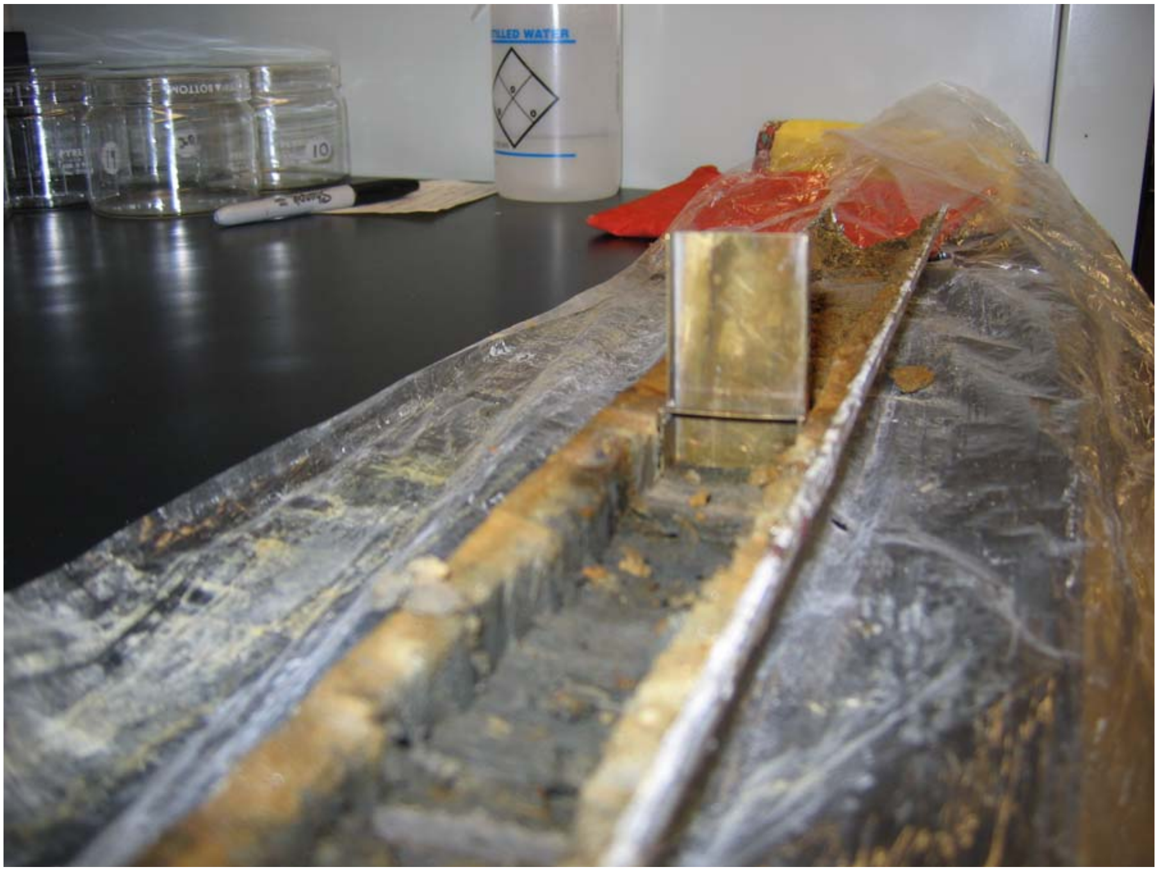

Figure 4. 3. The 4 cc brass sampler in the lengthwise trough in a core section created by its use.

Sediment samples for macroscopic charcoal analysis were placed in c. 120 or 300 ml plastic containers and weighed. Following Schlachter (2005), I treated each sample by placing it in 3% U.S.P. cosmetic grade H_2O_2 for at least 24 hours. The hydrogen peroxide helps to disaggregate the sediment and also bleaches some of the non-charred organic matter, making it easier to quantify macroscopic charcoal (Schlachter, 2005). After treatment in peroxide, I rinsed the samples through two nested sieves with mesh sizes of 250 and 500 µm using distilled water sprayed from a RL Flo-Master 7.6 liter capacity sprayer designed for lawn and garden use. The particles that remained on the sieves were transferred to glass petri dishes and dried overnight in an oven at a temperature of 60 ºC.

I used a stereozoom microscope at 10–40x magnification to identify and count the charcoal particles. Particles that appeared to be black or a very dark gray carbon color, and were opaque, angular, and had iridescent sheen properties, were tallied as charcoal. I recorded charcoal particle totals for each size class and for each 1 cm core increment in a spreadsheet in Microsoft® Office Excel 2004, and divided these charcoal fragment counts by a sediment volume of 4 cm^3 to calculate charcoal concentrations (particles/cm^3). The charcoal concentration values were then multiplied by the sedimentation rate (as calculated by Arford, 2007), to determine charcoal influx (particles/cm^2/yr). Concentration and influx were plotted using the C2 software (http://www.campus.ncl.ac.uk/staff/Stephen.Juggins/software/c2home.htm) written by Stephen Juggins.

I used charcoal analysis programs (CHAPS) developed at the University of Oregon in an attempt to better understand downcore patterns in charcoal influx,

producing graphs of CHAPS output using the C2 software. CHAPS is used in many temperate fire history studies to determine which charcoal peaks may represent fire events, and to estimate background levels of charcoal (Long et al., 1998; Brunelle-Daines, 2002). Schlachter (2005) used CHAPS in his analysis of macroscopic charcoal from Laguna Estero Blanco. Aside from this example, the programs have not been used in studying fire history from tropical sediments.

CHAPS separates the charcoal influx values (called charcoal accumulation rates or CHAR in the programs) into two components. First is the background component, which represents secondary charcoal brought into the lake through runoff or wind and also charcoal that has been redeposited within the lake (Whitlock and Millspaugh, 1996; Bradbury, 1996; Brunelle-Daines, 2002). The peak component is the other component considered in CHAPS. The peaks are created when the CHAR values are above the background and a specified peak threshold ratio. These peaks are assumed to represent fire events (Long et al., 1998; Mohr et al., 2000; Brunelle-Daines, 2002).

CHAPS was designed for use in the temperate forests of the northwestern United States, where trees grow with distinct annual growth rings. The peak threshold ratios are set by the user, ideally based on calibrations using dendrochronological records of fire history near the lake studied. This requirement makes the use of CHAPS experimental in tropical areas that lack dendrochronological records of fire history. Schlachter (2005) selected his peak threshold values by experimenting with threshold values used in studies in the northwest U.S. He selected the value which he thought represented the fire regime most accurately. I selected peak threshold values and background window-widths for my experiments with CHAPS by starting with the ones used in Schlachter (2005). The peak

threshold ratios in Schlachter (2005) were 1.05, 1.10, and1.15, and the background window-widths were 300, 450, 600, and 900 year intervals. I then expanded my analysis by experimenting with other peak threshold ratios (1.07, 1.08, and 1.12) not used in Schlachter (2005) to explore more possible representations of the fire regime at Laguna Martínez.

The background-window widths in CHAPS were selected in a two step process. First, the interval between interpolated values must be selected. Then, the locally weighted mean window width (in samples) is selected. The number of samples selected is multiplied by the interpolated values selected. The result is the desired smoothing background-window width.

Chapter 5

Results

Charcoal Concentrations and Influx

The macroscopic charcoal concentration (particles/cm^3) (Figure 5.1) and charcoal influx (particles/cm^2/yr) (Figures 5.2, 5.3) values for the Laguna Martínez core varied downcore. Concentration values were greatest between 4.72 and 4 m depth (0–1079 particles/cm^3). The values found in the middle portion of the core, from about 4 to 1.57 m in depth, ranged from 6–332 particles/cm^3. Macroscopic charcoal concentration was slightly higher from 1.57–1.12 m (4–480 particles/cm^3) before a gap in the sediment core from 1.11–0.97 m in depth. The concentration values for the depths from 97–53 cm were higher and more variable (131–913 particles/cm^3). The mud-water interface samples and upper portions of the core (52–0 cm) had concentration values that ranged from 0.0 to 112 particles/cm^3. Within that section, only one level had values above 100 particles/cm^3. The values for all of the other levels were less than or equal to 73 particles/cm^3.

Macroscopic charcoal influx was high to extremely high from 4.72–4.05 m (10–326 particles/cm^2/yr). Influx values dropped significantly after 4.05 m in depth and were mainly moderate from 4.05–2.12 m (1–169 particles/cm^2/yr). From 2.12–0.92 m macroscopic charcoal influx remained low to moderate, ranging from 1–18 particles/cm^2/yr. From 0.92–0.19 m, macroscopic charcoal influx values were low (below 1–13 particles/cm^2/yr). Macroscopic charcoal influx (Figures 5.2, 5.3) was very low (below 1 particle/ cm^2/yr) in the upper 19 cm of the Martínez core.

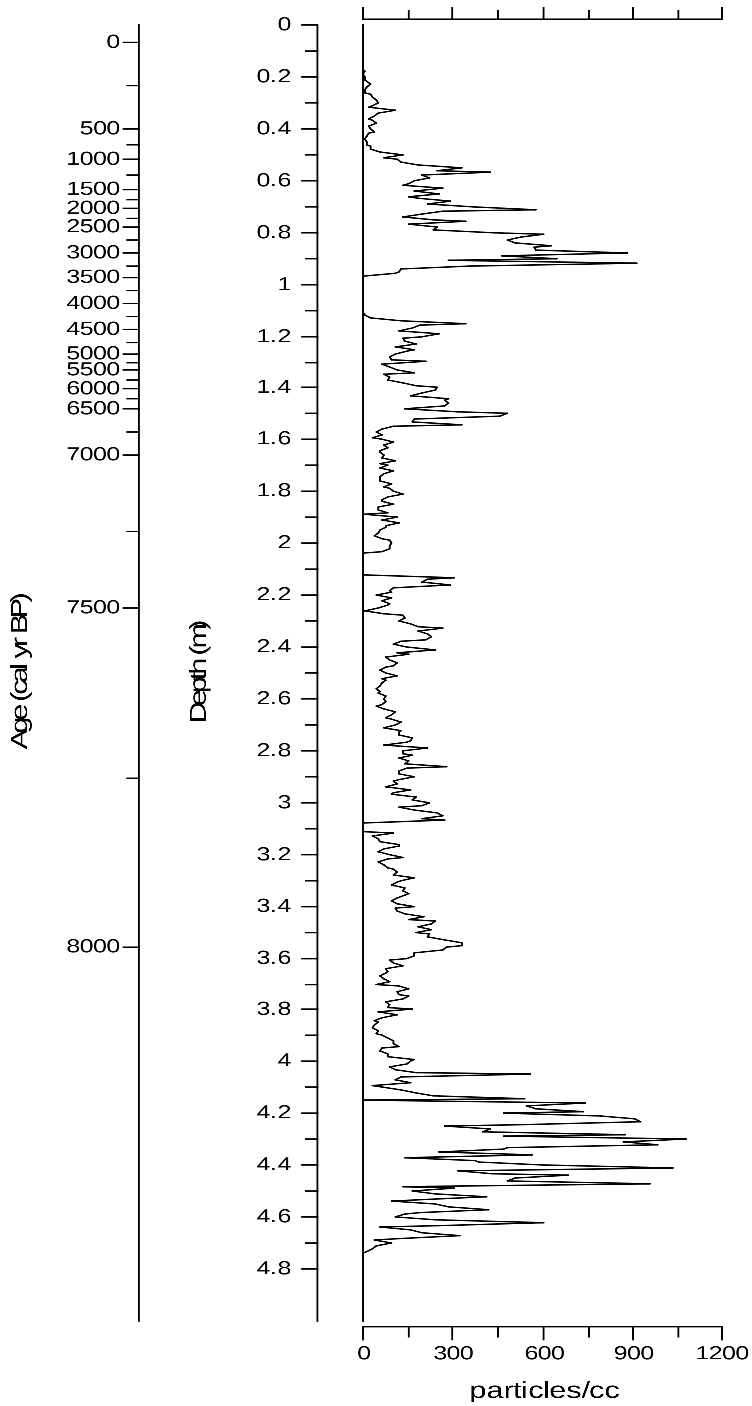

Figure 5.1. Total charcoal concentration in the Laguna Martínez sediment core. Ages are weighted means of the probability distributions of the two-sigma calibrations. The base of the section analyzed corresponds to an age of 8400 cal yr BP (Table 4.2).

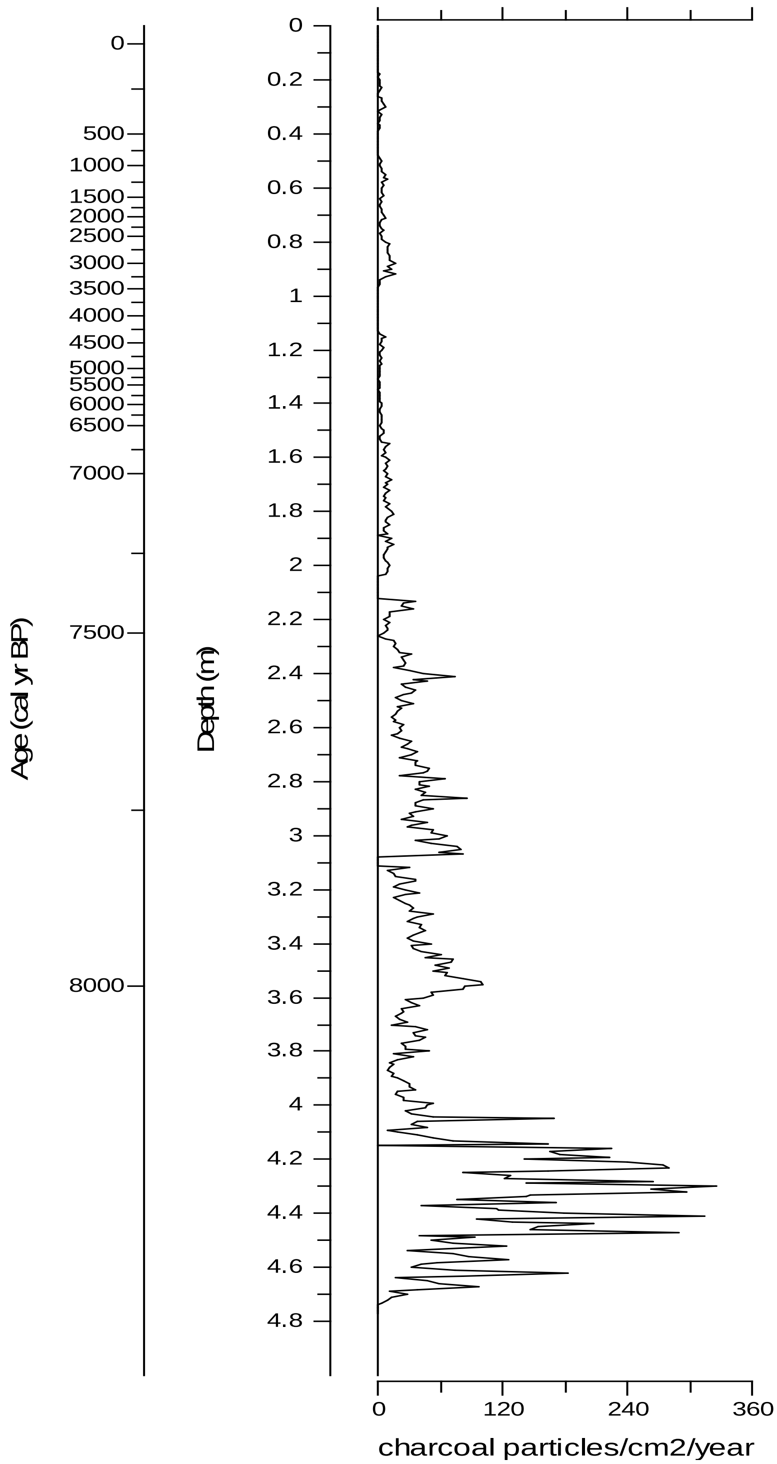

Figure 5.2. Total macroscopic charcoal influx in the Laguna Martínez sediment core. Ages are weighted means of the probability distributions of the two-sigma calibrations. The base of the section analyzed corresponds to an age of 8400 cal yr BP (Table 4.2).

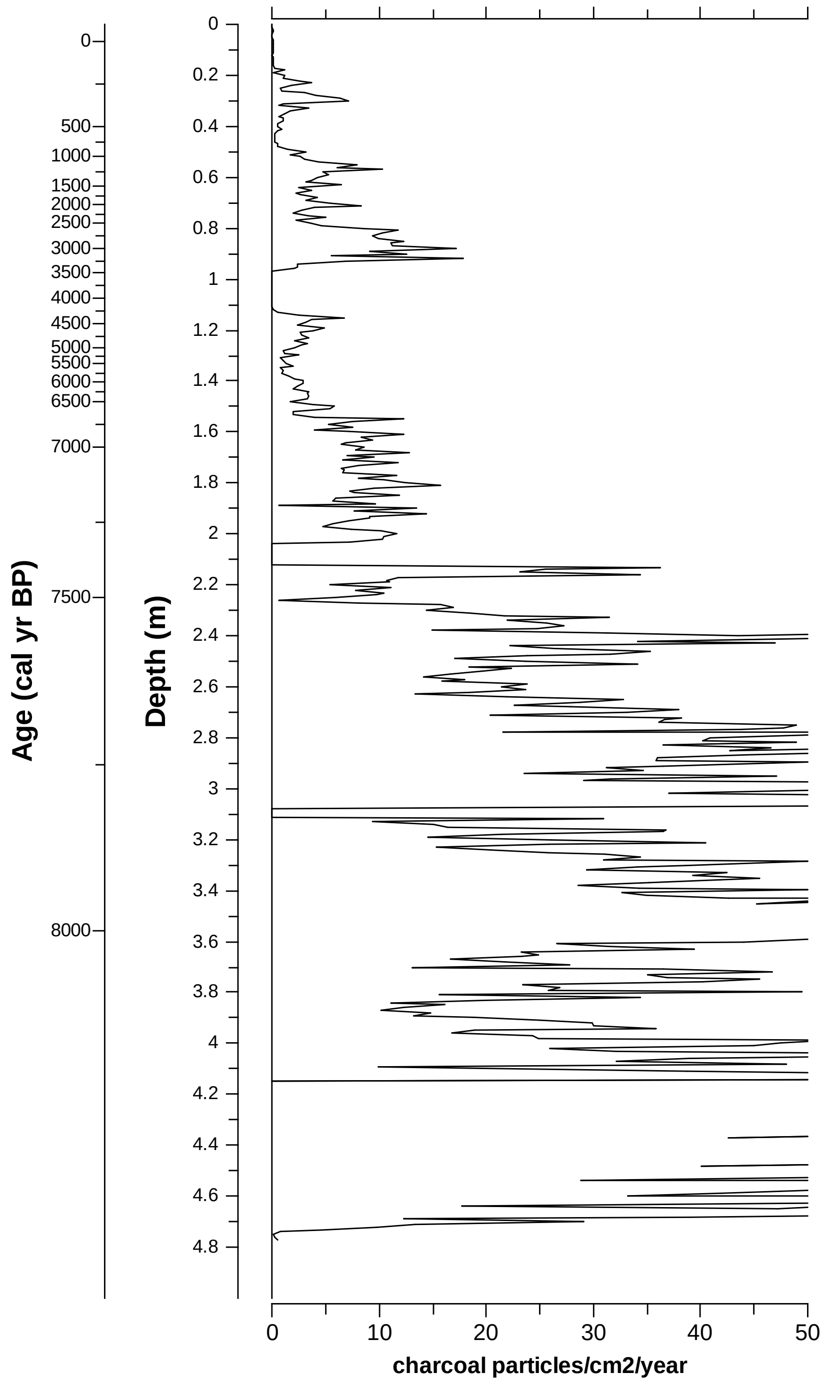

Figure 5.3. Total macroscopic charcoal influx in the Laguna Martínez sediment core. Ages are weighted means of the probability distributions of the two-sigma calibrations. The base of the section analyzed corresponds to an age of 8400 cal yr BP (Table 4.2). ***Same as Figure 5.2 but scale changed to show variations in influx after 7500 cal yr BP.***

Macroscopic charcoal concentration (Figure 5.4) and influx values (Figures 5.5, 5.6) for the 250–500 µm size class are much higher than those for the ≥500 µm size class (Figures 5.7, 5.8, 5.9). The largest difference in concentration between the two sizes is at depths of 0.92–0.8 m, where the concentration of the smaller sized charcoal reached up to 813 particles/cm^3 compared to 118 particles/cm^3 in the ≥500 µm class. The 250–500 µm size fraction represents over 60% of the total charcoal in all but a few levels of the core (Figure 5.10).

Peak-Threshold and Background-Window Width Selection

I selected several different background-window widths and peak-threshold ratios in my experiments using CHAPS. The trial background-window widths were 300, 450, 600, and 900 years. The background-window width selected determines the length of the period over which each of the pseudo-annual interpolated values are averaged. The 900-year background-window width produced a curve that was very smooth and generalized (Figure 5.11). Some peaks that were evident in charcoal influx were eliminated by the 900-year background-window width analysis. The curve produced using the 300-year background-window width matched the charcoal influx almost exactly, but small fluctuations in data between the windows produced many apparently extra peaks (Figure 5.12).

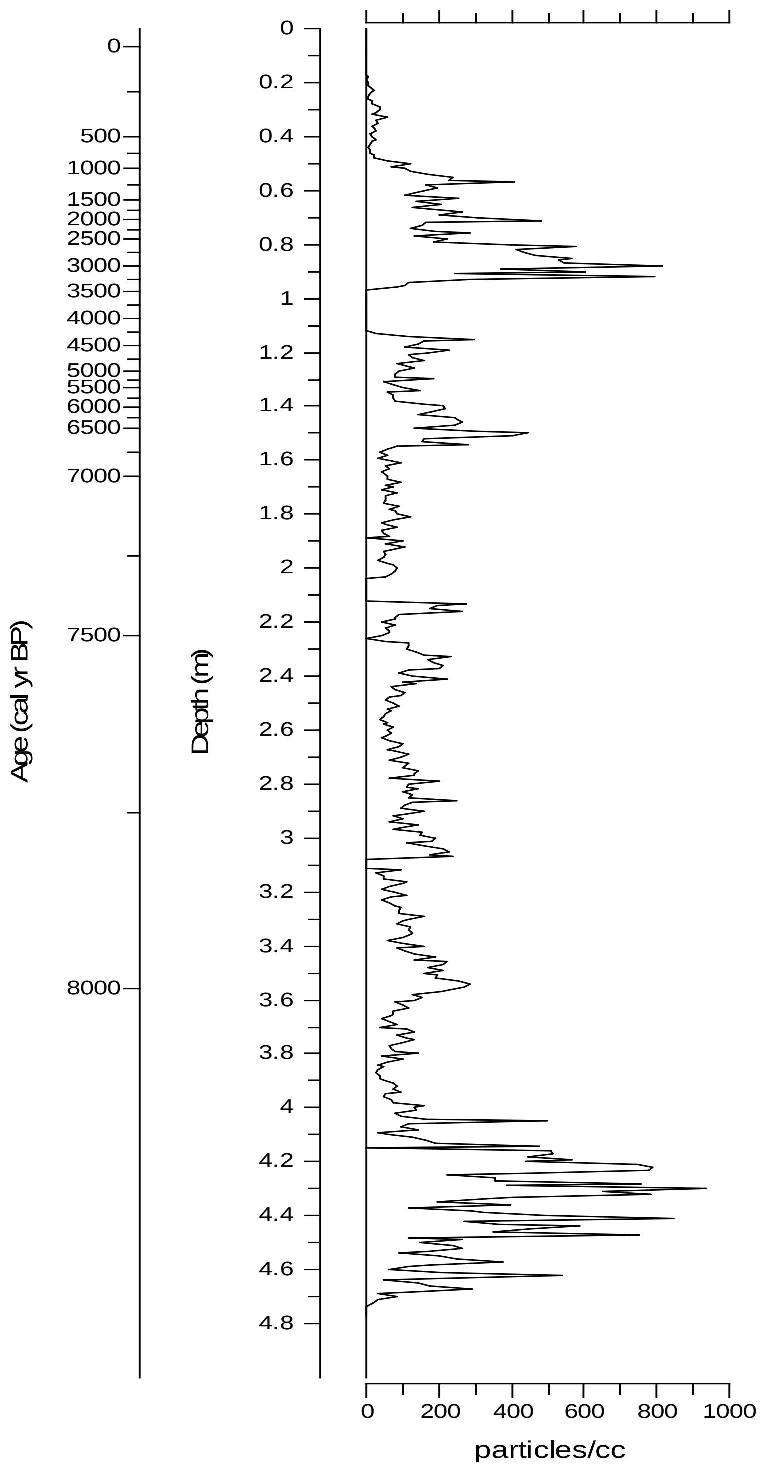

Figure 5.4. Macroscopic charcoal concentration (250–500 µm). Ages are weighted means of the probability distributions of the two-sigma calibrations. The base of the section analyzed corresponds to an age of 8400 cal yr BP (Table 4.2).

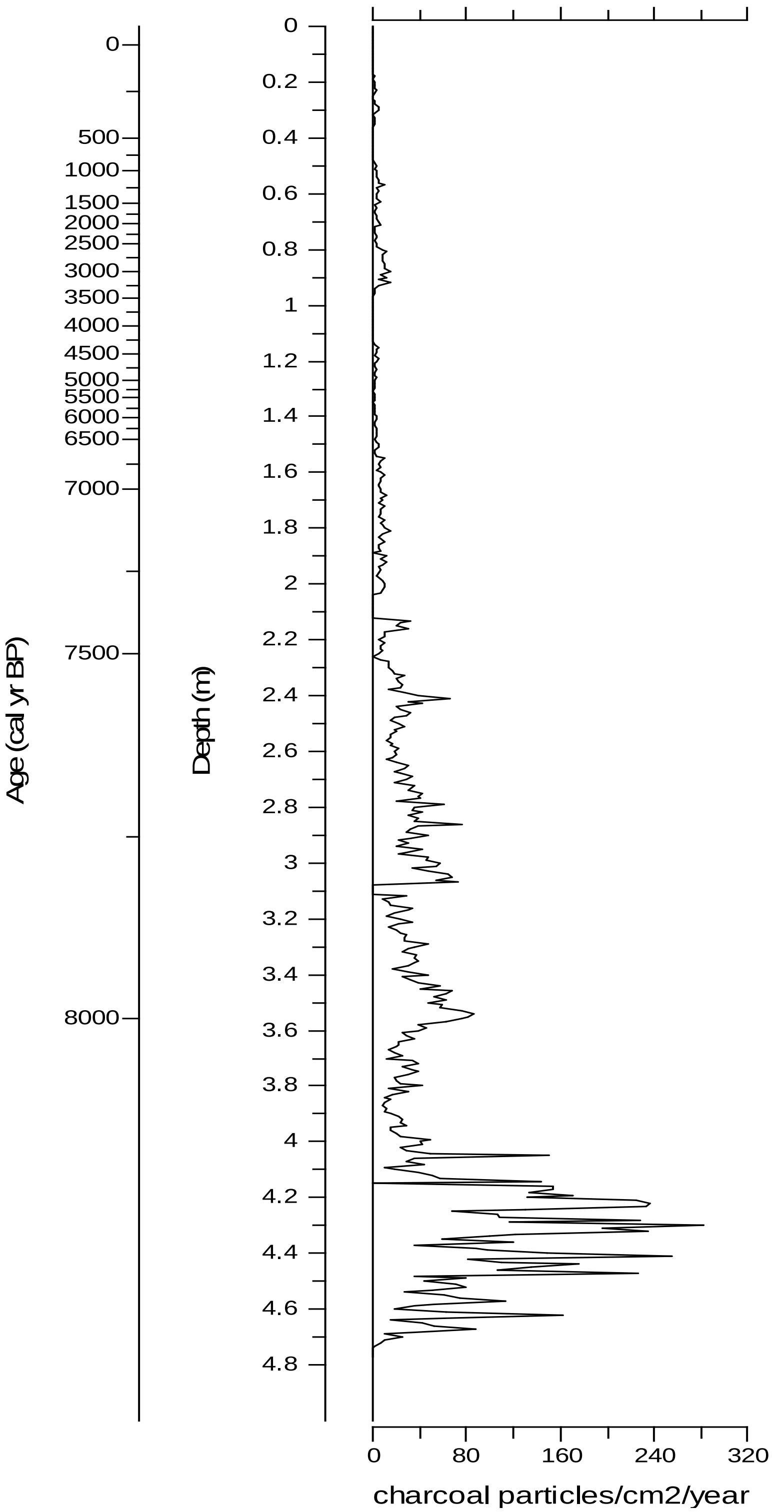

Figure 5.5. Macroscopic charcoal influx (250–500 µm). Ages are weighted means of the probability distributions of the two-sigma calibrations. The base of the section analyzed corresponds to an age of 8400 cal yr BP (Table 4.2).

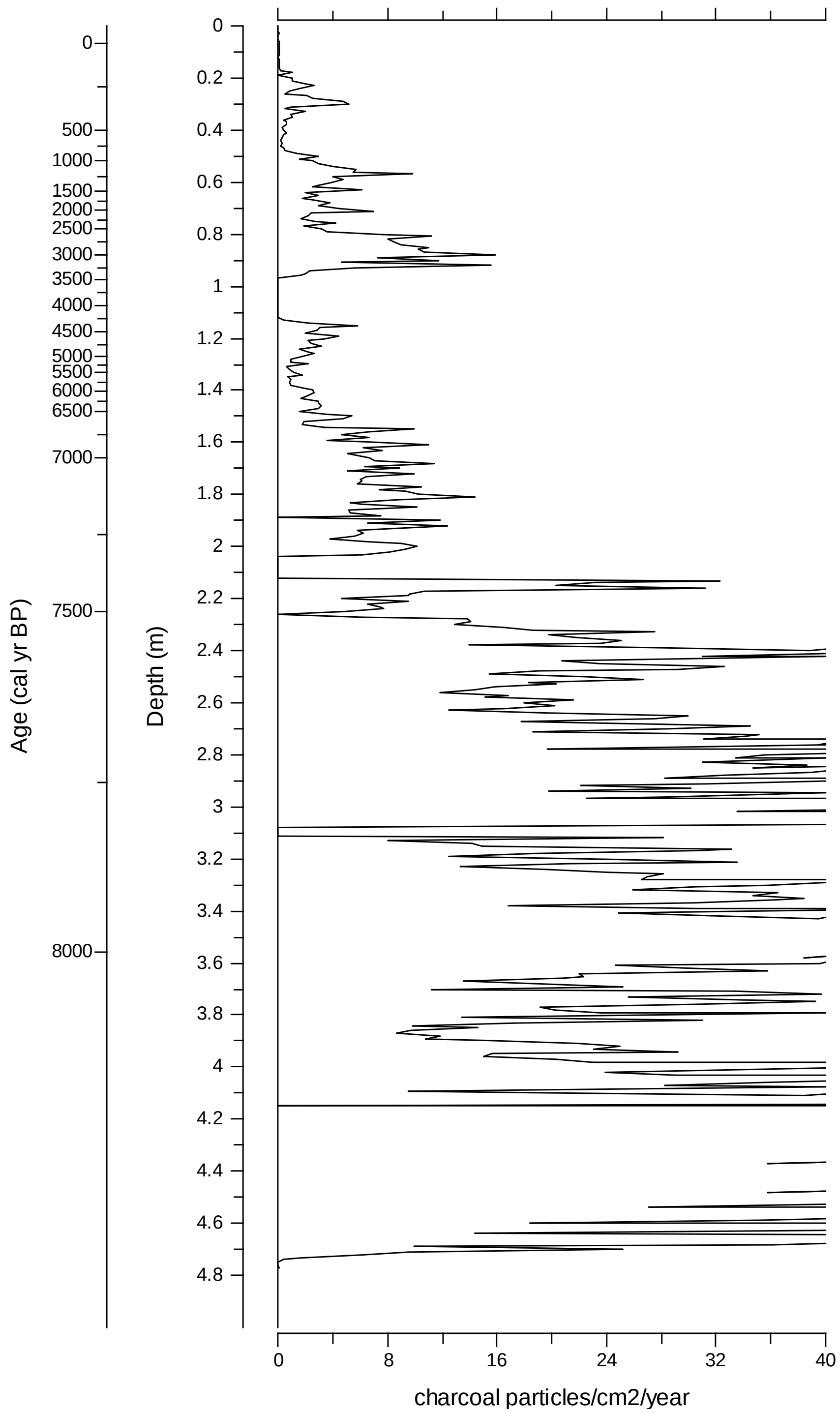

Figure 5.6. Macroscopic charcoal influx (250–500 µm). Ages are weighted means of the probability distributions of the two-sigma calibrations. The base of the section analyzed corresponds to an age of 8400 cal yr BP (Table 4.2). *Same as Figure 5.5 but scale changed to show variations in influx after 7500 cal yr BP.*

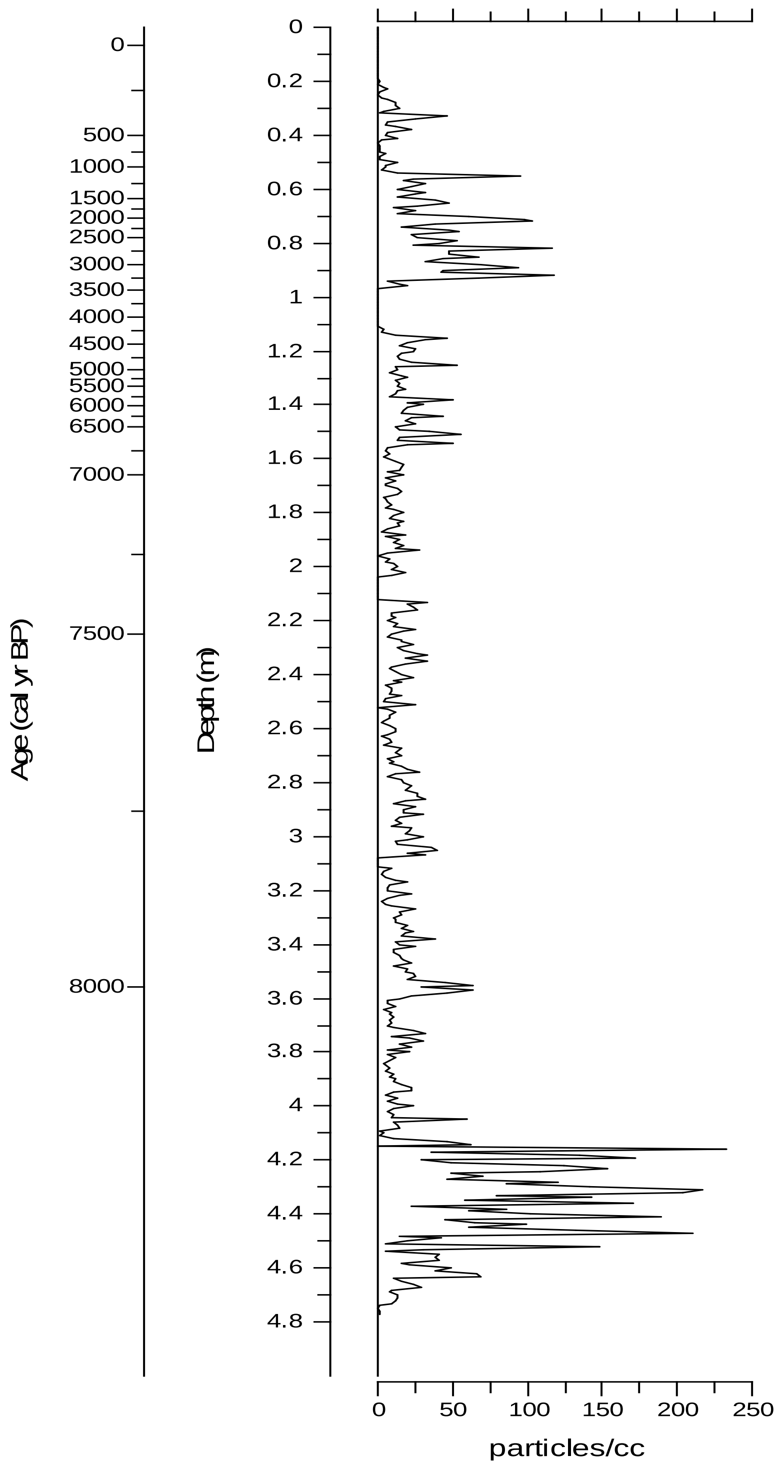

Figure 5.7. Macroscopic charcoal concentration (≥500 µm). Ages are weighted means of the probability distributions of the two-sigma calibrations. The base of the section analyzed corresponds to an age of 8400 cal yr BP (Table 4.2).

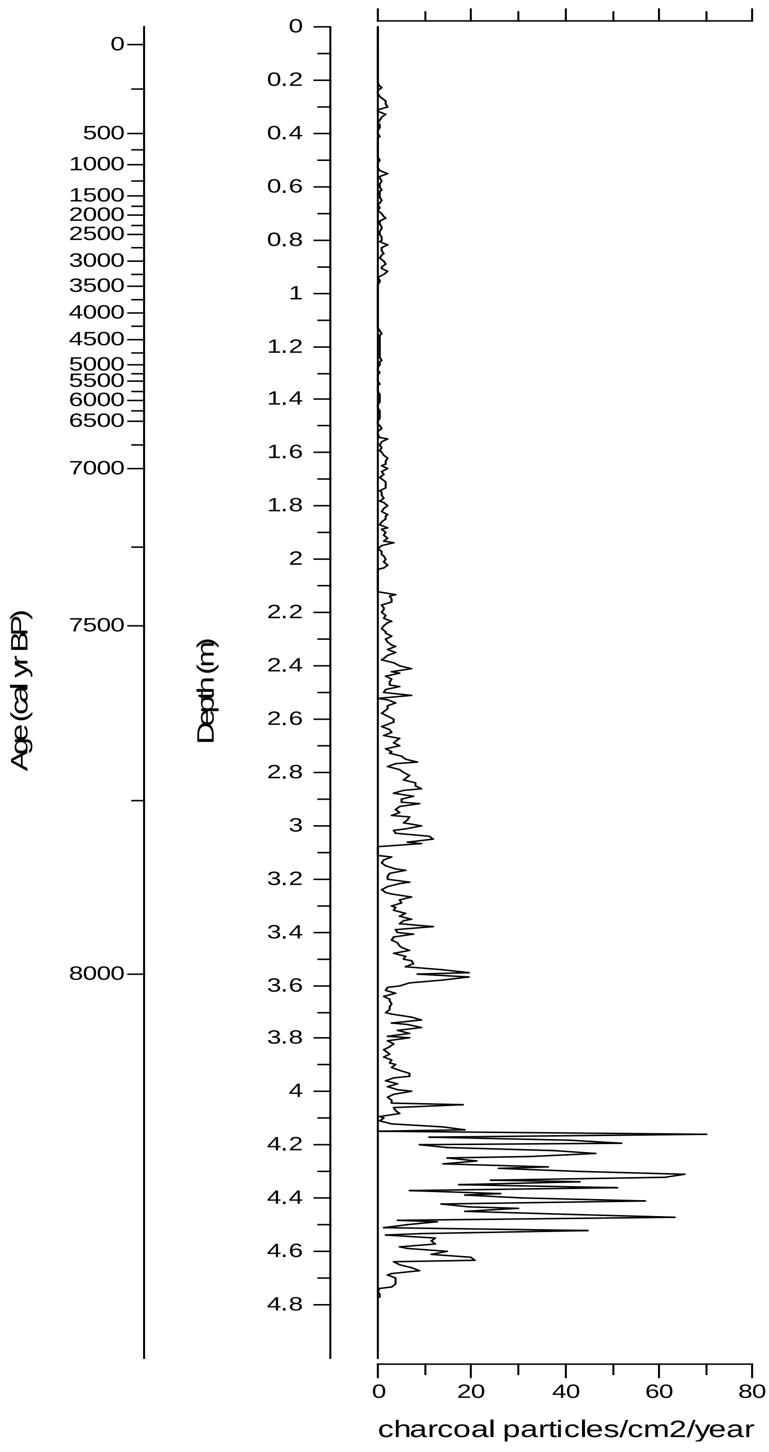

Figure 5.8. Macroscopic charcoal influx (≥500 µm). Ages are weighted means of the probability distributions of the two-sigma calibrations. The base of the section analyzed corresponds to an age of 8400 cal yr BP (Table 4.2).

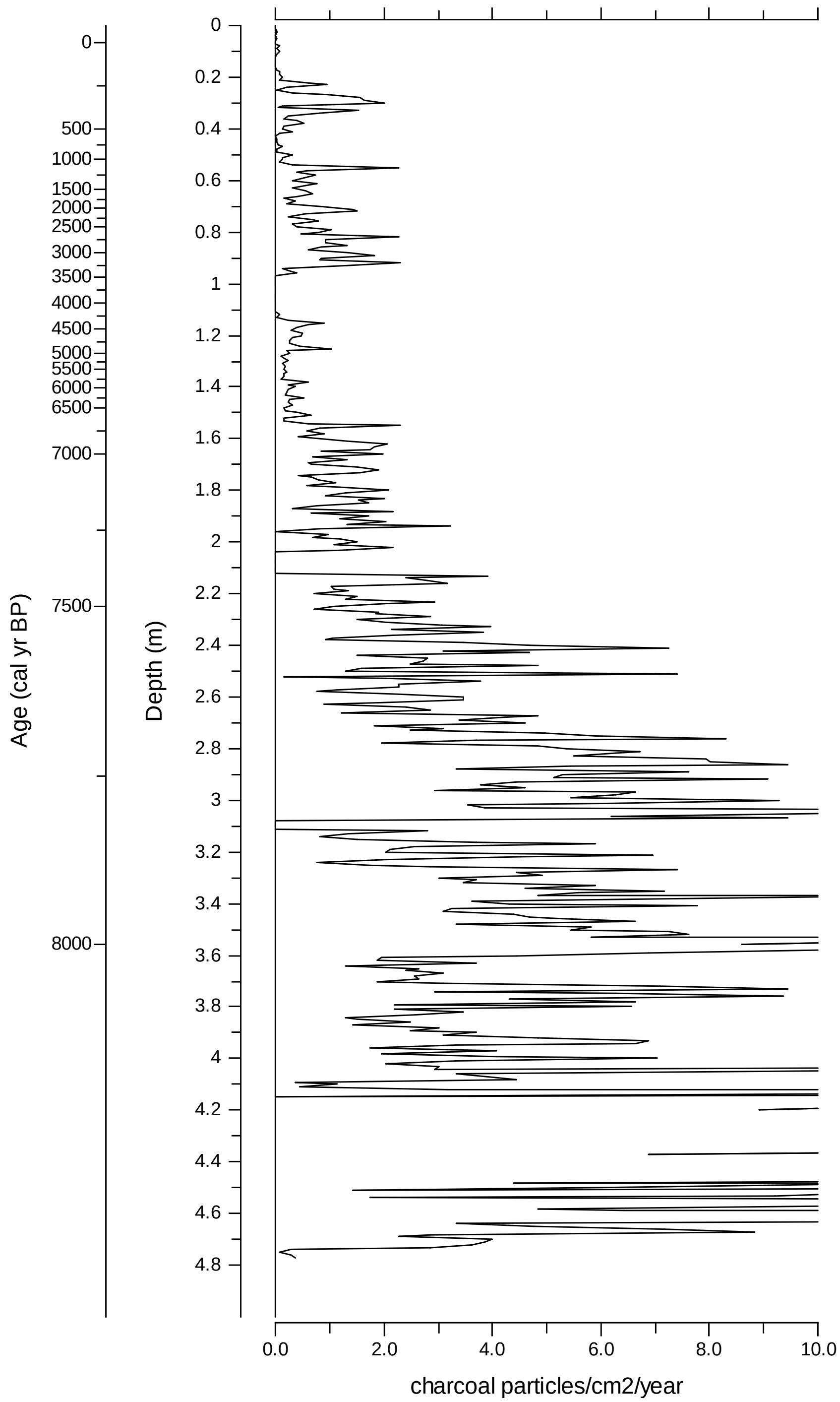

Figure 5.9. Macroscopic charcoal influx (≥500 µm). Ages are weighted means of the probability distributions of the two-sigma calibrations. The base of the section analyzed corresponds to an age of 8400 cal yr BP (Table 4.2). *Same as Figure 5.8 but scale changed to show variations in influx after 7500 cal yr BP.*

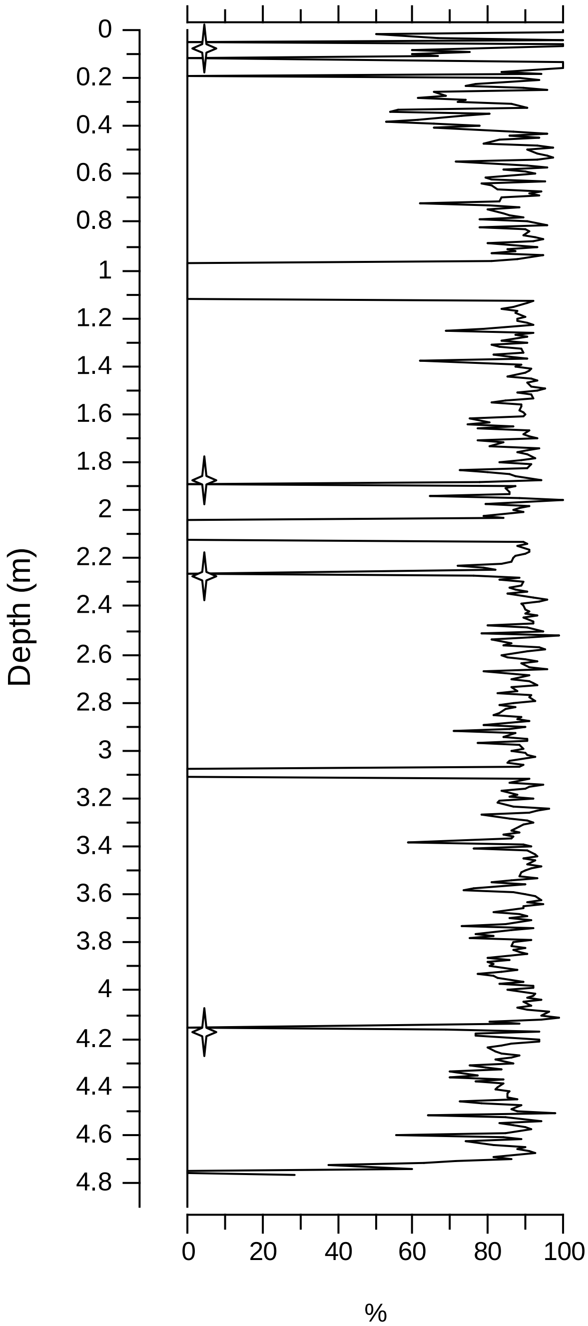

Figure 5.10. Percent of charcoal from the 250–500 µm size class throughout the core. All values of "0%" except where marked with the star symbol represent missing samples because of gaps between core sections.

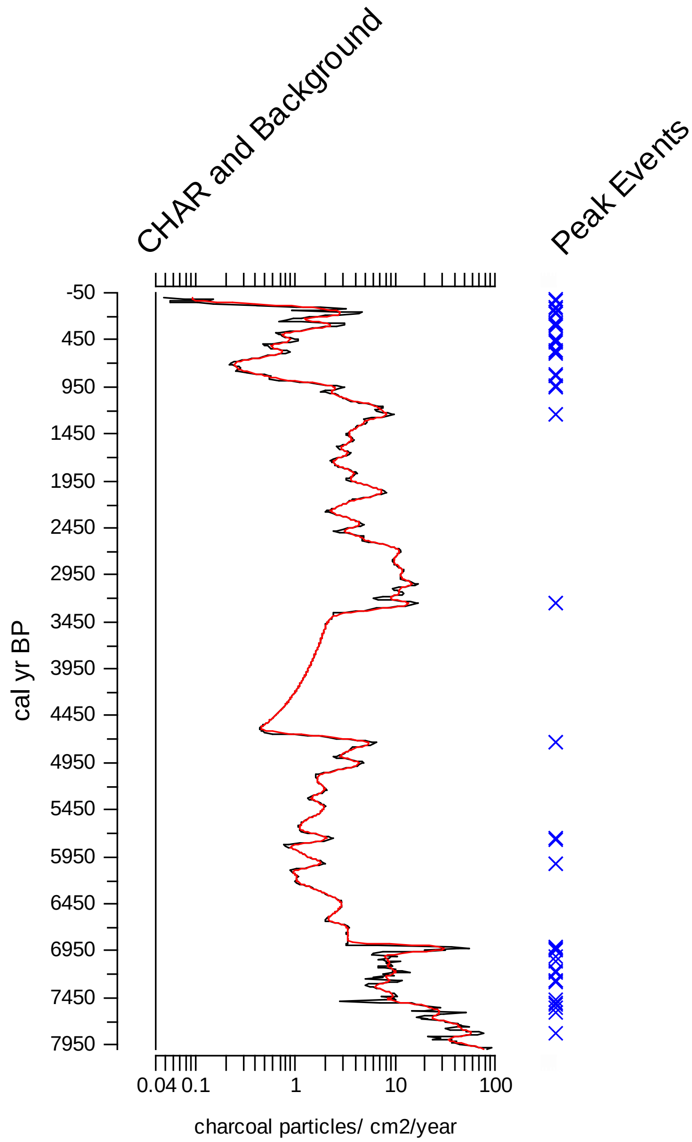

Figure 5.11. CHAPS output using a 900 yr background window width and 1.07 peak threshold ratio. In this and all similar diagrams, the "jog" in the curve between about 4600 and 3400 cal yr BP represents a gap in the core.

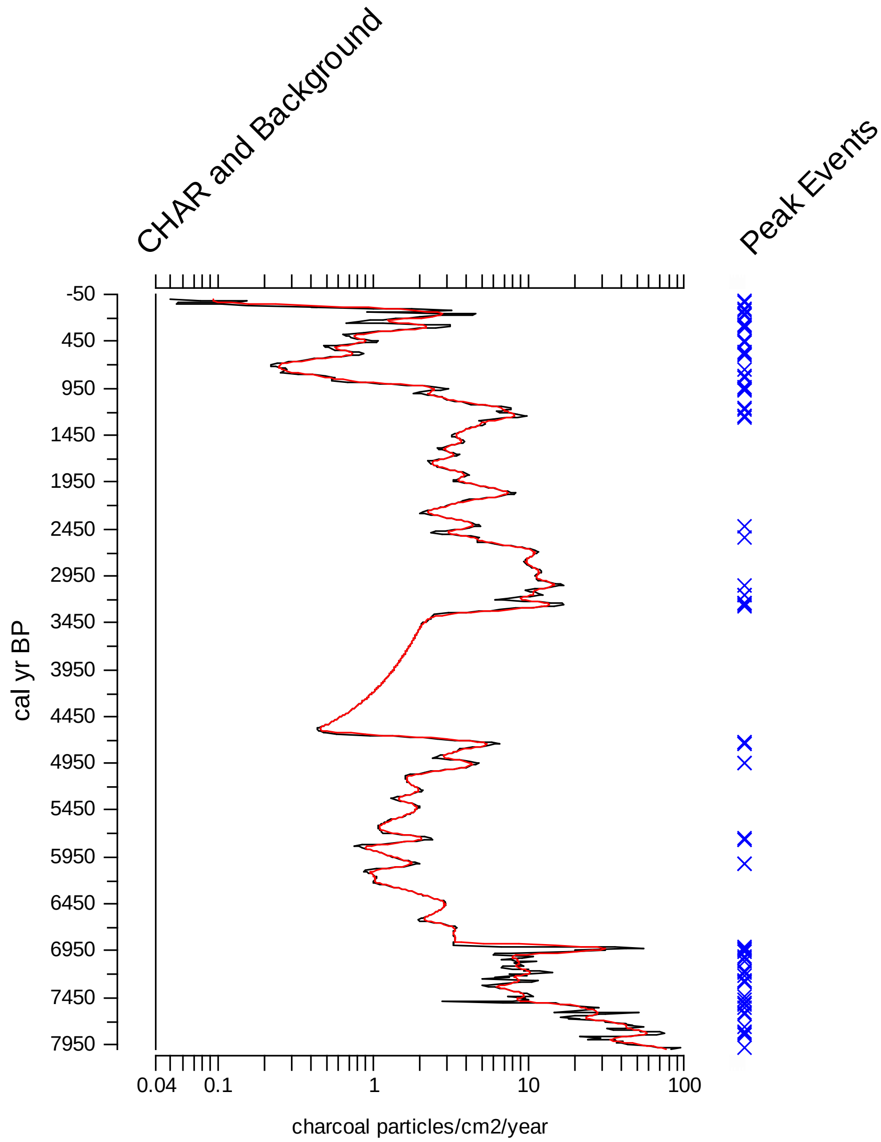

Figure 5.12. CHAPS output using a 300 yr background window width and 1.05 peak threshold ratio.

The 450-year background-window width produced a curve that is slightly smoother than the CHAR record (Figure 5.13). Very large background-window widths (such as 900 years) produced a still smoother curve, but allowed high charcoal influx values from fires during periods of known volcanism shortly after lake formation to influence the CHAPS analysis upcore. The 600-year background-window width (Figure 5.14) produced a curve that was smoother than the CHAR and reduced the amount of years averaged to lower the effects of charcoal from these early fires.

I used multiple peak-threshold ratios along with different window widths in my experiments with CHAPS. The peak-threshold ratio determines what is considered a peak in the analysis. For example, using a peak-threshold of 1.05 means that CHAR must be 1.05 times higher than the background to be considered a peak. The peak-threshold values I selected to experiment with for this study were 1.05, 1.07, 1.08, 1.10, 1.12, and 1.15. Applying these different peak-threshold ratios with the 600 year background-window width produced 78, 49, 42, 31, 23, and 14 peaks respectively, (Figure 5.14 and other figures not shown).

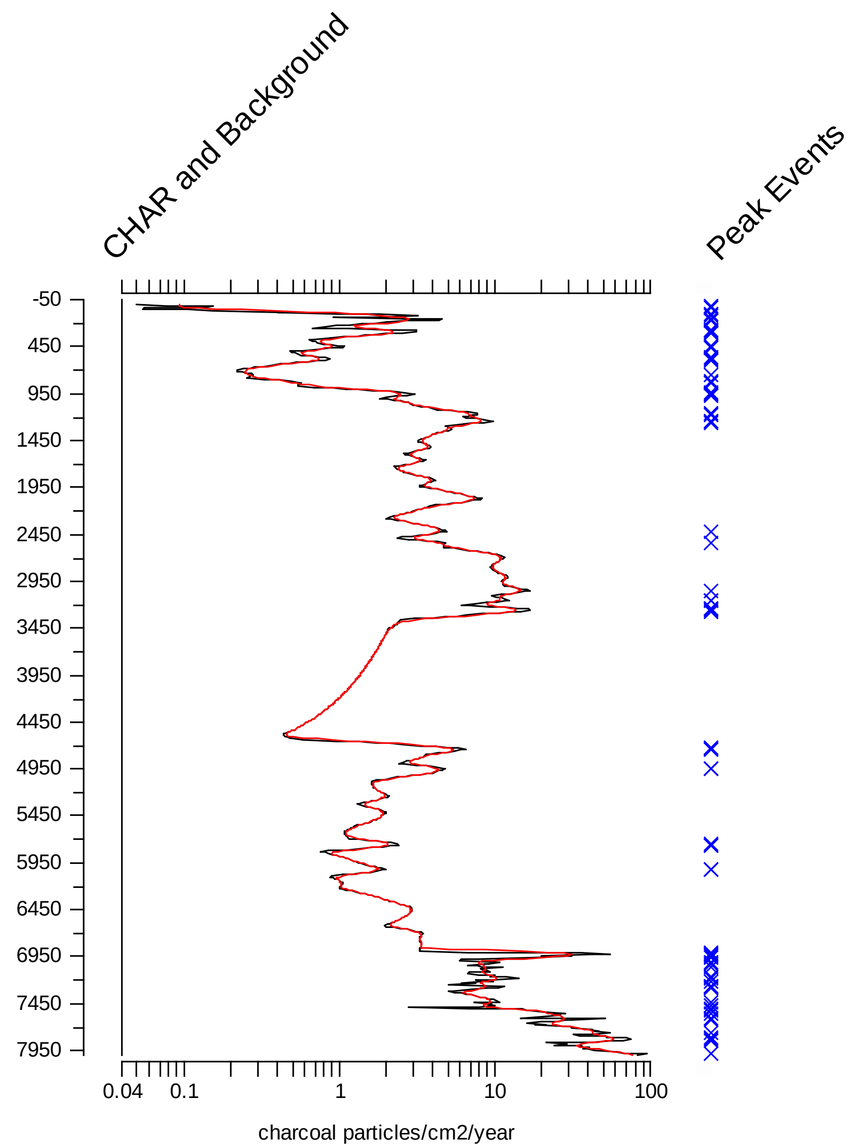

Figure 5.13. CHAPS output using a 450 yr background window width and 1.05 peak threshold ratio.

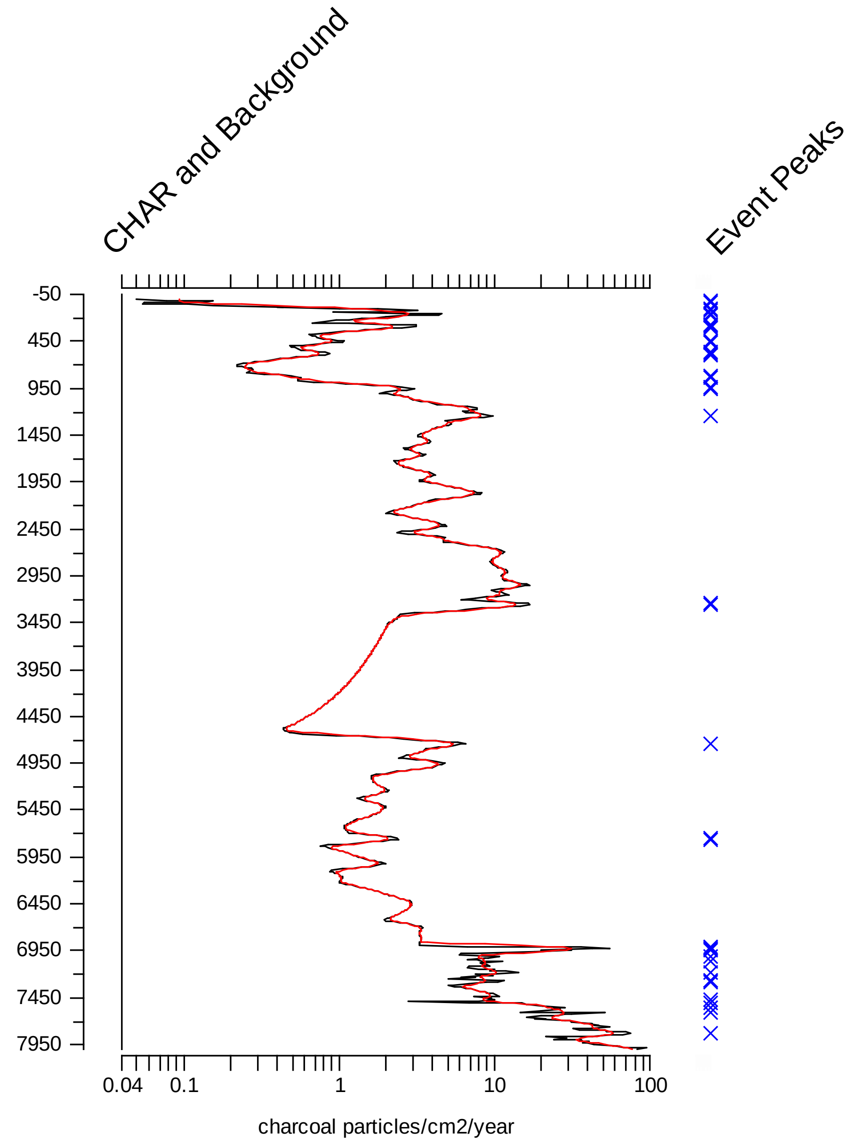

Figure 5.14. CHAPS output using a 600 yr background window width and 1.08 peak threshold ratio.

Chapter 6

Discussion

My analysis of macroscopic charcoal in lake sediments of Laguna Martínez provides a high-resolution fire history extending to ca. 8400 cal yr BP. This study demonstrates that fires ignited naturally or by people have long altered the tropical dry forest ecosystem at Laguna Martínez. Macroscopic charcoal influx has varied during the history of the lake, and likely so has the source of fires. The macroscopic charcoal record supports the idea that humans used fire near the lake around or prior to the time of the earliest maize pollen deposition at Laguna Martínez, around 5500 cal yr BP (Arford, 2007). High macroscopic charcoal influx and concentration found much earlier than the first evidence of maize agriculture at Laguna Martínez could indicate earlier human-set fires not associated with agriculture, or possibly natural fires set by lightning or volcanism.

Very high charcoal concentration and influx values in the earliest portions of the Martínez record reveal an environment where fire was very common. Several lava and pyroclastic flows extended from the west and southwest flanks of the Miravalles volcano about 8000 years ago (Alvarado, 2000; Arford, 2007) and it is likely that the charcoal deposited in the lower section of the lake profile resulted from fires set by this volcanic activity. Macroscopic charcoal influx decreased after 7500 cal yr BP, but still remained moderate until 6700 cal yr BP. Volcanic eruptions have been identified in this time interval, so these fires may have a different cause. They may have been set by lightning, or perhaps by people visiting the area to hunt or for other purposes. After 6700 cal yr BP,

macroscopic charcoal influx values decreased dramatically, indicating that fires became less frequent within the watershed. Macroscopic charcoal influx remained low to moderate throughout the remainder of the sediment core, in comparison with values in the lower part of the core. Macroscopic charcoal concentration showed a small peak during the period with the evidence of the oldest maize pollen (5500 cal yr BP). Influx was low at this time but increased after 5500 cal yr BP, as did concentration, though both curves are spiky. Concentration and influx values were also elevated from about 3200–2600 cal yr BP, near 2000 cal yr BP, and near 1200 cal yr BP. The presence of pollen evidence of maize cultivation during both of these intervals argues that the fires were associated with human activity, possibly the clearing or maintenance of agricultural fields. They may also have been set accidentally from cooking fires.

How do patterns of macroscopic charcoal abundance relate to pollen evidence of local maize cultivation, and how does this differ between the time of early maize cultivation and later?

The earliest maize cultivation yet documented in Costa Rica occurred near Laguna Martínez. Arford and Horn (2004; Arford, 2007) discovered the earliest maize pollen grain at a depth of 135 cm in the Laguna Martínez sediment core, and dated the interval to ca. 5500 cal yr BP (4760± 40^{14}C). Arford (2007) discovered an increase in microscopic charcoal influx slightly before and during the time of the earliest maize pollen. The high-resolution macroscopic charcoal record also indicates slightly elevated charcoal concentrations just prior to the first maize pollen grain, and a subsequent

increase in both charcoal influx and concentration (Figures 5.1–5.3). This charcoal likely reflects local anthropogenic fires used to clear land for maize cultivation. Arford (2007) found a shift from tree pollen to grass and sedge pollen at this time.

The macroscopic charcoal record illustrates that local fires continued to burn frequently up until about 1000 cal yr BP. The macroscopic charcoal data and the microscopic charcoal record from Arford (2007) suggest that agricultural slash and burn techniques were being used to clear more fields and maize cultivation was gaining importance throughout this period, not only in the Laguna Martínez watershed but, throughout the Miravalles region.

Archaeological studies near the Miravalles volcano conducted by Norr (1982–1983) and Ryder (1982–1983) found that indigenous populations had been declining in the region for the past 2000 years. The macroscopic, microscopic, pollen, and archaeological proxies indicate that fire activity was lower near Laguna Martínez in the last 1000 years, perhaps because most of the inhabitants had migrated to other areas in Costa Rica by this time (Arford, 2007). However, low macroscopic charcoal concentrations and influx indicate that small groups of inhabitants continued doing some burning.

How does the macroscopic charcoal record compare to the microscopic charcoal and pollen record from Laguna Martínez developed by Arford (2007)?

The Laguna Martínez high-resolution macroscopic charcoal record is visually congruent with the microscopic charcoal record (Figure 6.1). The peaks of macroscopic

charcoal match up with the peaks in microscopic charcoal during some instances, and the trends of both records are similar. There are four periods (8350–8150, 8000–7950, 5250–4350, and 3250–1050 cal yr BP) in the core where distinct peaks occur in both records.

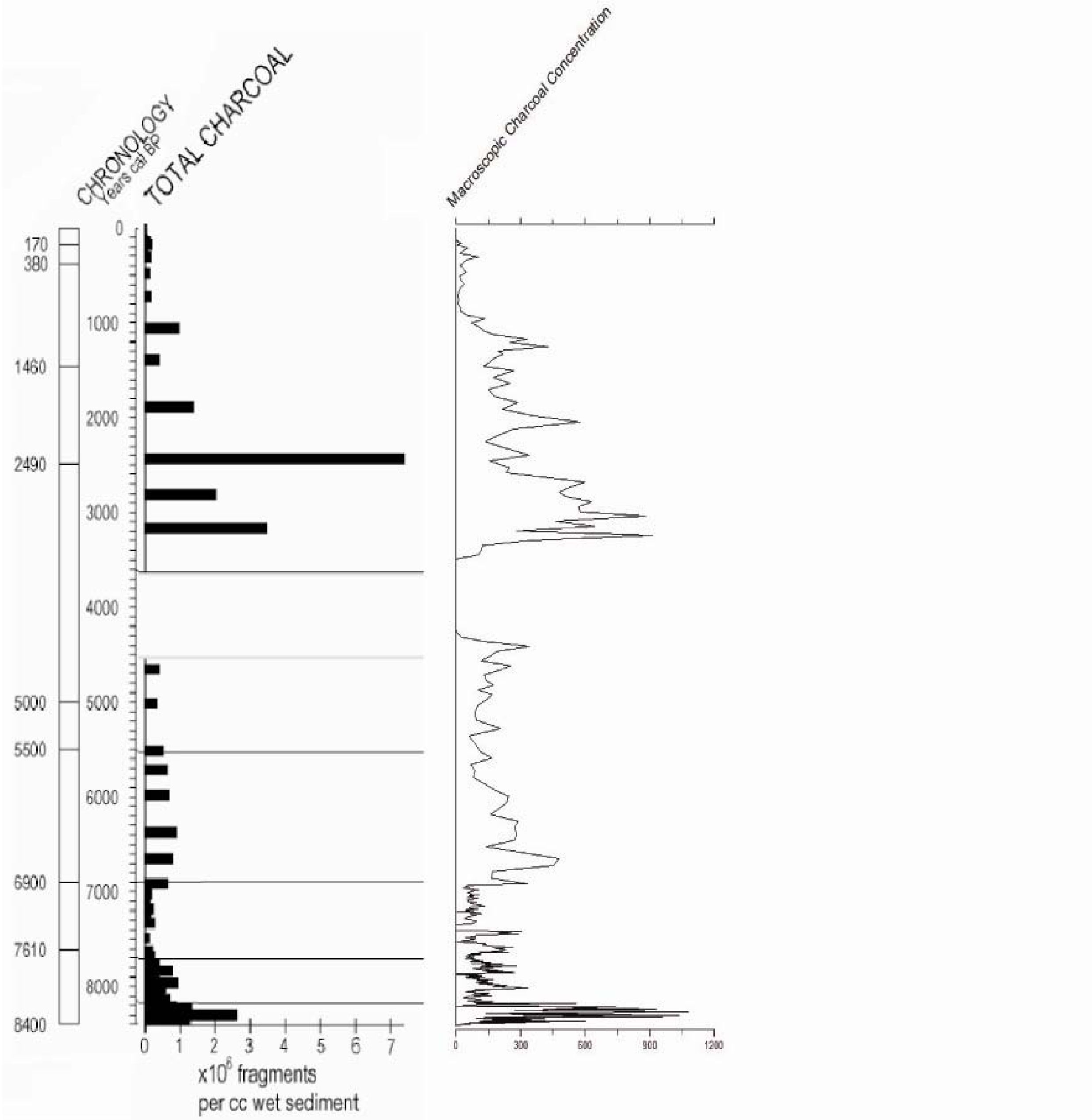

Figure 6.1. Comparison of the microscopic (Arford, 2007) and macroscopic charcoal concentration records from Laguna Martínez. Macroscopic charcoal is expressed as fragments per cc wet sediment.

The earliest fire events indicated in the Laguna Martínez charcoal record are at depths from 4.62–4.05 m, soon after 8400 cal yr BP. These fires occurred in Arford's (2007) pollen zone 6 (>8000 yr cal BP) (Figures 6.2). It is doubtful that they were anthropogenic fires based on results from archaeological studies in the region (Norr 1982–1983, Ryder 1982–1983). Arford (2007) found evidence of *Pityrogramma* fern spores and Asteraceae pollen during this period. These are two taxa that can be used as indicators of disturbance. Tryon and Tryon (1982) described *Pityrogramma* as a pioneer fern species that tends to colonize recently disturbed sites.

In Arford's (2007) pollen zone 5 (8000–7400 cal BP), the macroscopic charcoal record for Laguna Martínez indicates that fire was still prevalent during this period, but there was a slight decrease in charcoal influx. In this zone, the largest spike in charcoal indicated a charcoal concentration about one fourth that of the macroscopic charcoal concentration of the largest peak in Zone 6 (Arford, 2007). Arford (2007) also found a decrease in total microscopic charcoal influx (cm^2/year) in his study. The influx values for Zone 5 in Arford (2007) were slightly half of the influx values found in Zone 6 (Figure 6.3, 6.4). It seems that the area was still marked by disturbance, probably still by volcanism during this period. But, there may have been less disturbance from fire in the region during this period than in the times prior to and just after the formation of Laguna Martínez.

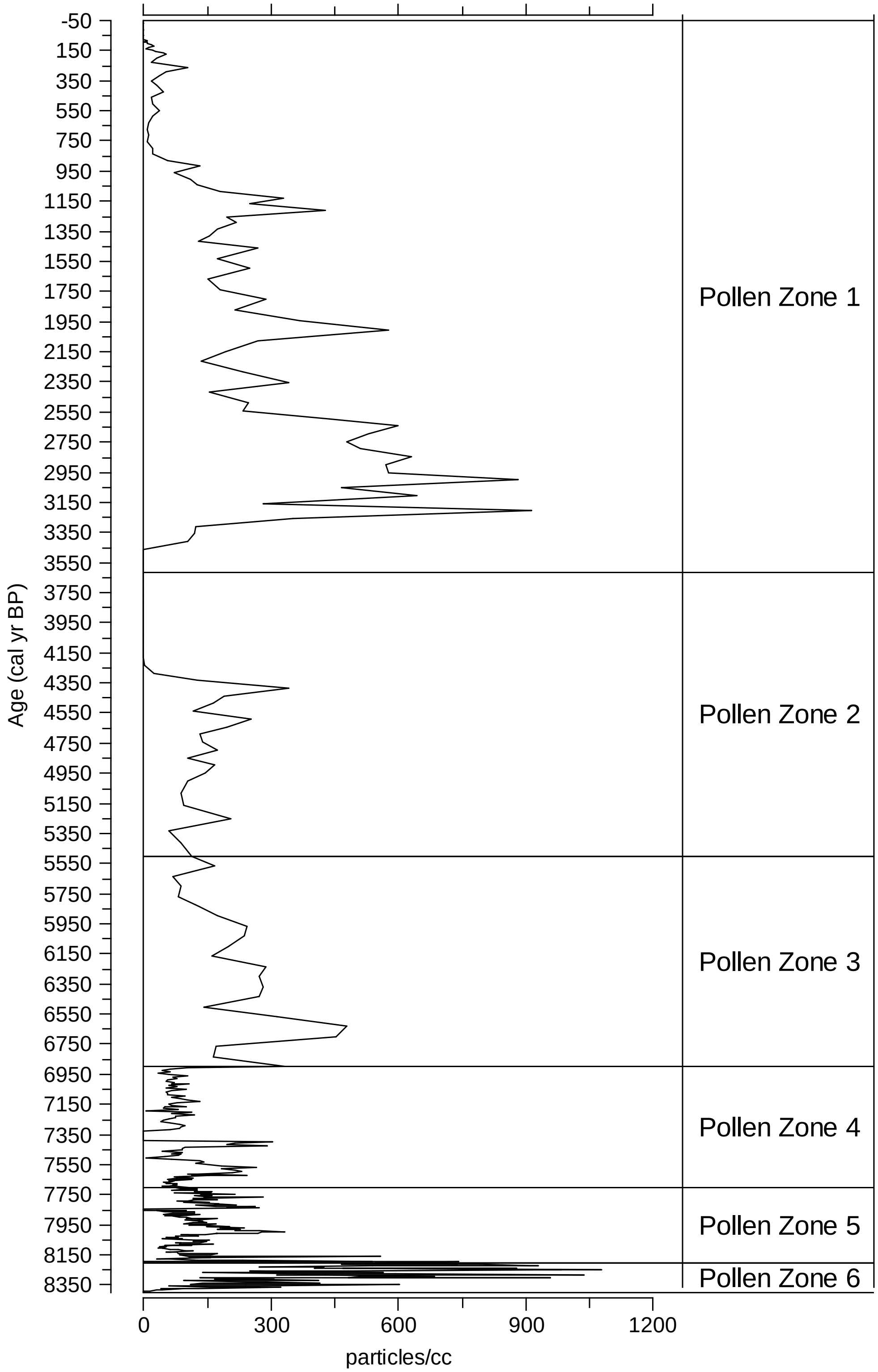

Figure 6.2. Total Macroscopic Charcoal concentration and Arford's (2007) pollen zones. Note that values are plotted by time rather than by depth as in Chapter 5.

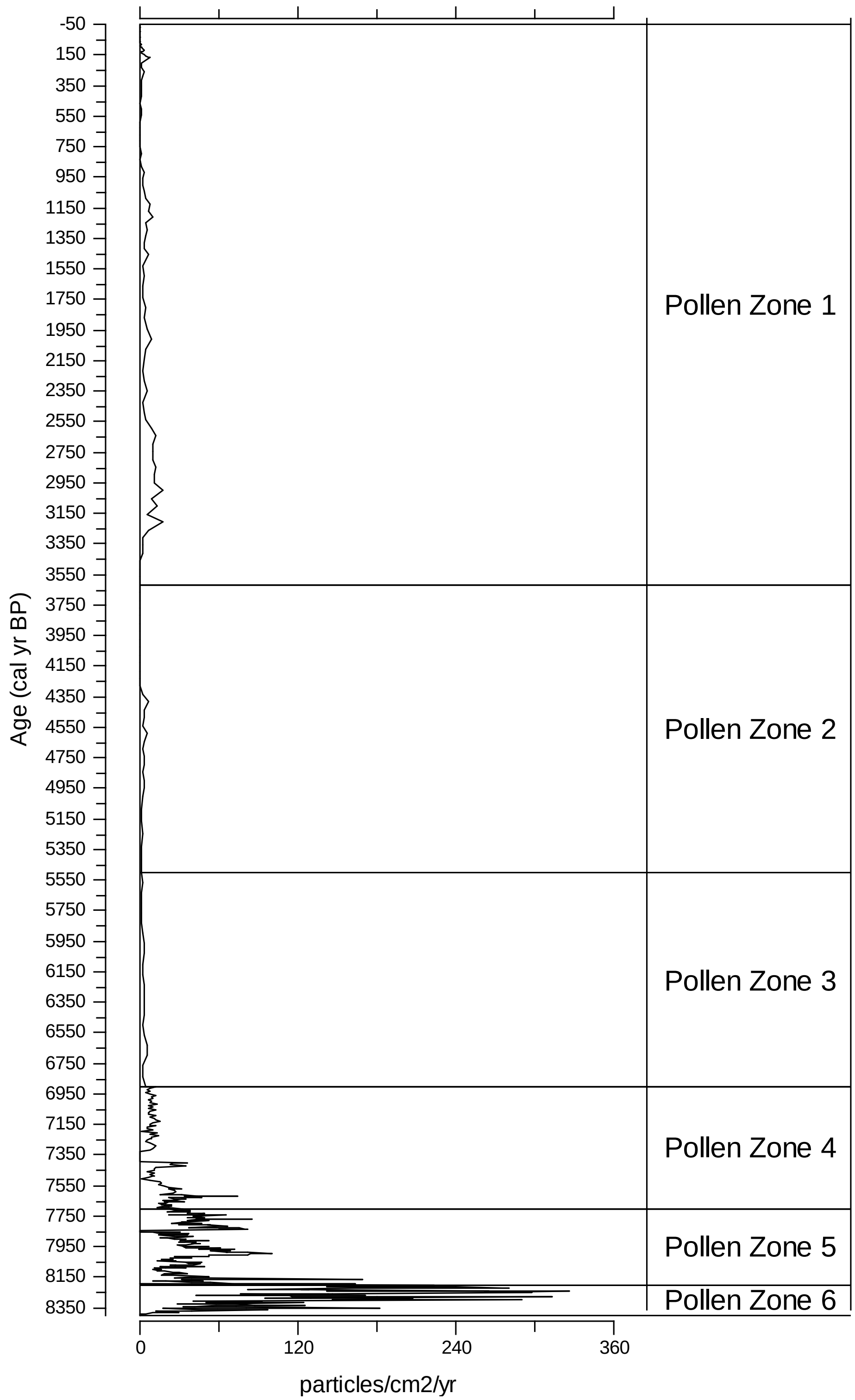

Figure 6.3. Macroscopic charcoal influx and Arford's (2007) pollen zones.

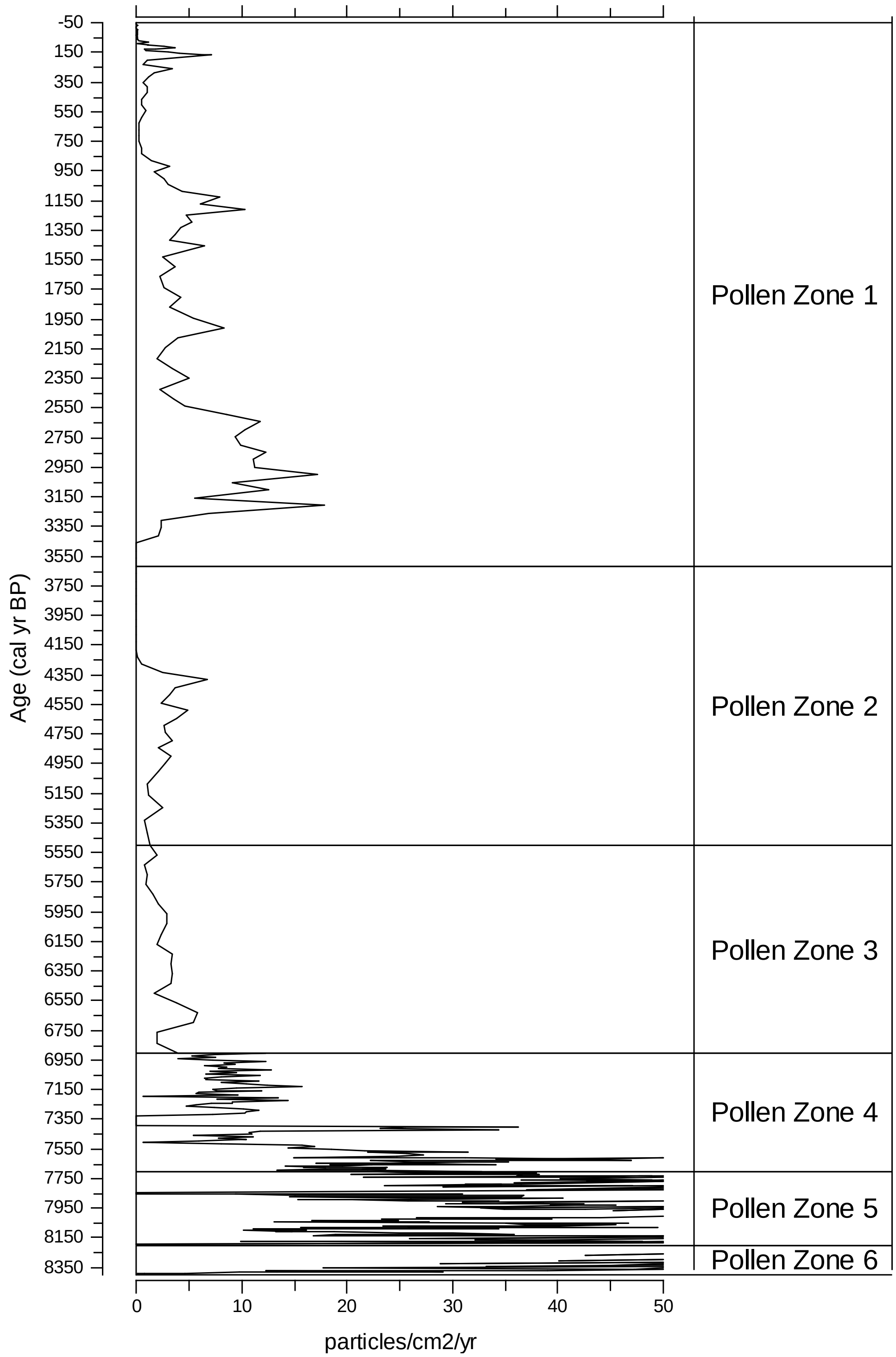

Figure 6.4. Macroscopic charcoal influx and Arford's (2007) pollen zones. *Same as Figure 6.3 but with scale altered to reveal variation in charcoal influx after 7500 cal yr BP*.

Arford's pollen zone 4 (7700–6900 cal yr BP) is a period of transition from the disturbance regime brought about through volcanism and regrowth with a changing climate. The macroscopic charcoal record shows that fire events were moderate to high in number from about 7600 to 7400 cal yr BP. Macroscopic charcoal influx decreased from high to moderate levels, suggesting that fire frequency decreased throughout the period. Arford (2007) found microscopic charcoal to be very low during this period. Based on his pollen results, he concluded that the local area around Laguna Martínez was moister and that the moisture limited the amount of dry fuels to burn. The increased moisture and lower fire frequency allowed closed forests to develop around Laguna Martínez (Arford, 2007). The moderate to high macroscopic charcoal influx values found in this study paint a different picture of the role fire played in the ecosystem in the Laguna Martínez watershed. The macroscopic charcoal data indicate that the area around the lake was still burning frequently. It is possible that the microscopic charcoal record is indicative of fire frequency decreasing within the region, while climate and human activity still allowed and promoted fire ignition locally near the lake. Also, the macroscopic charcoal record is a high-resolution proxy and the microscopic charcoal is a low-resolution proxy. The low-resolution microscopic charcoal may have been sampled at levels with low charcoal concentration and have missed levels with moderate to high levels of charcoal concentration. The high-resolution macroscopic charcoal proxy was sampled at contiguous intervals, capturing the whole fire history picture.

In pollen zone 3 (6800–5500 cal yr BP) (Arford, 2007), the macroscopic charcoal particle influx dramatically decreased from the values found in pollen zone 4. In contrast, Arford (2007) found a moderate increase in microscopic charcoal particles

during this period. There is lower variation in macroscopic charcoal influx during this period. The macroscopic charcoal record showed a slight decrease in charcoal particle influx between 6400 and 6200 cal yr BP, while microscopic charcoal fragments were not found during this same period. After 6200 cal yr, the charcoal influx decreased a little more steadily. Arford (2007) suggested that Laguna Martínez had a moister climate in pollen zone 3. The moister climate would have limited the amount of dry fuels available to be burned, an interpretation that appears supported by the steep drop off in charcoal influx.

In pollen zone 2 (5500–3620 cal yr BP), the macroscopic charcoal record indicates a fire regime similar to that of pollen zone 3, but with a slight increase in influx up until the gap in the sediment core. This includes a minor spike in charcoal concentration around the time when the first maize pollen grain was found (5500 cal yr BP). A small spike of microscopic charcoal was also evident at this time and a bit beforehand (Arford, 2007). The charcoal evidence indicates that humans within the Laguna Martínez watershed were using fire to clear land for maize agriculture. This may have been happening at other lakes in the region, but by chance, maize pollen was not captured at this early of a date in the other lakes sampled.

In the beginning to middle of pollen zone 1 (3800 cal yr BP to the present), the macroscopic charcoal record for Laguna Martínez indicates that fire was a significant factor in the environment. Influx in macroscopic charcoal during the first third of pollen zone 1 was almost three times higher than the largest influx peaks found in pollen zone 2. Arford (2007) also found elevated microscopic charcoal values in pollen zone 1, followed by a steady decline in microscopic charcoal. In the last 1000 cal yr BP, the macroscopic

charcoal influx (charcoal particles/cm^2/year) also decreased. The low macroscopic charcoal influx, low microscopic charcoal influx, and pollen shifts in the Laguna Martínez watershed indicate that anthropogenic fire activity had almost ceased around 1100–1000 cal yr BP. Some inhabitants had apparently left the area, allowing closed forests to develop and tree pollen to become dominant (Arford, 2007). However, some maize was still being cultivated and some burning was taking place to prepare or maintain fields. Within the last 1000 cal yr BP, small peaks in microscopic and macroscopic charcoal influx were found by both Arford (2007) and this study. Some of these peaks in the last century or two may be from fires used to clear land for pasture within the watershed and regionally.

How does the Laguna Martínez macroscopic charcoal record compare to the macroscopic charcoal record from nearby Laguna Estero Blanco?

Comparing the high-resolution macroscopic charcoal records from Laguna Estero Blanco (Schlachter, 2005) and Laguna Martínez, it is evident that the lakes share a somewhat similar fire history. Schlachter found charcoal influx at Laguna Estero Blanco was high from 8050–7400 cal yr BP. Charcoal influx declined slightly through 7400–3600 cal yr BP. At Laguna Martínez, charcoal influx was highest from 8400–8000 cal yr BP, likely reflecting volcanism early in the lake's history. Charcoal influx then steadily decreased until about 3420 cal yr BP, when fires began to play a large role in agriculture for populations within the watershed. The timing of this late Holocene increase was similar at the two sites. At Laguna Estero Blanco, as at Laguna Martínez, there was a

peak in macroscopic charcoal prior to the first pollen evidence of maize cultivation (charcoal peak at ca. 3600 cal yr BP; first maize pollen at 2788 cal yr BP; Schlachter, 2005; Arford, 2007).

Schlachter (2005) found that macroscopic charcoal influx and concentration significantly decreased again after the peak at 3600 cal yr BP until 400 cal yr BP. He postulated that this was a time when agricultural fields had already been converted from forested lands, and humans were growing crops on these cleared lands near the edge of the lake. In contrast, the influx data in this study indicate that fires may have increased in the area around Laguna Martínez during this period 3250 cal yr BP to about 960 cal yr BP. However, this interpretation is complicated by the gap in the Martínez sediment core spanning approximately 4600 to 3400 cal yr BP. At Laguna Martínez, macroscopic charcoal influx was moderate from 3250 to 960 cal yr BP after a fire peak at about 3260 cal yr BP. The peak in charcoal influx around 3260 cal yr BP might represent the last major period of land conversion to agricultural fields near Laguna Martínez. Perhaps the lower charcoal influx after this peak was from very small fires used to maintain the agricultural fields rather than clear new lands, or from secondary deposition of charcoal. Some agricultural fields were abandoned towards the end of this period, which allowed forests to start to regenerate.

Data from Laguna Estero Blanco showed resurgence in macroscopic charcoal about 400 cal yr BP related to European settlement. Stern et al. (2002) noted that fire was necessary to manage and maintain the pasture lands in Central America. However, the lack of large peaks in macroscopic charcoal influx in the last few centuries at Laguna Martínez seems to indicate that fire was not used much at this site, or that for some

reason charcoal from fires used for historic land clearance did not reach the core site. However, the CHAPS analysis (described below) does show fire events during the historic period, even though the influx values are not as high as at Laguna Estero Blanco.

What are possible limitations of using CHAPS for analyses of fire history in tropical dry forests and what do the results reveal about fire history?

Several macroscopic charcoal studies have used CHAPS for the analysis of local fire history (Long et al., 1998; Millspaugh et al., 2000; Mohr et al., 2000; Long and Whitlock, 2002; Brunelle and Anderson, 2003; Brunelle and Whitlock, 2003). The peak-threshold values and background-window widths in these studies were selected by calibrating them with dendrochronological evidence of fire history. Almost all of the studies that used CHAPS to analyze fire history patterns were in temperate forest ecosystems in the northwestern United States.

Schlachter (2005) is the only researcher to have used CHAPS to analyze fire regimes in a tropical forest. He used peak-threshold ratios of 1.05, 1.10, and 1.15 with a background-window width of 450 years. I used his study for selecting the criteria for determining proper peak-threshold ratios for this study because of the similar location and ecosystem type. I expanded on his work by experimenting with even more ratios (1.07, 1.08, and 1.12) to model different representations of the past fire regime. The CHAPS program is designed to estimate background charcoal and fire peak events that surpass the specified peak-threshold value. CHAPS was designed to use a locally weighted mean to break down the influx into the background and peak outputs (Long et

al., 1998). One significant problem associated with the use of CHAPS is that it was designed with the intention of being correlated with dendrochronolgical data in temperate ecosystems. In his experimental use of CHAPS at Laguna Estero Blanco, Schlachter (2005) concluded that a peak-threshold value comparable to the values used in the studies from the northwestern United States worked well.

The CHAPS analysis for Laguna Martínez was also experimental in nature because, as at Laguna Estero Blanco, there were no dendrochronolgical data to calibrate the peak threshold ratios and background-window widths. I could only visually assess what I thought to be the best representation of the fire history by trying different peak threshold ratios and background-window widths, a method that can be very subjective. I did use the pollen and microscopic charcoal proxy data available to look for changes that would likely signal disturbances, including fire. I postulated that the evidence of maize agriculture should be associated with a fire event either during or prior to the earliest maize pollen grain. Maize is a plant that grows only in cultivation, which at least initially would require forest clearance, likely by fire. However, it should be noted that using the presence of a fire peak in CHAPS at the time of the earliest maize cultivation to select the best CHAPS parameters means that my interpretation could become circular. I can not conclude too much about the use of CHAPS to provide evidence of fire at this time if I made choices to ensure this.

I found the 1.05 peak-threshold ratio to yield many peaks in the earliest and latest portions of the record. My interpretation is that this ratio may be too “lenient” in determining fire peaks, but I cannot rule out that all of these peaks do not, in fact, document actual past fires. The 1.15 and 1.12 ratios were at the other extreme and

produced outputs with few fire peaks. These two ratios present no evidence of any fire peaks near the period of the first evidence of maize pollen, and based on that I consider them unlikely to provide the best model. A ratio of 1.10 created an output with one peak occurring around a pseudo-annual interpolated age of 5760 cal yr BP. The analyses with peak-threshold ratios of 1.07 and 1.08 revealed fire peaks throughout the time represented by the core. The peaks occurred during periods when archaeological studies document human presence in the region and during periods of volcanism. With these ratios of 1.07 and 1.08, a fire peak is apparent close to the period of the first evidence of maize pollen (ca. 5500 cal yr BP). The outputs using these parameters produced a peak at 5760 cal yr BP, 260 years prior to the first evidence of maize agriculture. One problem with both of these two peak threshold ratio and background-window width parameters is that fire peaks are absent after fires used to initiate maize agriculture at Laguna Martínez. The charcoal influx from ca 3260 cal BP until about 1250 cal yr BP does not meet the criterion of surpassing the 1.08 peak-threshold. It is possible that fires used to maintain the agriculture indicated by the continued presence of maize pollen were too small to loft enough charcoal particles into the air to be distributed into the lake and to the core site to register a fire peak in CHAPS. The CHAPS analysis instead shows fire peaks from around 900 cal yr BP through close to the present. Some of the fires in the later part of this period were likely associated with the creation and maintenance of pasture for cattle by European settlers.

My experiments with CHAPS provided estimates of fire frequency at Laguna Martínez. Fire frequency is calculated by CHAPS by determining the number of peaks per 1000 years using a 1000 yr sliding background-window width (Figure 6.5). The fire

event frequency is near 4 fire episodes per 1000 years at the base of the profile and is near 3 fire episodes per 1000 years in the upper part of the profile, with lower values in between. The low values correspond to the generally low charcoal influx values in that part of the record, but the results are also influenced by the gap in the sediment core between about 4600 and 3400 cal yr BP.

Despite the limitations associated with CHAPS, the programs may be useful in revealing fire peaks that might not be evident in charcoal influx data alone. This was true in my study of Laguna Martínez, where a fire peak was found at 5760 cal yr BP by CHAPS (Figure 5.14) that is hardly apparent in the influx data (Figure 5.9, 6.4). There might be other means, besides dendrochronological data, of calibrating the CHAPS parameters in studies at tropical locations. It is possible that radiocarbon-dated soil charcoal could help determine fire return intervals and be used to calibrate background-window widths. It might also be possible to calibrate the CHAPS parameters by analyzing pollen type shifts, especially those known to represent fire disturbance, if sediment cores were dated and analyzed for pollen at high resolution. More care would be needed when using pollen data to calibrate CHAPS because pollen data may represent regional vegetation history rather than local vegetation history. Studies of macroscopic charcoal transportation and deposition in tropical watersheds could help researchers make

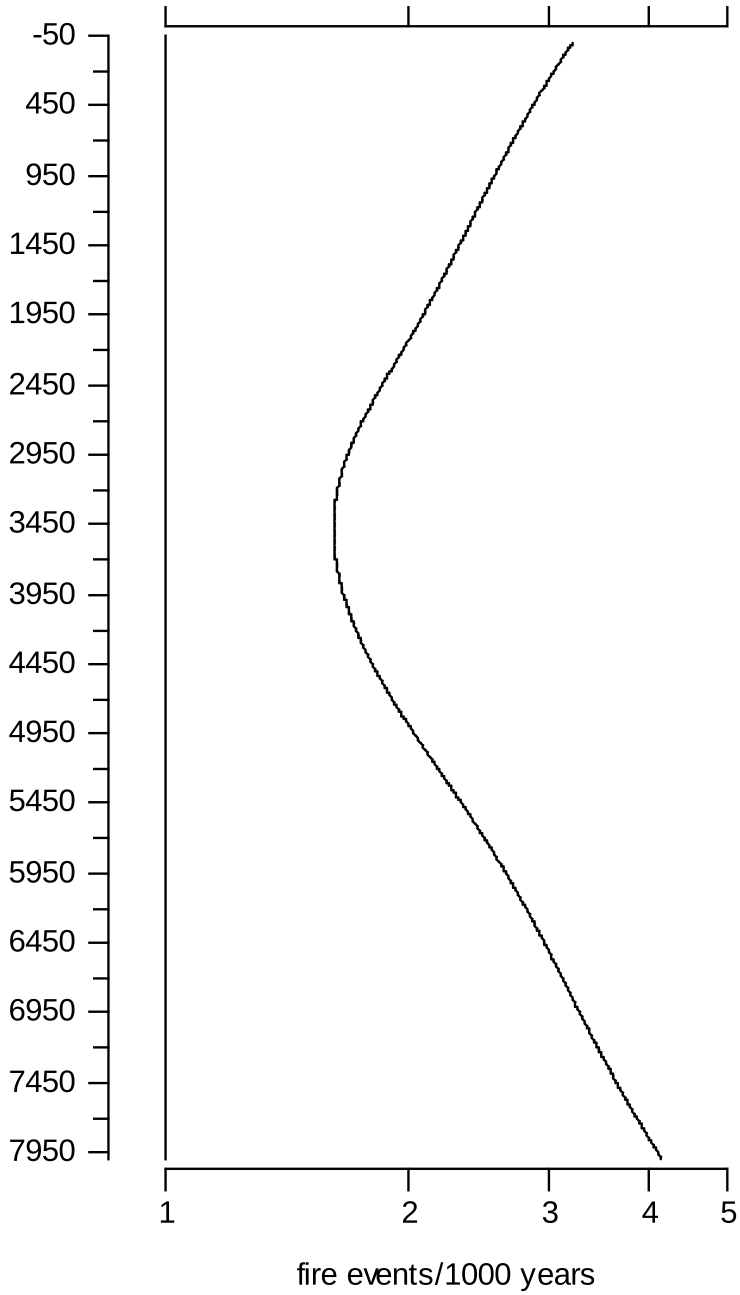

Figure 6.5. Fire frequency per 1000 years based on total macroscopic charcoal (250-500 µm and >500 µm in size) in the Laguna Martínez profile, as estimated based on experimental use of CHAPS. The gap in the sediment core between about 4600 and 3400 cal yr BP exerts an influence on the curve.

better decisions when using CHAPS, or perhaps modify routines to be more appropriate in tropical environments. GIS might be usefully applied to these studies to create models to determine areas most likely to contain macroscopic charcoal. It is possible that local fire peaks in CHAPS could be mapped using GIS, if data were available from many sites in a region. The GIS could examine fire events using CHAPS data with a Z-value of time.

Chapter 7

CONCLUSIONS

High-resolution macroscopic charcoal data from the sediments of Laguna Martínez show that fire has long played a role in the tropical dry forest ecosystem in the Miravalles region of northwestern Costa Rica. The presence of macroscopic charcoal in almost every 1 cm interval of a core extending to 8400 cal yr BP demonstrates repeated burning of surrounding vegetation by natural fires or people. Early fires in the area were likely natural fires ignited by volcanic eruptions. Lightning may also have set fires in the area.

The fire history in the Laguna Martínez watershed has been heavily influenced by anthropogenic fires. The macroscopic charcoal data show evidence of fires that were likely human set near the time of the earliest maize pollen at the site, which presently constitutes the earliest evidence of maize agriculture in Costa Rica (Arford and Horn, 2004; Arford, 2007). The CHAPS analysis revealed a fire event around 5760 cal yr BP, or 2670 years prior to the date of the first maize. Humans presumably set fires to clear forests to establish fields and to release nutrients into the soil for maize agriculture. Anthropogenic fire has been a part of the Laguna Martínez ecosystems at least since that time, but charcoal influx has varied, suggested changes in fire frequency. These variations may indicate that population levels in the local area have fluctuated since humans first used the land near the lake for maize agriculture. The frequency of human-set as well as natural fires at the site likely also varied in response to changes in climate that altered the accumulation and drying of fuels in forests and fields.

My research at Laguna Martínez and the similar study by Schlachter (2005) at Laguna Estero Blanco extended the range of ecosystems in which CHAPS has been used for reconstructing fire history from sedimentary charcoal. However, the absence of dendrochronological records of fire in the area makes the use of CHAPS highly experimental. The selection of peak threshold values is a subjective process without an independent source of data for calibration. The fire frequency estimates provided by the CHAPS analysis at Laguna Martínez should be regarded as a first attempt to quantify fire occurrences, to be refined and tested against other lines of evidence that may become available in the future.

The findings of this study and other studies in the Miravalles region have provided a detailed chronology of climate, ecosystem, and land use change. My results and those of Schlachter (2005) provide high-resolution data on local fire history that complement coarse-resolution data from microscopic charcoal on pollen slides. Our work and companion studies of other proxies establish the long-term importance of both climate and humans in shaping tropical dry forest ecosystems in northwestern Costa Rica. Such studies can help us understand past human-environment dynamics and potentially inform discussions of ecosystem management and the impacts of future global change.

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