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To the Graduate Council:

I am submitting herewith a dissertation written by Zachary P Taylor entitled "Spatial Variation in Organic Carbon and Stable Isotope Composition of Lake Sediments at Laguna Zoncho, Costa Rica." I have examined the final electronic copy of this dissertation for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Doctor of Philosophy, with a major in Geography.

Sally P. Horn, David B. Finkelstein, Major Professor

We have read this dissertation and recommend its acceptance:

Carol P. Harden, 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 Dissertation
Presented for the
Doctor of Philosophy Degree
University of Tennessee, Knoxville

Zachary Paul Taylor
May 2011

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Dedication

This dissertation is dedicated to my wife, Laura Taylor. It would not have been possible for me to complete my graduate work without her support, patience, and encouragement. No matter the circumstances, Laura has been with me every step of way. For this and so much more, I am, and always will be, extremely grateful.

I am also deeply indebted to my parents, Doc and Norma Taylor, and my sister, Betsy Taylor. They have been behind me at every turn and I have drawn much strength from their constant encouragement.

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Throughout my PhD, I have been extremely fortunate to have the support of many talented and dedicated individuals. My co-advisor Sally Horn handled all of the arrangements for fieldwork in Costa Rica, cored the lake with me, assisted with radiocarbon dating, and helped oversee the maize pollen portion of the research. My co-advisor David Finkelstein guided me in isotope analyses and interpretation. I am also extremely appreciative of Carol Harden and Ken Orvis, who both gave of their time to serve on my dissertation committee. Claudia Mora taught me to use isotopes and provided important feedback during the early stages of my dissertation.

Many people contributed their time and assistance to the laboratory portion of my research. Zheng-Hua Li was extremely helpful in the Stable Isotope Laboratory and the isotope portion of the project would not have been possible without him. Liesel Goethert spent many hours assisting with isotope sample preparation and Jeff Malik helped greatly with weighing isotope samples. Jessica Blackwell and Jessica Kelfer performed all of the maize pollen scans and the control spore counts. Greg Metcalf contributed to isotope sample preparation as well as core opening and core logging. I also appreciate the assistance with data interpretation provided by Xiaocun Sun of the University of Tennessee’s Research Computing Service.

Fieldwork in Costa Rica would not have been possible without logistical assistance from Maureen Sánchez at the University of Costa Rica in San José. I am grateful for the permission to work at Laguna Zoncho given by landowners Gail and Harry Hull and by the Costa Rican Ministry of Environment and Energy. I also appreciate the staff at the Los Cruces Biological Station and the Organization for Tropical Studies for their help in the field and for permission to sample soil in the Las Cruces reserve. Greg Metcalf was an amazing field assistant and his hard work and positive attitude under adverse conditions made the trip to Costa Rica a success.

I am pleased to acknowledge several grants and other funds that supported the work described here. For two years of my Ph.D. work I was supported as a Fellow by the University of Tennessee’s GK–12 Earth Project, funded by the National Science Foundation through Grant No. 0538420 to Sally Horn, Ken Orvis, and Lynn Champion. The GK–12 Earth Project covered some of the field and laboratory costs of the project, and made possible the participation of Heritage Middle School teacher Greg Metcalf. Other laboratory costs were covered by a National Science Foundation grant that I received together with S. Horn and David Finkelstein (NSF Grant No. 0825406), and a grant awarded to me from the Geological Society of America’s Dissertation Grant Program. Additional support for laboratory costs was provided by D. Finkelstein from the Jones Environmental Geochemistry Endowment at the University of Tennessee.

Abstract

Lake sediments are valuable paleoenvironmental archives that provide information on past climate and land-use change. Most lake sediment studies rely on a single core, usually recovered from the center of a lake, and do not consider spatial variability in the lake basin. My dissertation presents a spatially-explicit record of prehistoric agriculture from Laguna Zoncho, Costa Rica and evaluates spatial variability in lake sediment proxies based on a network of five sediment cores. Results extend earlier proxy analyses of a single core collected near the center of the lake, which documented prehistoric agriculture and forest clearance from 3000 to about 500 years ago, followed by strong forest recovery at the time of the Spanish Conquest. Analyses of the new suite of cores show that agricultural activities increased erosion in the watershed, which lowered organic content from 16% to 5%, and resulted in a shift in bulk sediment stable carbon isotope values from –27 ‰ to –23 ‰ VPDB due to forest clearance. Agriculture made the lake slightly more productive, shown by a decrease in carbon/nitrogen ratios from 16 to 13 and an increase in stable nitrogen ratios from 1 to 3 ‰. Basinwide trends in organic matter and stable carbon isotopes ratios show two distinct periods of agricultural decline (1150–960 and 840–650 cal yr BP) that coincide with intervals of drought detected in regional paleoclimate records. This finding suggests that climate change, not the Spanish Conquest, was the driving force of site abandonment at Laguna Zoncho, and by extension throughout the region.

Inter-core variability in proxies for agricultural activity reveals that crop cultivation may have continued longer in some portions of the watershed, and highlights the influence of sediment-focusing processes on proxy signatures of agriculture in lake basins. Maize pollen concentrations in the sediment cores did not correspond to geochemical and isotopic agricultural indicators, suggesting a need for caution in using the abundance of maize pollen to infer the scale of agriculture in neotropical watersheds.

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Chapter 1: Introduction

1.1 Introduction

Lake sediments are established archives of paleoenvironmental information. Traditionally, fossil pollen has been the most heavily used proxy indicator of paleoenvironments in lake sediments. Before pollen was used with confidence, many studies examined the details of pollen source area (Davis et al., 1971; Jacobson and Bradshaw, 1981; Jackson, 1990; Calcote, 1995), spatially differentiated pollen deposition (Davis and Brubaker, 1973), pollen redeposition (Davis, 1973), and sediment focusing (Lehman, 1975; Davis et al., 1984; Larson and MacDonald, 1994). The results of these studies, along with the time-consuming nature of laboratory analysis, created a paradigm for lake sediment studies where a single core from the deepest portion of a lake is considered an adequate sampling strategy.

While pollen analysis remains an important tool in paleoenvironmental reconstruction, many additional proxy indicators are often studied. Stable isotope analyses are now common in environmental reconstructions that use lake sediments. Analyses of stable carbon isotopes in lake sediments have proven useful in reconstructing the dominant photosynthetic pathway of past vegetation. Because photosynthetic pathway is largely dictated by environmental conditions, most notably temperature, aridity, and atmospheric CO_2 concentration (Ehleringer et al., 1997; Boom et al., 2001), stable carbon isotopes are also valuable proxy indicators of environmental conditions. Unlike pollen, which is primarily transported by wind, the organic component of lake sediment analyzed for stable isotope ratios has a more complex origin, as it includes terrestrial carbon washed into the lake through erosion processes as well as autochthonous inputs. Despite this obvious difference, the single-core paradigm that was verified for pollen has been accepted without comparable calibration for stable isotope studies.

Spatial heterogeneity in lake sediments was first noticed after analysis of pollen percentages in surface sediments. Davis et al. (1971) recovered 28 surface sediment samples from a lake in Michigan and compared pollen assemblages from shallow and deep water locations. Species that grew near the edges of the lake made up a greater proportion of the pollen assemblage in shallow areas, whereas tree pollen was relatively evenly distributed through the samples. Davis et al. (1971) suggested that some pollen types were not widely dispersed and remained near the parent plant, while deciduous tree pollen, with superior production and dispersal, reached all parts of the lake with little evident spatial variation. This finding was reinforced in several cases where particular pollen types were only found in the portion of the lake adjacent to populations of the parent plant. In addition to differential deposition, the spatial heterogeneity in pollen deposition was interpreted to also result from settling processes that separate pollen grains by morphological type. Davis and Brubaker (1973) found that small, low density grains remain in suspension longer and are preferentially carried to the littoral zone where they are deposited. Davis (1973) found that sediment is remobilized by lake overturn after initial deposition. In shallow environments, she found that the upper 6–12 mm of sediment was disturbed and tended to move toward the deepest part of the lake before it was redeposited. Sediment-focusing processes continue the movement of material toward the deepest part of the lake. This suite of processes, which includes sediment slumping as well as wave- and current-induced mixing driven in part by winds, generally moves sediment toward the deepest part of the lake basin (Lehman, 1975; Davis and Ford, 1982; Larson and MacDonald, 1994). The importance of these processes is strongly controlled by lake basin morphology and can be roughly estimated (Lehman, 1975; Larson and MacDonald, 1994).

Aside from this initial work to calibrate pollen studies, few studies have looked at how sediment properties vary spatially within a lake. Kumke et al. (2005) examined variations in particle size, total organic carbon, total nitrogen, stable carbon isotopes, and numerous geochemical properties from a large lake (~320 km^2) in Siberia. As expected in a lake of this size, significant variations existed in sediment properties across the lake, as demonstrated with a principal components analysis. Riverine inputs, lake-basin morphology, wind currents, and resuspension of sediment in shallow water were singled out as important contributors to spatial heterogeneity. Wang et al. (2009) analyzed total organic carbon, total inorganic carbon, and grain size in four cores recovered from a 290 km^2 lake on the Tibetan Plateau. The four cores showed similar patterns of change in sedimentary characteristics, with relatively little variation. The core from the deepest portion of the lake had the highest sedimentation rate, which Wang et al. attribute to sediment-focusing processes. In a much smaller lake (0.5 km^2) in Sweden, Korsman et al. (1999) used near infrared spectroscopy to analyze surface sediment. Near infrared spectroscopy provides information about the chemistry of organic and inorganic matter by analyzing absorbance in the near infrared spectrum. When combined with a calibration dataset, absorbance spectra can determine chemical constituents. Korsman et al. (1999) found that clear-cutting in the watershed and inlets, along with the amount of organic matter and water depth, were key factors in creating spatial variability in the lake's sediments. Schiefer (2006) analyzed varve sequences sampled along a 100 m grid from a lake (~2 km^2) in montane British Columbia to isolate mechanisms that control sediment accumulation. He found that flood and other deposits were unevenly distributed in the lake and that lake basin morphology was an important control. He also noticed increased deposition rates from anthropogenic disturbance within 100 m of shore.

Spatial variability of stable carbon isotopes in sediments has been examined in both marine and lacustrine environments. Huang et al. (2000) and Dahl et al. (2005) used compound-specific techniques to examine terrestrial plant waxes in marine sediments. Huang et al. (2005) were able to differentiate between C3 and C4 inputs off the coast of Northwest Africa and determine the source area within Africa for the terrestrial carbon. Dahl et al. (2005) analyzed the circulation patterns associated with the Indian monsoon using similar techniques off the coast of the Arabian Peninsula. Kumke et al. (2005) analyzed the spatial variability of $\delta^{13}C$ values in Lake Lama in Siberia. They found a relatively low amount of variation, but the high latitude location of this lake makes it unlikely that the sediments contained carbon other than that from C3 terrestrial vegetation and autochthonous sources. Vizzini et al. (2005) analyzed the stable carbon and nitrogen isotopic composition of two widely separated sediment cores recovered from a 37.3 km^2 coastal lagoon in southern France to examine differences between marine and terrestrial inputs. They found a 1.5–2 ‰ $\delta^{13}C$ difference between the location dominated by freshwater inputs and the core site more open to the sea.

No studies have looked at spatial variation in organic carbon composition and stable isotope composition in small lakes. The pollen studies provide good background information on how lakes incorporate material into their sediments, but there are potential differences between the sedimentation of pollen and organic matter (Figure 1.1). Unlike pollen, for which aeolian processes integrate local and regional inputs, terrestrial organic material largely originates in the catchment of the lake from point and non-point sources. A portion is blown by wind or falls

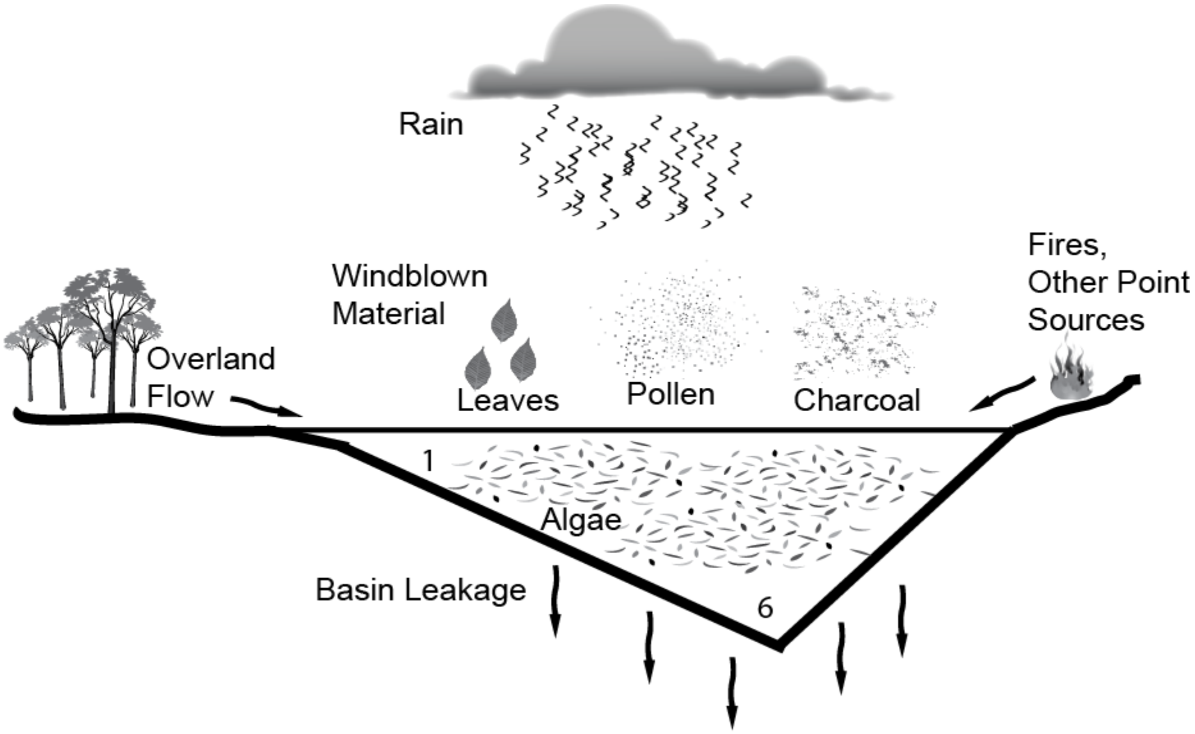

Figure 1.1: Summary of inputs to Laguna Zoncho. The numbers indicate the relative position of core 1 and core 6. Modified from Bohacs et al. (2000).

directly into the lake from overhanging trees, but much of the material that reaches the lake arrives through overland flow and other fluvial processes. The source of organic material should therefore be more local than that of pollen grains, and watershed morphology should dictate the transportation and deposition of material in the lake. Autochthonous carbon from algae can also mask evidence of changes in the terrestrial environment preserved in sedimented organic matter. My dissertation will add to understanding of how these factors interplay within a lake basin, an important step in calibrating records based on the analysis of the organic component of lake sediments.

Laguna Zoncho, a small lake in southwestern Costa Rica, provides an ideal setting to examine intra-basin spatial variability. Previous analyses of pollen and microscopic charcoal (Clement and Horn, 2001), bulk carbon $\delta^{13}C$ (Lane et al., 2004), diatoms (Haberyan and Horn, 2005), and phosphorus (Filippelli et al., 2010) documented prehistoric forest clearance, maize agriculture, and post-Conquest forest recovery. I will use the impacts of agriculture as stratigraphic markers to evaluate spatial variation across a network of cores using geochemical and isotopic indicators as well as maize pollen concentrations.

1.2 Research Objectives

My dissertation has six main research objectives. (1) Create a high-resolution record of agricultural activities at Laguna Zoncho for comparison to regional climate records. (2) Characterize the spatial variability of % OM, total N, C/N ratios, $\delta^{13}C_{OM}$, and $\delta^{15}N$ in the lake basin to examine the processes that control organic matter deposition in lake sediments. (3) Use the suite of geochemical and isotopic indicators to reconstruct the impacts of agriculture on the aquatic and terrestrial environment at Laguna Zoncho. (4) Examine the spatial patterns of %

OM, $\delta^{13}C_{OM}$, and maize pollen concentrations to assess the utility of maize pollen concentrations as an indicator of the scale of prehistoric maize agriculture. (5) Determine the feasibility of creating a spatially-explicit record of agriculture by analyzing a network of lake sediment cores. (6) Evaluate the use of a single core from the center of the lake as a sampling strategy for studies that use organic matter–based proxies and the presence of maize pollen grains as an indicator of agriculture.

1.3 Lake Sediment Indicators

1.3.1 Bulk Sediment Geochemical Indicators

Geochemical analyses of bulk sediment in lakes provide a great deal of paleoenvironmental information. Total organic matter (% OM) and atomic C/N ratios (henceforth C/N ratios) are particularly useful because they help constrain inputs coming into the lake. Percent OM is sensitive to a variety of factors. Depending on the lake, OM is controlled by autochthonous inputs, allochthonous inputs, or a combination of both. In eutrophic lakes, OM is often closely connected to productivity. In mesotrophic and oligotrophic lakes, terrestrial inputs control % OM. Disturbance in the watershed, including agriculture, is also a common control of OM. Disturbances tend to accelerate erosion processes resulting in increased mineral inputs that lower OM values (Oldfield et al., 2003; Enters et al., 2006; Lane et al., 2009; Bookman et al., 2010).

C/N ratios provide information about the origin of organic material in lake sediments. Algal material is protein-rich and cellulose-poor, whereas organic matter from terrestrial plants has the opposite composition. Consequently, low C/N ratios (4–10) are associated with terrestrial inputs and higher ratios (>20) with algae (Ficken et al., 1998; Meyers, 2003). This can be a useful way to assign relative sources, but it is often complicated by the presence of the alga *Botryococcus brauni*. This alga uses multiple metabolic pathways during photosynthesis, producing organic matter with C/N ratios of >30 (Huang et al., 1999).

1.3.2 Lake Sediment Stable Carbon and Nitrogen Isotopes

Carbon isotope ratios in lake sediments provide a means for inferring the dominant photosynthetic pathway of watershed vegetation. There are three main photosynthetic pathways: C3 (Calvin Cycle), C4 (Hatch-Slack), and CAM (Crassulacean Acid Metabolism) (Ehleringer et al., 1997). Each of these pathways has evolved to enable the plants that use the pathway to be the most efficient in their environment. Each pathway also imparts a distinctive stable carbon isotopic signature to the plant tissues because of the way each of the photosynthetic processes takes in carbon, in the form of CO_2, from the atmosphere. C3 photosynthesis is the most common, especially in dicotyledonous plants such as most trees, shrubs, and other higher plants. C3 plants are adapted to cooler, more mesic habitats and are the least efficient in their water use (Huang et al., 2001). They leave their stomata open during photosynthesis and preferentially incorporate ^{12}C, into their tissues, giving them lighter isotope values ranging from –32 to –20 ‰ (PDB) (Bender, 1971; O'Leary, 1981). C4 plants have a higher water use efficiency because they have developed a four carbon sugar that allows them to open their stomata at night, take in carbon dioxide, and then use the stored carbon during the day for photosynthesis. Since they consume most of this stored carbon, they are not able to preferentially uptake ^{12}C, resulting in a smaller fractionation that gives their tissues $\delta^{13}C$ values that range from –17 to –19 ‰ (PDB) (Bender, 1971; O'Leary, 1981). C4 plants tend to prefer open areas with higher amounts of light and warmer temperatures. They also outcompete C3 plants in areas with lower precipitation, particularly if the precipitation is concentrated during the warm part of the year. CAM plants use a hybrid photosynthetic pathway that combines the C3 and C4 pathway. This pathway is used mainly by succulents and by some aquatic species, and is rarely dominant in a landscape.

Stable carbon isotope analysis on bulk carbon from lake sediments provides a useful paleoenvironmental proxy in many cases (e.g. Aucor et al., 1999; Boom et al., 2001; Lane et al., 2004; Taylor et al., 2010). The principal drawback of analyzing total organic matter is the lack of control on the source of the organics analyzed. In cases where the terrestrial component overwhelms the autochthonous input, bulk $\delta^{13}C$ values are reliable indicators of the predominant photosynthetic pathway in the watershed. However, in lakes with high proportions of autochthonous carbon from algal production, the terrestrial signal can be hard to distinguish. Despite this limitation, bulk isotopes are useful in many non-eutrophic lakes dominated by terrestrial inputs, and bulk isotope analysis has the advantage over other techniques for organic matter analysis that large numbers of samples can be analyzed in little time.

Lane et al. (2004) offered a new method for detecting forest clearance using bulk carbon $\delta^{13}C$ analysis. The test sites for the work were Laguna Zoncho and a swamp at the La Selva Biological Station, in northeastern Costa Rica, from which Horn and Kennedy (2001) previously reported pollen evidence of maize cultivation. Since forest clearance and agriculture cause significant shifts in the dominant photosynthetic pathway of an environment, and each photosynthetic pathway has its own unique isotopic signature, this is a powerful reconstructive technique. It also allows for an estimation of the extent of forest clearance. Lane et al. (2009) developed a $\delta^{13}C$ record for a third site in Costa Rica, Laguna Bonillita, and entered $\delta^{13}C$ values into a mixing model (Phillips and Gregg, 2001; Phillips and Gregg, 2003) to produce an estimate of land clearance within that watershed.

Stable nitrogen analysis of lake sediments is useful because it can help identify organic matter sources and provide information about past lake productivity (Gu et al., 1996; Meyers, 2003). Most algae use dissolved inorganic nitrogen, which has a heavier isotopic value than nitrogen available to land plants, and as a result algae $\delta^{15}N$ values average 8.5 ‰ while terrestrial plant $\delta^{15}N$ values average 0.5 ‰ (Meyers, 2003). Interpreting $\delta^{15}N$ is complicated by eutrophication, which can cause more negative values due to the increased importance of cyanobacteria (Gu et al., 1996). Because cyanobacteria fix nitrogen directly from the atmosphere, they have $\delta^{15}N$ values similar to land plants. Gu et al. (1996) found that $\delta^{15}N$ values were negatively correlated with the degree of eutrophication in Florida lakes.

1.3.3 Maize Pollen Concentrations as Indicators of the Scale of Prehistoric Agriculture

Lake sediments can provide sensitive records of prehistoric agriculture (Bush et al., 1992; Islebe et al., 1996; Northrop and Horn, 1996; Fisher et al., 2003; Oldfield et al., 2003; Horn, 2006). Pollen and charcoal have been the most common proxy indicators used to detect prehistoric agriculture. The main pollen type used to infer past agriculture is that of maize, *Zea mays* subsp. *mays*, since pollen of other cultigens is rare. Maize pollen is relatively large (up to100 µm in maximum dimension), though slightly smaller grains (63–90 µm) make up the majority of fossil maize pollen found in Costa Rica (Horn, 2006). In experiments, 99% of maize pollen tends to fall within 60 m of the parent plant (Raynor et al., 1972), but this can vary with wind speed and surface roughness (Jarosz et al., 2003; Jarosz et al., 2005). As a result, maize pollen may only be found in sediment records from lakes where maize is grown right on the lake shore (Islebe et al., 1996). Since maize grains are so rare in sediment records, they are often difficult to interpret. Lane et al. (2010) analyzed the distribution of maize pollen grains in surface sediments from four lakes in Wisconsin and found that maize pollen concentrations were positively correlated with area under cultivation. The correlation was relatively weak and was complicated by other variables, but the finding suggests the possibility of using maize pollen concentrations to estimate the scale of agricultural activities.

1.4 Site Description

1.4.1 Physical Setting

Laguna Zoncho (8.813ºN, 82.963ºW, 1190 m elevation) is a small (0.75 ha) lake in the southern Pacific lowlands of Costa Rica. The lake sits in a depression that likely formed due to faulting and/or mass wasting processes (Clement and Horn, 2001). The lake has no inlet or outlet streams and is a balance-fill basin in which sediment and water supply and potential accommodation are in approximate equilibrium (Bohacs et al., 2000). The entire Zoncho watershed covers approximately 7 ha (Filippelli et al., 2010). The nearby Lomalinda Meterological Station (http://www.ots.ac.cr/meteoro/default.php?pestacion=3) reports a mean annual temperature in the region of ~20 °C, and average annual precipitation of ~3300 mm, mostly arriving from April through November. Laguna Zoncho is located in the premontane rainforest life zone of the Holdridge bioclimatic classification (Hartshorn, 1983), and the predisturbance vegetation surrounding the lake would have almost exclusively employed the C3 photosynthetic pathway (Brown, 1999; Sage et al., 1999). This was shown to be the case by Lane et al. (2004), who found the sediments in a core recovered from the lake in 1997 (Clement and Horn, 2001) to have a bulk carbon value of –30 ‰ when the pollen record indicated forested conditions and little disturbance in the watershed. The presence of pollen grains of *Zea mays* subsp. *mays* through the profile indicates that maize agriculture began in the watershed around 3000 cal yr BP and continued to modern times (Clement and Horn, 2001). Changes in maize pollen abundance, percentages of pollen of disturbance and forest taxa, and fluctuations in $\delta^{13}C$ values reveal variations in the extent of forest clearance during the pre-Columbian period, and a strong signal of reforestation following the Spanish Conquest. Diatom (Haberyan and Horn, 2005) and phosphorus records (Filippelli et al., 2010) also show that agricultural activities profoundly affected the lake and its watershed.

1.4.2 Regional and Local Archaeological Context

Laguna Zoncho is located within the Diquís sub-region of the archaeological region known as the Greater or Gran Chiriquí, which includes western Panama and southwestern Costa Rica. Anchukaitis and Horn (2005) included a review of the archeology of the Diquís subregion in their publication on the pollen and charcoal record of Laguna Santa Elena, located about 15 km north of Laguna Zoncho. Their review, based in part on original, unpublished reports in Spanish available only in Costa Rica, is the principal source of the information I include below.

The Diquís subregion has been continuously inhabited by humans for thousands of years (Anchukaitis and Horn, 2005; Palumbo, 2009). Some uncertainty exists over the dating of archeological sites in the Diquís subregion, but the two oldest sites suggest that permanent habitation began between 1500 and 300 B.C. (Anchukaitis and Horn, 2005). Maize pollen indicates occupation of the Zoncho watershed at 1000 B.C. (Clement and Horn, 2001). More is known about the Bugaba or Aguas Buenas Period, which began somewhere between 500 B.C. and A.D. 200 (there is debate about the precise timing). Though referred to as the Bugaba

Period, several authors (Drolet, 1984; Haberland, 1984; Hoopes, 1996; Corrales, 2000) have argued that there was significant spatial and temporal heterogeneity among the populations in the area, which were likely small and widely dispersed. Villages are thought to have been preferentially located on stream terraces during this time.

According to Anchukaitis and Horn (2005), there is disagreement among researchers about the subsistence strategies employed by the Bugaba people, particularly the role of maize (Hoopes, 1991; Hoopes, 1996). Some authors have suggested that agriculture was intense and maize and beans were staple crops (Linares and Sheets, 1980). Others have argued that maize was grown on a limited basis, perhaps only for ceremonial purposes (Drolet, 1988). Lake sediment archives in the area have provided some evidence to help answer these questions. Maize pollen from Laguna Zoncho indicates that maize has been grown for at least the last 3000 years (Clement and Horn, 2001) and stable carbon isotope ratios and pollen percentages indicate that forest clearance was extensive (Lane et al., 2004). Extensive maize cultivation in the Diquís subregion during this period has also been detected at Laguna Vueltas from pollen and stable carbon isotopes (Horn et al., 2004; Taylor et al., 2004). Maize pollen from this period has also been recorded at Laguna Santa Elena (Anchukaitis and Horn, 2005) and Laguna Gamboa (Horn, 2006) in Costa Rica, and at Laguna Volcán in westernmost Panama (Behling, 2000).

The Bugaba Period was followed by the Chiriquí Period, which began around A.D. 800 and ended approximately A.D. 1500 with the arrival of the Spanish. Again, there is disagreement over the start date for the period (Linares, 1977; Linares, 1980; Drolet, 1992; Quilter and Blanco, 1995; Baudez et al., 1996; Corrales, 2000; Sánchez and Rojas, 2002). Archeological evidence indicates that the Chiriquí Period differed greatly from the Bugaba

Period, with more elaborate ceramics and the use of metal tools (Drolet, 1992). Large, complex settlements were more common and the placement of villages varied from the piedmont pattern seen in the previous period (Linares, 1977; Sheets, 1980). As during the Bugaba period, the importance of maize agriculture is unclear. Some researchers have conjectured that maize agriculture allowed more politically sophisticated societies with distinct hierarchies (Corrales, 1988; Drolet, 1992). However, Hoopes (1996) pointed out that directly tying the increase in maize agriculture with new societal organizations is problematic because either one could stimulate the other (Hoopes, 1996).

The Chiriquí Period ended upon the arrival of the Spanish, who reached the Pacific coast of Costa Rica in 1519. The area comprising the Diquís subregion was conquered by Juan Vásquez de Coronado in A.D. 1562–1563. Coronado reported a fierce defense by the inhabitants of numerous fortified villages, suggesting that rival chiefdoms of the period frequently engaged in conflict. He also noted the presence of extensive maize, bean, and fruit agriculture (Fernández Guardia, 1913).

After the Conquest, the region was lightly settled until the mid-1900s. Until the arrival of the Inter-American highway in 1946 (Clement and Horn, 2001) the region’s inhabitants mostly practiced subsistence agriculture. Following the arrival of the highway, the current land use of coffee agriculture became dominant.

Two archeological surveys at Laguna Zoncho revealed evidence of prehistoric human occupation of the watershed. Laurencich de Minelli and Minelli (1966) described four cemeteries on hilltops with artefacts associated with the Bugaba and Chiriquí periods. Soto and Gómez (2002) examined the western portion of the watershed (Finca Cántaros property) and found large numbers of ceramic and lithic artefacts. Charcoal associated with artefacts in three excavations yielded AMS radiocarbon dates that fall within the Bugaba period. Soto and Gómez (2002) also identified an arrangement of boulders from a prehistoric structure near the lake. An AMS date on material found immediately below the structure suggests it was built around 650 BP, during the Chiriquí period.

1.5 Methods

1.5.1 Sample Collection and Description

Sediment cores for this study were recovered from six sites within Laguna Zoncho in June 2007. Core sites 1–5 were arranged in a radial pattern around core site 6, each approximately halfway between the center of the lake and the shore. Sally Horn, Greg Metcalf, and I recovered sediments using a Colinvaux-Vohnout (C-V) locking piston corer (Colinvaux et al., 1999) from an anchored floating platform. To guarantee complete sediment records, we recovered two parallel cores (A and B) at each site. To ensure recovery of the Barú tephra (Clement and Horn, 2001) and the end of the agricultural period, we began recovery of the A core at each site approximately 30 cm below the sediment-water interface and, using two successive 1 m drives, recovered sediments up to 230 cm deep. To recover the overlapping B core, we moved the raft approximately 1 m and recovered a 1-m core section beginning approximately 80 cm below the sediment-water interface. The same methodology was employed at site 6, but we recovered 3 m of sediment in the A core and 2 m in the B core.

I opened core sections lengthwise, using a specially modified router, and sliced the sediment in the tube longitudinally into two halves using a thin wire. I immediately photographed both halves and described them in terms of texture and Munsell color. I sampled one core half and archived the other for possible later analyses.

1.5.2 Chronology

The Barú tephra (ca. 537 BP; Behling, 2000) and a total of 13 AMS radiocarbon dates from the Zoncho cores provided chronological control. Eleven AMS samples consisted of macrofossils extracted from the sediment cores and two consisted of bulk sediment from core sections that lacked datable macrofossils. Twelve radiocarbon samples were analyzed by the Center for Applied Isotope Studies located at the University of Georgia and one by Beta Analytic, Inc. in Miami, Florida. Each date was calibrated with CALIB 5.01 (Stuiver and Reimer, 1993) using the dataset from Stuiver et al. (1998). For each date, I calculated the weighted mean of the calibration probability distribution (Telford et al., 2004) to yield a single age estimate for use in age models.

1.5.3 Organic Matter Abundance, Total Nitrogen, $\delta^{13}C_{OM}$, and $\delta^{15}N$

All six cores were sampled at 1-cm resolution. Each sample was frozen, freeze-dried, and homogenized using an agate mortar and pestle. A portion of this material was decalcified using 1 N hydrochloric acid, with the remaining sediment reserved for biomarker analysis. Decalcified samples were freeze-dried a second time and then analyzed using a Cos-Tech Elemental Analyzer coupled to a Thermo-Finnigan XL+ Mass Spectrometer. Organic content (OC) and total N concentrations were determined using the provided software and elemental analyzer standards. Nitrogen and carbon isotope data are presented in per mil (‰) notation, where $\delta = (R_{\text{sample}}/R_{\text{standard}}-1)*1000$. The $\delta^{15}N$ data were standardized to air using internal standards (SD = 0.10, n = 238), and $\delta^{13}C$ data were standardized to the Vienna PeeDee

Belemnite (V-PDB) isotope standard using internal standards (SD < 0.13, n = 237). A total of 1547 samples were analyzed, with duplicate analyses performed on approximately 10 % of samples. Mean variation on replicate analyses of samples was 0.47 ‰ for $\delta^{13}C$ and 0.8 ‰ for $\delta^{15}N$.

1.5.4 Maize Pollen Concentration Determinations

Pollen samples were processed using standard techniques (Berglund, 1986) and mounted in silicone oil. A known number of *Lycopodium* control spores were added to each sample to enable the calculation of pollen concentrations (Stockmarr, 1971). For each sample, five slides were prepared, and scanned in their entirety for maize pollen. The number of *Lycopodium* spores on each slide was estimated and used to calculate maize pollen concentrations.

1.6 The Dissertation

I have prepared my dissertation as a series of manuscripts intended for publication. The first manuscript (Chapter 2) describes the relationship between climate change and prehistoric agricultural activities at Laguna Zoncho (objectives 1 and 3). The very succinct style of presentation follows that of articles published in the journal *Nature*, to which my co-authors and I plan to submit the manuscript. Chapters 3 and 4 are manuscripts designed for journals with higher page limitations. Chapter 3, in preparation for submission to the *Journal of Paleolimnology*, describes the isotopic and geochemical spatial variability found in Laguna Zoncho (objectives 2, 3, and 5). Chapter 4, in preparation for submission to *Quaternary Research*, focuses on the spatial and temporal variation of maize pollen concentrations and evaluates their utility as indicators of the scale of prehistoric agriculture (objectives 4, 5and 6). In Chapter 5, I summarize my results and offer suggestions for future study.

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Chapter 2: Precipitation and Pre-Hispanic Agriculture in Southern Central America

This chapter is in preparation for submission to *Nature* by me, David B. Finkelstein, and Sally P. Horn. My use of "we" in this chapter refers to my co-authors and myself.

2.1 Abstract

Existing archeological and paleoenvironmental records from southern Central America attribute population collapse to the Spanish Conquest (Clement and Horn, 2001). Paleoclimate records from the circum-Caribbean have shown evidence of severe, regional droughts that contributed to the collapse of the Mayan Civilization (Hodell et al., 1995; Haug et al., 2003), but there are few records of these droughts in southern Central America and no records of their effects on prehistoric populations in the region. Here we present a high-resolution lake sediment record of prehistoric agricultural activities from Laguna Zoncho, Costa Rica. We find that agriculture was nearly absent from the watershed approximately 220 years prior to the Spanish arrival in Costa Rica and identify two distinct periods of agricultural decline, 1150–960 and 850–640 cal yr BP, which correspond to severe droughts in central Mexico (Stahle et al., 2011). We attribute decreases in agriculture to a weakened Central American monsoon, which would have shortened the growing season at Laguna Zoncho, reduced crop yields, and negatively affected prehistoric populations.

2.2 Manuscript

Indigenous populations in southern Central America have practiced widespread maize agriculture for at least the past 3000–4000 years (Behling, 2000; Clement and Horn, 2001). Lake sediment records from the region have helped researchers reconstruct a timeline of agricultural activities, providing an important complement to archeological evidence. Maize pollen grains found in lake sediments are the most commonly used indicator of agriculture, but may not provide evidence sufficient to estimate the scale of agriculture (Lane et al., 2009). Recently, stable carbon isotope analyses of lake sediments have enabled semi-quantitative estimates of agricultural activities (Lane et al., 2004; Lane et al., 2009). These isotope records are particularly valuable because they offer the potential to examine the connection between climate change and agriculture. Paleoclimatological research has revealed that climate change, specifically drought, played a major role in the collapse of the Maya civilization (Haug et al., 2003; Hodell et al., 2005; Stahle et al., 2011). In southern Central America as throughout the circum-Caribbean, population collapse has been associated with the Spanish Conquest (Anchukaitis and Horn, 2005). Here, here we present a high-resolution record of agricultural activities in southern Central America that reveals effects of climate change on the prehistoric inhabitants of the region and contains evidence of population collapse prior to the arrival of the Spanish.

Laguna Zoncho is located in southwestern Costa Rica (8.813ºN, 82.963ºW, 1190 m elevation), on the Pacific side of the continental divide (Figure 2.1). The 0.75 ha lake sits in a small (7 ha) watershed that likely formed as the result of a mass wasting event. Undisturbed areas near Laguna Zoncho support tropical premontane rainforest (Hartshorn, 1983), but most forest in the area has been cleared. The modern regional climate is characterized by a mean annual temperature of ~20 °C and annual rainfall of ~3300 mm, with the Central American monsoon strongly controlling the timing of regional precipitation (Lomalinda Meteorological Station, http://www.ots.ac.cr/meteoro/default.php?pestacion=3) (Figure 2.2). Northward migration of the Intertropical Convergence Zone (ITCZ) over Costa Rica creates a minor peak in precipitation in May, and a July dry period as the ITCZ moves over northern Central America.

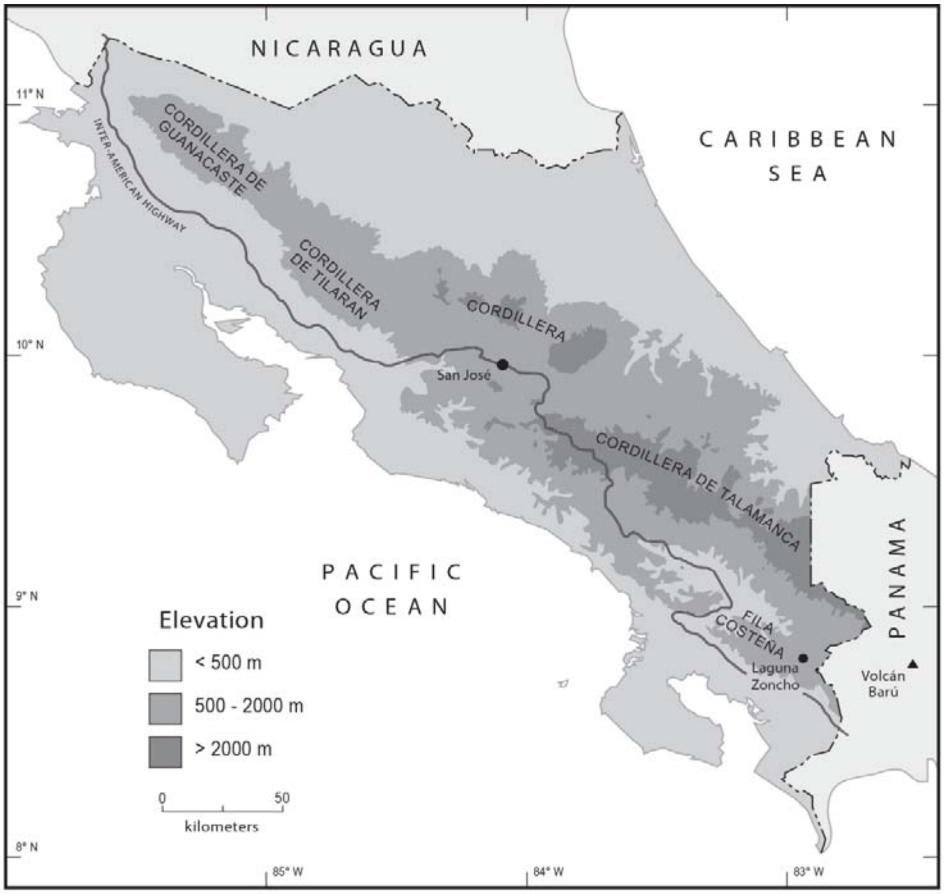


Figure 2.1: Location of Laguna Zoncho and Volcán Barú in southwestern Costa Rica and westernmost Panama. From Clement and Horn (2001).

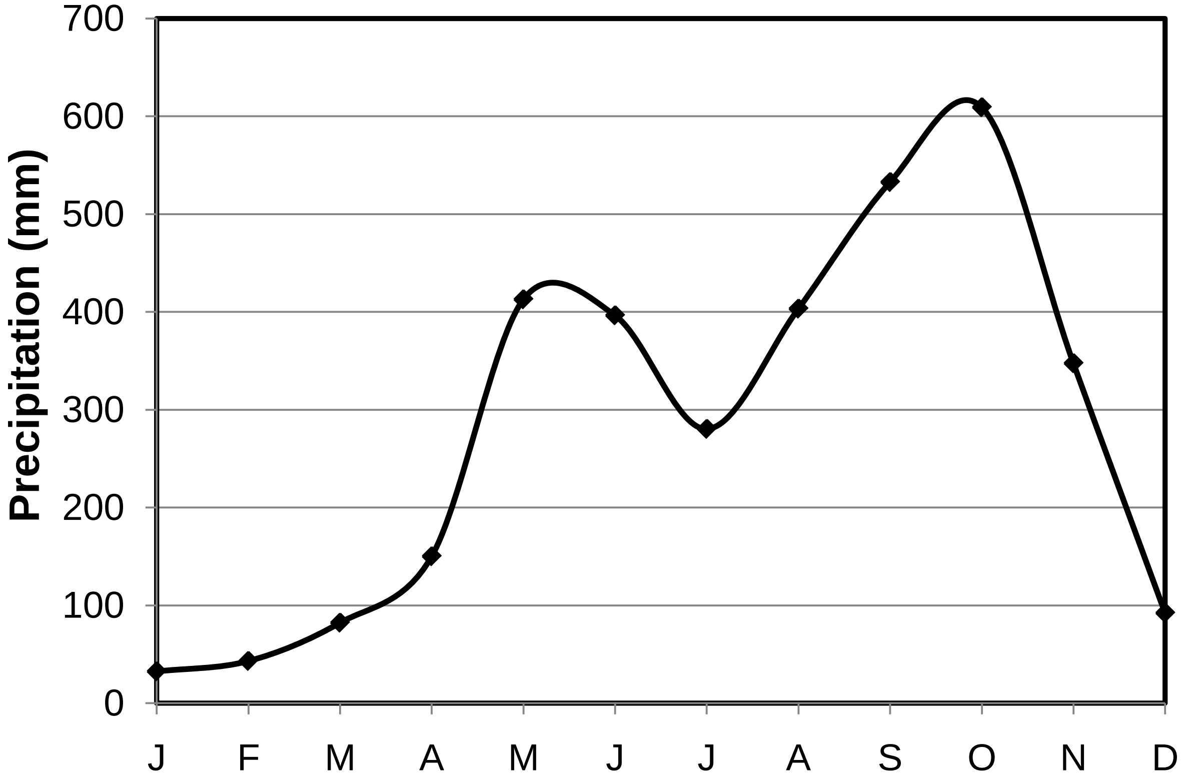


Figure 2.2 Monthly rainfall at the Lomalinda Meteorological Station, located 10 km northwest of Laguna Zoncho. Rainfall data was collected from 1974–1981 and 1996–2008.

From August through October, the monsoon is sufficiently strong and far enough north to create a westerly flow over southwestern Costa Rica that brings moisture from the eastern Pacific (Hastenrath, 2002; Poveda et al., 2006).

Laguna Zoncho lies within the Diquís subregion of the Greater or Gran Chiriquí archeological area, which includes southwestern Pacific Costa Rica and western Panama. Archeologists recognize two distinct cultural periods in the past 2000 years, the Bugaba or Aguas Buenas (1650–1050 BP) and the Chiriquí (1050–450 BP) (Palumbo, 2009). Maize was grown during both periods, but the Chiriquí was characterized by a complex hierarchical society that may have resulted from an increased reliance on maize agriculture (Anchukaitis and Horn, 2005). The area was conquered by the Spanish in 1562, who recorded the presence of large-scale agriculture, extensive fortifications, and frequent conflicts among territorial chieftains (Fernández Guardia, 1913).

Clement and Horn (2001) analyzed a sediment core taken from near the center of Laguna Zoncho and found maize pollen to be present nearly continuously from lake formation ca. 3300 cal yr BP. Pollen data also showed that forest species were partially replaced by disturbance-adapted grasses and weedy herbaceous taxa during times of greater agricultural activity. Archeological surveys in the watershed have documented extensive evidence of human occupation around Zoncho. Cemeteries on nearby hilltops contain artefacts consistent with the Bugaba and Chiriquí periods (Laurencich de Minelli and Minelli, 1966), and large numbers of ceramic and lithic artefacts have been found immediately adjacent to the lake (Soto and Gómez, 2002). Charcoal associated with ceramics in three excavations by Soto and Gómez (2002) yielded radiocarbon dates that fall within the Bugaba period. Their archeological survey also identified a large structure made of boulders that dates to approximately 650 cal yr BP.

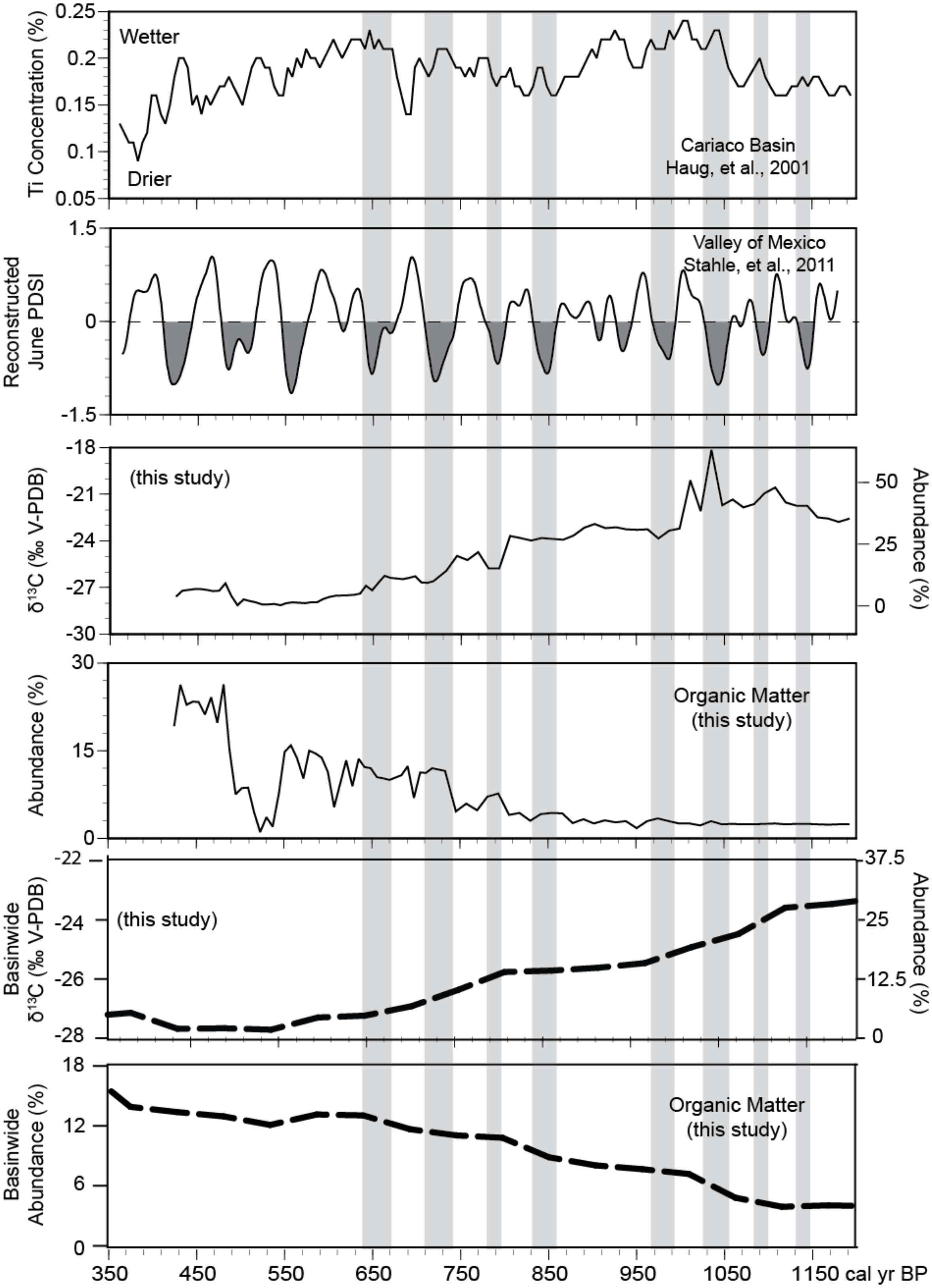
Past agricultural activities in the watershed were characterized in a network of five sediment cores using the abundance of organic matter (% OM) as a proxy for mineral inputs (Lane et al., 2008) and bulk sediment $\delta^{13}C$ ($\delta^{13}C_{OM}$) as a proxy of the scale of forest clearance (Lane et al., 2004; Lane et al., 2008; Lane et al., 2009). Percent OM and $\delta^{13}C_{OM}$ cannot differentiate algal and terrestrial carbon, but other evidence at Laguna Zoncho suggests their values are primarily driven by changes in terrestrial inputs. Diatoms indicate that the lake never became eutrophic during agriculture (Haberyan and Horn, 2005), and CN ratios (4.5–27.5, mean 15.0) are terrestrial in origin (Meyers et al., 1984). Decreased % OM during the agricultural period results from increased mineral inputs diluting organic inputs. $\delta^{13}C_{OM}$ values at Zoncho reflect the dominant photosynthetic pathway of the watershed, making them sensitive to forest clearance associated with maize agriculture. Tropical forest species predominantly use the C3 photosynthetic pathway, but the warmer, drier, and brighter conditions in agricultural fields favor plants that employ the C4 pathway, including grasses (Ehleringer et al., 1997), agricultural weeds (Brown, 1999), and maize. We used a two-endmember mixing model to calculate the contribution of C4 carbon to the sediments of five cores as an estimate of the amount of agriculture in the watershed (Phillips and Gregg, 2001).

Percent OM and $\delta^{13}C_{OM}$ data showed strong agriculture impacts from 2000 cal yr BP until 1150 cal yr BP (Chapter 3). Low % OM values result from greater mineral inputs and increased C4 inputs suggest considerable forest clearance. Basinwide inputs, determined by averaging values from cores 1–4, indicate a significant decline in agricultural activities from

1150–960 cal yr BP (Figure 2.3), while core 6 experienced a dramatic increase in C4 inputs with no corresponding change in % OM. This interval corresponds with a number of severe droughts reported in the circum-Caribbean (Hodell et al., 1995; Haug et al., 2001; Hodell et al., 2005; Medina-Elizalde et al., 2010), the Pacific coast of Panama (Lachniet et al., 2004), and central Mexico (Metcalfe and Davies, 2007; Metcalfe et al., 2010; Stahle et al., 2011) that have been attributed to a southward displacement of the ITCZ and a weakened Central American monsoon. An altered monsoon would have resulted in a shorter wet season and overall drier conditions at Zoncho that favored C4 plants and negatively affected agricultural activities. A second period of agricultural decline, between 850 and 640 cal yr BP, in all five cores corresponds with droughts documented in Panama (Lachniet et al., 2004) and central Mexico (Stahle et al., 2011). Even though maize pollen is present in sediments after 640 cal yr BP (Clement and Horn, 2001), % OM and stable carbon isotope data suggest most agricultural activities concluded ~220 years before the Spanish arrived.

Although drought records from several sites in Central America show a broad correspondence with agricultural activities at Zoncho, fluctuations in core 6 $\delta^{13}C_{OM}$ values correspond especially well to reconstructed June Palmer Drought Severity Index (PDSI) from a tree-ring study in central Mexico (Stahle et al., 2011). Both locations rely on a strong Central American monsoon for growing season precipitation. Unlike other records sensitive to total annual precipitation, the June PDSI reconstruction is specific to early season conditions, which strongly influence agriculture by controlling growing season length. A weakened and altered monsoon would have reduced total precipitation at Zoncho and likely affected the length and/or

Figure 2.3: Regional climate indices, core 6 % OM and $\delta^{13}C_{OM}$, and basinwide % OM and $\delta^{13}C_{OM}$.


Ti Concentration (%)
0.25
0.2
0.15
0.1
0.05
Wetter
Drier
Cariaco Basin
Haug, et al., 2001
Reconstructed June PDSI
1.5
0
-1.5
Valley of Mexico
Stahle, et al., 2011
δ13C (‰ V-PDB)
-18
-21
-24
-27
-30
(this study)
C4 Abundance (%)
50
25
0
Abundance (%)
30
15
0
Organic Matter
(this study)
Basinwide δ13C (‰ V-PDB)
-22
-24
-26
-28
(this study)
C4 Abundance (%)
37.5
25
12.5
0
Basinwide Abundance (%)
18
12
6
0
Organic Matter
(this study)
350
450
550
650
750
850
950
1050
1150 cal yr BP

timing of the growing season. A shorter or more unpredictable growing would have stressed cropping systems designed for longer growing seasons.

Droughts in Mexico prior to 960 cal yr BP correspond to positive excursions in $\delta^{13}C_{OM}$ at Zoncho. We interpret this signal, especially the large peak at 1035 cal yr BP with no corresponding increase in % OM, as a temporary increase in agriculture by an indigenous population attempting to maintain crop production at pre-drought levels. After this peak, all cores indicate a decline in agricultural activities and thus a possible decrease in the population at Zoncho. For the remainder of the record, droughts in Mexico correspond to decreases in C4 input, which we attribute to temporarily reduced agricultural activities of a smaller population.

As a whole, these data suggest regional precipitation patterns controlled agricultural activities at Zoncho. While it is difficult to quantify the exact relationship between agricultural impacts and population size, sharp declines in agriculture at 1150 cal yr BP and 850 cal yr BP imply a corresponding decrease in population. Extended periods of drought appear to have played a major role in this the population decline, as was likely the case with the Mayan collapse, despite the fact that Zoncho receives almost three times the annual precipitation of the Yucatan.

Population collapse prior to the arrival of the Spanish may not be a purely local phenomenon. In western Panama, a paucity of ceramics and other archeological evidence during the Chiriquí Period has been interpreted as evidence of widespread abandonment of population centers (Palumbo, 2009). Drought may also have fueled the warfare among the indigenous populations reported by the Spanish explorers (Fernández Guardia, 1913) and could help explain the presence of the large structure in the Zoncho watershed, constructed during the 850–640 cal yr BP dry period (Soto and Gómez, 2002). While additional high-resolution records are needed to determine the spatial extent of the drought, climate change, not the arrival of the Spanish, appears to have been the driving force behind population collapse in southern Central America.

2.3 Supplementary Materials

2.3.1 Field Methods

Sediment cores were recovered from six core sites in June 2007 using a Colinvaux-Vohnout (C-V) locking piston corer (Colinvaux et al., 1999) from an anchored floating platform. Overlapping cores were taken at each site, and coring depths were calculated to ensure the recovery of sediments from 2000–500 BP, which spans the latter part of the major archaeological period and the period of forest recovery.

2.3.2 Lab Methods

Cores were sliced longitudinally and sampled at a resolution of 1 cm. Each sample was freeze-dried and homogenized prior to decalcification using 1 N hydrochloric acid. After a second freeze-drying, samples were analyzed using a CosTech Elemental Analyzer coupled to a Thermo-Finnigan XL+ Mass Spectrometer. C and N concentrations were determined using CosTech software and CosTech elemental analyzer standards. δ^{13}C and δ^{15}N values were calibrated using several internal laboratory standards selected to bracket experimental values. δ^{13}C data were standardized to V-PDB using internal standards (SD < 0.13, n = 237). A total of 1547 samples was analyzed with duplicate analyses performed on approximately 10 % of samples. Mean variation on replicate analyses of samples was 0.47 ‰ for δ^{13}C and 0.8 ‰ for δ^{15}N. We used the following equations to calculate C4 input (Phillips and Gregg, 2001):

$$\delta_M = f_A\delta_A + f_B\delta_B$$

$$1 = f_A + f_B$$

where δ_M is the mean isotopic composition of the bulk sediment; δ_A and δ_B represent the mean isotopic composition of sources A (C4 vegetation) and B (C3 vegetation), respectively; f_A and f_B are the proportion of A and B in the mixture (M). The proportion of source A (C4 inputs) was then calculated using the equation: $f_A = (\delta_M - \delta_B) / (\delta_A - \delta_B)$ (Balesdent and Mariotti, 1996). The C3 endmember (–27 ‰) was determined using a local calibration set of surface soil samples collected from primary forest at the nearby Las Cruces Biological Station. The C4 endmember (–13 ‰) was determined from literature values for C4 plants (Bender, 1971).

The entirety of core 5 showed evidence of oxidation and was excluded from the analysis.

2.3.3 Chronology

We obtained a total of 13 AMS radiocarbon dates (Table 2.1), which, along with the Barú tephra provided chronological control. Each date was calibrated with CALIB 5.01 (Stuiver and Reimer, 1993) using the Intcal 98 dataset (Stuiver et al., 1998). We calculated the weighted means of the probability distributions of the calibrated ages (Telford et al., 2004) to yield a single age estimate for each date. We excluded three out-of-sequence dates UG-04551, UG-04554, and UG-04555. Based on a recalibration of the AMS date from Laguna Volcán, the date of the Barú tephra was fixed at 537 cal yr BP (Behling, 2000). These data were used to create linear age models for each core to allow inter-core comparisons.

2.3.4 Calculation of Basinwide Inputs

We determined basinwide inputs by calculating mean $\delta^{13}C$ and % OM values for 50-year increments in cores 1–4. Basinwide inputs are the mean of incremented values for cores 1–4.

Table 2.1: Radiocarbon determinations from the Laguna Zoncho cores.

Lab Number[a]	Core and Depth (cm)	δ^{13}C (‰)	Uncalibrated ^{14}C Age (^{14}C yr BP)	Calibrated Age Range[b] (cal yr BP) ± 2 σ	Area Under Probability Curve	Weighted Mean Calibration[c] (cal yr BP)	Material Dated
UGAMS-04068	1A 134	–25.3	920 ± 25	778–920	1	847	Leaf fragments
β-233111	1B 201	–26.8	1640± 40	1413–1620 1673–1687	0.975 0.025	1530	Plant material
UGAMS-04069	1B 209	–25.2	1670 ± 25	1524–1624 1670–1688	0.945 0.055	1576	Wood
UGAMS-04550	2B 150	–26.0	1340 ± 25	1185–1203 1242–1304	0.083 0.917	1271	Plant material
UGAMS-04551[d]	2B 157	–25.4	530 ± 25	513–557 605–626	0.869 0.031	546	Charcoal
UGAMS-07205	3B 132.5	–28.1	690±20	567–584 648–678	0.165 0.835	646	Bulk sediment
UGAMS-04070	3B 141	–24.1	730±25	655–699 702–711 719–721	0.975 0.019 0.006	675	Wood
UGAMS 04552	3B 167	–27.7	1620 ± 25	1416–1560	1	1494	Wood
UGAMS-04554[d]	4B 145.5	–25.6	430 ± 35	332–355 434–532	0.070 0.930	477	Plant material
UGAMS-04553	4B 180	–23.2	1990± 30	1878–1997	1	1938	Charcoal
UGAMS-07206	6A 85.5	–27.6	810±20	683–743 752–762	0.974 0.026	715	Bulk sediment
UGAMS-04555[d]	6B 144	–23.3	3880 ± 45	4156–4207 4221–4420	0.102 0.898	4307	Plant material
UGAMS-04071	6B 163	–23.3	1745 ± 25	1569–1585 1591–1714	0.047 0.953	1652	Plant material

[a] Letters before lab numbers denote samples processed at the University of Georgia Center for Applied Isotope Studies (UGAMS) or Beta Analytic, Inc. (β).

[b] Calibrations were made using CALIB vers. 5.0.1 (Stuiver and Reimer, 1993) and the dataset of Stuiver et al. (1998).

[c] Weighted mean of the probability distribution of the calibrated age.

[d] Dates excluded from age/depth models.

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Chapter 3: Assessing Geochemical and Isotopic Intra-Basin Spatial Variability in a Small Neotropical Lake

This chapter is in preparation for submission to the *Journal of Paleolimnology* by me, David B. Finkelstein, and Sally P. Horn. My use of "we" in this chapter refers to my co-authors and myself.

3.1 Abstract

We examined geochemical and isotopic intra-basin spatial variability using a network of five sediment cores from a small lake in southern Costa Rica with a history of prehistoric maize agriculture in its watershed. All cores showed a similar pattern of agricultural activity, a transitional period of forest recovery, and a period after forest reestablishment. During the agricultural period, bulk sediment stable carbon isotope ratios ($\delta^{13}C_{OM}$) indicate significant forest clearance, and organic matter percentages (% OM) are low due to accelerated erosion and dilution from mineral inputs to the lake. Within the lake, stable nitrogen isotopes ($\delta^{15}N$) and carbon/nitrogen (C/N) ratios are consistent with an increase in productivity. At the conclusion of the agricultural period, $\delta^{13}C_{OM}$ and % OM indicate rapid forest recovery and reduced mineral inputs, and $\delta^{15}N$ and C/N ratios suggest lower lake productivity. Comparisons between cores taken near the shore show little variation in the magnitude of the agricultural signal, but indicate a non-simultaneous end to agriculture in the watershed. Three of the four cores indicate agriculture ended by 1000 cal yr BP, but agricultural indicators persist in one core until 675 cal yr BP. The core from the center of the lake shows a gradual decline in agriculture from 1000–525 cal yr BP resulting from the redistribution of sediment from the edge to the deeper portions of the lake basin.

3.2 Introduction

Paleoenvironmental researchers usually recover cores from the deepest portions of lakes (Davis et al., 1984), hoping to take advantage of continuous sedimentation that can produce uninterrupted sediment profiles with high accumulation rates (Lehman, 1975; Larson and MacDonald, 1994). Particularly for palynological studies (Davis, 1973), this approach has been widely seen as offering the best chance to obtain a representative core. Single-core studies are also common due to the time intensive nature and high cost of analyzing multiple cores. In light of the now widespread use of proxy records that analyze the organic component of lake sediments, it is critical to reevaluate the utility of a single core. Such studies will improve our understanding of the processes that govern organic matter deposition and will subsequently enable the selection of sediment coring locations that provide representative records.

Spatial variability in lake sediments can be caused by differential inputs from the watershed and from processes that operate within the lake. Several studies have found that inlet streams contribute to spatial variability (Hilton et al., 1986; Lebo and Reuter, 1995; Korsman et al., 1999; Kumke et al., 2005). Korsman et al. (1999) suggested that land-use changes such as clear-cutting can also impart spatial variability to lake sediments. Once material reaches a lake, it is susceptible to a variety of factors that affect the location of final deposition. Hilton (1985) identified four main factors that control sediment deposition: sliding and slumping on slopes, intermittent mixing, peripheral wave action, and random sediment redistribution. Wind-induced currents can randomly redistribute sediment (Hilton, 1985; Whitmore et al., 1996), but the other sediment-focusing processes tend to move material towards the deepest part of the lake basin. Hilton et al. (1986) found that 59% of the spatial variation of the sediment accumulation rate in a lake in England could be attributed to sediment-focusing processes. Lehman (1975) created several models to describe how sediment-focusing processes operated in lakes and concluded that basin morphology is a key factor; additionally, time was an important factor because as basins fill with sediment, they change shape, which alters sediment-focusing patterns.

A number of studies have examined the impact of sediment focusing on the distribution of paleoenvironmental indicators, most notably pollen grains, diatoms, and sediment organic content as determined by loss-on-ignition (LOI). Analysis of multiple sediment cores, sediment traps, and surface samples from Mirror Lake, New Hampshire indicated that pollen influx varies considerably as the result of sediment-focusing processes, suggesting that no single core provided an accurate record of influx (Davis et al., 1984). Multiple cores were also used in Lough Augher in Northern Ireland to examine spatial variations in diatom concentrations, accumulation rates, and assemblages (Anderson, 1989; Anderson, 1990a; Anderson, 1990b; Anderson, 1998). In general, all cores showed similar patterns; however, cores from deeper locations in the lake showed much less variability than those from littoral areas. Diatom accumulation rates were especially variable from core to core, and littoral diatom species tended to be underrepresented in profundal cores, suggesting that sediment-focusing processes were not sufficient to homogenize the sediments before deposition.

Spatial variation in the organic and inorganic content of lake sediments can be significant and offer the opportunity for a holistic paleoenvironmental interpretation. Anderson (1990a) found that deepwater LOI profiles were similar (20–40 %), but that cores from shallower water exhibited more variability (5–40 %). He suggested that stream inflow can exert a strong, though local, influence on both organic and inorganic sediment profiles. At Mirror Lake, Davis and

Ford (1982) also found significant differences between deep and shallow water cores and stressed that multiple cores are essential for an accurate estimation of whole basin sediment influx (Chapter 2).

In this paper, we present a high resolution, spatially-explicit record of organic content, total nitrogen, C/N ratios, $\delta^{13}C_{OM}$, and $\delta^{15}N$ from a small lake in Costa Rica with a known history of prehistoric maize agriculture. We assessed spatial variability in lake sediments by examining the timing and magnitude of the agricultural signal across a network of sediment cores recovered from the lake basin. This research helps to illustrate the variability between shallow and deep cores and the importance of the transfer of material from the watershed to shallow- and deep-water core sites.

3.3 Study Site

Laguna Zoncho (8.813ºN, 82.963ºW, 1190 m elevation) is a small lake (0.75 ha) located in the southern Pacific lowlands of Costa Rica (Figure 3.1). The lake sits in a 7 ha basin (Filippelli et al., 2010) that likely formed due to faulting and/or mass wasting processes (Clement and Horn, 2001). The lake has no inlet or outlet streams and is a balance-fill basin in which sediment and water supply and potential accommodation are in approximate equilibrium (Bohacs et al., 2000). The lake has a relatively smooth and flat bottom, an effective fetch of approximately 75 m, and an average depth (based on the 6 coring locations in June 2007) of 392 cm. Our observations at the lake, confirmed by landowners, is that the water level was relatively high at this time. The Lomalinda Meteorological Station (http://www.ots.ac.cr/meteoro/default.php?pestacion=3) reports a mean annual temperature of ~20 °C and mean annual rainfall of ~3300 mm, with most precipitation occurring between April

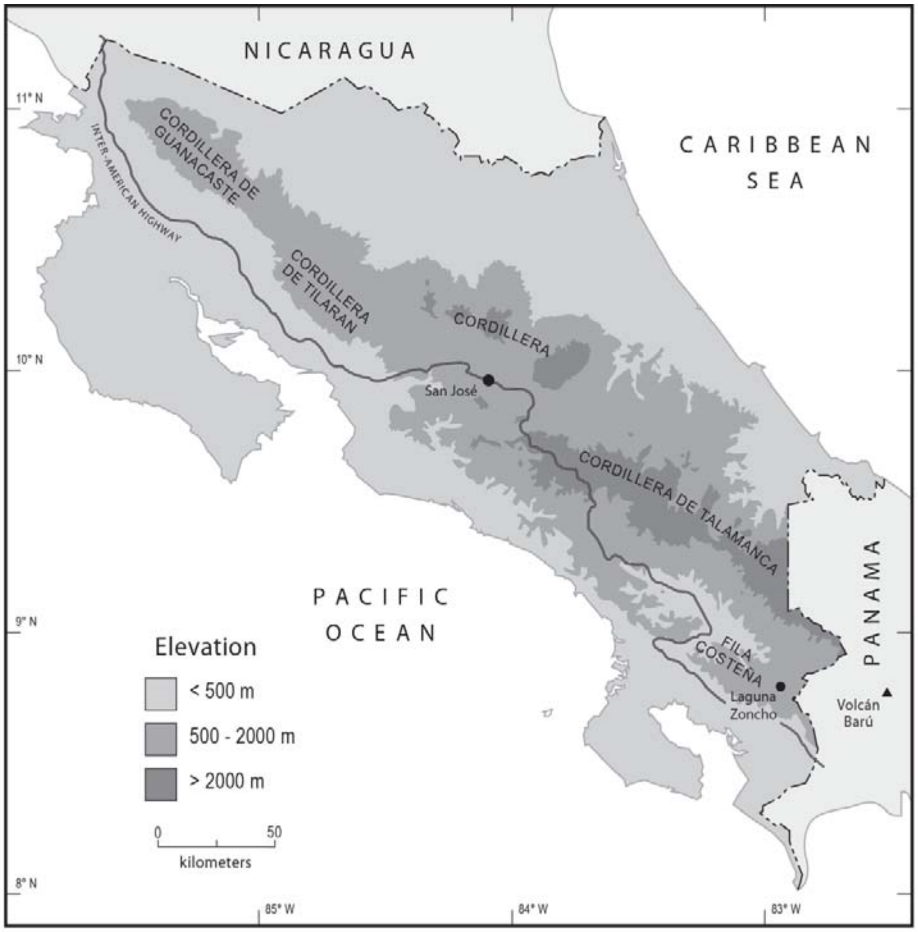

Figure 3.1: Location of Laguna Zoncho in southwestern Costa Rica. Volcán Barú is located just across the border with Panama. From Clement and Horn (2001).

and November. Although areas near Laguna Zoncho support remnant premontane rainforest (Hartshorn, 1983), paleoecological records show a long history of anthropogenic disturbance in the Zoncho watershed. Pollen and charcoal (2001), bulk sediment $\delta^{13}C$ (Lane et al., 2004), diatom (Haberyan and Horn, 2005), and phosphorus analyses (Filippelli et al., 2010) all show that the lake and its watershed were strongly affected by land-use changes. The sediments of Laguna Zoncho, like those of several other, nearby lakes (Behling, 2000; Anchukaitis and Horn, 2005; Horn, 2006) contain evidence of prehistoric agriculture in the form of *Zea mays* subsp. *mays* pollen grains. The watershed also preserves archeological evidence of prehistoric occupation (Laurencich de Minelli and Minelli, 1966; Soto and Gómez, 2002). Tephra from the 537 cal yr BP (Behling, 2000) eruption of Volcán Barú in western Panama provides a stratigraphic marker in the Zoncho sediments.

3.4 Methods

We recovered sediment cores from six core sites in Laguna Zoncho in June 2007. We located core site 6 near the center of the lake. Core sites 1–5 were located approximately equidistant between the center of the lake and the shore in a radial pattern around core site 6 (Figure 3.2). We recovered sediments using a Colinvaux-Vohnout locking piston corer (Colinvaux et al., 1999) from an anchored, floating platform. To guarantee complete sediment records, we recovered two parallel cores (A and B) at sites 1–5. To ensure recovery of the Barú tephra and the end of the agricultural period, we began sediment recovery of the A core approximately 30 cm below the sediment-water interface using two successive 1-m drives that recovered sediments up to 230 cm deep. To recover the overlapping B core, we moved the raft approximately 1 m and recovered a 1-m core section beginning approximately 80 cm below the

Figure 3.2: Aerial photo of Laguna Zoncho and locations of core sites within the lake. Thiessen polygons are used to divide the lake for purposes of display. Thiessen polygons define the area that is closest to each point relative to all other points. Core site locations are imprecise due to theft of the GPS base station in the field. The aerial photograph was taken in 1968 by the National Geographic Institute of Costa Rica. The dark line is the Inter-American highway; the lighter lines are other roads.

sediment-water interface. Although the same method was used at site 6, we recovered 3 m of sediment in the A core and 2 m in the B core.

Upon return to the University of Tennessee, core sections were opened using a modified router, sliced longitudinally, photographed, and stratigraphy was logged in terms of Munsell color, sediment texture, and grain size. Cores were then sampled at 1-cm resolution and each sample was frozen, freeze-dried, and homogenized using an agate mortar and pestle. A portion of each sample was then decalcified using 1 N hydrochloric acid; the remaining sediment was reserved for later analysis. Decalcified samples were freeze-dried a second time and then analyzed using a CosTech Elemental Analyzer (EA) coupled to a Thermo-Finnigan XL+ Mass Spectrometer. Organic matter (% OM) and total N abundances were determined using the provided software and elemental analyzer standards. Nitrogen and carbon isotope data are presented in per mil (‰) notation, where $\delta = (R_{\text{sample}}/R_{\text{standard}} - 1)*1000$. The δ^{15}N data were standardized to air using internal standards (Standard Deviation, SD = 0.10; n = 238), and δ^{13}C data were standardized to V-PDB using internal standards (SD < 0.13, n = 237). A total of 1547 samples were analyzed with duplicate analyses performed on approximately 10 % of samples. Mean variation on replicate analyses of samples was 0.47 ‰ for δ^{13}C and 0.8 ‰ for δ^{15}N.

The Barú tephra and 13 AMS radiocarbon dates provided chronological control (Table 3.1). Eleven AMS samples consisted of macrofossils extracted from the sediment core; the remaining two samples consisted of bulk sediment. Twelve radiocarbon samples were analyzed by the Center for Applied Isotope Studies located at the University of Georgia and one by Beta Analytic, Inc. Each date was calibrated with CALIB 5.01 (Stuiver and Reimer, 1993) using the

Table 3.1: Radiocarbon determinations from the Laguna Zoncho cores

Lab Number[a]	Core and Depth (cm)	$\delta^{13}C$ (‰)	Uncalibrated ^{14}C Age (^{14}C yr BP)	Calibrated Age Range[b] (cal yr BP) ± 2 σ	Area Under Probability Curve	Weighted Mean Calibration[c] (cal yr BP)	Material Dated
UGAMS-04068	1A 134	–25.3	920 ± 25	778–920	1	847	Leaf fragments
β-233111	1B 201	–26.8	1640± 40	1413–1620 1673–1687	0.975 0.025	1530	Plant material
UGAMS-04069	1B 209	–25.2	1670 ± 25	1524–1624 1670–1688	0.945 0.055	1576	Wood
UGAMS-04550	2B 150	–26.0	1340 ± 25	1185–1203 1242–1304	0.083 0.917	1271	Plant material
UGAMS-04551[d]	2B 157	–25.4	530 ± 25	513–557 605–626	0.869 0.031	546	Charcoal
UGAMS-07205	3B 132.5	–28.1	690±20	567–584 648–678	0.165 0.835	646	Bulk sediment
UGAMS-04070	3B 141	–24.1	730±25	655–699 702–711 719–721	0.975 0.019 0.006	675	Wood
UGAMS 04552	3B 167	–27.7	1620 ± 25	1416–1560	1	1494	Wood
UGAMS-04554[d]	4B 145.5	–25.6	430 ± 35	332–355 434–532	0.070 0.930	477	Plant material
UGAMS-04553	4B 180	–23.2	1990± 30	1878–1997	1	1938	Charcoal
UGAMS-07206	6A 85.5	–27.6	810±20	683–743 752–762	0.974 0.026	715	Bulk sediment
UGAMS-04555[d]	6B 144	–23.3	3880 ± 45	4156–4207 4221–4420	0.102 0.898	4307	Plant material
UGAMS-04071	6B 163	–23.3	1745 ± 25	1569–1585 1591–1714	0.047 0.953	1652	Plant material

[a] Letters before lab numbers denote samples processed at the University of Georgia Center for Applied Isotope Studies (UGAMS) or Beta Analytic, Inc. (β).

[b] Calibrations were made using CALIB vers. 5.0.1 (Stuiver and Reimer, 1993) and the dataset of Stuiver et al. (1998).

[c] Weighted mean of the probability distribution of the calibrated age.

[d] Dates excluded from age/depth models.

dataset from Stuiver et al. (1998). We calculated the weighted means of the calibration probability distributions (Telford et al., 2004) to yield a single age estimate for each date.

3.5 Results

3.5.1 Sediment Recovery

Twenty-four 1-m long core sections were collected from six sites in Laguna Zoncho (Table 3.2). At each location, we successfully recovered the Barú tephra layer. The lowermost section of core 6 (6A 739–839) consists of material that almost certainly came from higher up in the sediment profile, due to a coring malfunction. For this reason, we considered this core section unsuitable for analysis. Core 5 sediments were analyzed even though they showed evidence of oxidation. The geochemical and isotopic data are complacent and are therefore not presented here.

3.5.2 Chronology and Age/Depth Models

AMS radiocarbon measurements (Table 3.1) and the Barú tephra were used in combination to develop age/depth models for the Laguna Zoncho cores. Behling (2000) dated the tephra layer in Laguna Volcán, located 15 km from Volcán Barú in western Panama, and obtained an age estimate of 500 ± 60 BP that we recalibrated to yield an estimate of 537 cal yr BP. We chose this date for the Barú tephra over a slightly older date from Laguna Santa Elena (located approximately 25 km from Zoncho) (Anchukaitis and Horn, 2005) because it aligns better with the chronology of the 1997 core from Zoncho (Clement and Horn, 2001). Of the 13 AMS dates, we chose to exclude three from the age/depth model calculations because they were clearly out of sequence. UG-04551 (2B 157) came from the lowermost section of core 2 and confirmed our suspicion that the bottom of the core contained material that was out of sequence. UG-04554

Table 3.2: Sediment recovery from Laguna Zoncho.

Core Site	Water Depth (cm)	Core Section (Depths from platform)	Depth below Mud-Water Interface (cm)	Sediment Recovered (cm)
1	412	1A 573–673	74–174	94
		1A 641–741	178–278	50.5
		1B 600–700	137–237	90
2	400	2A 500–600	50–150	98
		2A 600–700	150–250	88
		2B 550–650	91–189	98
3	410	3A 500–600	40–140	100
		3A 600–700	140–240	49
		3B 550–650	90–190	80
4	344	4A 450–550	56–156	99
		4A 550–650	156–242	81.5
		4B 500-600	106–206	100
5	354	5A 450–550	46–146	83
		5A 550–600	146–196	50
		5B 475–575	71–171	66
6	429	6A 520–620	40–140	94
		6A 620–720	140–240	90.5
		6A 720–820	240–340	86
		6A 739–839	340–368	28
		6B 570–670	90–190	85.5
		6B 670–770	190–290	76

(4B 145.5) was lower than the tephra layer, but the sample postdates the Barú eruption; the UG-04555 (6B 144) date of 4307 cal yr BP predates the establishment of the current lake around 3300 BP (Clement and Horn, 2001).

We used point-to-point linear interpretation to develop the age/depth models presented in Figure 3.3. Sedimentation rates varied from 0.03 cm/year to 0.35 cm/year. Assuming these sedimentation rates were relatively consistent between radiocarbon dates, our records have a temporal resolution between 2.9 and 31.5 years. We plotted all data by age to facilitate inter-core comparisons.

3.5.3 Percent Organic Matter, Total Nitrogen, and C/N Ratios

Across the cores, % OM varied from approximately 16 % during the post-recovery period to between 0.5 % and 5 % during the agricultural period (Figure 3.4A). The increase in OM after agricultural cessation was abrupt, taking 60–100 years to reach post-recovery values. Total nitrogen was low in all cores (< 3 %), but did vary between the agricultural and post-recovery periods (Figure 3.4B). All five cores had lower N levels during the agricultural period, with values ranging from 0.10 % to 1.4 %. After forest recovery, N increased to 0.10–1.6 %; however, the increase was briefly interrupted by Barú tephra deposition. Atomic C/N ratios (henceforth C/N ratios) averaged 15 during the agricultural period and increased to 16.7 during the post-recovery period (Figure 3.4C). There is considerable noise in the N data, especially in core 6, which likely results from samples near the detection limit of the EA. The noise in the total N records, particularly from core 6, carries over into the C/N data.

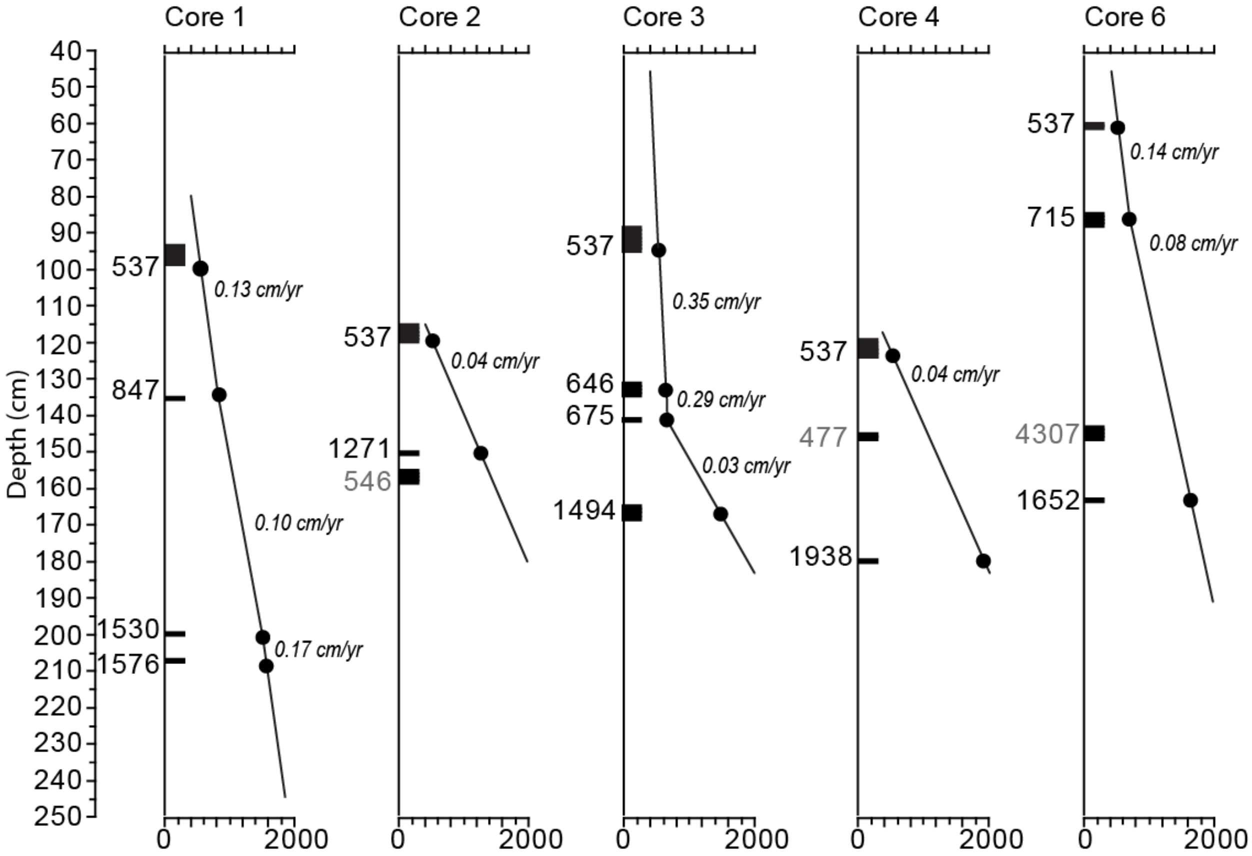

Figure 3.3: Age/depth diagram for Laguna Zoncho cores. Black bars represent locations and size of radiocarbon samples and tephra layers. Dates shown are the weighted means of the probability distributions of the calibrated radiocarbon ages. The 537 cal yr BP date is based on calibration with CALIB 5.0.1 of the date Behling (2000) obtained immediately below the Barú tephra at Laguna Volcán, Panama; that date is also a weighted mean. Dates shown in gray were excluded from the age model. Point-to-point linear interpretation was used to develop the models. Sedimentation rates are also shown between each pair of chronological markers.

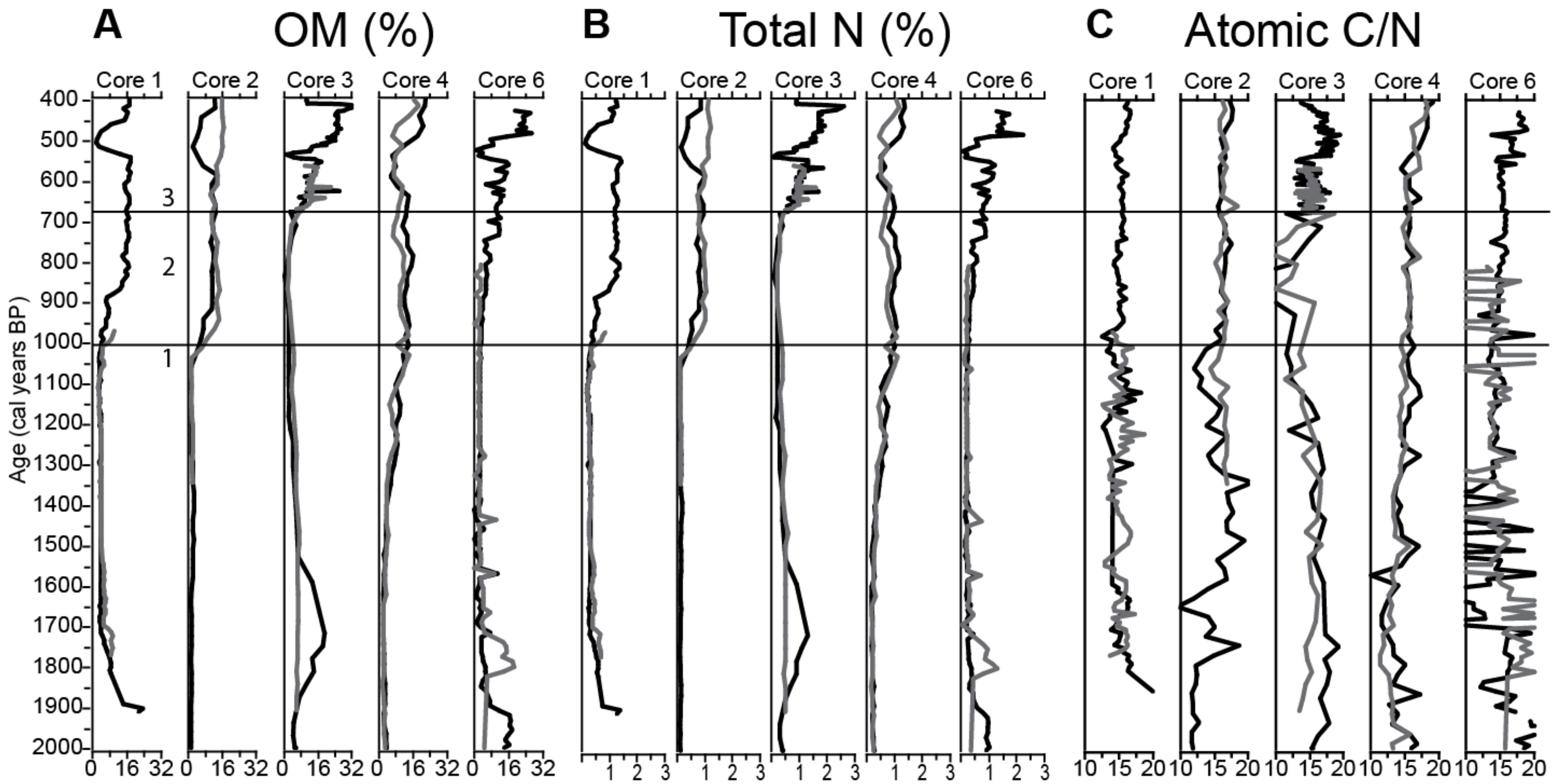

Figure 3.4: A) Total organic matter as a percent of dry mass. B) Total nitrogen as a percent of dry mass. C) Atomic C/N ratios. Black lines are the A cores, gray lines are overlapping B cores. Zone 1 is the agricultural period, Zone 2 the transition period, and Zone 3 the period after forest recovery.

3.5.4 $\delta^{15}N$ and $\delta^{13}C_{OM}$

$\delta^{15}N$ values were slightly more positive during agriculture, compared to those after forest recovery (Figure 3.5A). As with the other N-based proxies, there is considerable noise in the data. $\delta^{13}C_{OM}$ values during agriculture average –23.9 ‰ V-PDB and become more negative (–27.5 ‰ V-PDB) after forest recovery (Figure 3.5B). The transition between agricultural signals and post-recovery values took between 70 and 200 years, with core 6 (from the center of the lake) taking the longest. $\delta^{13}C_{OM}$ varied considerably between cores, with core 6B and 3B having large less negative excursions between 1200–1000 cal yr BP and 770–675 cal yr BP, respectively.

3.6 Discussion

3.6.1 The Geochemical and Isotopic Signatures of Agriculture and Forest Recovery

The high-resolution records from this study combined with the existing pollen and charcoal (Clement and Horn, 2001), diatom (Haberyan and Horn, 2005), and phosphorus (Filippelli et al., 2010) records provide an extremely detailed record of agricultural impacts. The five cores document the geochemical and isotopic signatures of prehistoric maize agriculture, forest recovery, and the period following forest reestablishment. For purposes of discussion, we used the geochemical and isotopic indicators to divide our record into three zones where the agricultural period is zone 1 (2000–1000 cal yr BP), the transition period is zone 2 (1000–675 cal yr BP), and the period after forest recovery is zone 3 (675–400 cal yr BP).

During zone 1, sediments were strongly influenced by agricultural activities. Percent OM values were low (0.12–18.8, mean = 4.8) due to the combination of forest clearance and soil

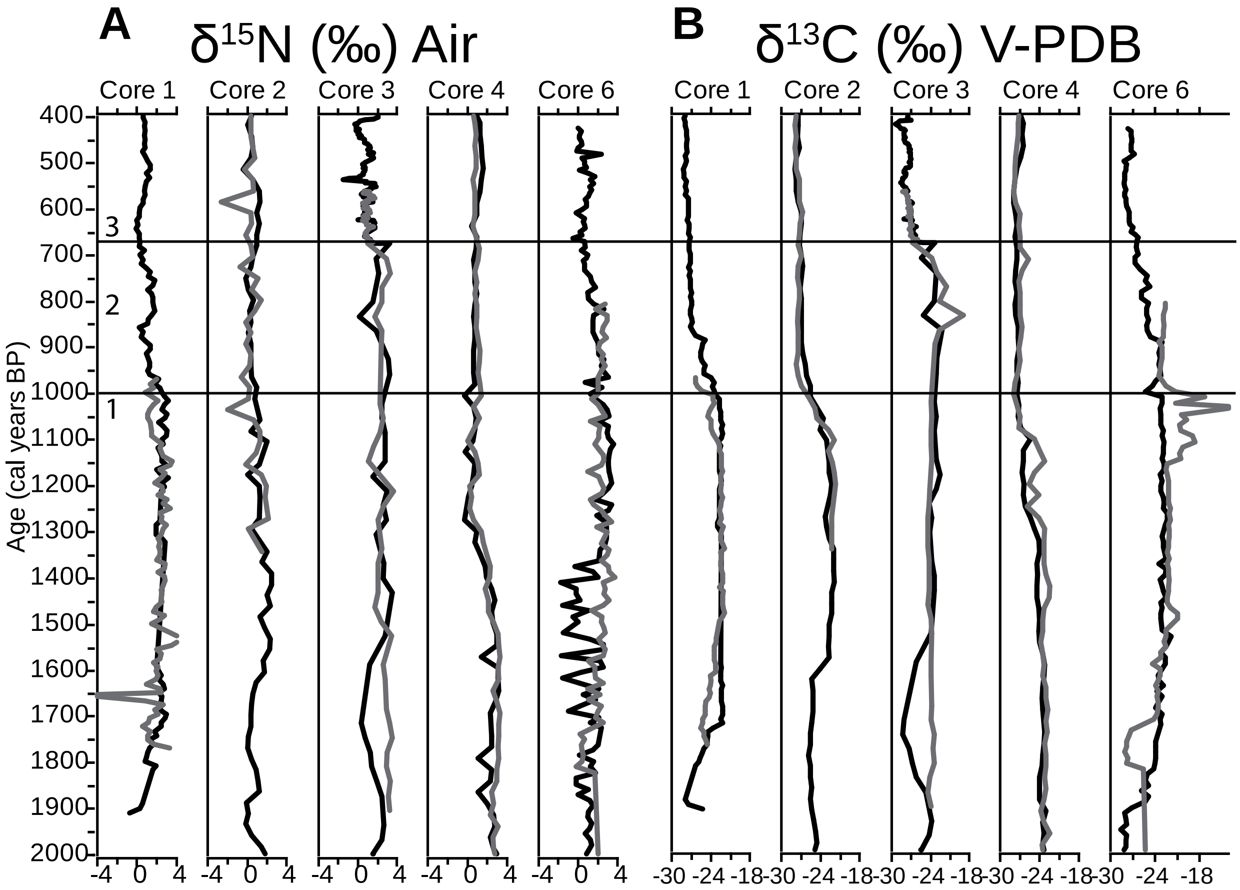

Figure 3.5: A) δ^{15}N (‰) Air. B) δ^{13}C$_{OM}$ (‰) V-PDB. Black lines are the A cores, gray lines are overlapping B cores. Zone 1 is the agricultural period, Zone 2 the transition period, and Zone 3 the period after forest recovery.

disturbance increasing mineral inputs from the watershed. Incoming mineral matter was sufficient to dilute the organic component of the lake sediments and lower % OM.

The zone 1 increase in terrestrial inputs coincides with increased lake productivity. Consistent with the existing diatom record (Haberyan and Horn, 2005), $\delta^{15}N$ (–1.8–4.9, mean = 1.8) and C/N ratios (4.5–24.7, mean =15.0) indicate a slight increase in carbon produced by algae. Gu et al. (1996) found a positive correlation between $\delta^{15}N$ values and lake productivity in a series of lakes in Florida. Zoncho $\delta^{15}N$ values during zone 1 correspond most closely with lakes that are mesotrophic (Gu et al., 1996). Algally-derived carbon has C/N ratios between 4 and 10, whereas terrestrial carbon ratios are 20 or higher (Meyers, 1994) Zone 1 C/N ratios average 15.0 and indicate slightly higher productivity compared to zone 3. Both characterizations correspond well to the diatom record, which indicated a more productive, but not eutrophic, lake during zone 1.

Interpreting the $\delta^{13}C_{OM}$ record is complicated because stable carbon isotopes have contributions from both the watershed and the lake. $\delta^{13}C_{OM}$ values in zone 1 (–18.1 to –28.7, mean = –23.9) likely stem from changes in watershed vegetation and, to a lesser extent, increased algal productivity. This hypothesis is supported by $\delta^{15}N$ and C/N ratios, which both show only a slight increase in lake productivity. Agricultural activities, especially forest clearance, would have changed the dominant photosynthetic pathway of watershed vegetation. Almost all plants in undisturbed tropical forests use the C3 photosynthetic pathway (Brown, 1999; Sage et al., 1999), which produces biomass with $\delta^{13}C$ values ranging from –35 to –20 ‰ V-PDB (Bender, 1971; O'Leary, 1981). Forest clearance to establish agricultural fields removes the C3 plants, creating a warmer, brighter, and drier environment that favors plants that use the C4 pathway. In addition to maize, many agricultural weeds (Brown, 1999) and native grasses

(Chazdon, 1978) use the C4 pathway. With $\delta^{13}C$ values between –10 and –14 ‰ V-PDB (Bender, 1971; O'Leary, 1981), sediment $\delta^{13}C_{OM}$ can distinguish between the two pathways and discern land-use changes (Lane et al., 2004; Lane et al., 2008; Lane et al., 2009). The presence of algally-produced organic matter in lake sediments can complicate this relationship because it has $\delta^{13}C$ values from –30 ‰ to, in extremely productive lakes, –9 ‰ (Meyers, 2003). While it is difficult to determine the exact contributions of algal and terrestrial materials, we attribute $\delta^{13}C_{OM}$ values of –23 ‰ to forest clearance because the lake did not become eutrophic, the less negative values correspond temporally to the pollen record of forest clearance, and the small size of Zoncho makes it particularly sensitive to changes in the watershed.

Zone 2 (% OM 1.3–13.9, mean = 6.5; % N 0.2–1.4, mean = 0.5; C/N 8.5–19.8, mean = 14.6; $\delta^{15}N$ –1.8–4.9, mean = 1.7 ‰; $\delta^{13}C_{OM}$ –21.4 to –27.7, mean = –24.7 ‰) is characterized by agricultural decline and forest recovery. Agricultural indicators in cores 1, 2, and 4 indicate a rapid decline from 1150–960 cal yr BP, but the decline does not begin at core site 3 until 675 cal yr BP (Figure 3.5). Pollen analysis of the 1997 core revealed maize pollen throughout the sediment profile (Clement and Horn, 2001), but the geochemical and isotopic data suggest a rapid period of forest recovery, reduced mineral inputs, and lowered lake productivity. Indicators from the outer cores (cores 1–4) show that forest recovery took approximately 150 years. Core 6 indicates a more gradual forest recovery (~300 years); however, this is likely the result of sediment-focusing processes incorporating material from the entire watershed (discussed in detail below).

Conditions in zone 3 (% OM 1–33.7, mean = 17.2; % N 0.1–2.6, mean = 1.2; C/N 13.0–19.7, mean = 16.7; $\delta^{15}N$ –1.5–2.5, mean = 0.6 ‰; $\delta^{13}C_{OM}$ –25.5 to –29.3, mean = 27.5 ‰)

indicate completed forest recovery aside from the deposition of the Barú tephra. The sudden input of mineral material caused a brief negative peak in % OM and total N. Otherwise, the indicators describe a forested environment dominated by C3 vegetation with low mineral inputs to the lake. Within the lake, productivity is lower than in zones 1 and 2, and $\delta^{15}N$ values are consistent with oligotrophic conditions (Gu et al., 1996). The record does not extend to the present, but historical evidence and data from the 1997 core suggests that disturbance associated with the modern occupation of the watershed started around 1950 (Clement and Horn, 2001).

3.6.2 Spatial Variability within Laguna Zoncho

In all five indicators, there was little variation in the magnitude of the agricultural and post-recovery signals between cores (Figure 3.6). Other studies (Anderson, 1989; Anderson, 1990a; Anderson, 1990b; Anderson, 1998) found significant differences in diatom community composition and accumulation between littoral and profundal cores. However, the lake in these studies were much larger (5.4 ha) and deeper than Zoncho, making direct comparisons difficult.

While the signal varies little across the cores, the timing of the start of forest recovery differs greatly between cores (Figure 3.6). Core sites 1, 2, and 4 show that agriculture ended around 1000 cal yr BP, with complete forest recovery by 850 cal yr BP. Agricultural signals persist at core site 3 until 675 BP, when the 150-year transition to forest begins at that location. Core 6 shows a gradual decline in agriculture from 1000–525 cal yr BP. This spatial variation provides insight into both the location of past activities in the watershed and the sediment transport processes operating within the lake. Based on these data, we suggest that while the majority of agriculture had ended by around 1000 cal yr BP, some persisted in the portion of the watershed adjacent to core site 3 for an additional 325 years.

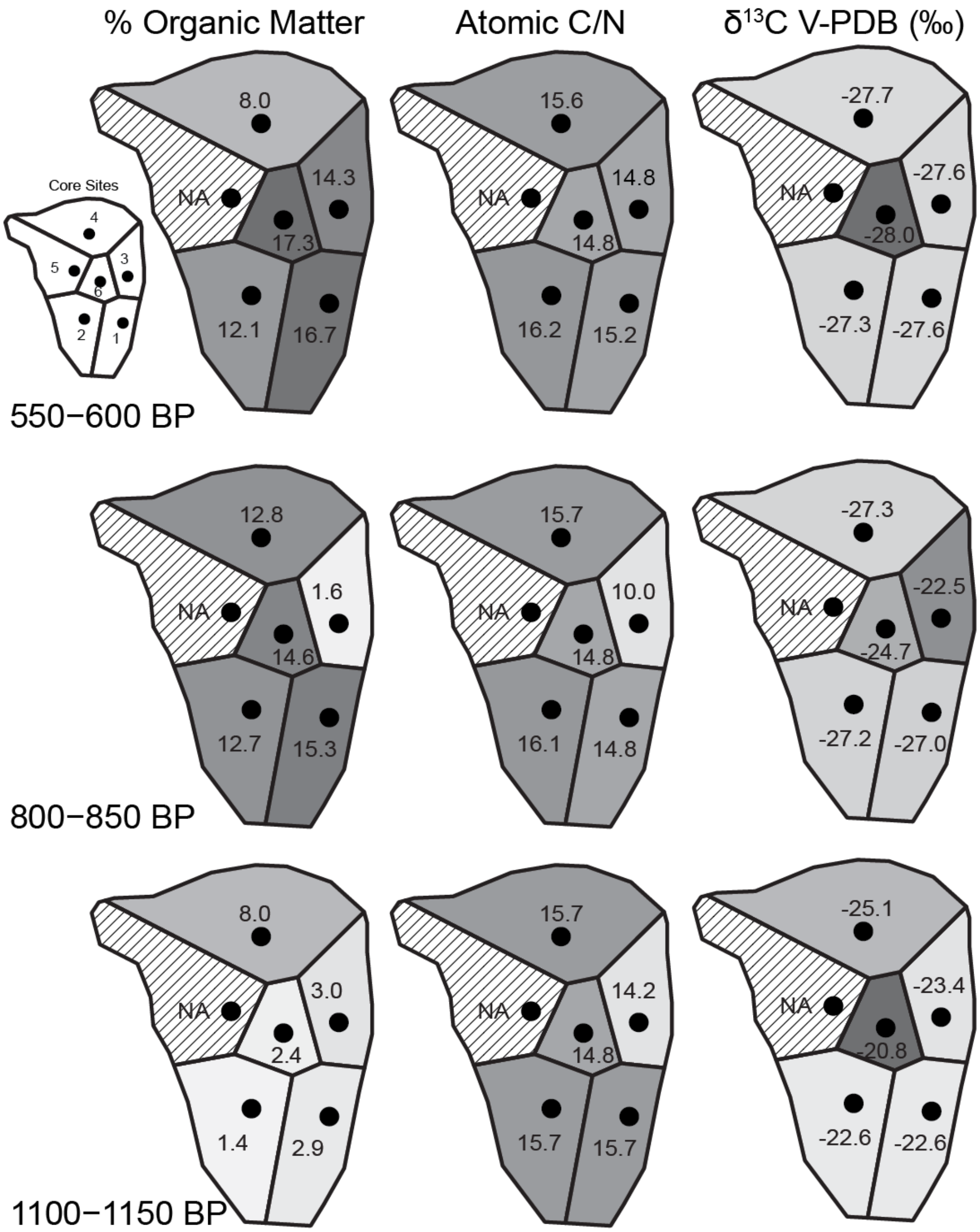

Figure 3.6: Diagrams showing spatial arrangement of percent organic content, atomic C/N ratios, and $\delta^{13}C_{OM}$ during the agricultural, transition, and post-recovery periods at Laguna Zoncho. Each value shown on the diagram represents the average of at least 6 analyses on sediments from both the A and B cores at each location. Small inset shows core locations. Core 5 was excluded.

We interpret the evidence for a gradual decline of the agricultural signal at core site 6 near the center of the lake to be the result of sediment reworking from shallow to deep sites within the lake. These processes, particularly wave- and current-induced mixing, transport material from the edges to the deepest part of the lake where the mixture is deposited (Davis et al., 1984; Larson and MacDonald, 1994). During the transition period (zone 2), this would mean the deeper portions of the lake received the majority of its organic matter from portions of the watershed with recovering forest and a small amount of material from the part of the watershed with active agriculture. Sediment focusing averages these inputs and results in a core from the deepest portion of the lake that generalizes watershed conditions.

3.6.3 Implications for Core Site Selection

The presence of spatial variability in the Laguna Zoncho sediments illustrates the importance of core site selection even in small and relatively shallow lakes. Most multiple-core studies have examined lakes larger than Zoncho, where variation is expected because of large differences between shallow and deep water, inflowing streams, and large disturbances in the watershed. However, our study shows that smaller lakes may also contain spatially heterogeneous sediments. While Zoncho may be an extreme case with widespread and persistent disturbance in the watershed, small lakes may be more likely to contain spatially heterogeneous sediments because of their close connection to the watershed. This variability would be especially noticeable in proxies closely tied to terrestrial inputs such as % OM, mineral influx, and, in Zoncho’s case, $\delta^{13}C_{OM}$.

Sediment reworking also strongly affects terrestrial indicators because the material is transported from the edge of the lake to deeper waters prior to deposition. Despite the fact that the current lake bottom in Laguna Zoncho is relatively flat, our data show that sediment was still effectively transported to the deepest part of the basin. As pointed out by Lehman (1975), the strength and direction of sediment-focusing processes can change as a lake basin fills in with sediment, making it possible that these processes behaved differently in the past. In repeated visits over the past 15 years, we have observed lake level changes of over 1 m. Changes in the shoreline shape and distance to the center of the lake when lake levels rise or fall can also affect sediment reworking and redistribution.

Our results from Laguna Zoncho show the value of recovering and analyzing multiple sediment cores. Cores closer to the shore are more sensitive to changes in the watershed. The outer cores from Zoncho provided valuable information that refined the estimate of agricultural scale in the watershed and helped constrain the timing of agriculture decline. While the core from the deepest part of the lake basin recorded “average” watershed conditions and sediment reworking, its record of agricultural decline was less sensitive then the records from the outer cores. Agricultural indicators from the center of the lake may also lag behind the outer cores due to the time it takes sediment-focusing processes to transport material to the deepest portion of the lake basin. At Zoncho, this delay, along with lower resolution records, led earlier studies to associate agricultural decline with the arrival of the Spanish (Clement and Horn, 2001; Lane et al., 2004). The greater sensitivity provided by multiple cores was essential to identifying two distinct periods of agricultural decline, both of which preceded the Spanish Conquest.

The analysis of multiple cores has the capability to greatly improve the accuracy of certain lake-sediment-based paleoenvironmental reconstructions. However, as illustrated by the unusable sediments in core 5, it is possible to get too close to the shore for a reliable record.

Studies that use ground penetrating radar, seismic reflection, and other techniques to image lake basins and accumulated sediments to inform core site selection offer a model for future studies in lakes with spatially variable sediments (Moorman, 2002; Anselmetti et al., 2006).

3.7 Conclusions

Geochemical and isotopic records from a network of cores recovered from Laguna Zoncho showed evidence of spatial variability across the lake basin and helped constrain the timing of agricultural activities in the watershed. All five cores showed a similar pattern of widespread agriculture, forest recovery, and post-recovery forest with little disturbance. The outer cores identified two distinct periods of agricultural decline. Three of the outer cores showed agriculture ending in the basin around 1000 cal yr BP, but one core indicated that agriculture continued until approximately 675 cal yr BP. Because of the integration of geochemical and isotopic signals by sediment-focusing processes, the core recovered from the center of the lake suggested a gradual decline in agricultural activities from 1000–675 cal yr BP. Cores closer to the lakeshore provided a more sensitive record of agricultural activities and revised earlier estimates of the timing of agricultural decline. Spatially variable sediments in a lake as small as Laguna Zoncho suggest the possibility of spatially reconstructing past disturbances in the watershed and highlight the importance of sediment-focusing processes when interpreting terrestrial indicators in sediment records.

3.8 Acknowledgements

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Chapter 4: Maize Pollen Concentrations in Lake Sediments as an Indicator of Prehistoric Agriculture

This chapter is in preparation for submission to *Quaternary Research* by me, Sally P. Horn, and David B. Finkelstein. My use of "we" in this chapter refers to my co-authors and myself.

4.1 Abstract

We evaluate the potential of maize pollen concentrations in lake sediment profiles as indicators of the extent of prehistoric agriculture in neotropical lake basins by comparing indicators from a network of five sediment cores recovered from Laguna Zoncho, Costa Rica. The watershed of this lake in the Diquís archaeological region has a ca. 3000-year history of prehistoric agriculture and subsequent forest recovery, as documented through previous studies of pollen, charcoal, diatoms, and phosphorus fractions in a single core recovered from the center of the lake. In our new network of cores, we compared maize pollen concentrations with two independent proxies for the scale of agriculture in the same cores: organic matter percentages (% OM), which are indicators of soil erosion, and bulk sediment stable carbon isotope ratios ($\delta^{13}C_{OM}$), which reflect the proportion of forested and cleared land within the watershed. In none of the five cores did maize pollen concentrations correspond with either % OM or $\delta^{13}C_{OM,}$ suggesting that sedimentary maize pollen concentrations are not sensitive to the scale of maize agriculture in watersheds. We found maize pollen in relatively high concentrations in two of the four cores taken near the lakeshore, but the others contain little or no maize pollen. The core from the center of the lake consistently recorded maize pollen, which we attribute to sediment-focusing processes.

4.2 Introduction

The presence of maize (*Zea mays* subsp. *mays*) pollen grains in lake sediments is definitive evidence of human occupation and prehistoric agriculture (e.g. Goman and Byrne, 1998; Clement and Horn, 2001; Anchukaitis and Horn, 2005; Dull, 2007; Wahl et al., 2007). This makes maize pollen a key paleoenvironmental indicator, but low numbers of maize grains in the sediment record has led most researchers to only use maize pollen as confirmation of agriculture. However, some investigators have used maize pollen abundance to infer the scale of prehistoric agricultural activities (Northrop and Horn, 1996; Leyden et al., 1998; Dull, 2004; Dull, 2007; Lane et al., 2008). Most of these studies examined maize pollen percentages or concentrations in single sediment cores from near the centers of lakes, as is typically the case for pollen analyses. But a recent study by Lane et al. (2010) found large intrabasin spatial variability in maize pollen deposition in lakes in an agricultural setting in Wisconsin, suggesting a need for caution in inferring the scale of agriculture from maize pollen abundance. Lane et al. (2010) determined maize pollen concentrations in 44 surface sediment samples from four lakes surrounded by various arrangements of corn fields and found only a weak (but positive) correlation with the percent area under cultivation within 200 m of the sampling sites, leading the authors to postulate that numerous factors other than distance to maize fields influenced patterns of maize pollen deposition. Investigating the causes of spatial variability of maize pollen concentrations for prehistoric agriculture is more difficult because the former extent and arrangement of maize fields is unknown. The next best approach, used by Lane et al. (2008), is to compare prehistoric maize pollen concentrations with other agricultural indicators. Applying this approach across multiple cores from the same lake can increase the utility of sedimentary maize pollen as a proxy for ancient agriculture.

The primary difficulty in interpreting maize pollen stems from its poor representation in pollen records. Maize pollen grains usually make up <5 % of the total pollen sum because of limited pollen dispersal (Lane et al., 2009). While maize is wind-pollinated, its pollen does not travel far from the parent plant, with 99% of grains dispersing less than 60 m (Raynor et al., 1972), although this can vary with wind speed and surface roughness (Jarosz et al., 2003; Jarosz et al., 2005). Maize pollen grains may also be washed into a lake by fluvial processes (Lane et al., 2010). Once the maize grains reach the lake, they may behave differently than other pollen grains due to their large size (up to 100 μm in diameter). While no studies have specifically addressed maize pollen, other large pollen types sink quickly and are preferentially deposited close to lake shores (Davis et al., 1971). This pattern has been observed in surface sediments (Davis et al., 1971) and is suggested by pollen source models (Sugita, 1993). These processes potentially create spatial variability in maize pollen concentrations, but once incorporated into the sediment, maize grains will be transported towards the deepest portion (usually the center) of the lake basin by sediment-focusing processes, which tend to reduce variability as distance from the shore increases (Davis and Ford, 1982). Most studies rely on a single core recovered from the center of the lake that takes advantage of the average of basin inputs created by sediment-focusing processes, but this approach does not necessarily lend itself to capturing large, poorly-dispersed pollen types such as maize (Burden et al., 1986).

Recent lake sediment studies have made use of geochemical and isotopic indicators to assess the scale of prehistoric agriculture. Agricultural activities in a watershed tend to increase the erosion of mineral material which, when incorporated into lake sediments, results in lower proportions of organic matter (% OM) (Oldfield et al., 2003; Enters et al., 2006; Lane et al., 2008; Bookman et al., 2010). Stable carbon isotope ratios can also indicate agricultural extent because they reveal changes in watershed vegetation (Lane et al., 2004; Lane et al., 2008; Lane et al., 2009). This approach is effective in locations where forest is cleared to create agricultural fields. Forest vegetation, especially in the tropics, is dominated by plants (trees) that use the C3 photosynthetic pathway (Brown, 1999; Sage et al., 1999) and produce organic matter that has $\delta^{13}C$ values between –35 and –20 ‰V-PDB (Bender, 1971; O'Leary, 1981). Forest clearance not only removes the trees that are the source of C3 carbon, but also creates warmer and drier conditions that favor C4 plants. Maize and many agricultural weeds (Brown, 1999) use the C4 pathway, which produces organic material with $\delta^{13}C$ values ranging from –10 to –14 ‰V-PDB (Bender, 1971; O'Leary, 1981). Since terrestrial organic material from the watershed is eventually deposited in the lake sediments, sedimentary $\delta^{13}C_{OM}$ values can reveal the relative importance of each photosynthetic pathway in the watershed and thus provide an estimate of the amount of agriculture.

Evaluating the potential of maize pollen concentrations as paleoenvironmental indicators requires comparing this proxy with other agricultural indicators across both time and space. Here, we assess the temporal and spatial variability of maize pollen concentrations using a network of five sediment cores recovered from a small lake in Costa Rica with a well-established record of prehistoric maize agriculture. We compare maize pollen concentrations to $\delta^{13}C_{OM}$ and % OM and evaluate their utility as indictors of the scale of prehistoric maize cultivation. This work provides a prehistoric agricultural counterpart to studies of modern maize pollen deposition in lake sediments and offers insight on how to best use maize pollen concentrations as agricultural indicators.

4.3 Study Site

4.3.1 Physical Setting

Laguna Zoncho (8.813ºN, 82.963ºW, 1190 m elevation) is located in the southern Pacific lowlands of Costa Rica (Figure 4.1). The lake is small (0.75 ha) and located in a 7 ha basin that formed as the result of faulting and/or mass wasting processes (Clement and Horn, 2001). The nearby Lomalinda Meteorological Station (http://www.ots.ac.cr/meteoro/default.php?pestacion=3) reports a mean annual temperature of ~20 °C and yearly rainfall of ~3300 mm, with a distinct rainy season between April and November. Zoncho is located in the premontane rainforest life zone of the Holdridge bioclimatic classification (Hartshorn, 1983), but most modern forests in the area are heavily disturbed. Currently the area around Laguna Zoncho is home to Finca Cántaros, a 10 ha reforested private nature reserve open to the public.

4.3.2 Cultural Setting

Laguna Zoncho is located within the Diquís sub-region of the archaeological region known as the Greater or Gran Chiriquí, which includes western Panama and southwestern Costa Rica. Humans have continuously inhabited the Diquís subregion for thousands of years (Anchukaitis and Horn, 2005; Palumbo, 2009). The two most recent periods recognized by archeologists are the Bugaba Period and the Chiriquí Period. The Bugaba (also called the Auguas Buenas) Period began somewhere between 500 B.C. and A.D. 200 (there is debate about the precise timing) and ended around A.D. 800. Bugaba peoples grew maize and other crops, though there is debate

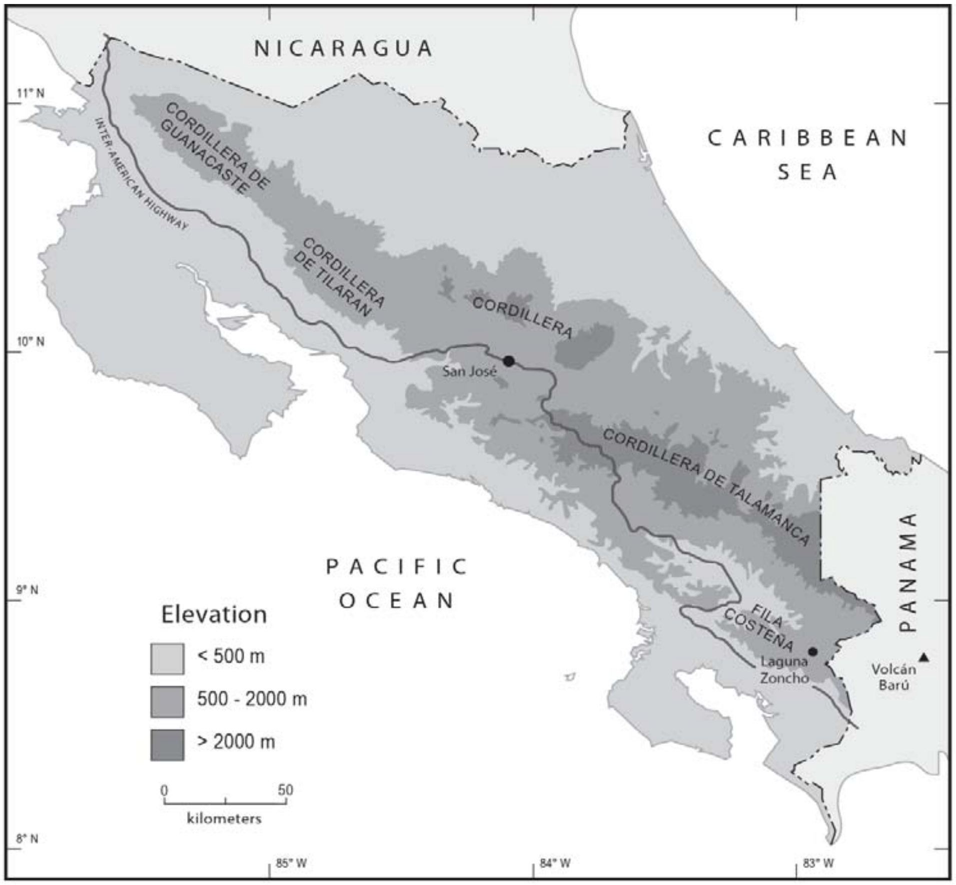

Figure 4.1: Location of Laguna Zoncho in southwestern Costa Rica. From Clement and Horn (2001).

about the contribution of maize to prehistoric diets (Anchukaitis and Horn, 2005). The Chiriquí Period followed the Bugaba and ended with the arrival of the Spanish in the early 1500s. During this period, large, complex settlements became more common and ceramics became more elaborate. As with the Bugaba period, the importance of maize as a staple crop is unclear (Palumbo, 2009).

4.3.3 Sedimentary Evidence of Maize Agriculture in Southwestern Costa Rica

The timing and effects of maize agriculture have been intensely studied at Laguna Zoncho. Working with a core recovered near the center of the lake in 1997, Clement and Horn (2001) found that maize pollen had been deposited nearly continuously in Zoncho sediments since the lake formed ca. 3300 years ago. Variations in the abundance of maize pollen and charcoal fragments, and in pollen percentages of disturbance and forest taxa, indicated changes in the extent of agricultural activity. Using the same core, Lane et al. (2004) identified intervals of forest clearance using stable carbon isotope analysis, Haberyan and Horn (2005) inferred changes in lake productivity from diatom assemblages, and Filippelli et al. (2010) found evidence in phosphorus fractions of soil alterations, all resulting from maize agriculture in the watershed. All of these studies suggested that maize agriculture largely stopped and forest recovery began in the watershed around 500 cal yr BP. However, new, high-resolution geochemical and isotopic records from Laguna Zoncho show that agriculture declined earlier, with a large decline around 1150 cal yr BP and a smaller decline around 850 cal yr BP (Chapter 2).

Three other lakes in the Diquís subregion contain evidence of maize agriculture. Pollen and stable carbon isotope evidence indicates significant forest clearance and prehistoric agriculture at Laguna Vueltas (Horn, 2006). Sediments from Laguna Santa Elena (Anchukaitis and Horn, 2005) and Laguna Gamboa (Horn, 2006) also contain maize pollen.

4.4 Materials and Methods

We recovered six sediment cores from Laguna Zoncho in the summer of 2007. We recovered core 6 from the center of the lake to replicate the 1997 core. Core sites 1–5 were arranged in a radial pattern around core site 6, halfway between the center of the lake and the shore (Figure 4.2). At each core site, we recovered overlapping core sections to ensure complete representation of the latter portion of the agricultural period and subsequent forest recovery.

We used high-resolution stable isotope and geochemical data to identify the agricultural period and took maize pollen samples from the end of that period. We removed 0.5 cm^3 samples at 4 cm intervals. We processed pollen samples using standard techniques, including treatment with HCl, HF, KOH, acetolysis, and safranin stain (Berglund, 1986) and mounted the residues in silicone oil. We added *Lycopodium* control spores to calculate maize pollen concentrations (Stockmarr, 1971).

For each sample, we prepared five slides. Each slide was scanned in its entirety for maize grains, which we defined as spherical grains with a diameter of at least 62.5 µm and a single annulated pore. These parameters are appropriate in Costa Rica, which lacks natural populations of teosinte (Horn, 2006). We counted *Lycopodium* spores on ten randomly chosen transects on each slide, and used the percentage of the slide counted to estimate the number of spores on the entire slide. For each slide, we used the following equation to calculate maize pollen concentration:

Figure 4.2: Aerial photo of Laguna Zoncho and locations of core sites within the lake. Thiessen polygons are used to divide the lake for purposes of display. Thiessen polygons define the area that is closest to each point relative to all other points. Core site locations are imprecise due to theft of the GPS base station in the field. Aerial photograph was taken in 1968 by the National Geographic Institute of Costa Rica. The dark line is the Inter-American highway, and the lighter lines are other roads.

Maize grain concentration (grains/cm^3) = ([controls$_{\text{sample}}$ * maize$_{\text{slide}}$] / controls$_{\text{slide}}$) / volume (cm^3)

where controls$_{\text{sample}}$ is equal to the number of *Lycopodium* spores added to each sample (13,911 or 18,583 depending on sample), maize$_{\text{slide}}$ is the number of maize grains found on each slide, controls$_{\text{slide}}$ is the extrapolated number of controls on each slide, and volume is the volume of the sample processed for pollen analysis. We averaged concentration values from all five slides to yield a single estimate of maize pollen concentration for each sample level.

We compared our maize pollen data to high-resolution % OM and stable carbon isotope data from the same levels. Each sample was frozen, freeze-dried, homogenized using an agate mortar and pestle, decalcified using 1 N hydrochloric acid, and freeze-dried again prior to analysis using a Cos-Tech Elemental Analyzer coupled to a Thermo-Finnigan XL+ Mass Spectrometer. Percent OM was determined using the provided software and elemental analyzer standards. $\delta^{13}C_{OM}$ data are presented in per mil (‰) notation, where $\delta = (R_{\text{sample}}/R_{\text{standard}} - 1)*1000$ and were standardized to V-PDB using internal standards (SD < 0.13, n = 237).

4.5 Results

We determined maize pollen concentrations from a total of 36 levels (Table 4.1). We analyzed samples from cores 1–4 and core 6, but excluded core 5 from our analysis because it showed evidence of oxidation. Maize pollen was present in all cores, but there is considerable intra- and inter-core variability. Core 4 had the lowest average concentration (2.9 grains/cm^3 wet sediment) and core 3 had the highest (22.7 grains/cm^3 wet sediment). Two samples from core 1 and three samples from core 4 contain no maize pollen though the slides showed good pollen preservation.

Table 4.1: Summary table of maize pollen concentrations

	n	Mean	Max.	Min.	No Maize	Standard Dev.
Core 1	9	8.5	29.7	0	2	10.32
Core 2	6	11.1	25.9	2.45	0	10.10
Core 3	6	22.7	63.1	11.9	0	10.22
Core 4	6	2.9	9.2	0	3	8.25
Core 6	9	11.2	20	3.5	0	8.29
All Cores	36	11.3	63.1	0	5	9.44

Maize pollen concentrations are reported in grains/cm^3 wet sediment, summarized by core. “No Maize” refers to the number of levels in which no maize pollen grains were found.

Maize pollen concentrations do not correlate with % OM (Figure 4.3) or $\delta^{13}C_{OM}$ (Figure 4.4). Plotted by depth, there is also no correspondence between maize pollen concentrations and % OM (Figure 4.5) or $\delta^{13}C_{OM}$ (Figure 4.6).

We also calculated maize pollen influx (grains/cm^2/yr) by multiplying concentrations by sedimentation rates calculated from calibrated AMS radiocarbon dates (Chapter 3). Influx values show high variability (Table 4.2) but no correspondence with % OM or $\delta^{13}C_{OM}$ (not shown).

4.6 Discussion

4.6.1 Comparisons to % OM and $\delta^{13}C_{OM}$

Previous work at Zoncho and other lakes with a history of prehistoric agriculture indicates that % OM and $\delta^{13}C_{OM}$ are strongly controlled by terrestrial inputs and are sensitive to disturbance and forest clearance, respectively (Lane et al., 2008). All five Zoncho cores show the same pattern of low % OM during the agricultural period and higher values after forest recovery stabilized watershed soils. Based on this pattern, and similar work in the Dominican Republic by Lane et al. (2008), we surmise that mineral inputs from agricultural fields are sufficient to overwhelm any change terrestrial or aquatic organic matter production and are controlling the % OM in Zoncho sediments. Since fluvial processes predominantly transport mineral material to the lake, % OM should provide an extremely sensitive record of the scale of agricultural activities. Variations in % OM between cores suggest that this record is spatially explicit and contains information on the location of past agricultural activities in the watershed.

We also hypothesize that terrestrial inputs control $\delta^{13}C_{OM}$ values at Zoncho. While our approach analyzes bulk sediment that contains carbon from both terrestrial and aquatic sources,

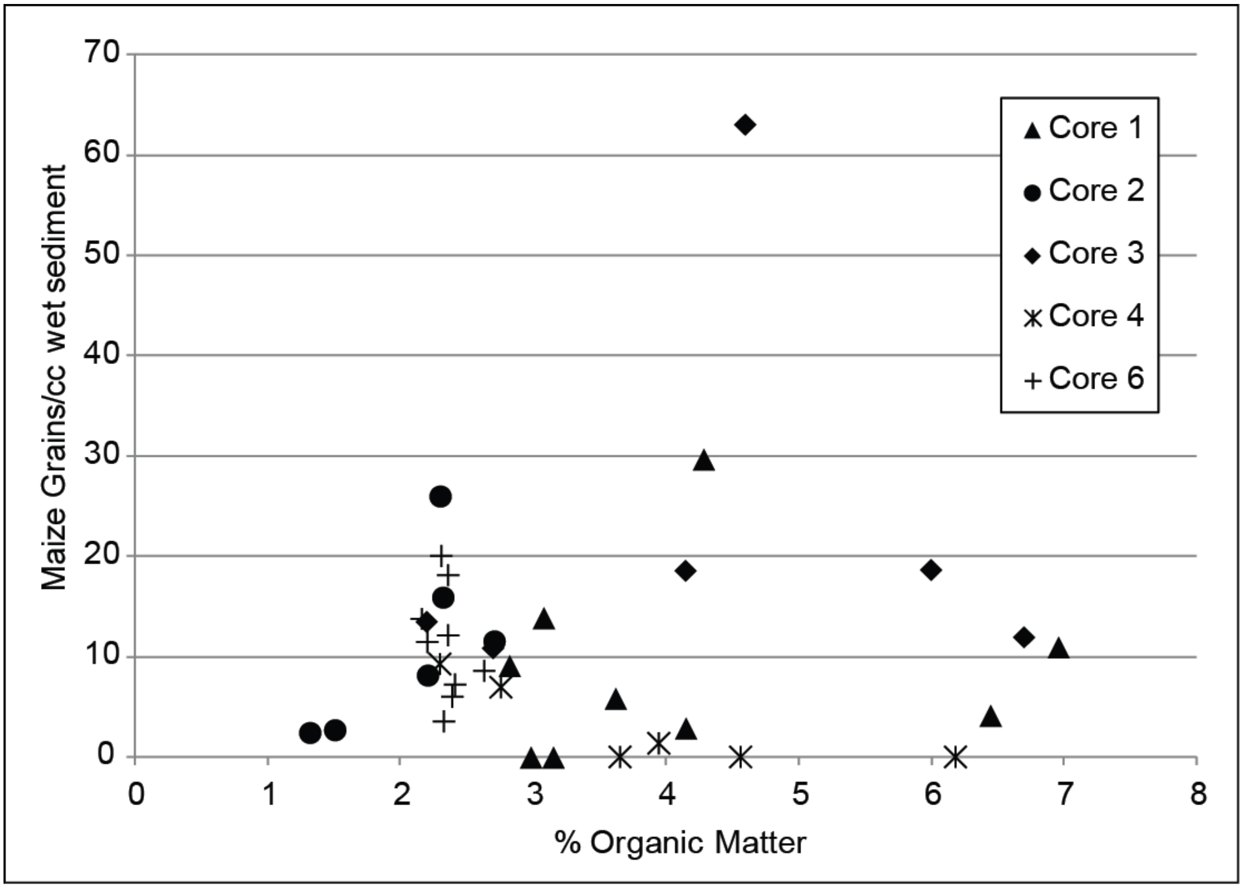

Figure 4.3: Maize pollen concentrations vs. % OM.

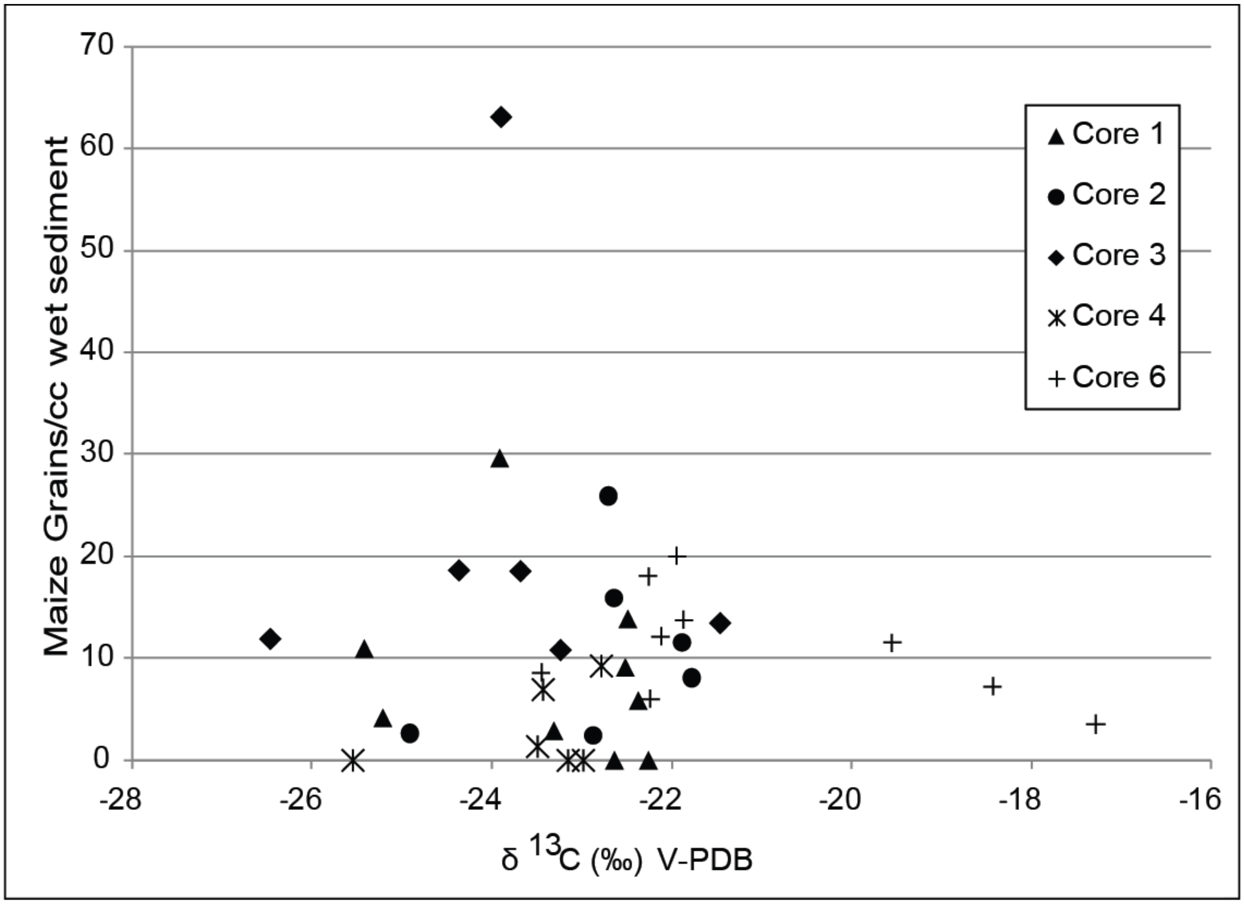

Figure 4.4: Maize pollen concentrations vs. $\delta^{13}C_{OM}$.

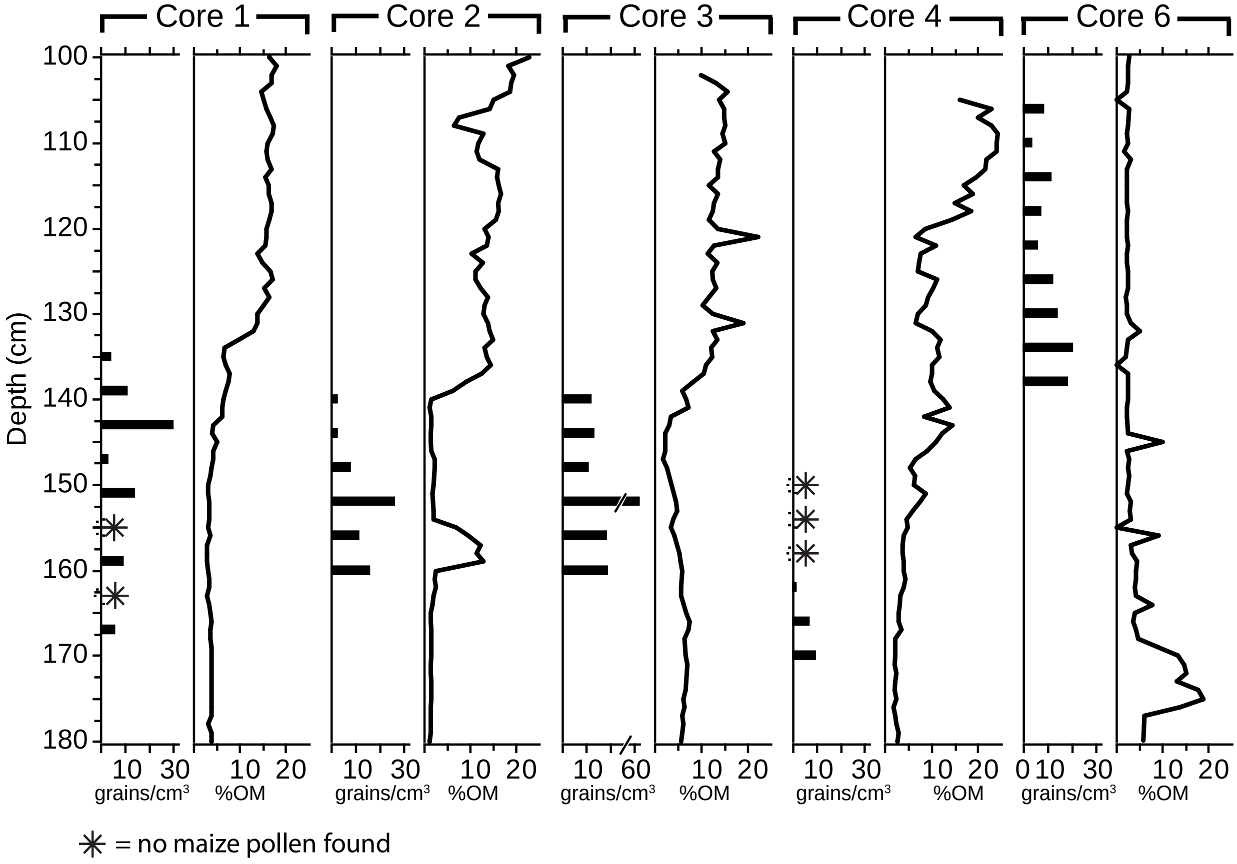

Figure 4.5: Maize pollen concentrations and % OM plotted by depth.

Note the scale change for Core 3 maize pollen concentrations.

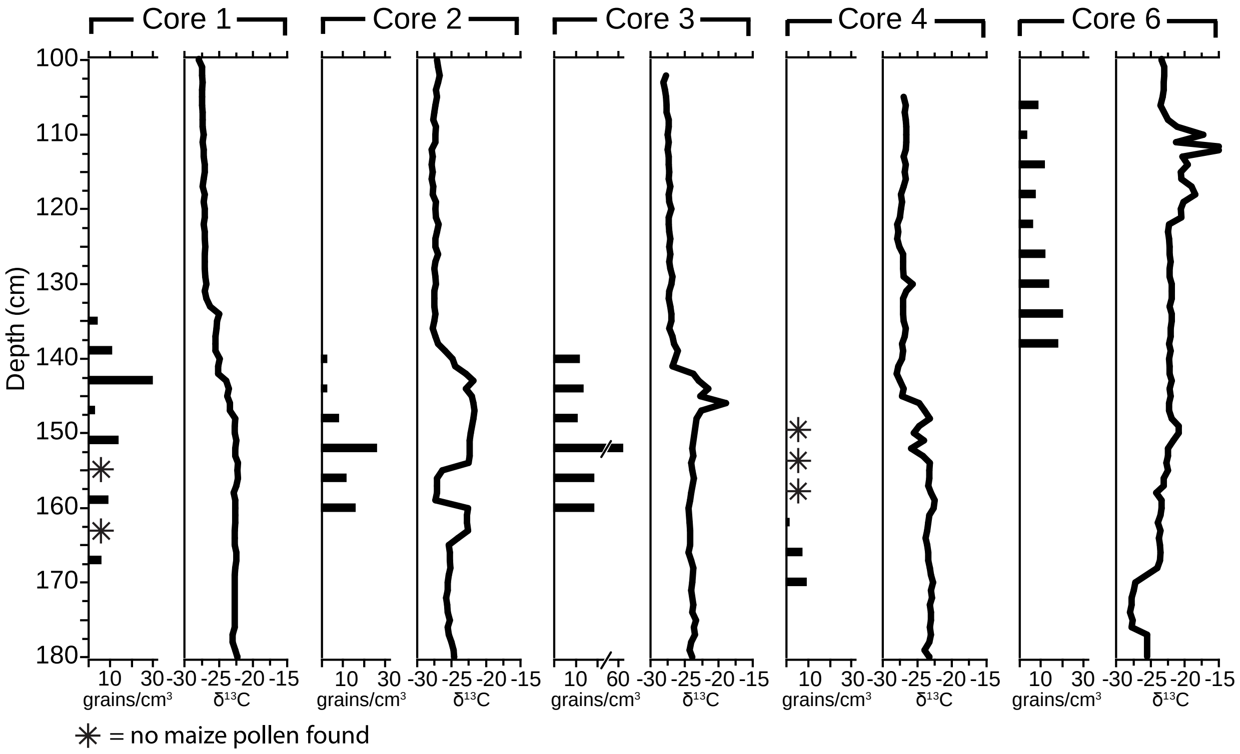

Figure 4.6: Maize pollen concentrations and $\delta^{13}C_{OM}$ plotted by depth.

Note the scale change for Core 3 maize pollen concentrations.

Table 4.2: Summary table of maize pollen influx values

	n	Mean	Max.	Min.	No Maize	Standard Dev.
Core 1	9	0.85	3.00	0	2	0.93
Core 2	6	0.44	1.03	0.01	0	0.36
Core 3	6	1.20	3.44	0.32	0	1.24
Core 4	6	0.12	0.37	0.	3	0.16
Core 6	9	0.90	1.60	0.28	0	0.44
All Cores	36	0.55	3.44	0	5	0.69

Maize pollen influx values are reported in grains/cm^2/yr, summarized by core. “No Maize” refers to the number of levels in which no maize pollen grains were found.

three separate indicators suggest that terrestrial material is driving changes in $\delta^{13}C_{OM}$. Both the diatom record from Zoncho (Haberyan and Horn, 2005) and $\delta^{15}N$ values (Chapter 3) indicate that the lake did not become eutrophic during agriculture. Furthermore, carbon/nitrogen ratios average 15 during the agricultural period (Chapter 3), suggesting that much of the carbon entering the lake came from nitrogen-poor terrestrial vegetation (Meyers, 2003).

Given the strong terrestrial controls on % OM and $\delta^{13}C_{OM}$, the lack of connection to maize pollen concentrations is somewhat surprising. All three indicators should be highly sensitive to agricultural activity adjacent to the lake, especially the outer cores (1–4) that were recovered closer to the shoreline.

4.6.2 Spatial Variability of Maize Pollen Concentrations

There is considerable intra-basin heterogeneity in the maize pollen data. Core 3 is an obvious outlier with much higher mean, maximum, and minimum maize pollen concentrations than any of the other cores. The sample at 152 cm had by far the highest maize pollen concentration, but % OM and $\delta^{13}C_{OM}$ do not suggest an unusually large amount of agriculture. Core 3 is unique at Zoncho because it contains evidence of agriculture 325 years later than cores 1, 2, and 4 (Chapters 2 and 3). The persistence of agricultural indicators in this core suggests that the adjacent portion of the watershed may have been preferred for agriculture or was the site of particularly strong agricultural impacts during the late agricultural period. Percent OM and $\delta^{13}C_{OM}$ suggest the rest of the basin experienced relatively uniform impacts from agriculture despite differences in the steepness and orientation of slopes adjacent to the lake, making it difficult to connect watershed morphology with maize pollen concentrations. The lack of maize pollen in several Zoncho samples is not surprising, given the absence of maize pollen in lake surface samples collected within 50 m of corn fields in Wisconsin (Lane et al., 2010), and the suggestion by Islebe et al. (1996), from their work in the neotropics, that maize might need to be grown nearly along lake shorelines for its pollen to show up in pollen records. Zoncho maize pollen concentrations are, on average, much lower than those found by Lane et al. (2010) in modern lakes in Wisconsin, including one lake the approximate size of Laguna Zoncho. This may reflect differences in other lake characteristics, or between modern and ancient agricultural methods, maize plants, maize pollen grains, or other factors.

Maize pollen concentrations had a low standard deviation in core 6, likely due to processes of sediment focusing carrying material from the entire lake basin to the center of the lake (Davis and Ford, 1982; Larson and MacDonald, 1994). As these processes operate, they average inputs from the basin, which may explain the relative consistency in maize pollen concentrations at core site 6. When cored in 2007, Zoncho had a relatively flat bottom with less than 0.6 m difference in depth among the core sites. However, it is important to note that as lake basins fill with sediment, basin morphometry is changed, altering the direction and/or intensity of sediment focusing (Lehman, 1975).

While maize grains are diagnostic and easily identifiable, their relative rarity makes them less than ideal to study the processes that control particle deposition in lake sediments. Other microfossils in the same size range as maize grains, possibly charcoal, could be studied instead. Charcoal particles are not perfect analogues for maize grains, but they are far more common, would produce more robust data sets, and are easily studied in modern and ancient sediments.

4.6.3 Maize Pollen as an Indicator of Prehistoric Agricultural Activity

Maize pollen concentrations vary spatially and temporally independently of % OM and $\delta^{13}C_{OM}$, suggesting they are not reliable indicators of the scale of prehistoric agricultural activities. Low maize pollen concentrations, even in cores taken near the shore, where maize pollen deposition should have been highest, increases the likelihood that these variations are caused by chance, and not changes in the landscape. Studies that rely on maize pollen concentrations from pollen counts (usually one or two slides) would have a lower sample size and be even more vulnerable to the effects of random variation.

In their study of modern maize agriculture and maize pollen deposition, Lane et al. (2010) identified a number of factors beyond area under cultivation that control maize pollen deposition, including the presence and arrangement of vegetation buffers, distance to agricultural fields, and the duration of field cultivation. In the case of prehistoric agriculture, it is impossible to reconstruct these conditions. Variations in lake level can also affect maize pollen deposition by changing lake and watershed conditions. For instance, lake low (high) stands could increase (decrease) the size of vegetation buffers, decrease (increase) the distance between core sites and agricultural fields, and alter sediment-focusing processes. The complexity of factors that influence maize pollen deposition severely limits the utility of maize pollen as a paleoenvironmental indicator.

For studies seeking to use maize pollen presence to detect prehistoric agriculture, our results suggest that recovering a single core from the center of a lake may be an effective sampling strategy because it takes advantage of sediment-focusing processes. However, Zoncho is a relatively small lake where maize pollen dispersal and/or sediment-focusing processes only have to transport maize grains a short distance for them to be deposited in the deepest part of the lake. In larger lakes, cores recovered closer to the shore may be more likely to contain maize pollen grains than cores from central locations (Burden et al., 1986; Northrop and Horn, 1996). Our results support the suggestion of Lane et al. (2010) that capturing evidence of maize cultivation in such lakes might best be accomplished using a combination of cores from nearshore environments and locations closer to the center of the lake. The usefulness of this strategy could be tested by analyzing maize concentrations in multiple cores recovered from a larger lake with a history of maize agriculture.

4.7 Conclusions

We compared maize pollen concentrations with % OM and $\delta^{13}C_{OM}$ in a network of five sediment cores recovered from Laguna Zoncho, Costa Rica to assess their utility as indicators of the scale of prehistoric agriculture. All cores contained maize pollen, but there is no correspondence between maize pollen concentrations and % OM or $\delta^{13}C_{OM}$ in any of the cores, indicating that maize pollen concentrations are not reliable indicators of the scale of prehistoric agriculture. With the possible exception of core 3, maize pollen concentrations do not systematically vary, and cannot spatially reconstruct agricultural activities. Core 6, recovered from the deepest part of the lake, had maize pollen in all sample levels and had the second lowest standard deviation of maize pollen concentration for the five cores. We attribute the decreased variability in core 6 to sediment-focusing processes and suggest, at least in small lakes, that a core from the deepest part of the lake basin is an effective sampling strategy to detect maize agriculture. Overall, our results suggest that maize pollen concentrations are useful only to detect agriculture and are not sensitive to the scale of prehistoric agricultural activities.

4.8 Acknowledgements

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Chapter 5: Summary and Conclusions

5.1. Summary and Study Objective Conclusions

5.1.1. Prehistoric Agricultural Activities and Climate

Previous work at Laguna Zoncho documented prehistoric agricultural activities in the watershed (Clement and Horn, 2001; Lane et al., 2004; Haberyan and Horn, 2005; Filippelli et al., 2010), but at relatively low resolution. This study employed a nearly continuous sampling strategy that greatly refined the existing record. Sedimentary indicators suggest that agricultural activities began to decline around 1150 cal yr BP, stabilized briefly, declined again at 850 cal yr BP, and were nearly absent by 640 cal yr BP. The end of agriculture predates the arrival of the Spanish by approximately 220 years, suggesting that the Spanish Conquest was not the cause of agricultural and population decline at Laguna Zoncho or, by extension, through the region. The two main periods of agricultural decline correspond with known droughts in Central America (e.g. Hodell et al., 1995; Haug et al., 2003; Stahle et al., 2011), suggesting that preColombian agriculture at Zoncho was sensitive to climate change. Small fluctuations in the indicators, especially $\delta^{13}C_{OM}$ from core 6, match regional drought records and imply that these droughts affected agricultural activities and, presumably, the inhabitants of Laguna Zoncho. It is difficult to make a direct link between agricultural indicators and population decline, but stresses caused by droughts likely catalyzed inter-group conflict in the region.

5.1.2. Spatial Variability of Geochemical and Isotopic Indicators

The analysis of multiple cores at Zoncho revealed the presence of spatial variability, provided insight into processes that control organic matter deposition in lakes, and greatly refined the record of agricultural decline in the watershed. All five cores analyzed were sensitive to agricultural activities and showed a similar pattern of widespread agriculture, forest recovery, and post-recovery forested conditions, but there were important differences. All of the outer cores showed that agriculture ended rather abruptly and was followed by a 150-year period of forest recovery. The end of agriculture occurs in cores 1, 2, and 4 by 1000 cal yr BP, while indicators suggested ongoing agriculture at core 3 until 675 cal yr BP. Proxies in core 6 indicated a gradual decline in agriculture from 1000 cal yr BP until 640 cal yr BP. This progressive decline in core 6 is likely the result of sediment-focusing processes integrating material from the lake basin and depositing it in the deepest portion of the lake basin. Consequently, a core from this location presents an "average" of inputs and is less sensitive than the outer cores to changes in the terrestrial environment.

Sediment-focusing processes take time to operate, and may cause records from the deepest portions of the lake basin to lag behind watershed conditions. At Zoncho, this delay may have contributed to earlier interpretations that agricultural decline corresponded with the Spanish Conquest (Clement and Horn, 2001; Lane et al., 2004). The more responsive records from the outer cores clearly show that agriculture ended around 220 years before the Spanish arrived, and imply that other factors, including inter-group conflict fueled by prolonged drought, were responsible for agricultural decline at Zoncho.

5.1.3. Impacts of Prehistoric Agriculture

The multiple-proxy approach used to develop the high-resolution record from Laguna Zoncho yielded evidence of strong impacts of agriculture. The suite of indicators — % OM, total N, C/N ratios, $\delta^{13}C_{OM}$, and $\delta^{15}N$ — provided information about conditions in both the terrestrial and aquatic environments at Zoncho and, taken together, allowed for more detailed and confident interpretations. The C/N ratios and $\delta^{15}N$ are particularly useful because they helped constrain the influence of autochthonous carbon on OM and $\delta^{13}C_{OM}$. Along with the diatom record (Haberyan and Horn, 2005), C/N ratios and $\delta^{15}N$ showed that the lake did not become eutrophic as a result of increased inputs during the agricultural period, confirming the utility of OM and $\delta^{13}C_{OM}$ as terrestrial indicators. OM and $\delta^{13}C_{OM}$ are also complementary indicators since the OM provides a measure of disturbance while stable carbon isotopes provide information on watershed vegetation. Therefore, variations in $\delta^{13}C_{OM}$ with no concurrent changes in OM helped identify periods of drought from the amalgamated signals of climate and land-use change.

5.1.4. Maize Pollen Concentrations as Paleoenvironmental Indicators

Maize pollen concentrations at Zoncho were highly variable and did not coincide spatially or temporally with two other indicators of the scale of prehistoric agriculture, % OM and $\delta^{13}C_{OM}$. This lack of a relationship strongly suggests that sedimentary maize pollen concentrations are not useful indicators of the scale of prehistoric agriculture in neotropical lake basins, and that their use should be restricted to confirming the presence of maize agriculture.

5.1.5. Determine the Feasibility of Creating a Spatially-Explicit Record of Agriculture

The network of sediment cores was partially successful at spatially reconstructing agriculture. Agricultural indicators were sensitive to a non-simultaneous decline in agriculture in the watershed, but were unable to provide information on the spatial arrangement or the relative amount of agriculture in different sectors of the watershed.

5.1.6. Evaluation of the Single Core Sampling Strategy

Results from Laguna Zoncho suggest that many of the assumptions made for pollen analysis in lake sediment studies are valid for studies that analyze the organic component of sediments, but also demonstrate the value of cores from closer to the shore. Previous work stressed the importance of sediment-focusing processes in determining core site selection (Lehman, 1975; Davis and Ford, 1982; Davis et al., 1984; Larson and MacDonald, 1994). Evidence from Zoncho suggests that sediment-focusing processes strongly affected the core from the deepest part of the lake basin. Geochemical, isotope, and maize pollen concentrations were less variable in core 6 than at core sites located closer to the shore because, as predicted by earlier studies, sediment-focusing processes transported and integrated material at core site 6 prior to deposition.

While a core from the deepest portion of the lake basin does record “lake average” values for the geochemical and isotopic indicators, sediment-focusing processes limit its interpretability. Multiple cores from Zoncho provided a more sensitive record of agriculture that was less muted by sediment focusing. Bulk sediment proxies are likely more affected by sediment-focusing processes because a large amount of terrestrial inputs are deposited by fluvial processes at or near the shore and must then be transported farther into the lake. Cores recovered closer to shore reduce the delay imparted by and the influence of sediment-focusing processes. In lakes larger than Zoncho, cores closer to the shore would be even more important because the alteration of the terrestrial signal caused sediment-focusing processes would be greater.

Lake-sediment studies in which the goal is to reconstruct average conditions in a watershed will be well-served by a single core from the deepest portion of the lake basin. However, a need for detailed information about spatial variability or a true measure of basinwide inputs may justify the added work and cost of obtaining, dating, and analyzing multiple cores. A sampling design that includes several nearshore cores as well as a central core may be ideal when affordable. But sampling closer to shore is not without risk. Core 5 is a testament to the challenges of analyzing sediment cores from near-shore locations. The entire core showed evidence of oxidation, likely from previous drying during a low lake stand, and its isotopic and geochemical record is complacent.

In practice, the recovery of a core from the deepest part of the lake and several cores from different portions of the lake basin would provide flexibility for paleoenvironmental researchers. The core from the deepest part of the basin could be analyzed first and additional cores could be analyzed later if deemed useful. Recovering several cores has the added benefit of providing extra sediment if a core, like core 5 at Zoncho, proves unsuitable for analysis.

5.2. Suggestions for Future Research

The presence of spatial variation and the importance of sediment-focusing processes highlight the role of lake basin morphology in controlling sediment deposition. Lake sediment studies, especially those that are employing multiple cores, would benefit from information about basin morphology and sediment depth prior to core site selection. Ground penetrating radar, seismic reflection, and other techniques to image the lake basin and accumulated sediments now make this possible (e.g. Moorman, 2002; Anselmetti et al., 2006). Since this study collected material from several portions of the lake basin, Zoncho could serve as a calibration site for the use of these techniques in small tropical lakes.

Though the suite of geochemical and isotopic indicators provides strong evidence that terrestrial material is driving the changes observed in Zoncho sediments, compound-specific techniques would allow more precise analysis. Compound-specific techniques allow the isolation of individual compounds with known origins, termed biomarkers. Analyzing stable carbon isotopes in biomarkers from terrestrial, emergent, and algal sources yields more precise paleoenvironmental indicators (e.g. Ficken et al., 1998; Huang et al., 1999; Huang et al., 2001; Boom et al., 2002). Stable hydrogen isotope analysis (δD), also measured on the same biomarkers, is increasingly used in lake sediment research as a proxy for several environmental factors, most notably temperature, source water, local hydrology, and moisture balance (Huang et al., 2002). In small, closed-basin lakes, evaporation largely determines the δD value (Sachse et al., 2004) making δD analysis an important tool for reconstructing moisture stress and drought. Biomarker and stable hydrogen data from Laguna Zoncho sediments would be valuable complements to the existing agricultural record.

The existing cores also provide the opportunity to examine spatial variability in other micro- and macrofossils. Examining charcoal particles would be particularly useful. Charcoal fragments in the size range of maize pollen grains (63–99 µm) could serve as an analogue for maize pollen grains and offer insight into the processes that control their deposition.

The connection between agricultural decline, population collapse, and regional climate should be investigated at other lakes in Central America, especially between 1200–500 BP. High-resolution geochemical and isotopic studies from lakes in the Diquís region would help reveal the regional impacts of climate change. Records from lakes in eastern Costa Rica could allow a comparison between conditions on the east and west coasts of Costa Rica, which would help elucidate the climatological controls exerted by conditions in the Caribbean and the Pacific on the Central American monsoon.

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Appendix A: Pollen Processing Procedure

The following procedure was used to process sediment samples from Laguna Zoncho for pollen analysis. Samples were processed in 15 ml Nalgene® polypropylene centrifuge tubes. The centrifuge used was an IEC model CL benchtop centrifuge with a 6 x 15 ml swinging bucket rotor. All centrifugations were carried out at the highest speed.

1. Add 1 *Lycopodium* tablet to each centrifuge tube.

2. Add a few ml 10% HCl, and let reaction proceed; slowly fill tubes until there is about 10 ml in each tube. Stir well, and place in hot water bath for 3 minutes. Remove from bath, centrifuge for 2 minutes, and decant.

3. Add hot distilled water, stir, centrifuge for 2 minutes, and decant. Repeat for a total of 2 washes.

4. Add about 10 ml 5% KOH, stir, remove stick, and place in boiling bath for 10 minutes, stirring after 5 minutes. Remove from bath and stir again. Centrifuge 2 minutes and decant.

5. Wash 4 times with hot distilled water. Centrifuge for 2 minutes each time.

6. Fill tubes about halfway with distilled water, stir, and pour through 125 µm mesh screen, collecting liquid in a labeled beaker underneath. Use a squirt bottle of distilled water to wash the screen, and to wash out any material remaining in the centrifuge tube.

7. Centrifuge down material in beaker by repeatedly pouring beaker contents into correct tube, centrifuging for 2 minutes, and decanting.

8. Add 8 ml of 49–52% HF and stir. Place tubes in boiling bath for 20 minutes, stirring after 10 minutes. Centrifuge 2 minutes and decant.

9. Add 10 ml hot Alconox® solution, made by dissolving 4.9 cm^3 dry commercial Alconox® powder in 1000 ml distilled water. Stir well and let sit for 5 minutes. Then centrifuge and decant.

10. Add more than 10 ml hot distilled water to each tube, so top of water comes close to top of tube. Stir, centrifuge for 2 minutes, and decant.

    Assuming that no samples need treatment with HF, continue washing with hot distilled water as above for a total of 3 water washes.

11. Add 10 ml of glacial acetic acid, stir, centrifuge for 2 minutes, and decant.

12. Make acetolysis mixture by mixing together 9 parts acetic anhydride and 1 part concentrated sulfuric acid. Add about 8 ml to each tube and stir. Remove stirring sticks and place in boiling bath for 5 minutes. Stir after 2.5 minutes. Centrifuge for 2 minutes and decant.

13. Add 10 ml glacial acetic acid, stir, centrifuge for 2 minutes and decant.

14. Wash with hot distilled water, centrifuge and decant.

15. Add 10 ml 5% KOH, stir, remove sticks, and heat in vigorously boiling bath for 5 minutes. Stir after 2.5 minutes. After 5 minutes, centrifuge for 2 minutes, and decant.

16. Add 10 ml hot distilled water, centrifuge for 2 minutes, and decant for a total of 3 washes.

17. After decanting last water wash, use the vortex genie for 20 seconds to mix sediment in tube.

18. Add 1 drop of safranin stain to each tube. Use vortex genie for 10 seconds. Add distilled water to make 10 ml. Stir, centrifuge for 2 minutes, and decant.

19. Add a few ml TBA, use the vortex genie for 20 seconds. Fill to 10 ml with TBA, stir, centrifuge for 2 minutes, and decant.

20. Add 10 ml TBA, stir, centrifuge for 2 minutes, and decant.

21. Vibrate samples using the vortex genie to mix the small amount of TBA left in the tubes with the microfossils. Centrifuge down vials.

22. Add several drops of 2000 cs silicone oil to each vial. Stir with a clean toothpick.

23. Place uncorked samples in the dust free cabinet to let the TBA evaporate. Stir again after one hour, adding more silicone oil if necessary.

24. Check samples the following day; if there is no alcohol smell, cap the samples. If the alcohol smell persists, give them more time to evaporate.

Vita

Zachary Paul Taylor was born in Colorado Springs, CO. Growing up in Colorado Springs, he was active in many activities, including Boy Scouts, becoming an Eagle Scout in 1995. Zack graduated from the International Baccalaureate Program at William J. Palmer High School in Colorado Springs. He then earned a B.S. in Environmental Science from the University of Denver in 2003. He received his M.S. in Geography from the University of Tennessee, Knoxville in 2005.

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