LAKE SEDIMENT RECORDS OF HOLOCENE PALEOCLIMATE AND ENVIRONMENTAL CHANGE IN COSTA RICA: EVIDENCE FROM SEDIMENT GEOCHEMISTRY, CHARCOAL AND INSECT FAUNA

by

JIAYING WU

(Under the Direction of David F. Porinchu)

ABSTRACT

This dissertation develops novel high-resolution paleoclimate and paleoenvironmental reconstructions for Chirripó National Park of Costa Rica in Central America, using sub-fossil chironomid remains, macroscopic charcoal and the geochemical signals extracted from sediment cores recovered from glacial lakes located in the park. Comparison is made between the late Holocene hydroclimate and paleoenvironmental conditions at mid- and high-elevation sites in Costa Rica and the surrounding regions, to facilitate an assessment of the relationship between possible driver(s) of hydroclimate variability and paleoenvironmental change in this region between ~640 and 1230 CE. Lastly, highly resolved charcoal and geochemical data are analyzed to identify how fire events have influenced nutrient flux and vegetation dynamics within the Chirripó páramo during the late Holocene. The results generated in this dissertation indicate that the glacial highlands in central Costa Rica experienced a relatively warm and wet climate between ~5290 and 2780 cal yr BP, with evidence of an abrupt climate change event found at ~5200 cal yr BP. The intervals between ~8770 and

5290 cal yr BP and between ~2780 cal yr BP and the present were generally characterized by cold and dry conditions, with the most frequent wildfires occurring during approximately the past 3300 years. The chironomid-inferred thermal variations, which are tightly coupled with fire history, vegetation dynamics and nutrient fluxes in the glacial highlands of Chirripó National Park, can provide useful reference for the park staff to manage the páramo ecosystem in light of projected climate change. The timing and the expression of hydroclimate change observed in southern Central America during the Terminal Classic Drought (TCD: ~770-1100 CE) and the early Medieval Climate Anomaly (MCA: ~950-1250 CE) supports the hypothesis that depressed sea surface temperatures in the tropical North Atlantic, in conjunction with a stronger North Atlantic Subtropical High and a southward shifted Intertropical Convergence Zone (ITCZ), were responsible for the dry conditions observed between ~750 and 1100 CE in this region.

INDEX WORDS: Paleoclimate, Holocene hydroclimate, paleoenvironmental reconstruction, tropical Americas, Costa Rica, sub-fossil chironomids, sediment charcoal, geochemistry, Terminal Classic Drought (TCD), Medieval Climate Anomaly (MCA)

LAKE SEDIMENT RECORDS OF HOLOCENE PALEOCLIMATE AND ENVIRONMENTAL CHANGE IN COSTA RICA: EVIDENCE FROM SEDIMENT GEOCHEMISTRY, CHARCOAL AND INSECT FAUNA

by

JIAYING WU

B.S., China Agricultural University, China, 2010

M.S., University of Georgia, 2012

A Dissertation Submitted to the Graduate Faculty of The University of Georgia in Partial Fulfillment of the Requirements for the Degree

DOCTOR OF PHILOSOPHY

ATHENS, GEORGIA

2018

LAKE SEDIMENT RECORDS OF HOLOCENE PALEOCLIMATE AND ENVIRONMENTAL CHANGE IN COSTA RICA: EVIDENCE FROM SEDIMENT GEOCHEMISTRY, CHARCOAL AND INSECT FAUNA

by

JIAYING WU

Major Professor:	David F. Porinchu
Committee:	Sally P. Horn
	David S. Leigh
	George A. Brook
	Suzanne Pilaar-Birch

Electronic Version Approved:

Suzanne Barbour
Dean of the Graduate School
The University of Georgia
May 2018

DEDICATION

To myself

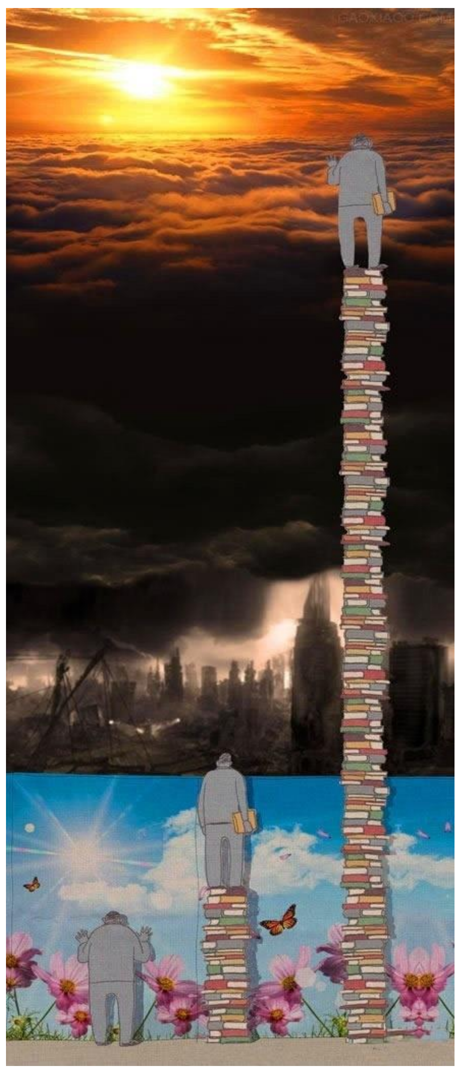
“**What Doesn’t Kill You Makes You Stronger**.”

-Friedrich Nietzsche

&

“Why We Read?”

−Picutre is from the Internet



ACKNOWLEDGEMENTS

The funding supporting my dissertation project was cobbled together from different sources, including the www.experiement.com crowd-funding platform and the Geological Society of America (GSA). I would like to thank all the backers (special thanks for Dr. Marguerite Madden from geography department of UGA), and my good friends and families from both the United States and China, who contributed to my project through experiment.com. Big thanks also go to the GSA which provided me with the Graduate Student Research Grants as well as the On To the Future (OTF) travel award to attend GSA's 2018 annual meeting. The Center for Archeological Sciences and the Center for Applied Isotope Studies (CAIS) of UGA, who jointly offered the CAS Norm Herz Award Small Grant, are also appreciated. Without all this financial support, the project would never have been accomplished.

I am very grateful for all the advice and help from my advisor, Dr. David Porinchu, in the past seven years. I will always appreciate his encouragement and patience. I will never forget that he used his faculty travel grant to initiate my dissertation project, and what he said to me in the field "Once you make it, you will do better next time". I admire his serious attitude on doing research. Without his effective and valuable comments on the revision, my dissertation wouldn't have been half as good as it is now. I am very glad that under his strict supervision, my dissertation generated solid results that will potentially benefit other paleoclimatologists in the future.

I would also like to thank all my committee members for offering me not only valuable advice to improve the overall quality of my dissertation, but also mental support throughout these years. Particularly, I appreciate Dr. Sally Horn for providing me with rich information of my study sites and fieldwork, and extremely helpful feedbacks for refining my research. Thanks also go to Drs. Steve Padgett-Vasquez, Germain Esquivel Hernandez, Roberto Arguedas Pérez, Mark Bush, Bas van Geel, Philip Higuera, Stephen Juggins, Maarten Blaauw, Daniel Gavin, Chris Larsen, Kirk Li and Wenhao Pan for offering useful sources of geographic mapping and selfless assistance on the techniques of statistical analysis. Additionally, I would like to thank Licho who provided great assistance in the field, the national park systems of Costa Rica who permitted my research, and park staffs in Chirripó National Park who facilitated my fieldwork. My gratefullnes also extends to Ny riavo Gilbertinie Voarintsoa, Pete Akers and Christopher Stephen Cooper who spent time on proofreading my chapters and giving comments. Additionally, I would like to thank all my undergraduate students (Taylor Mae Mordecai, Evan Alden, Nicole Campbell and Tyler D Ellison) for assisting with my lab work.

Last but not the least, I would like to show my great appreciation to my dear husband who has always accompanied me and supported me mentally. I wouldn't have had the courage to confront the loneliness, depression and frustration without him. I thank him for giving me such a sweet home and for our pets Thomas and Pichu. I thank my parents, my besties (Xiang Li and Guannan Ding) and good friends (Zhili Chen, Xueying Hu, Kirk Li, Lixing Fu, Peter Chen, Lixin Wang, Wenhao Pan and Xiaochuan Wang) for all the financial and mental support.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

Page

CHAPTER 1

LAKE SEDIMENT RECORDS OF HOLOCENE PALEOCLIMATE AND ENVIRONMENTAL CHANGE IN COSTA RICA: EVIDENCE FROM SEDIMENT GEOCHEMISTRY, CHARCOAL AND INSECT FAUNA

1.1. INTRODUCTION AND LITERATURE REVIEW

Uncertainties about the impacts of future environmental change, including global warming, have led to growing public concern. The Intergovernmental Panel on Climate Change (IPCC) has documented that average global surface temperature increased ~0.85 °C between 1880 and 2012 CE, resulting in severe droughts, frequent wildfires, reduced global water availability and food scarcity (IPCC, 2014). Global climate models project significant increases in global surface temperatures by 2100 CE, and different responses are expected to occur at regional and sub-regional scales (Mitchell et al., 2004; Christensen et al., 2007). Reconstruction of local and regional environmental responses to past climate change can help us better understand potential environmental responses to projected climate change. The development of high-resolution paleoclimate reconstructions provides a broader temporal perspective on climate variability than that offered solely by instrumental records. These high-resolution reconstructions are particularly needed in low-latitudes as tropical insolation powers global atmospheric and oceanic circulation (Chiang and Koutavas, 2004; Thompson, 2011). Despite this need, a limited number of paleoclimate reconstructions currently exist for the tropics relative to the mid- and high-latitudes (Horn, 2007; Bradley, 2015).

There is a necessity to improve our understanding of past, present and future climate dynamics and variability in the tropical Americas, as the societal and economic impacts of climate change in this region will be tremendous (Waylen et al., 1996; IPCC, 2014 and 2016). ENSO-driven hydroclimate variability is expected to increase through the 21st century in Central America (Seager et al., 2012), and activities such as hydropower generation, cereal production, and cattle ranching have been identified as particularly vulnerable to climate change in southern Central America (IPCC, 2014 and 2016). In addition, this region is also considered as a climate change "hotspot", where notable changes have already been observed in physical and biological systems (Giorgi, 2006; Diffenbaugh and Giorgi, 2012). Improving our understanding of long-term climate variability in this region can help us identify the mechanisms driving climate change in the tropics and develop meaningful regional responses to projected global climate change.

This dissertation will employ multi-proxy analysis of lake sediment cores recovered from glacial lakes in Chirripó National Park (N.P.), Costa Rica, in order to produce high-resolution (sub-decadal to sub-centennial-scale) reconstructions of Holocene hydroclimate and paleoenvironmental change for the highlands of southern Central America. The results produced in this dissertation will refine our knowledge of the linkages between long-term hydroclimate variability, fire regimes and vegetation dynamics during the Holocene in the northern tropical Americas. Additionally, the physical processes and forces responsible for the late Holocene hydroclimate anomalies obsereved in this region will be discussed in this dissertation.

1.2 REGIONAL CLIMATE AND ENVIRONMENTAL HISTORY

Costa Rica has been a focus of intensive paleoclimate and paleoenvironmental research with numerous, multi-proxy lake and bog-based studies undertaken during recent decades (e.g. Hooghiemstra et al., 1992; Horn, 1993; Islebe et al., 1995 and 1996; Northrop and Horn, 1996; Rodgers and Horn, 1996; Islebe and Hooghiemstra, 1997; League and Horn, 2000; Orvis and Horn, 2000; Clement and Horn, 2001; Lane et al., 2004; Haberyan and Horn, 2005; Kennedy and

Horn, 2008; Lane et al., 2009 and 2011; Taylor et al., 2010; Lane and Horn, 2013; Taylor et al., 2013ab; Wu et al., 2017). Several of these studies were conducted on glacial lakes in Chirripó N.P. using pollen, charcoal and lake sediment geochemisty to reconstruct the long-term history of paleoenvironmental and climate change (e.g. vegetation, fire and hydrology) in this region. The highland vegetation of Chirripó N.P. consists of treeless páramo (Kappelle and Horn, 2016).

In 1985, sediment cores, raised from Lago Chirripó in the Valle de los Lagos by Dr. Sally Horn, enabled the development of a 4000-yr fire history (Horn, 1989). Analyses of two longer cores, recovered in 1989 from Lago Morrenas 1 (LM1), a glacial lake located in the adjacent Valle de las Morrenas, provided detailed fire and vegetation histories for the late Quaternary (Horn, 1993). The charcoal record from LM 1 confirms and extends the fire history record of Lago Chirripó with the charcoal stratigraphies for both lakes corresponding fairly well for the late Holocene (Horn, 1993). High charcoal values, which were observed in both records at ~2400 cal yr BP and 1100 cal yr BP, were inferred to reflect the occurrence of lower lake levels (Horn, 2007). In addition, palynological analysis documented that the position of timberline remained relatively stable in Chirripó N.P. through the Holocene (Horn, 1993).

More recently, the records of bulk and compound-specific carbon isotope composition of lake sediments from LM1 provide new evidence of late Quaternary climate and vegetation change (Lane et al., 2011). The stable carbon isotope ratios of n-alkanes indicate that the relative abundance of the C_4 grass, *Muhlenbergia*, increased in the páramo (Lutyen, 1999; Kappelle and Horn, 2016) during the late Pleistocene to early Holocene (~13,000-9000 cal yr BP) and the late Holocene (~3000-1000 cal yr BP). This increase of C_4 vegetation may be related to decreased atmospheric carbon dioxide concentrations and/or more arid conditions during these intervals. Likewise, the decrease in C_4 vegetation between these two intervals during the middle Holocene likely reflects increasing effective moisture (Lane et al., 2011). Lane and Horn (2013) also make use of n-alkane hydrogen isotopes (δD) extracted from the LM1 sediment core to more directly assess ecosystem drought stress. The δD results coincide with the findings in Lane et al. (2011), supporting the hypothesis that the migration of the Intertropical Convergence Zone (ITCZ) in the circum-Caribbean region on millennial timescales impacted not only the hydrology of tropical lowlands, but also the high-elevation páramo ecosystem in Costa Rica (Lane and Horn, 2013). The results from these studies have led to the rejection of earlier assumptions of tropical hydroclimatic and paleoenvironmental stability during the Holocene in the tropical Americas (CLIMAP, 1981 and 1984; Thompson et al., 1997 and 2005; Horn, 2007).

Although earlier research has provided important insight into vegetation and hydroclimate changes in this region, much remains to be discovered. As the total number of paleoenvironmental records from Central America is still low, additional high-resolution records are necessary to better connect the inferred paleoclimate changes from the páramo of Costa Rica with the wider hydroclimate anomalies reported from the tropical Americas (e.g. Douglas et al., 2016). In particular, we lack knowledge regarding Holocene thermal variability and how thermal variation affected fire regimes and vegetation communities in the tropical Americas, but this is achievable via the analysis of paleoenvironmental proxies that are sensitive to temperature (e.g. chironomids).

This dissertation expands upon an earlier chironomid-based reconstruction of the late Holocene thermal conditions for southern Costa Rica (Wu et al., 2017) to develop new high-resolution Holocene records of temperature, fire history, and hydroclimate for the glacial highlands in Costa Rica. Additionally, late Holocene hydroclimate and paleoenvironmental conditions spanning from 1700 cal yr BP to the present are compared between mid- and high-elevation sites in Costa Rica and the surrounding regions to better understand the drivers of regional hydroclimate anomalies observed between ~640 and 1230 cal yr BP. Lastly, highly resolved charcoal and geochemical data are used to identify how fire events have influenced nutrient flux and vegetation dynamics within the Chirripó páramo during the past 1700 years.

1.3 RESEARCH QUESTIONS AND DESCRIPTION OF CHAPTERS

This dissertation involves analyzing multiple proxies, including sub-fossil chironomid remains, sediment charcoal and geochemistry (specifically C%, N%, $\delta^{13}C$, $\delta^{15}N$ and C/N ratios), extracted from lake sediment cores collected from glacial lakes located in the páramo of Chirripó N.P., to reconstruct Holocene hydroclimate and paleoenvironmental change. The specific questions motivating the research are outlined below, followed by short description of each chapter:

RQ1. How did temperature, hydroclimate and fire regimes vary during the Holocene in the glacial highlands of the Cordillera Talamanca in Costa Rica? Is evidence of abrupt hydroclimate or environmental change apparent during the Holocene in this region?

RQ2. Did the fire regime in Chirripó N.P. vary during the late Holocene? Can lake sediment geochemistry be used to identify discrete fire episodes and assess the influence of fire events on vegetation dynamics and nutrient loading over time?

RQ3. Did Costa Rica experience hydroclimate anomalies between ~500 and 1500 CE corresponding to the widely observed drought in the tropical Americas during the Terminal Classic Drought (TCD: ~770-1100 CE) and/or the Medieval Climate Anomaly (MCA: ~950-1250 CE) intervals? What were the climatic drivers and the related physical processes responsible for the hydroclimate anomalies in these regions?

Chapter 2 presents multi-decadal to sub-centennial-scale thermal and paleoenvironmental reconstructions developed for southern Central America during the Holocene. The results indicate that the glacial highlands of the Cordillera Talamanca in Chirripó N.P. were characterized by: 1) relatively cold, dry conditions, low lake level, and limited fire activity between ~8770 and 5290 cal yr BP; 2) a persistent interval of elevated mean annual air temperature, increased effective moisture and frequent, moderate- to high-severity fires from ~5290 to 2780 cal yr BP; and 3) cool, dry conditions and frequent, low-severity fires between 2780 cal yr BP and the present. An abrupt climate change event, detected at ~5200 cal yr BP, is interpreted to reflect the occurrence of elevated temperature and increased precipitation. This study provides a much- needed continuous, high-resolution hydroclimate and paleoenvironmental reconstruction for the glacial highlands of Costa Rica, and in addition, offers important insight in the nature of tropical climate and environmental change during the Holocene.

Chapter 3 characterizes fire regimes and the post-fire patterns of nutrient loading and vegetation change in the Chirripó páramo during the late Holocene. This chapter examines microscopic charcoal and sediment geochemistry extracted from sediment cores recovered from Lago Morrenas 3C and Lago Ditkebi in Chirripó N.P., for purposes of: 1) identifying fire frequency and intensity for the past 1700 years in the high-elevation watersheds in Chirripó N.P.; 2) assessing if fire events were reflected in lake sediment geochemistry; and 3) exploring the correlation between geochemical variation and the nutrient loss/recovery following fire episodes. This study indicates that the Chirripó páramo experienced repeated wildfires during the last 1700 years with intervals of elevated fire frequency occurring between ~550 and 730 CE and between ~980 and 1230 CE. Fire events are reflected in sediment geochemistry, with reduced C% and N% and highly increased $\delta^{15}N$ observed in lake sediment following severe wildfires. This research pioneers the use of highly resolved charcoal and geochemical data to identify post-fire nutrient changes and vegetation dynamics in the Chirripó páramo during the late Holocene.

Chapter 4 provides thermal reconstructions spanning the past 2000 years in Costa Rica, with an emphasis on the Mesoamerican Terminal Classic Drought (TCD: ~770-1100 CE) and the Medieval Climatic Anomaly (MCA: ~950-1250 CE). This study documents the existence of a similar signal of hydroclimate variability along an elevation gradient in Costa Rica between ~750 to 1100 CE (1200-850 cal yr BP). The results generated in this chapter are compared to existing paleoclimate and paleoenvironmental studies conducted in the tropical Americas to assess linkages between Costa Rica and the adjacent terrestrial region and ocean. This study provides evidence of the occurrence of terrestrial cooling during TCD and early MCA in Central America and provides support for the hypothesis that dry condition during the TCD and early MCA in southern Central America and more broadly in the northern tropical Americas is linked to thermal variability in the tropical North Atlantic.

The development of high-resolution, long-term reconstructions of thermal records in Costa Rica offers an outstanding opportunity to further our knowledge of how thermal change influenced fire regimes and vegetation dynamics in Chirripó N.P. during the Holocene (Chapter 2 and 4). Importantly, the thermal reconstructions generated in this dissertation will refine our understanding of the connections between thermal variation and hydrologic change, particularly during the late Holocene in the northern tropical Americas (Chapter 4), giving additional insight into the possible mechanisms driving the hydroclimate anomalies that characterized this interval in this region. The charcoal and geochemistry analysis-based assessment of post-fire nutrient recovery provides useful reference for staff in Chirripó N.P. to manage the páramo ecosystem in light of projected climate change (Chapter 3).

1.4 REFERENCES

Bradley, R.S., 1999. *Paleoclimatology: reconstructing climates of the Quaternary* (Vol. 68). Elsevier.

Chiang, J.C. and Koutavas, A., 2004. Climate change: tropical flip-flop connections. *Nature*, 432(7018), pp.684.

Christensen, Jens Hesselbjerg, Bruce Hewitson, Aristita Busuioc, Anthony Chen, Xuejie Gao, R. Held, Richard Jones et al. "Regional climate projections." In *Climate Change, 2007: The Physical Science Basis. Contribution of Working group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, University Press, Cambridge, Chapter* 11, pp. 847-940. 2007.

Clement, R.M. and Horn, S.P., 2001. Pre-Columbian land-use history in Costa Rica: a 3000-year record of forest clearance, agriculture and fires from Laguna Zoncho. *The Holocene*, 11(4), pp.419-426.

CLIMAP Project Members. 1981. Seasonal Reconstruction of the Earth's Surface at the Last Glacial Maximum. : Geological Society of America Map and Chart Series, Map MC-36. pp.

CLIMAP Project Members. 1984. The Last Interglacial Ocean. *Quaternary Research*, 21, pp.123-224

Diffenbaugh, N.S. and Giorgi, F., 2012. Climate change hotspots in the CMIP5 global climate model ensemble. *Climatic Change*, 114(3-4), pp.813-822.

Giorgi, F., 2006. Climate change hot- spots. *Geophysical research letters*, *33*(8).

Haberyan, K.A. and Horn, S.P., 2005. Diatom paleoecology of Laguna Zoncho, Costa Rica. *Journal of Paleolimnology*, 33(3), pp.361-369.

Hooghiemstra, H., Cleef, A.M., Noldus, C.W. and Kappelle, M., 1992. Upper Quaternary vegetation dynamics and palaeoclimatology of the La Chonta bog area (Cordillera de Talamanca, Costa Rica). *Journal of Quaternary Science*, 7(3), pp.205-225.

Horn, S.P., 1989. Prehistoric fires in the Chirripó highlands of Costa Rica: Sedimentary charcoal evidence. *Revista de Biología Tropical* 37, pp.139-148.

Horn, S.P., 1993, Postglacial vegetation and fire history in Chirripó páramo of Costa Rica. *Quaternary research* 40, pp.107-116.

Horn, S.P., 2007. Late Quaternary lake and swamp sediments: recorders of climate and environment. *Central America: geology, resources, hazards*, *1*, pp.423-441.

IPCC, 2014: Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, R.K. Pachauri and L.A. Meyer (eds.)].

IPCC, 2016. http://www.ipcc.ch/ipccreports/tar/wg2/index.php?idp=524

Islebe, G.A. and Hooghiemstra, H., 1997. Vegetation and climate history of montane Costa Rica since the last glacial. *Quaternary Science Reviews*, 16(6), pp.589-604.

Islebe, G.A., Hooghiemstra, H. and Van der Borg, K., 1995. A cooling event during the Younger Dryas Chron in Costa Rica. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 117(1-2), pp.73-80.

Islebe, G.A., Hooghiemstra, H. and van't Veer, R., 1996. Holocene vegetation and water level history in two bogs of the Cordillera de Talamanca, Costa Rica. *Vegetatio*, 124(2), pp.155-171.

Kappelle, M. and Horn, S.P., 2016. The Páramo ecosystem of Costa Rica's highlands. In *Costa Rican ecosystmes*. University of Chicago Press, pp. 492-523.

Kennedy, L.M. and Horn, S.P., 2008. A late Holocene pollen and charcoal record from La Selva biological station, Costa Rica. *Biotropica*, 40(1), pp.11-19.

Lachniet, M. S., Burns, S. J., Piperno, D. R., Asmerom, Y., Polyak, V. J., Moy, C. M., Christenson, K., 2004. A 1500-year El Ninõ Southern Oscillation and rainfall history for the Isthmus of Panama from speleothem calcite. *Journal of Geophysical Research*: Atmospheres 109 (D20).

Lachniet, M.S. and Seltzer, G.O., 2002. Late Quaternary glaciation of Costa Rica. *Geological Society of America Bulletin*, 114(5), pp.547-558.

Lane, C. S., Horn, S. P., Mora, C. I., Orvis, K. H., and Finkelstein, D. B., 2011. Sedimentary stable carbon isotope evidence of late Quaternary vegetation and climate change in highland Costa Rica. *Journal of Paleolimnology* 45, pp.323-338.

Lane, C.S. and Horn, S.P., 2013. Terrestrially derived n-alkane δD evidence of shifting Holocene paleohydrology in highland Costa Rica. *Arctic, Antarctic, and Alpine Research*, 45, pp.342-349.

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

League, B.L. and Horn, S.P., 2000. A 10 000 year record of Páramo fires in Costa Rica. *Journal of Tropical Ecology*, pp.747-752.

Luteyn, J., 1999. Introduction to the páramo ecosystem. Páramos: A Checklist of Plant Diversity, Geographical Distribution, and Botanical Literature. The New York Botanical Garden Press. NY, pp.1-39.

Mitchell, T.D., Carter, T.R., Jones, P.D., Hulme, M. and New, M., 2004. A comprehensive set of high-resolution grids of monthly climate for Europe and the globe: the observed record (1901–2000) and 16 scenarios (2001–2100). *Tyndall Centre for Climate Change Research*

Working Paper, 55(0), pp.25.

Northrop, L.A. and Horn, S.P., 1996. Pre-Columbian agriculture and forest disturbance in Costa Rica: palaeoecological evidence from two lowland rainforest lakes. *The Holocene*, *6*(3), pp.289-299.

Orvis, K.H. and Horn, S.P., 2000. Quaternary glaciers and climate on Cerro Chirripó, Costa Rica. *Quaternary Research* 54, pp.24-37.

Rodgers III, J.C. and Horn, S.P., 1996. Modern pollen spectra from Costa Rica. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 124(1-2), pp.53-71.

Seager, R., Graham, N., Herweijer, C., Gordon, A.L., Kushnir, Y. and Cook, E., 2007. Blueprints for Medieval hydroclimate. *Quaternary Science Reviews*, *26*(19-21), pp.2322-2336.

Taylor, Z.P., Horn, S.P., Mora, C.I., Orvis, K.H. and Cooper, L.W., 2010. A multi-proxy palaeoecological record of late-Holocene forest expansion in lowland Bolivia. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 293(1-2), pp.98-107.

Taylor, Z.P., Horn, S.P. and Finkelstein, D.B., 2013a. Pre-Hispanic Agricultural Decline Prior to the Spanish Conquest in Southern Central America. *Quaternary Science Reviews* 73, pp.196-200.

Taylor, Z.P., Horn, S.P. and Finkelstein, D.B., 2013b. Maize pollen concentrations in Neotropical lake sediments as an indicator of the scale of prehistoric agriculture. *The Holocene*, *23*(1), pp.78-84.

Thompson, L.G., 2011. Abrupt Climate Change: A Paleoclimate Perspective from the World's Highest Mountains. *Abrupt Climate Change: Mechanisms, Patterns, and Impacts*, pp.215-233.

Thompson, L.G., Mosley-Thompson, E., Brecher, H., Davis, M., León, B., Les, D., Lin, P.N., Mashiotta, T. and Mountain, K., 2006. Abrupt tropical climate change: Past and present. *Proceedings of the National Academy of Sciences*, 103(28), pp.10536-10543.

Thompson, L.O., Yao, T., Davis, M.E., Henderson, K.A., Mosley-Thompson, E., Lin, P.N., Beer, J., Synal, H.A., Cole-Dai, J. and Bolzan, J.F., 1997. Tropical climate instability: The last glacial cycle from a Qinghai-Tibetan ice core. *Science*, 276(5320), pp.1821-1825.

Wu, J., Porinchu, D.F. and Horn, S.P., 2017. A chironomid-based reconstruction of late-Holocene climate and environmental change for southern Pacific Costa Rica. *The Holocene* 27, pp.73 -84.

CHAPTER 2

HOLOCENE HYDROCLIMATE AND ENVIRONMENTAL CHANGE INFERRED FROM A HIGH-RESOLUTION MULTI-PROXY RECORD FROM LAGO DITKEBI, CHIRRIPÓ NATIONAL PARK[1]

[1] Wu, J., Porinchu, D.F., Campbell, N.E., Mordecai, T.M., and Elden, E. To be submitted to *Palaeogeography, Palaeoclimatology* and *Palaeoecology*

2.1 ABSTRACT

Multi-proxy analysis of a sediment core recovered from Lago Ditkebi in Chirripó National Park, Costa Rica, was undertaken to develop a multi-decadal to sub-centennial-scale reconstruction of Holocene hydroclimate and paleoenvironmental change for the region. The core spans ~8800 years and analysis of sub-fossil chironomid assemblages, macroscopic charcoal, and bulk sediment geochemistry (N%, C%, $\delta^{13}C$, $\delta^{15}N$ and C/N ratios) suggests that the glacial highlands in Chirripó National Park were characterized by notable long-term variability in hydroclimate over that interval. A single chironomid taxon, *Procladius*, which is associated with the cold profundal of glacial lakes in Costa Rica, dominates the Holocene sub-fossil chironomid assemblage in Lago Ditkebi. The shifts in the chironomid assemblage and the low $\delta^{13}C$ values that characterize the interval between ~5290 and 2780 cal yr BP are inferred to represent the contraction of *Muhlenbergia*, a C_4 grass. The contraction of *Muhlenbergia* is inferred to reflect the onset of increasing temperatures and wetter conditions relative to the intervals between ~8770 and 5290 cal yr BP and between 2780 cal yr BP and the present. Macroscopic charcoal analysis indicates that wildfires periodically occurred throughout the Holocene, with the interval between ~3300 and 1500 cal yr BP characterized by the highest fire frequency. A significant, abrupt increase in fire frequency and severity was detected at ~5290 cal yr BP. The concurrent maxima in C/N, charcoal accumulation rate and the abundance of thermophilous chironomid taxon, *Polypedilum* N type, at ~5200 cal yr BP suggests that this abrupt climate change event was characterized by warmer conditions, increased effective moisture and an intense wildfire.

2.2 INTRODUCTION AND LITERATURE REVIEW

Our understanding of late Quaternary paleoclimate and paleoenvironmental change in the Neotropics (tropical Americas) remains relatively limited in comparison to the mid- and high latitude regions of the northern hemisphere. Recent paleoenvironmental reconstructions have demonstrated that significant fluctuations in precipitation (amount and intensity) and sea surface temperatures (SSTs) characterized the late Quaternary in the Neotropics and adjacent oceans (e.g. Horn, 2007). This has led to the rejection of the earlier assumption of tropical climate stability during the late Quaternary (CLIMAP, 1981 and 1984; Thompson et al., 1997 and 2005; Horn, 2007). Multiple lines of evidence indicate that temperatures during the Last Glacial Maximum (LGM) in the tropics were lower than at present, and that the Holocene itself was a time of considerable climatic variability (Mayle et al., 2000; Petersen et al., 2000; Haug et al., 2001; Hodell et al., 2005; Horn, 2007; Lachniet et al., 2012). Re-evaluation of CLIMAP (Climate: Long range Investigation, Mapping, and Prediction) results also supports the interpretation of notable variability in tropical ocean SSTs during the Holocene (Bauch et al., 2001).

Central America, which extends from 7°N to 17.5°N, is characterized by tropical climate type. The contemporary climate in southern Central America is influenced by the position of the Intertropical Convergence Zone (ITCZ) (Pierrehumbert, 2000). The position of the ITCZ is extremely sensitive to tropical SSTs, which vary on inter-annual timescales (Chiang and Koutavas, 2004). A change of ~1 K in the tropical SST gradient is sufficient to influence the extent of the annual migration of the ITCZ, which in turn greatly influences the distribution of rainfall in the region (Hastenrath and Heller, 1977; Coen, 1983; Taylor et al., 2013). The sensitivity of the ITCZ to variations in SSTs increases the vulnerability of the tropical Americas to on-going and projected climate change (Bundschuh and Alvarado, 2007). The Cordillera de Talamanca, a rugged and high northwest trending mountain range in southern Central America, acts as an orographic barrier and greatly affects regional climate, particularly in Costa Rica (Bush and Metcalfe, 2012). The vulnerability of high-elevation regions to global climate change is extremely high, due in part to vertical amplification of warming (Beniston and Haeberli, 2001; Karmalkar et al., 2011; Pepin et al., 2015). Developing a longer-term perspective of climate variability for Central America broadly, and Costa Rica more specifically, through paleoclimate studies, can help place observed climate variability in this region in a broader temporal context.

This in turn can help improve our understanding of the mechanisms driving climate change in the Neotropics.

Chirripó National Park (N.P.), which is located in the central massif in Costa Rica, has been the subject of numerous paleoecological studies utilizing various proxies, including pollen, charcoal, diatoms, and sediment geochemistry (e.g. Lane et al., 2011; Lane and Horn, 2013). The presence of glacial lakes within Chirripó N.P. enables the development of long-term histories of paleoecological and paleoenvironmental change for this region. Sediment cores recovered from lakes in Valle de los Lagos (Lago Chirripó) and Valle de las Morrenas (Lago Morrenas 1) document high charcoal concentrations at ~1180, ~2400 and ~3800 years before present (yr BP), suggesting the occurrence of intense droughts at these times (Horn, 1989 and 1993). These charcoal records also revealed that wildfires periodically burned in the Chirripó páramo during the entire Holocene, with the highest fire frequency occurring during the past ~4200 years (League and Horn, 2000). More recently, analyses of bulk and compound-specific carbon isotopes extracted from lake sediments have provided new evidence of climate and vegetation change for the region. The carbon isotope ratio ($\delta^{13}C$) of n-alkanes (C_{27}-C_{33}) indicates an increase in the abundance of C_4 plants in the páramo of Chirripó N.P. during the late Pleistocene, the early Holocene (~12000 to 9000 cal yr BP) and the late Holocene (~3000 cal yr BP to the present) (Lane et al., 2011). The inferred increase in C_4 plants may reflect the influence of low atmospheric carbon dioxide concentrations and low relative humidity on the vegetation community surrounding Lago Morrenas 1, while the decrease in C_4 plant abundance likely suggests the occurrence of a more humid period from 7700 to 4800 cal yr BP (Lane et al., 2011). Lane and Horn (2013) measured and characterized terrestrial n-alkane hydrogen isotope (δD) variability, a more direct proxy of ecosystem drought stress, and determined that the δD results agree with the findings of Lane et al. (2011). The stable isotope data ($\delta^{13}C$, δD) suggests that the hydroclimate of the tropical highlands and páramo in Costa Rica during the late Quaternary was influenced by the migration of the ITCZ in the wider circum-Caribbean region on millennial timescales (Lane and Horn, 2013). These investigations have provided important insights into fire activity, vegetation dynamics, and hydrologic change in the Chirripó páramo of Costa Rica during the Holocene.

Chironomids (Insecta: Diptera: Chironomidae) are the most abundant insect found in freshwater ecosystems (Cranston, 1995). They are sensitive to air and water temperature, thus they can offer independent estimates of thermal conditions (Porinchu and MacDonald, 2003). The influence of air and water temperature on the developmental stages of chironomids and the ecological response of chironomids to temperature has been well documented (Eggermont and Heiri, 2012). The strong direct relationship between chironomids and summer temperature, which has been demonstrated to drive changes in their distribution (Walker and Cwynar, 2006; Barber et al., 2013), make chironomids excellent proxies for temperature during the late Quaternary (Brooks et al., 2012). The existence of strong, statistically significant correlations between chironomid assemblages and temperature (surface water and air) have facilitated the development of chironomid–based temperature inference models in the low, middle and high latitudes of the Northern and Southern Hemispheres (e.g. Dieffenbacher-Krall et al., 2007; Massaferro et al., 2009; Eggermont et al., 2010; Heiri et al., 2011; Chang et al., 2015; Fortin et al., 2015). The application of such models to sub-fossil chironomid stratigraphies has enabled researchers to develop robust thermal reconstructions with high temporal resolution in North America (Rolland et al. 2009; Reinemann et al., 2014), Europe (Larocque et al., 2009), and more recently in Asia (Mackay et al., 2012), Africa (Eggermont et al., 2010) and South America (Massaferro and Larocque-Tobler, 2013). However, high-resolution chironomid–based paleoenvironmental reconstructions spanning the Holocene have not been undertaken in Central America.

This research project uses an existing chironomid-based calibration set from Costa Rica (Wu et al., 2015), and sedimentary charcoal and geochemistry extracted from a sediment core recovered from Lago Ditkebi, a glacial lake in Chirripó N.P., Costa Rica, to reconstruct hydroclimate variability and paleoenvironmental change in southern Central America during the Holocene. The goals of this study include: 1) developing a high-resolution (multi-decadal to sub-centennial scale) reconstruction of Holocene thermal variability; 2) characterizing fire frequency and intensity through the Holocene; 3) discovering if evidence for abrupt climate events are recorded at Lago Ditkebi; and 4) assessing whether a relationship exists between thermal variability, fire history, sediment geochemistry, and vegetation change in the páramo of Chirripó N.P. This record of climate and environmental change can provide important insights into centennial and millennial-scale climate variability and in doing so, help park managers to anticipate the potential impacts associated with projected climate change in the páramo ecosystem within Chirripó N.P. (Horn and Kappelle, 2009).

2.3 STUDY SITE

The glacial lake, Lago Ditkebi (9°28'06" N, 83°28'49"W), incorporated in this study is located in Chirripó N.P., to the east of the crest of the Cordillera de Talamanca, in Costa Rica (Fig. 2.1A). Lago Ditkebi was formed by glacial activity during the late Quaternary (Haberyan et al., 2003). It is a permanent, natural lake (3493 m.a.s.l.; depth = 8 m; Fig 2.1B; Horn et al., 2005), underlain by pyroclastic deposits (Haberyan et al., 2003). It is characterized by extremely dilute (specific conductivity = 0.029 S/cm), slightly alkaline (pH = 8) water. The lake was characterized by a relatively uniform temperature profile, with surface and bottom water temperature of 10.7 °C and 10.3 °C, respectively, in July 2014 (Fig. 2.2). Inflowing streams enter the lake to the northwest and to the southeast (Fig 2.1BC). An outflowing stream at the southeast margin of the lake connects Lago Ditkebi to Rio Ditkebi, a small river that flows to the Atlantic coast (Fig. 2.1B).

Instrumental data is available from the Cerro Páramo meteorological station (3466 m a.s.l.), which is located ~30 km west of the study site (Horn, 1993). Precipitation records from the

Cerro Páramo station reveal a distinct wet and dry season within the Chirripó páramo, with ~90% of the precipitation falling between May and November (Horn et al., 2005). High atmospheric humidity moderates the dry season, but intervals of cloud-free weather associated with the northeast (NE) trade wind inversion lowers humidity sufficiently enough to support fires (Horn and Kappelle, 2009). Distinct seasonality in precipitation is produced by the shift in the position of the equatorial low pressure trough and sub-tropical high pressure over Central America in response to the seasonal migration of the ITCZ (Bundschuh and Alvarado, 2007). Generally, the wet season begins in May when the ITCZ shifts northward over Costa Rica and ends in November when the ITCZ migrates southward (Coen, 1983). The southward migration of the ITCZ allows sub-tropical high pressure to exert control during the winter dry season (Bundschuh and Alvarado, 2007). The amount and spatial distribution of annual precipitation in Costa Rica is strongly influenced by topography (Coen, 1983; Bundschuh and Alvarado, 2007). The presence of elevated highlands and the resultant orographic effect are very pronounced on the eastern side of the Cordillera Central in Costa Rica, with orographic-induced lifting and cooling of air masses resulting in high amounts of precipitation in alpine environments in Costa Rica (Coen, 1983; Clawson, 1997).

The high elevations of Chirripó N.P. are dominated by páramo, an alpine ecosystem composed of a diverse and mixed shrub, grass, and perennial herbaceous plant assemblage of Andean origin (Kappelle and Horn, 2016). The most abundant shrub within Chirripó páramo is dwarf bamboo (*Chusquea subtessellata*), covering up to 60% of the open area (Kappelle and Horn, 2016). The vegetation present in the catchment of Lago Ditkebi is typical of the páramo found within park, with the herbaceous cover at the site dominated by dwarf bamboo, sedges and grasses, including *Muhlenbergia*, a C_4 grass that is associated with well-drained, coarse and less-humid substrates, and widely distributed in Chirripó N.P. (Horn, 1990; Lane et al., 2011).

Evidence for the existence of glaciers during late Quaternary in Costa Rica exists in the highlands, although there are no modern glaciers in Central America and no reliable records of snowfall occurring in Costa Rica at present (Coen, 1983; Seltzer, 1994; Kaser and Osmaston, 2002). The Chirripó massif contained the most extensive glaciers in Costa Rica during the late Quaternary (Orvis and Horn, 2000). However, evidence of glacial expansion in Chirripó N.P. during the Younger Dryas (12,900 to 11,600 cal yr BP) is inconclusive (Orvis and Horn, 2000; Lachniet, 2007). A temperature reduction of 2-3 ^{o}C, inferred from a montane pollen profile, appears to provide evidence of limited cooling during the Younger Dryas (Islebe and Hooghiemstra, 1997; Orvis and Horn, 2000). However, sediments recovered from tarns in Valle de las Morrenas clearly indicate that glaciers retreated to above 3500 m a.s.l. prior to 10,140 ± 120 ^{14}C yr BP (Orvis and Horn, 2000).

Meteorological data and sedimentary evidence indicate that fire plays an important role in shaping the Chirripó páramo ecosystem. Fires have occurred throughout the 20th century; most of the recent fires (1953, 1958, 1976, 1977, 1981, 1992) affecting the páramo in Chirripó N.P. appear to have been ignited by cigarettes and cooking and campfires (Horn and Kappelle, 2009). Helicopter and plane crashes have also been identified as causes of recent fires (Horn and Kappelle, 2009). Large fires within the Chirripó páramo in Costa Rica are also directly related to the severity of the dry season (Horn, 1991; Horn and Kappelle, 2009). Large (>100 ha) fires occurred in the Chirripó páramo and the adjacent montane forests during the driest months (February, March, <0.5 mm precipitation) in 1961, 1976 and 1985 (Horn and Kappelle, 2009). The causes of fire episodes in the páramo are complex and depend on various meteorological, geographical, and ecological factors. However, the ancient fires predating humans occurred in the páramo of Chirripó N.P. were most likely ignited by lightning or, with less likelihood, by volcanism (Horn and Kappelle, 2009). The Talamanca Mountains of Costa Rica, in which the Chirripó páramo is located, experience a high frequency of thunderstorms (Horn and Kappelle, 2009). Lightning has been observed striking the high elevations of the park (Horn, 1990), and has ignited as least one forest fire (Chaverri-Polini and Esquivel, 2005). Fires in the páramo of Chirripó N.P. can also be ignited by dry lightning (in the absence of precipitation) or by lightning with sufficient fuel and the appropriate antecedent moisture conditions (Keane and Finney, 2002). Climate, which influences the rate of fuel accumulation and the moisture content of fuels, and the rate of vegetation recovery, which influences fuel availability, can work together to affect fire frequency in the páramo of Chirripó N.P. (Horn and Kappelle, 2009).

Macroscopic charcoal records extracted from sediment cores recovered from glacial lakes located in the Chirripó páramo reveal that fires occurred repeatedly throughout the Holocene, with more frequent fires occurring during the late Holocene (Horn, 1993; League and Horn, 2000). Elevated macroscopic charcoal influx is observed during the late Holocene (last ~4200 ^{14}C years), when human population density was higher and when climate of the circum-Caribbean was drier, particularly after ~3000 ^{14}C yr BP (Hodell et al., 2000; League and Horn, 2000). Relatively low charcoal influx occurred between 6800 and 4200 ^{14}C yr BP, an interval that overlaps with a mid-Holocene wet interval in the circum-Carribean region (Hodell et al., 2000; League and Horn, 2000). The macroscopic charcoal record from Lago Morrenas 1 is the only existing high-resolution sedimentary charcoal record of local fires presently available from Chirripó páramo (League and Horn, 2000). It provides strong evidence of the long-term history of past fires in the Chirripó páramo, and suggests that the frequency of fire has varied over time in response to changes in climate and anthropogenic activity.

2.4 METHODS

A 5.75 m sediment core was recovered from the center of Lago Ditkebi (DKB) at a water depth of 8.0 m in July 2014. The upper 0.84 m of sediment was recovered using a plastic tube fitted to a modified Livingstone corer, with the remainder of the sediment recovered using a stainless-steel barrel. The Livingstone corer was deployed from a platform established on two inflatable rafts. The upper 0.84 m of the sediment core was sub-sectioned in the field at 0.25 cm intervals and stored in Whirl-Paks. The remainder of the lake sediment core was cut into ~50 cm sections, wrapped with plastic film and aluminum foil, encased in PVC tubes for transporting to the United States, and later sectioned at 0.50 cm intervals in the Environmental Change Lab at the University of Georgia. The stratigraphy of the DKB core was well preserved, but a depth adjustment was undertaken following sectioning to account for core compression.

Chronological control for the Lago Ditkebi lake sediment core is based on eight AMS radiocarbon (^{14}C) dates obtained on charcoal and aquatic moss (Table 2.1). Radiocarbon dates were converted to calendar years using the most recent IntCal13 calibration curve (CALIB 7.10: calib.org/calib/calib.html; Reimer et al., 2013) with full set of calibrated ±2σ age ranges reported. An age-depth model (Fig. 2.3) was constructed based on a probability sampling method implemented using Clam 2.2 (Blaauw, 2010) with setting of smooth-spline (type = 4) and default smooth level (smooth = 0.3). The sample point at 77.6 cm showing a distance away from the age-depth line is potentially an outlier, due to deposited old charcoal. All ages are reported in CE or cal yr BP relative to 1950 CE. The calibrated basal age of the Lago Ditkebi sediment core is ~ 8770 cal yr BP. Radiocarbon dating was conducted at the Center for Applied Isotope Studies (CAIS) at the University of Georgia.

Analysis of sub-fossil chironomid remains followed the procedures outlined in Walker (2001). A total 98 sediment samples was analyzed for sub-fossil chironomid remains at a sub-centennial scale resolution (~90 years/sample). A known volume of sediment (3-5 ml) was placed in a beaker with 50 ml of 5% KOH and heated at 50°C for approximately 30 minutes. The KOH treatment facilitates the break-up of colloidal matter. The deflocculated sediment was washed through a 95μm mesh and rinsed using distilled water. The material retained on the mesh was backwashed into a beaker. Samples were poured into a Bogorov plankton counting tray and the chironomid head capsules were isolated from the sediment matrix using a dissection microscope at 50X magnification. The chironomid head capsules were permanently mounted on slides in Entellan® for identification. A minimum of 50 chironomid head capsules was identified in each sample for further statistical analysis (Heiri and Lotter, 2001). Taxonomic identification was conducted at 400X, typically to genus, relying primarily on Wu et al. (2015) and larval keys for Florida and North and South Carolina (Epler, 1995 and 2001), with Brooks et al. (2007), Cranston (2010), Eggermont et al. (2008) and Spies et al. (2009) providing additional diagnostic information. Chironomid percentage diagrams, plotted using C2 (Juggins, 2003), were based on the relative abundance of all identifiable chironomid remains. The zonation of the chironomid diagram, based on visually observed shifts in a key chironomid taxon, *Polypedilum* N type, was tested using differencing analysis (DA) (Hyndman and Athanasopoulos, 2014). In this analysis, the difference between consecutive relative abundances of the key taxon is computed ($y'_n = y_n - y_{n-1}$) to stabilize its time series and to eliminate any trends. Significant variation observed in the consecutively differenced values reflects a distinctive change in the abundance of the key taxon's time series. Samples with differenced values exceeding the 0.95 (mean $\pm \sigma$) and 0.99 (mean $\pm 2\sigma$) confidence intervals are identified as having a 'distinctive change' or 'remarkably distinctive change' in the time series, respectively (Hyndman and Athanasopoulos, 2014). Faunal turnover was assessed using detrended canonical correspondence analysis (DCCA) (Zuur et al., 2007). All numeric analyses (DA, DCCA) were based on all identifiable chironomid remains. The chironomid percentage data were square-root transformed prior to optimize the 'signal' to 'noise' ratio and to stabilize variance (Prentice, 1980). The DCCA was implemented using CANOCO version 4.0 (ter Braak and Smilauer, 1998).

Macroscopic charcoal fragments were analyzed using a protocol available from the Limnological Research Center at the University of Minnesota (*http://lrc.geo.umn.edu/laccore/procedures.html*). Charcoal analysis for the Lago Ditkebi core was based on 367 sediment samples, consisting of 1.5-2 cm^3 of material. The sediment was sampled contiguously at 1 cm intervals between the surface and 84 cm, at 1.1-1.2 cm interval between 84 cm and 138 cm, at 1.6-2.5 cm interval between 138 and 373.9 cm, at 2 cm interval between 374 and 453 cm, at 1 cm interval between 453 to 485 cm and 2 cm interval between 485 and 575 cm. Sediment samples were washed into beakers using distilled water. Samples were treated with a 30 ml solution of 6% hydrogen peroxide (H_2O_2) to bleach the organic matter present. Beakers were covered by aluminum foil to avoid contamination and placed into a drying oven and heated at 50°C for ~24 hours to amplify the bleaching reaction. Samples were washed through nested sieves of 125 μm and 250 μm mesh size; the material remaining on the sieves were transferred into labeled petri dishes. To disperse the charcoal and make counting and identification easier, ~2 ml of a detergent solution (dilute [0.5%] sodium hexametaphosphate) was added to each petri dish. Charcoal fragments were tallied using a gridded counting sheet at 100x magnification after the water in the petri dishes evaporated. Analysis and interpretation of the charcoal is limited to the fraction that is >125 μm because charcoal of this size class is typically transported locally from the fire source and can serve as a signal of local fire (Whitlock and Millspaugh, 1996; Walsh et al., 2008). Macroscopic charcoal fragments/particles were tallied and classified under microscope manually as either woody, grass, or lattice-type based on appearance to provide additional information on fuel type. Woody charcoal, produced by trees and shrubs, can be identified by its sheen, and thick, layered and prismatic structure. Charcoal derived from grass, is usually thin, flat and characterized by stomata in the epidermal walls (Walsh et al., 2008 and 2014). Charcoal produced by the burning of thin leaves is characterized by a flat, single-layered, lattice pattern (Jensen et al., 2007; Walsh et al., 2008 and 2014). Charcoal counts were divided by the volume of the sample to calculate charcoal concentration (particles/cm^3), and then converted to charcoal accumulation rate (CHAR, particles/cm^2/yr) by multiplying the charcoal concentration by the sedimentation rate. Analysis of the charcoal data followed methods outlined in Higuera et al. (2009) and used the statistical program CharAnalysis (Higuera et al., 2009; http://charanalysis.googlepages.com/). A LOWESS smooth of 100 years was applied to the charcoal record and used to estimate background CHAR ($C_{background}$). Fire peak threshold is locally defined based on the final positive CHAR threshold (threshFinalPos). A fire peak is considered significant when CHAR residuals (CHAR- $C_{background}$) are greater than the final positive CHAR threshold calculated as the 0.95 percentile cut-off (threshold 2 in this study) based on the Gaussian mixture model-based noise distribution (C_{noise}) (Higuera, 2009). Fire peak magnitude (particles/cm^2/peak) is defined as the difference of CHAR residuals and the final positive thresholds at each identified fire peak.

Geochemical analyses of the lake sediment recovered from Lago Ditkebi included total organic carbon (C%), total organic nitrogen (N%), and the stable isotopes of carbon ($\delta^{13}C$) and nitrogen ($\delta^{15}N$). The geochemical analyses were based on 146 samples that were freeze-dried for 24 to 72 hours. Approximately 3-4 mg of sediment for each sample was weighed out on a high-precision digital scale and placed in silver capsules. These samples were pretreated, prior to being combusted, with 10-50 μm^3 of diluted hydrochloric acid (5% HCl) using a pipet to remove any carbonates. The sediment samples were not milled following freeze-drying due to the fine-grained nature of the sediment. For the few samples that contained coarser-grained material, three replicate samples were run and the average value of geochemical data was calculated to ensure the representativeness of the results. All geochemical analyses were conducted at the Center for Applied Isotope Studies (CAIS) at the University of Georgia.

2.5 RESULTS

2.5.1 Chironomids

A total of 18 chironomid taxa were present in the DKB core (Fig. 2.4), with 15 of the taxa (83%) present in the modern training set (Wu et al., 2015). *Diamesa*, *Corynocera*, and *Parochlus* are absent in the modern training set (Wu et al., 2015); however, *Corynocera* and *Parochlus* have been previously found in Costa Rica (Spies et al., 2009). *Diamesa*, a Holarctic taxon favoring cold conditions (Brooks et al., 2007; Cranston, 2010), has been observed in high-elevation lakes in tropical Africa (Eggermont et al., 2010) and very high-elevation sites in the Neotropics (Ward, 1994). This is the first documented occurrence of *Diamesa* in Costa Rica (Watson and Heyn, 1992; Spies and Reiss, 1996; Spies et al., 2009; Petra, 2012 thesis; Wu et al., 2015). Taxon richness varies from 1 to 10, with maximum richness occurring at ~6900 cal yr BP (Fig. 2.4). Taxon richness begins to decrease at ~ 5200 cal yr BP, approximately at the onset of zone DKB-II. The relative abundance of *Procladius*, which dominates the chironomid assemblage throughout the entire record, varies between 84% and 100%. *Psectrocladius* is the second most abundant taxon, however, its relative abundance never exceeds 14.9%. Seven taxa, Unknown ii, *Smittia/Pseudosmittia*, *Corynoneura/Thienemanniella*, *Polypedilum* N type, *Cricotopus/Orthocladius*, *Parochlus* and *Synorthorcladius*, are also present in DKB core, albeit at relatively low levels, with the maximum relative abundance of these taxa < 6% of the total identifiable chironomid remains. Eleven of the 18 chironomid taxa present in Lago Ditkebi during the Holocene are associated with cold, high-elevation lakes (highlighted in blue in Fig. 2.4) in the modern training set (Wu et al., 2015). *Polypedilum* N type, a taxon associated with low-elevation lakes in the training set, is an indicator of warm conditions (highlighted in orange in Fig. 2.4), and is considered a key indicator taxon. The continuous presence of *Polypedilum* N type between ~5290 and 2780 cal yr BP was used to demarcate DKB-II. The intervals from 8770 to 5290 cal yr BP and from 2780 cal yr BP to the present represent zone DKB-I and zone DKB-III, respectively.

The chironomid assemblage in zone DKB-I, which is dominated by *Procladius*, also includes *Psectrocladius*, *Cricotopus/Orthocladius*, *Parochlus* and *Synorthocladius*, with lesser amounts of *Limnophyes*, Unknown ii, *Smittia/Psuedosmittia*, and *Corynoneura/ Thienemanniella* (Fig. 2.4). *Psectrocladius*, which reaches its maximum percentage (14.8%) in the core at ~6490 cal yr BP, fluctuates around 5% for most of the interval represented by zone DKB-I. Taxon richness averages 5.4 in zone DKB-I. Peak value in chironomid concentration (54.2 head capsules/ml) and taxon richness (10) occurs at ~6760 and ~6900 cal yr BP, respectively. The DCCA indicates that minimal faunal turnover occurred between 8770 and 5290 cal yr BP.

Procladius continues to dominate zone DKB-II, which spans the interval between ~5290 and 2780 cal yr BP. Most obviously, this zone is characterized by a sudden increase in the relative abundance of *Polypedilum* N type. The abundance of *Polypedilum* N type is relatively low, averaging ~1.8% through this zone, with a maximum abundance (4.4%) occurring at ~5230 cal yr BP. Taxa present in zone DKB-I, including *Psectrocladius*, *Cricotopus/Orthocladius*, *Parochlus*, *Synorthocladius*, Unknown ii, *Smittia/Psuedosmittia*, and *Corynoneura/Thienemanniella*, remain extant in zone DKB-II. *Smittia/Pseudosmittia* and *Limnophyes*, taxa associated with terrestrial or semi-terrestrial conditions, are found near the onset and the termination of the zone. Zone DKB-II is also characterized by the appearance of *Diamesa*, a taxon adapted to cold habitats (Brook et al., 2007; Anderson, 2012). DCCA scores and head capsule concentrations stay relatively stable, indicating minimal faunal turnover between ~5290 and 2780 cal yr BP. Although average taxon richness remains similar to zone DKB-I (5.4), sample–to–sample variability in taxon richness is greater in zone DKB-I.

DKB-III is dominated by *Procladius*, which comprises nearly the entire chironomid community in this zone. The interval between ~2500 and 2300 cal yr BP is characterized by a notable shift in the chironomid assemblage, as evidenced by the DCCA scores. This ~200 year interval is characterized by a distinctive decrease in the thermophilous taxon, *Polypedilum* N type, and an abrupt increase in the relative abundance of *Chironomus*, *Corynocera*, *Micropsectra* and *Tanytarsus* LU type. *Cricotopus/Orthocladius*, *Parochlus* and *Synorthocladius* decrease synchronously in this zone. The faunal turnover that occurs at the onset of zone DKB-III is followed by a notable reduction in *Polypedilum* N type, *Cricotopus/Orthocladius*, *Parochlus* and *Synorthocladius* with relatively muted faunal turnover and reduced taxon richness observed through the reminder of zone DKB-III.

The extremely high relative abundance of *Procladius* (minimum abundance > 84% of identifiable chironomid remains) precludes the application of the chironomid-based temperature inference model to the sub-fossil chironomid stratigraphy developed for Lago Ditkebi. The applicability of the existing chironomid-temperature relationship developed in Wu et al. (2015)

was assessed by determining the similarity of the sub-fossil chironomid assemblages from Lago Ditkebi to their closest modern analogues. This analysis indicated that the training set did not have a sufficient number of “good” analogues and that the squared residual distance between the calibration set samples and the Lago Ditkebi samples was a poor fit with temperature (Birks et al., 1990).

2.5.2 Charcoal analysis and sedimentation rate

Similar trends in woody and grass charcoal concentrations are observed throughout the Holocene (Fig. 2.5). Woody and grass charcoal concentrations are relatively low in zone DKB-I, with high charcoal concentrations observed at 7300, 6500 and 5900 cal yr BP. Charcoal concentration rapidly increases at the onset of zone DKB-II. The highest charcoal concentration observed for entire core, consisting of woody and grass morphotypes, occurs at ~5250 cal yr BP. Elevated charcoal concentrations also occur in zone DKB-II at ~4900, ~4400 cal yr BP and from 3350 to 2630 cal yr BP. The concentration of the lattice morphotype was at its highest level in zone DKB-II, reaching a concentration of 10 particles/cm^3 in this zone. The charcoal accumulation rate (CHAR) for all morphotypes ranges between 0 and ~88 particles/cm^2/yr. Following the trend observed in woody and grass charcoal concentration, CHAR increases abruptly at ~5250 cal yr BP, and reaches a core maximum at this time. A 1.5 cm-thick layer of large-size charcoal (3000-5000 μm) with high concentration of woody and grass charcoal at 471.5-473 cm in DKB core corresponded to this increase in CHAR. The sedimentation rate remains nearly unchanged in zone DKB-I but begins increasing after ~5250 cal yr BP, reaching a peak at ~3300 cal yr BP (0.123 cm/yr). The sedimentation rate declines gradually through the remainder of the DKB-III zone until the 19th century when it starts to rise.

CharAnalysis (Higuera, 2009) identifies the occurrence of 28 discrete charcoal fire events during the past ~8770 years within Lago Ditkebi catchment. Three of the 28 fire peaks occur in zone DKB-I (8770-5290 cal yr BP), with more than half of the fire events (18/28; 64.3%) occurring during the interval between ~3300 cal yr BP and the present. According to the fire peak results, the frequency of fire in DKB-I (8770-5290 cal yr BP) is relative low, with one fire peak occurring every 1000 years. Zone DKB-III (2780 cal yr BP-the present) is characterized by a much higher fire frequency, ranging from 1.13 to 4.81 peaks/ka (mean = 2.61 peaks/ka), relative to zone DKB-I and zone DKB-II. The interval with the highest fire frequency value (mean = 4.51 peaks/ka) throughout the core occurred between ~2340 and 2040 cal yr BP. Fire peak frequency increases between ~5290 cal yr BP and 2780 cal yr BP, decreases abruptly at ~ 2150 cal yr BP and remains low until ~ 1300 cal yr BP, at which time it begins to increase. The trend of increasing fire frequency that characterizes the interval between 1300 and 700 cal yr BP is followed by a trend of decreasing fire frequency until the late 19th century. An over-estimation of fire peak frequency during the past millennium may exist because this value was calculated based on a Lowess smoothed sum of fire peaks within a 1000-yr period (Higuera, 2009). Fire peak magnitude, providing evidence of fire severity, shows that significant, severe fire events occurred at ~5250 (2236.7 particles/cm^2/peak) and 1350 (1461.9 particles/cm^2/peak) cal yr BP. Three fire events with relatively lower severity (i.e. 731, 719 and 904 particles/cm^2/peak) are noted at ~ 4940, ~ 4460 and ~3080 cal yr BP, respectively.

2.5.3 Geochemistry

The Lago Ditkebi sediment core is characterized by a trend of increasing N% and C% through the Holocene (Fig. 2.6). The C% increases from 9.3% at the base of the core to 27.6% in the most recently deposited sediment. The N% increases approximately three-fold, from 0.7% at 8770 cal yr BP to 2.3% at present. The value of $\delta^{15}N$, which ranges between -3.1 and 1.7‰, remains below 0‰ during the majority of the record. Variation in $\delta^{15}N$ is most pronounced in zone DKB-II, particularly between ~4500 and 3750 cal yr BP, but with no discernable pattern.

DKB-II (~5290-2780 cal yr BP) is characterized by relatively low $\delta^{13}C$ values (average= −25.8 ‰) relative to the later portion of DKB-I (DKB-Ib: ~7500-5290 cal yr BP, average= −25.0 ‰) and zone DKB-III (average= −24.4 ‰). The $\delta^{13}C$ value of DKB-II is similar to the early interval of DKB-I (DKB-Ia: ~8770-7500 cal yr BP, average = −26.5 ‰). A pronounced trend of increasing $\delta^{13}C$ occurs beginning at ~2000 cal yr BP, with a $\delta^{13}C$ maximum of -21.8‰ observed at ~630 cal yr BP. The C/N value remains nearly unchanged for the duration of the record, with the exception of notable, abrupt shifts at ~ 7350 and 5250 cal yr BP, and minor fluctuations at 5000, 4700, 4200 and 2200 cal yr BP. The shift in C/N at ~5250 cal yr BP, which is characterized by a sharp increase from 12 to 20, is suggestive of abrupt increase in the delivery of terrestrial organic matter to the lake, likely due to a disturbance in the catchment.

2.6 DISCUSSION

2.6.1 Chironomid paleoecology

The chironomid assemblage preserved in Lago Ditkebi is dominated by taxa that are considered to be indicators of cold conditions (Wu et al., 2015), with 11 of the 18 identified taxa associated with cold, high-elevation lakes in the modern training set (colored blue in Fig. 2.4). *Procladius*, a profundal taxon tolerant of low-oxygen conditions (Brook et al., 2007; Spies et al., 2009), has amongst the lowest mean annual air temperature (MAAT) optima (14.9°C) of the chironomid taxa present in the calibration set (Wu et al., 2015). The high elevation and relative depth of Lago Ditkebi provide an ideal habitat for *Procladius*. *Psectrocladius,* which has the lowest temperature optimum (10.4 °C) in the modern training set in Wu et al. (2015), is also adapted to cold environments in Costa Rica. *Psectrocladius* is known to inhabit the littoral zone and is often associated with macrophytes (Brooks et al., 2007). *Cricotopus/Orthocladius*, *Synorthocla*dius and *Parochlus*, which are observed in zone DKB-I and zone DKB-II, reflect cold conditions as well. The modern distribution of *Cricotopus/Orthocladius* and *Synorthocladius* in

Costa Rica is restricted to lakes located above 3450 m a.s.l., including Lago Chirripó and Lago Morrenas, where MAAT is lower than 7.9 °C (Wu et al., 2015). Adult *Parochlus* have been found at high-elevation volcanic sites in Costa Rica (Watson and Heyn, 1993), with the larvae inhabiting alpine streams or springs or mosses in various small water bodies (Spies et al., 2009). Five additional taxa, *Limnophyes*, Unknown i*i*, *Smittia/Pseudosmittia*, *Corynoneura/Thienemanniella* and *Micropsectra contracta* type present in the DKB core, at relatively low abundance, are also associated with low temperatures (Wu et al., 2015), with *Limnophyes* and *Smittia/Pseudosmittia* typically preferring terrestrial or semi-terrestrial habitats (e.g. Brook et al., 2007).

Shifts in the composition of the sub-fossil chironomid assemblages are used to infer variations in thermal conditions during the Holocene at Lago Ditkebi (Fig. 2.7B). The continuous presence and high relative abundance of *Polypedilum* N type between ~5290 and 2780 cal yr BP is inferred to represent the occurrence of elevated MAATs during this interval. Today in Costa Rica, *Polypedilum* N type, which has a MAAT optimum of 22 °C, is most abundant in warm, low-elevation lakes (Wu et al., 2015). Differencing Analysis (DA) of the temporal variation in *Polypedilum* N type reveals that a distinctive change is detected in the abundance of this taxon in zone DKB-II, with little change observed in DKB-I and DKB-III (Fig. 2.7A). The low relative abundance of *Polypedilum* N type in zone DKB-I and zone DKB-III is inferred to reflect the existence of thermal conditions that are generally similar during the intervals from 8770 to 5290 cal yr BP and from 2780 cal yr BP to the present. The co-occurrence of *Diamesa* and *Polypedilum* N in zone DKB-II is notable (Fig. 2.7C). Larvae of *Diamesa* are considered cold stenotherms, with approximately 100 species of *Diamesa* are found in the Holarctic region and a lesser number of species in the Afrotropical region (Hansen and Cook, 1976; Willassen and Cranston, 1986; Brook et al., 2007; Cranston, 2010). The larvae of *Diamesa*, a winter active taxon that generally requires cool water, are typically limited to extremely cold habitats

(Anderson, 2012). This is the first confirmed report of this cold-adapted taxon in Costa Rica (Watson and Heyn, 1992; Brooks et al., 2007; Cranston, 2010; Spies et al., 2009; Petra, 2012 Thesis; Wu et al., 2015), The presence of *Diamesa* in zone DKB-II, albeit at low relative abundance (0-4.44%), likely reflects the existence of a persistent pool of cold bottom water at Lago Ditkebi during this interval. Lago Ditkebi is characterized by a deep central basin and a wide littoral shelf along its southeastern margin (Fig. 2.1B). The temperature profile of Lago Ditkebi indicates that, even in the presence of strong NE trade winds, the lake maintains weak stratification between June and October when average daily sunshine is 2.9 hours (Fig. 2.2; Coen, 1983). Pronounced stratification would be expected between November and May when the average daily duration of sunlight is 4.5 hours (Coen, 1983). When increased rainfall leads ot notable increase of lake level, the shallow shelf located along the southern margin of Lago Ditkebi would be flooded (Fig. 2.1B), and with elevated MAAT a warm epilimnetic layer of water could form. Expansion of littoral habitat associated with the deepening of the lake could facilitate an increase in the relative abundance of *Polypedilum* N type and terrestrial/semi-terrestrial taxa, and the persistent stratification would generate a deep pool of cold bottom water that is ideal for *Diamesa* (Fig. 2.7C).

2.6.2 Holocene paleoenvironmental change

The sensitivity of $\delta^{13}C$ to shifts in the relative abundance of C_3 and C_4 plants has been used to reconstruct vegetation dynamics during the Holocene (e.g. Meyers and Lallier-Vergès, 1999; Meyers and Teranes, 2002; Meyers, 2003; Gierlowski-Kordesch, 2004; Leng and Marshall, 2004; Lane et al., 2011). Variations in $\delta^{13}C$ in the DKB core offer insight into Holocene hydroclimate and paleoenvironmental change in the region. C_4 plants do not discriminate against ^{13}C during photosynthesis as effectively as C_3 plants (Meyers and Teranes, 2002). When the proportion of C_4 plants increases in a catchment the soil organic matter becomes relatively enriched in ^{13}C, and this signal can be archived by lake sediment when terrestrial organic matter is transported to the lake basin (Lane et al., 2011). The values of $\delta^{13}C$ in the DKB core, which range from -27 to -22 ‰, indicate that C_3 plants dominated the catchment through the Holocene (Fig. 2.7F) as they do today. The average $\delta^{13}C$ value (pink horizontal line in Fig. 2.7F) for DKB-I and III, particularly DKB-III, are notably higher than that of DKB-II, reflecting a shift in vegetation composition between ~5290 and 2780 cal yr BP. The more positive $\delta^{13}C$ values that characterize the DKB-III and DKB-I zones, particularly the later portion of DKB-I (DKB-Ib: average level displayed by blue dashed line), are inferred to reflect the expansion of C_4 grasses growing along the margin of Lago Ditkebi. *Muhlenbergia*, the sole C_4 grass widely distributed in the Chirripó páramo today and found within the DKB catchment, was inferred to be the main source of terrestrial C_4 input driving the variation in the $\delta^{13}C$ records developed for Lago Morrenas 1, another lake in Chirripó N.P. (Lane et al., 2011). *Mulenbergia*, which can tolerate low temperatures, is largely restricted to relatively dry, coarse substrates in the Chirripó páramo (Lane et al., 2011). The depleted $\delta^{13}C$ values between ~8770 and 7500 cal yr BP in the early portion of DKB-I (DKB-Ia: average level displayed by blue dashed line) are similar to the average value of $\delta^{13}C$ for DKB-II. The more negatice values of $\delta^{13}C$ observed during DKB-II likely reflect a reduction in the abundance of *Muhlenbergia* along the lake's margin (Fig. 2.7F). A scenario that could account for the inferred reduction in the abundance of *Muhlenbergia* between 5290 and 2780 cal yr BP involves the occurrence of elevated MAAT and increased precipitation, leading to an increase in lake level and an expansion of littoral habitat. An increase in the lake level at Lago Ditkebi could result in *Muhlenbergia* occupying habitat further from the lake margin and the coring location, which possibly led to a relative decrease in the ^{13}C contribution from the C_4 grass to the organic matter being transported to into the lake.

Variations in the stable isotope signature of $\delta^{13}C$, together with the chironomid-based inference of thermal conditions and the charcoal-based reconstruction of the local fire regime (Fig. 2.7), enable the development of an integrated record of hydroclimate and paleoenvironmental change spanning the past ~9000 years for the glacial highlands of Chirripó N.P.

The abundance of cool-adapted chironomids and the periodic presence of terrestrial and semi-terrestrial taxa (*Smittia*/*Pseudosmittia* and *Limnophyes*) together with minimal faunal turnover in zone DKB-I is inferred to reflect the occurrence of a interval of depressed temperatures between ~8770 and 5290 cal yr BP. The occasional presence of *Smittia*/*Pseudosmittia* and *Limnophyes* suggests that terrestrial/semi-terrestrial habitats were limited during this time. An explanation for the observed pattern is presented in Fig. 2.8A. Variations in lake level, due to fluctuations in effective moisture, would lead to the development of terrestrial/semi-terrestrial habitat occasionally (depicted as Horizon A in Fig. 2.8A) and thereby account for periodic presence of *Smittia*/*Pseudosmittia* and *Limnophyes* in DKB-I. In generally, more enriched $\delta^{13}C$ values during DKB-I indicate that *Muhlenbergia,* the C_4 grass, likely expanded along the margin of the lake as a result of lowered lake levels and an expansion of suitable habitat, driven by relatively cold and dry conditions. Charcoal-inferred fire frequency is low, suggesting that this interval may have been characterized by reduced convective activity and lightening–induced ignition.

The onset of DKB-II at ~ 5290 cal yr BP is punctuated by an abrupt increase the thermophilous chironomid, *Polypedilum* N type. The increase in *Polypedium* N type, together with the presence of *Smittia/Pseudosmittia* and *Limnophyes*, suggest the occurrence of a short-lived interval of elevated rainfall, which led to an increase in lake level and an expansion of terrestrial/semi-terrestrial habitats (Fig. 2.8B). *Diamesa*, a cold stenotherm that favors low temperature (Brooks et al., 2007; Cranston, 2010; Anderson, 2012), first appears at Lago Ditkebi at ~5200 cal yr BP. An increase in lake level and volume would enhance stratification and enable the development of a deep pool of cold water suitable for *Diamesa*. It appears that *Diamesa* only occurred when the warming-induced stratification and cold profundal water existed. A sharp and abrupt increase in CHAR indicate the occurrence of a large fire at ~5200 cal yr BP, suggesting that this short-lived interval may have also been characterized by elevated or enhanced lightning activity. The presence of a 1.5 cm-thick layer of large-size macroscopic charcoal (3000-5000 μm), and the high concentration of woody and grass charcoal indicate that the fire that occurred at this time was intense and severe. Dwarf bamboo, which is abundant in the DKB catchment would have provided sufficient fuel to support a severe fire (Horn, 1990; Horn and Kappelle, 2009), and together with shrubs in the catchment, could have generated a great amount of woody charcoal. The abrupt increase in C/N and the presence of multiple large woody charcoal fragments with area size as large as 0.25 cm^2 in the core also support the inference of a large, severe fire occurring at ~5200 cal yr BP. Additionally, mobilization and transport of these large charcoal fragments to the lake basin would likely require intense precipitation and elevated surface runoff. Limited fire activity, which characterized the interval from ~8770 to 5290 cal yr BP, would have facilitated the build up of fuel in the catchment of Lago Ditkebi and contributed to the severity of the fire at ~5200 cal yr BP as well.

Following the fire episode at ~5290 cal yr BP, the continued presence of *Polypedilum* N type, which remains relatively high throughout zone DKB-II, reflects the existence of a persistent interval of elevated MAAT between ~5290 and 2780 cal yr BP. The reduction in the terrestrial/semi-terrestrial chironomid taxa *Limnophyes* and *Smittia/Pseudosmittia* between ~4800 and 3000 cal yr BP, together with the appearance of *Diamesa*, is inferred to be a response to the deepening of the lake. An increase in lake level would increase the littoral zone expanse, accounting for the continued presence of *Polypedilum* N type and a reduction in terrestrial/semi-terrestrial habitat (Fig. 2.8C). Elevated temperature and an increase in lake level would promote stratification, resulting in the development of a deep, isolated pool of cold water in the profundal, providing suitable habitat for *Diamesa*. The depleted $\delta^{13}C$ values that characterize this interval are inferred to reflect the reduction in the abundance of *Muhlenbergia* in response to increasing temperature and elevated lake levels (Fig. 2.8C). Fire frequency generally increases through zone DKB-II, although CHAR is relatively low between ~4800 to 3300 cal yr BP, suggesting that this interval is characterized by more frequent, low-severity fires. Taken together, the multi-proxy analysis suggests that between ~4800 and 3300 cal yr BP Lago Ditkebi was warm, relatively wet, and experienced frequent fires. The termination of zone DKB-II, which is characterized by the reappearance of *Limnophyes* and *Smittia/Pseudosmittia* and an increase in CHAR and fire frequency, is inferred to reflect the onset of a gradually drying trend and a decrease in lake level, beginning at ~3300 cal yr BP. The inference of gradual drying is also supported by disappearance of *Diamesa* and the trend of increasingly high, albeit fluctuating, $\delta^{13}C$ values (reflecting the expansion of *Muhlenbergia*). The inference of drier conditions at Lago Ditkebi during the past ~3000 years corresponds to previous research, suggesting that the northern tropical Americas and the circum-Caribbean region received less precipitation during this interval (e.g. Horn, 1993; Islebe et al., 1996; Hodell et al., 2000; League and Horn, 2000; Peterson and Haug, 2006; Lane et al., 2011; Lane and Horn, 2013).

Fluctuations in the chironomid assemblage and $\delta^{13}C$ indicate that the last 2780 years at Lago Ditkebi (zone DKB-III) is characterized by cool and dry conditions. The reduction of *Polypedium* N type, a thermophilous chironomid taxon, and the disappearance of *Diamesa*, together with the intermittent presence of *Limnophyes* and *Smittia/Pseudosmittia*, imply a fluctuating, but generally lowered lake level during the interval of DKB-III (Fig. 2.8D). The high $\delta^{13}C$ values reflect a synchronous expansion of *Muhlenbergia* within the catchment and support the interpretation of drier conditions. However, zone DKB-III differs from zone DKB-I in terms of the observed fire regime. Specifically, the high fire peak frequency indicates that wild fires were more active during the past ~3000 years, although the fires were at relatively low-severity level during the past ~1600 years. These fires may reflect increased human activity during the late Holocene (Hodell et al., 2000), an increase in dry lightning strikes (Horn and Kappelle, 2009) or a reduction in standing biomass.

The multi-proxy record developed for Lago Ditkebi indicates that the intervals from 8770 to 5290 cal yr BP and from 2780 cal yr BP to the present were relatively cold and dry, and the interval from ~5290 to 2780 cal yr BP was characterized by increased temperature and rainfall lasting from ~5290 to 2780 cal yr BP, with more frequent fires beginning at ~3300 cal yr BP. This interpretation corresponds to existing paleoenvironmental studies conducted in Chirripó N.P. (e.g. Horn, 1989 and 1993; League and Horn, 2000, Lane et al., 2011; Lane et al., 2013) and generally agrees with earlier research in the northern tropics, documenting a trend of increasing precipitation during the mid-Holocene, which peaks during mid-Holocene, and then declines (Horn, 1993; Islebe et al., 1996; Hodell et al., 2000; League and Horn, 2000; Haug et al., 2001; Peterson and Haug, 2006; Atwood, 2015).

2.6.3 Evidence of an abrupt climate change event at ~5200 cal yr BP

The abrupt and synchronous response of chironomid taxa, sediment geochemistry, specifically C/N, and high CHAR at ~5200 cal yr BP is interpreted to reflect the occurrence of an abrupt climate event at this time. The results from this study suggest that this event was characterized by elevated temperatures, increased precipitation and possibly, enhanced thunderstorm activity. During the past two decades, a growing number of studies conducted in the tropics (Bar-Matthews et al., 1999; Chalié and Gasse, 2002; Thompson et al., 2002; Bar-Matthews and Ayalon, 2004; Magny and Haas, 2004; Staubwasser and Weiss, 2006; Cornoy et al., 2008; Strikis et al., 2011; Atwood, 2015) have identified an abrupt climate event at ~ 5200 cal yr BP. Evidence for an abrupt climate event in the Kilimanjaro ice core is suggestive of extremely cold conditions at 5200 cal yr BP (Fig. 2.9H; Thompson et al., 2002). Additional records from tropical Africa and the Asian monsoon region also document significant hydroclimate variability at this time (Fig. 2.9I; Bar-Matthew et al., 1997 and 1999). Studies from the tropical Americas (Fig. 2.9A-G), including Ecuador (Fig. 2.9F; Moy et al., 2002), Brazil (Fig. 2.9G; Strikis et al., 2011), the Galapagos (Fig. 2.9DE; Atwood, 2015) and Costa Rica (Fig. 2.9A-C; this study), document the existence of wetter conditions at ~5200 cal yr BP. For example, Moy et al. (2002), reconstructed ENSO variability during the Holocene and identified an increase in convective precipitation along the western slope of the Andes at ~5000 cal yr BP. Additionally, non-ENSO related rainfall in the eastern tropical Pacific increases at ~5200 cal yr BP in the Galapagos (Atwood, 2015).

A mechanism accounting for the expression of the abrupt climate event at ~5200 cal yr BP remains elusive (Mayewski et al., 2004; Chiang and Bitz, 2005; Thompson, 2011; Chiang and Friedman, 2012; Chiang et al., 2014). The correspondence between insolation variation and this abrupt climate change at ~5200 cal yr BP appears limited (Fig. 2.9J). It has been proposed that anomalous warming in the tropical North Atlantic at this time reduced the inter-hemispheric temperature gradient, resulting in the northward migration of the ITCZ and increased precipitation in the northern tropical Americas (Broccoli et al., 2006; Schneider et al., 2014). A more northerly positioned ITCZ would increase cloud coverage over the tropical North Atlantic, reduce the loss of longwave radiation and further warm the surface ocean in tropical North Atlantic (Xie and Carton, 2004; Chiang and Friedman, 2012;). Elevated sea surface temperatures (SSTs) would lead to increased evaporation and enhanced boundary layer moisture transport via the northeast trade winds, resulting in enhanced convection, rainfall and thunderstorm activity at Lago Ditkebi at 5200 cal yr BP (Bhattacharya et al., 2017).

2.6.4 Response of sediment geochemistry to fire events

Geochemistry records in DKB core provide insight into the how the nutrient cycle may respond to fire in the Chirripó páramo ecosystem (Fig. 2.10). Specifically, fluctuations in $\delta^{15}N$ appear to be coupled with fire events in the Ditkebi catchment during the Holocene. Nearly every fire event is characterized by an initial increase in $\delta^{15}N$, followed by a reduction in sedimentary $\delta^{15}N$ (Fig. 2.10AB). A similar pattern is evident in another sediment core recovered from a nearby glacial lake, Lago Morrenas 3C (Wu, 2018, dissertation Chapter 3). Synchronous “spikes” in charcoal concentration and $\delta^{15}N$ have been identified in the DKB core (Fig. 2.10AB); although, the spikes in $\delta^{15}N$ do not align perfectly with the CharAnalysis-inferred fire peaks (Fig. 2.10C). The relationship between fire and sedimentary $\delta^{15}N$ likely reflects the influence of the temperature-dependent volatilization of N (Romme et al., 2011; Morris et al., 2014). Because ^{14}N is lighter and can be volatilized more easily, a greater proportion of ^{15}N remains in the charred plant material, which can later be transported into the lake (Morris et al., 2014). However, there appears to be limited correlation between the inferred severity of the fire event and the relative increase in $\delta^{15}N$. For example, the severe fire at ~5200 cal yr BP only resulted in a small rise in $\delta^{15}N$ value, but a much less severe fire at ~4100 cal yr BP generated a notable increase in $\delta^{15}N$. Additionally, the fire-induced increase in sedimentary $\delta^{15}N$ may be relatively short-lived, with $\delta^{15}N$ returning to pre-fire levels within decades, which generally agrees with the finding in Horn (1990). This suggests that the rate of recovery of páramo vegetation may occur within decades. This broadly matches the finding that it took 10 to 20 years for bamboo and shrubs in the Chirripó páramo to attain their pre-fire size (e.g. height and stem diameter) following a severe fire in 1976 (Horn, 1990). A positive relationship between fire frequency and C% and N% is evident from ~8770 to 5290 cal yr BP and from 2780 cal yr BP to the present at Lago Ditkebi (Fig. 2.10). The loss of carbon and nitrogen stock, particularly carbon, in terrestrial biomass and soils appears to increase with increasing fire frequency. Thus, restoration and preservation of carbon and nitrogen in the catchment soil could gradually become difficult if repeated burning (Fig. 2.10D) leads to significant removal of vegetation and potential landscape degradation. Although some studies suggest that fire can enhance habitat and species diversity in the páramo (Horn, 1998; Sarmiento and Frolich, 2002; Keating, 2007). Due to rapid and destructive alteration on biotic landscape caused by fires, and because of the potential of increased fire risk in response to projected climate change, in Costa Rica (IPCC, 2016), fire management is important and necessary in Chirripó N.P. (Horn, 1998).

2.7 CONCLUSION

This high-resolution, multi-proxy reconstruction from Lago Ditkebi, provides evidence that glacial highlands of Costa Rica were characterized by: 1) relatively cold, dry conditions, decreased effective moisture, and limited fire activity between ~8770 and 5290 cal yr BP; 2) a persistent interval of elevated MAAT, increased effective moisture and frequent, low severity fires between ~5290 and 2780 cal yr BP; 3) cool, dry conditions, and generally frequent low severity fires between ~2780 cal yr BP and the present. Macroscopic charcoal analyses indicate that wildfires periodically occurred throughout the Holocene. An abrupt increase in fire frequency and severity occurred at ~5290 cal yr BP, with the interval between ~3300 and 1500 cal yr BP characterized by the highest fire frequency during the Holocene. Evidence for an abrupt climate event centered at ~5200 cal yr BP is found at Lago Ditkebi. The abrupt and synchronous response of chironomid taxa, C/N and CHAR at ~5200 cal yr BP are interpreted to reflect the occurrence of elevated MAAT, increased precipitation and possibly, enhanced thunderstorm activity. The finding for the 5200 cal yr event in the glacial highlands of Costa Rica corresponds well with paleoclimate records from the tropics and provides support for the hypothesis that an increase in temperature–dependent evaporation, resulting from increased SSTs, and amplified moisture transport in the northern tropical Americas could account for the enhanced convection, rainfall and thunderstorm activity observed at Lago Ditkebi at ~5200 cal yr BP.

2.8 REFERENCES

Anderson, A.M., 2012. *Winter-emerging chironomidae (Insecta: Diptera) in Minnesota trout streams*. University of Minnesota.

Andrews, P.L., 1986. BEHAVE: fire behavior prediction and fuel modeling system-BURN subsystem, Part 1.

Atwood, A., 2015. *Mechanisms of tropical Pacific climate change during the Holocene* (Doctoral dissertation).

Bar-Matthews, M., Ayalon, A. and Kaufman, A., 1997. Late Quaternary paleoclimate in the eastern Mediterranean region from stable isotope analysis of speleothems at Soreq Cave, Israel. *Quaternary Research*, *47*(2), pp.155-168.

Bar-Matthews, M., Ayalon, A., Kaufman, A. and Wasserburg, G.J., 1999. The Eastern Mediterranean paleoclimate as a reflection of regional events: Soreq cave, Israel. *Earth and Planetary Science Letters*, *166*(1), pp.85-95.

Barber, K., Brown, A., Langdon, P. and Hughes, P., 2013. Comparing and cross-validating lake and bog palaeoclimatic records: a review and a new 5000-year chironomid-inferred temperature record from northern England. *Journal of paleolimnology*, *49*(3), pp.497-512.

Bauch, H.A., Mueller-Lupp, T., Taldenkova, E., Spielhagen, R.F., Kassens, H., Grootes, P.M., Thiede, J., Heinemeier, J. and Petryashov, V.V., 2001. Chronology of the Holocene transgression at the North Siberian margin. *Global and Planetary Change*, *31*(1), pp.125-139.

Beniston, M. and Haeberli, W., 2000. *Sensitivity of mountain regions to climatic change*. Université de Fribourg.

Berger, A. and Loutre, M.F., 1991. Insolation values for the climate of the last 10 million years. *Quaternary Science Reviews*, *10*(4), pp.297-317.

Bhattacharya, T., Chiang, J.C. and Cheng, W., 2017. Ocean-atmosphere dynamics linked to 800–1050 CE drying in mesoamerica. *Quaternary Science Reviews*, *169*, pp.263-277.

Birks, H.J.B., Ter Braak, C.J.F., Line, J.M., Juggins, S. and Stevenson, A.C., 1990. Diatoms and pH reconstruction. *Phil. Trans. R. Soc. Lond*. B, 327(1240), pp.263-278.

Blaauw, M., 2010. Methods and code for 'classical'age-modelling of radiocarbon sequences. *Quaternary Geochronology*, *5*(5), pp.512-518.

Broccoli, A.J., Dahl, K.A. and Stouffer, R.J., 2006. Response of the ITCZ to Northern Hemisphere cooling. *Geophysical Research Letters*, *33*(1).

Brooks, S.J., Axford, Y., Heiri, O., Langdon, P.G. and Larocque-Tobler, I., 2012. Chironomids can be reliable proxies for Holocene temperatures. A comment on Velle et al. (2010). *The*

Holocene, *22*(12), pp.1495-1500.

Brooks, S.J., Langdon, P.G., Heiri, O., and Quaternary Research Association, 2007. *The Identification and use of Palaearctic Chironomidae Larvae in Palaeoecology*.Quaternary Research Association.

Bundschuh, J. and Alvarado, G.E. eds., 2007. *Central America, Two Volume Set: Geology, Resources and Hazards*. CRC Press.

Burgan, R.E. and Rothermel, R.C., 1984. BEHAVE: fire behavior prediction and fuel modeling system--FUEL subsystem.

Bush, M.B. and Metcalfe, S.E., 2012. Latin America and the Caribbean. *Quaternary Environmental Change in the Tropics*, pp.263-311.

Chalié, F. and Gasse, F., 2002. Late Glacial–Holocene diatom record of water chemistry and lake level change from the tropical East African Rift Lake Abiyata (Ethiopia). *Palaeogeography, Palaeoclimatology, Palaeoecology*, *187*(3), pp.259-283.

Chang, J.C., Shulmeister, J. and Woodward, C., 2015. A chironomid based transfer function for reconstructing summer temperatures in southeastern Australia. *Palaeogeography, Palaeoclimatology, Palaeoecology*, *423*, pp.109-121.

Chaverri-Polini, A. and Esquivel-Garrote, O., 2005. Páramos de Costa Rica. Kappelle, M.; Horn, SP (eds.).

Chaverri-Polini, A. and Cleef, A.M., 2005. Comunidades vegetales de los páramos de los macizos de Chirripó y Buenavista, Costa Rica.

Chiang, J.C. and Bitz, C.M., 2005. Influence of high latitude ice cover on the marine Intertropical Convergence Zone. *Climate Dynamics*, *25*(5), pp.477-496.

Chiang, J.C. and Friedman, A.R., 2012. Extratropical cooling, interhemispheric thermal gradients, and tropical climate change. *Annual Review of Earth and Planetary Sciences*, *40*.

Chiang, J.C. and Koutavas, A., 2004. Climate change: tropical flip-flop connections. *Nature*, *432*(7018), p.684.

Chiang, J.C., Lee, S.Y., Putnam, A.E. and Wang, X., 2014. South Pacific Split Jet, ITCZ shifts, and atmospheric North–South linkages during abrupt climate changes of the last glacial period. *Earth and Planetary Science Letters*, *406*, pp.233-246.

Clawson, D., 1997. Latin America and the Caribbean. *Dubuque, IA: Brown*.

CLIMAP Project Members. 1981. Seasonal Reconstruction of the Earth's Surface at the Last

Glacial Maximum. : Geological Society of America Map and Chart Series, Map MC-36. pp.

CLIMAP Project Members. 1984. The Last Interglacial Ocean. *Quaternary Research* 21, pp.123-224

Coen, E., 1983. Climate. Janzen, DH, editor: Costa Rican Natural History.

COHMAP Members. 1988. Climatic changes of the last 18,000 years: observations and model simulations. *Science* 241,pp.1043-52

Conroy, J.L., Overpeck, J.T., Cole, J.E., Shanahan, T.M. and Steinitz-Kannan, M., 2008. Holocene changes in eastern tropical Pacific climate inferred from a Galápagos lake sediment record. *Quaternary Science Reviews*, *27*(11), pp.1166-1180.

Cranston, P., 1995. *Chironomids: From Genes to Ecosystems.* CSIRO Australia.

Cranston, P., 2010. http://chirokey.skullisland.info/

Dieffenbacher-Krall, A.C., Vandergoes, M.J. and Denton, G.H., 2007. An inference model for mean summer air temperatures in the Southern Alps, New Zealand, using sub-fossil chironomids. *Quaternary Science Reviews*, *26*(19-21), pp.2487-2504.

Eggermont, H. and Heiri, O., 2012. The chironomid- temperature relationship: expression in nature and palaeoenvironmental implications. *Biological Reviews*, *87*(2), pp.430-456.

Eggermont, H., Heiri, O., Russell, J., Vuille, M., Audenaert, L. and Verschuren, D., 2010. Paleotemperature reconstruction in tropical Africa using fossil Chironomidae (Insecta: Diptera). *Journal of Paleolimnology*, *43*(3), pp.413-435.

Eggermont, H., Kennedy, D., Hasiotis, S.T., Verschuren, D. and Cohen, A., 2008. Distribution of living larval Chironomidae (Insecta: Diptera) along a depth transect at Kigoma Bay, Lake Tanganyika: implications for palaeoenvironmental reconstruction. *African Entomology* 16, 162–184.

Epler, J., 1995. Identification manual for the larval Chironomidae (Diptera) of Florida. Identification Manual for the Larval Chironomidae (Diptera) of Florida.

Epler, J., 2001. A guide to the taxonomy of the midges of the southeastern united states, including Florida.

Fortin, M.C., Medeiros, A.S., Gajewski, K., Barley, E.M., Larocque-Tobler, I., Porinchu, D.F. and Wilson, S.E., 2015. Chironomid-environment relations in northern North America. *Journal of paleolimnology*, *54*(2-3), pp.223-237.

Gierlowski-Kordesch, E., 2004. Paleolimnology: the history and evolution of lake systems.

Haberyan, K.A., Horn, S.P. and Umaña, V., 2003. Basic limnology of fifty-one lakes in Costa Rica. *Revista de biología tropical*, *51*(1), pp.107-122.

Hansen, D.C., and Cook, E.F., 1976, 'The systematics and morphology of the nearctic species of Diamesa Meigen'.

Hastenrath, S. and Heller, L., 1977. Dynamics of climatic hazards in northeast Brazil. *Quarterly Journal of the Royal Meteorological Society*, *103*(435), pp.77-92.

Haug, G.H., Hughen, K.A., Sigman, D.M., Peterson, L.C. and Röhl, U., 2001. Southward migration of the intertropical convergence zone through the Holocene. *Science*, *293*(5533), pp.1304-1308.

Heiri, O. and Lotter, A.F., 2001. Effect of low count sums on quantitative environmental reconstructions: an example using sub-fossil chironomids. *Journal of Paleolimnology*, *26*(3), pp.343-350.

Heiri, O., Brooks, S.J., Birks, H.J.B. and Lotter, A.F., 2011. A 274-lake calibration data-set and inference model for chironomid-based summer air temperature reconstruction in Europe. *Quaternary Science Reviews*, *30*(23-24), pp.3445-3456.

Higuera, P., 2009. CharAnalysis 0.9: diagnostic and analytical tools for sedimentcharcoal analysis. *User's Guide, Montana State University, Bozeman, MT*.

Hodell, D.A., Brenner, M. and Curtis, J.H., 2000. Climate change in the northern American tropics and subtropics since the last ice age. *Imperfect Balance: Landscape Transformation in the Precolumbian Americas*, pp.14-38.

Hodell, D.A., Brenner, M. and Curtis, J.H., 2005a. Terminal Classic drought in the northern Maya lowlands inferred from multiple sediment cores in Lake Chichancanab (Mexico). *Quaternary Science Reviews*, *24*(12-13), pp.1413-1427.

Hodell, D.A., Brenner, M., Curtis, J.H., Medina-Gonzalez, R., Can, E.I.C., Albornaz-Pat, A. and Guilderson, T.P., 2005b. Climate change on the Yucatan Peninsula during the little ice age. *Quaternary Research*, *63*(2), pp.109-121.

Horn, S.P., 1989, January. The Inter-American highway and human disturbance of páramo vegetation in Costa Rica. In *Yearbook. Conference of Latin Americanist Geographers* (pp. 13-22). Louisiana State University.

Horn, S.P., 1990. Vegetation recovery after the 1976 páramo fire in Chirripó National Park, Costa Rica. *Revista de Biologia Tropical*, *38*(2), pp.267-275.

Horn, S.P., 1993. Postglacial vegetation and fire history in the Chirripó Páramo of Costa Rica. *Quaternary research*, *40*(1), pp.107-116.

Horn, S.P., 1998. Fire management and natural landscapes in the Chirripó páramo, Chirripó National Park, Costa Rica. *Nature's Geography: New Lessons for Conservation in Developing Countries, Zimmerer, KS, Young, KR (Ed.)*, pp.125-46.

Horn, S.P., Orvis, K.H. and Haberyan, K.A., 2005. Limnología de las lagunas glaciales en el páramo del Chirripó, Costa Rica. *Páramos de Costa Rica*, pp.161-81.

Horn, S., 2007. Late Quaternary lake and swamp sediments: recorders of climate and environment. *Central America: geology, resources, hazards*, *1*, pp.423-441.

Horn, S.P. and Kappelle, M., 2009. Fire in the páramo ecosystems of Central and South America. In *Tropical fire ecology* (pp. 505-539). Springer Berlin Heidelberg.

Hyndman, R.J. and Athanasopoulos, G., 2014. *Forecasting: principles and practice*. OTexts.

IPCC, 2016. http://www.ipcc.ch/ipccreports/tar/wg2/index.php?idp=524

Islebe, G.A. and Hooghiemstra, H., 1997. Vegetation and climate history of montane Costa Rica since the last glacial. *Quaternary Science Reviews*, *16*(6), pp.589-604.

Islebe, G.A., Hooghiemstra, H. and van't Veer, R., 1996. Holocene vegetation and water level history in two bogs of the Cordillera de Talamanca, Costa Rica. *Vegetatio*, *124*(2), pp.155-171.

Jensen, K., Lynch, E.A., Calcote, R. and Hotchkiss, S.C., 2007. Interpretation of charcoal morphotypes in sediments from Ferry Lake, Wisconsin, USA: do different plant fuel sources produce distinctive charcoal morphotypes?. *The Holocene*, *17*(7), pp.907-915.

Juggins, S., 2003. C2 Program Version 1.4. *Department of Geology, University of Newcastle: Newcastle upon Tyne, UK*.

Kappelle, M. and Horn, S.P., 2016. The Páramo Grasslands of Costa Rica's Highlands. *Costa Rican Ecosystems. University of Chicago Press, Chicago*, pp.492-523.

Karmalkar, A.V., Bradley, R.S. and Diaz, H.F., 2011. Climate change in Central America and Mexico: regional climate model validation and climate change projections. *Climate dynamics*, *37*(3-4), pp.605.

Kaser, G. and Osmaston, H., 2002. Tropical glaciers. International hydrology series. *Cambridge: Cambridge University Press*, *207*, pp.329-339.

Keane, R.E. and Finney, M.A., 2003. The simulation of landscape fire, climate, and ecosystem dynamics. In *Fire and climatic change in temperate ecosystems of the Western Americas* (pp. 32-68). Springer New York.

Lachniet, M.S., 2007. Glacial geology and geomorphology. *Central America: geology, resources, and hazards. Taylor & Francis, London*.

Lachniet, M.S., Bernal, J.P., Asmerom, Y., Polyak, V. and Piperno, D., 2012. A 2400 yr Mesoamerican rainfall reconstruction links climate and cultural change. *Geology*, *40*(3), pp.259-262.

Lane, C.S. and Horn, S.P., 2013. Terrestrially derived n-alkane δD evidence of shifting Holocene paleohydrology in highland Costa Rica. *Arctic, Antarctic, and Alpine Research*, *45*(3), pp.342-349.

Lane, C.S., Horn, S.P., Mora, C.I., Orvis, K.H. and Finkelstein, D.B., 2011. Sedimentary stable carbon isotope evidence of late Quaternary vegetation and climate change in highland Costa Rica. *Journal of Paleolimnology*, *45*(3), pp.323-338.

Larocque, I., Grosjean, M., Heiri, O., Bigler, C. and Blass, A., 2009. Comparison between chironomid-inferred July temperatures and meteorological data AD 1850–2001 from varved Lake Silvaplana, Switzerland. *Journal of Paleolimnology*, *41*(2), pp.329-342.

League, B.L. and Horn, S.P., 2000. A 10 000 year record of Páramo fires in Costa Rica. *Journal of Tropical Ecology*, pp.747-752.

Leng, M.J. and Marshall, J.D., 2004. Palaeoclimate interpretation of stable isotope data from lake sediment archives. *Quaternary Science Reviews*, *23*(7-8), pp.811-831.

Mackay, A.W., Bezrukova, E.V., Leng, M.J., Meaney, M., Nunes, A., Piotrowska, N., Self, A., Shchetnikov, A., Shilland, E., Tarasov, P. and Wang, L., 2012. Aquatic ecosystem responses to Holocene climate change and biome development in boreal, central Asia. *Quaternary Science Reviews*, *41*, pp.119-131.

Magny, M. and Haas, J.N., 2004. A major widespread climatic change around 5300 cal. yr BP at the time of the Alpine Iceman. *Journal of Quaternary Science*, *19*(5), pp.423-430.

Massaferro, J. and Larocque-Tobler, I., 2013. Using a newly developed chironomid transfer function for reconstructing mean annual air temperature at Lake Potrok Aike, Patagonia, Argentina. *Ecological indicators*, *24*, pp.201-210.

Massaferro, J.I., Moreno, P.I., Denton, G.H., Vandergoes, M. and Dieffenbacher-Krall, A., 2009. Chironomid and pollen evidence for climate fluctuations during the Last Glacial Termination in NW Patagonia. *Quaternary Science Reviews*, *28*(5-6), pp.517-525.

Mayewski, P.A., Rohling, E.E., Stager, J.C., Karlén, W., Maasch, K.A., Meeker, L.D., Meyerson, E.A., Gasse, F., van Kreveld, S., Holmgren, K. and Lee-Thorp, J., 2004. Holocene climate variability. *Quaternary research*, *62*(3), pp.243-255.

Mayle, F.E., Burbridge, R. and Killeen, T.J., 2000. Millennial-scale dynamics of southern Amazonian rain forests. *Science*, *290*(5500), pp.2291-2294.

Meyers, P.A. and Lallier-Vergès, E., 1999. Lacustrine sedimentary organic matter records of Late Quaternary paleoclimates. *Journal of Paleolimnology*, *21*(3), pp.345-372.

Meyers, P.A. and Teranes, J.L., 2002. Sediment organic matter. In *Tracking environmental change using lake sediments* (pp. 239-269). Springer, Dordrecht.

Meyers, P.A., 2003. Applications of organic geochemistry to paleolimnological reconstructions: a summary of examples from the Laurentian Great Lakes. *Organic geochemistry*, *34*(2), pp.261-289.

Morris, J.L., Mueller, J.R., Nurse, A., Long, C.J. and McLauchlan, K.K., 2014. Holocene fire regimes, vegetation and biogeochemistry of an ecotone site in the Great Lakes Region of North America. *Journal of vegetation science*, *25*(6), pp.1450-1464.

Moy, C.M., Seltzer, G.O., Rodbell, D.T. and Anderson, D.M., 2002. Variability of El Niño/Southern Oscillation activity at millennial timescales during the Holocene epoch. *Nature*, *420*(6912), p.162.

Orvis, K.H. and Horn, S.P., 2000. Quaternary glaciers and climate on Cerro Chirripó, Costa Rica. *Quaternary Research*, *54*(1), pp.24-37.

Pepin, N., Bradley, R.S., Diaz, H.F., Baraër, M., Caceres, E.B., Forsythe, N., Fowler, H., Greenwood, G., Hashmi, M.Z., Liu, X.D. and Miller, J.R., 2015. Elevation-dependent warming in mountain regions of the world. *Nature Climate Change*, *5*(5), p.424.

Peterson, L.C. and Haug, G.H., 2006. Variability in the mean latitude of the Atlantic Intertropical Convergence Zone as recorded by riverine input of sediments to the Cariaco Basin (Venezuela). *Palaeogeography, Palaeoclimatology, Palaeoecology*, *234*(1), pp.97-113.

Peterson, L.C., Haug, G.H., Hughen, K.A. and Röhl, U., 2000. Rapid changes in the hydrologic cycle of the tropical Atlantic during the last glacial. *Science*, *290*(5498), pp.1947-1951.

Pierrehumbert, R.T., 2000. Climate change and the tropical Pacific: The sleeping dragon wakes. *Proceedings of the National Academy of Sciences*, *97*(4), pp.1355-1358.

Porinchu, D.F. and MacDonald, G.M., 2003. The use and application of freshwater midges (Chironomidae: Insecta: Diptera) in geographical research. *Progress in Physical Geography*, *27*(3), pp.378-422.

Prentice, I.C., 1980. Vegetation analysis and order invariant gradient models. In *Classification and Ordination* (pp. 27-34). Springer Netherlands.

Reimer, P.J., Bard, E., Bayliss, A., Beck, J.W., Blackwell, P.G., Ramsey, C.B., Buck, C.E., Cheng, H., Edwards, R.L., Friedrich, M. and Grootes, P.M., 2013. IntCal13 and Marine13 radiocarbon age calibration curves 0–50,000 years cal BP. *Radiocarbon*, *55*(4), pp.1869-1887.

Reinemann, S.A., Porinchu, D.F., MacDonald, G.M., Mark, B.G. and DeGrand, J.Q., 2014. A 2000-yr reconstruction of air temperature in the Great Basin of the United States with specific reference to the Medieval Climatic Anomaly. *Quaternary Research*, *82*(2), pp.309-317.

Rolland, N., Larocque, I., Francus, P., Pienitz, R. and Laperrière, L., 2009. Evidence for a warmer period during the 12th and 13th centuries AD from chironomid assemblages in Southampton Island, Nunavut, Canada. *Quaternary Research*, *72*(1), pp.27-37.

Romme, W.H., Boyce, M.S., Gresswell, R., Merrill, E.H., Minshall, G.W., Whitlock, C. and Turner, M.G., 2011. Twenty years after the 1988 Yellowstone fires: lessons about disturbance and ecosystems. *Ecosystems*, *14*(7), pp.1196-1215.

Sawyer, J.O. and Lindsey, A.A., 1971. Vegetation of the life zones in Costa Rica. *Vegetation of the life zones in Costa Rica.*

Schneider, T., Bischoff, T. and Haug, G.H., 2014. Migrations and dynamics of the intertropical convergence zone. *Nature*, *513*(7516), p.45.

Seltzer, G.O., 1994. A lacustrine record of late Pleistocene climatic change in the subtropical Andes. *Boreas*, *23*(2), pp.105-111.

Spies, M., Andersen, T., Epler, J.H. and Watson Jr, C.N., 2009. Chironomidae (non-biting midges). *Manual of Central American Diptera* 1, pp. 437-480.

Staubwasser, M. and Weiss, H., 2006. Holocene climate and cultural evolution in late prehistoric–early historic West Asia. *Quaternary Research*, *66*(3), pp.372-387.

Stríkis, N.M., Cruz, F.W., Cheng, H., Karmann, I., Edwards, R.L., Vuille, M., Wang, X., de Paula, M.S., Novello, V.F. and Auler, A.S., 2011. Abrupt variations in South American monsoon rainfall during the Holocene based on a speleothem record from central-eastern

Brazil. *Geology*, *39*(11), pp.1075-1078.

Taylor, Z.P., Horn, S.P. and Finkelstein, D.B., 2013. Pre-Hispanic agricultural decline prior to the Spanish Conquest in southern Central America. *Quaternary Science Reviews, 73,* pp.196-200.

Ter Braak, C.J.F. and Smilauer, P., 1998. Canoco release 4: reference manual and user's guide to Canoco for Windows: software for Canonical Community Ordination. *Microcomputer Power, Ithaca, NY*, pp.352.

Thompson, L.G., 2011. Abrupt Climate Change: A Paleoclimate Perspective from the World's Highest Mountains. *Abrupt Climate Change: Mechanisms, Patterns, and Impacts*, pp.215-233.

Thompson, L.G., Mosley-Thompson, E., Davis, M.E., Henderson, K.A., Brecher, H.H., Zagorodnov, V.S., Mashiotta, T.A., Lin, P.N., Mikhalenko, V.N., Hardy, D.R. and Beer, J., 2002. Kilimanjaro ice core records: evidence of Holocene climate change in tropical Africa. *Science*, *298*(5593), pp.589-593.

Thompson, L.O., Yao, T., Davis, M.E., Henderson, K.A., Mosley-Thompson, E., Lin, P.N., Beer, J., Synal, H.A., Cole-Dai, J. and Bolzan, J.F., 1997. Tropical climate instability: The last glacial cycle from a Qinghai-Tibetan ice core. *Science*, *276*(5320), pp.1821-1825.

Walker, I.R. and Cwynar, L.C., 2006. Midges and palaeotemperature reconstruction—the North American experience. *Quaternary Science Reviews*, *25*(15-16), pp.1911-1925.

Walker, I.R., 2001. Midges: Chironomidae and related diptera. In *Tracking environmental change using lake sediments* (pp. 43-66). Springer Netherlands.

Walsh, D., Russell-Smith, J. and Cowley, R., 2014. Fire and carbon management in a diversified rangelands economy: research, policy and implementation challenges for northern Australia. *The Rangeland Journal*, *36*(4), pp.313-322.

Walsh, M.K., Whitlock, C. and Bartlein, P.J., 2008. A 14,300-year-long record of fire–vegetation–climate linkages at Battle Ground Lake, southwestern Washington. *Quaternary Research*, *70*(2), pp.251-264.

Ward, J.V., 1994. Ecology of alpine streams. *Freshwater biology*, *32*(2), pp.277-294.

Watson, C.N. and Heyn, M.W., 1992. A preliminary survey of the Chironomidae (Diptera) of Costa Rica, with emphasis on the lotic fauna. *Netherland Journal of Aquatic Ecology*, *26*(2-4), pp.257-262.

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

Willassen, E. and Cranston, P.S., 1986. Afrotropical montane midges (Diptera, Chironomidae, Diamesa). *Zoological Journal of the Linnean Society*, *87*(2), pp.91-123.

Wu, J., Porinchu, D.F., Horn, S.P. and Haberyan, K.A., 2015. The modern distribution of chironomid sub-fossils (Insecta: Diptera) in Costa Rica and the development of a regional chironomid-based temperature inference model. *Hydrobiologia*, *742*(1), pp.107-127.

Xie, S.P. and Carton, J.A., 2004. Tropical Atlantic variability: Patterns, mechanisms, and impacts. *Earth's Climate*, pp.121-142.

Zuur, A., Ieno, E.N. and Smith, G.M., 2007. *Analyzing ecological data*. Springer Science & Business Media.

Table 2.1. AMS radiocarbon (^{14}C) dates obtained for the Lago Ditkebi core.

Lab code	Core code	Depth in core (cm)	Material	Uncalibrated ^{14}C age (^{14}C yr BP)	±	2σ Age range	Relative area under distribution
UGAMS#21660	DKB-PT	67.5-67.75	Charcoal	460	20	1422-1451 CE	1
UGAMS#28661	DKB-LC2A	77.3-77.8	Charcoal	1150	20	856-969 CE	0.804
						804-845 CE	0.126
						777-792 CE	0.069
UGAMS#23000	DKB-LC2A	112.6-114.2	Charcoal	1300	45	647-778 CE	0.955
						840-862 CE	0.02
						791-805 CE	0.014
						813-825 CE	0.01
UGAMS#28662	DKB-LC2A	140.6-143.4	Charcoal	1580	25	418-541 CE	1
UGAMS#18526	DKB-LCBb	176	Charcoal	2060	25	1967-2114 cal yr BP	0.954
						1949-1963 cal yr BP	0.046
UGAMS#18527	DKB-LCEa	340.8	Charcoal	3260	25	3445-3562 cal yr BP	0.958
						3409-3425 cal yr BP	0.042
UGAMS#18406	DKB-LCFb	472	Charcoal	4480	30	5152-5289 cal yr BP	0.575
						5037-5048 cal yr BP	0.379
						4979-5007 cal yr BP	0.046
UGAMS#18407	DKB-LCGa	539	Aquatic Moss	6150	20	6976-7158 cal yr BP	1

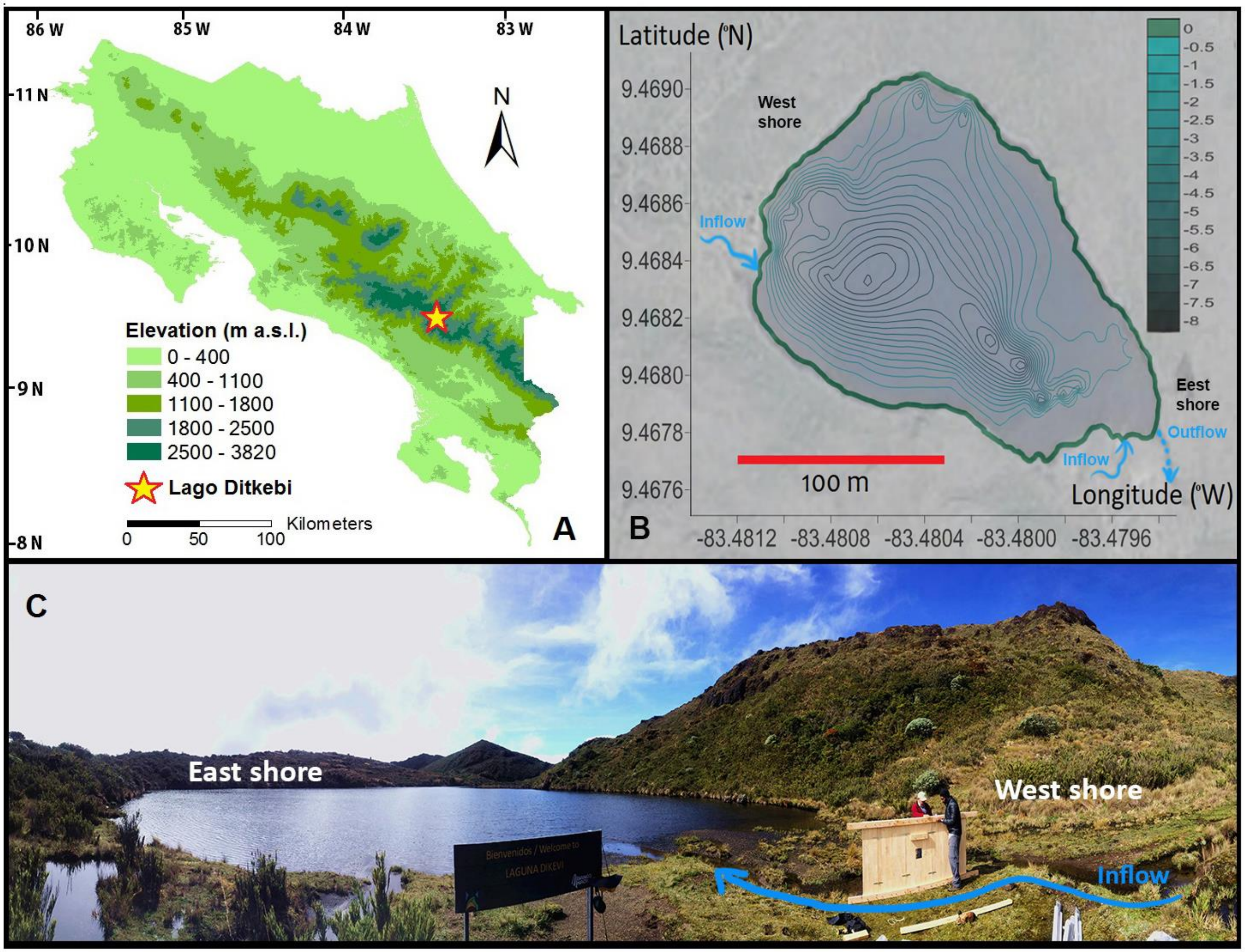


Figure 2.1 A) Location of Lago Ditkebi, Chirripó National Park, Costa Rica; B) Bathymetric map and location of inflowing and outflowing streams (Bathymetric measurements provided by Dr. Germain Esquivel Hernandez; map generated by Jiaying Wu; base map extracted from Google Earth); and C) View of Lago Ditkebi, looking east (Photo by Jiaying Wu).

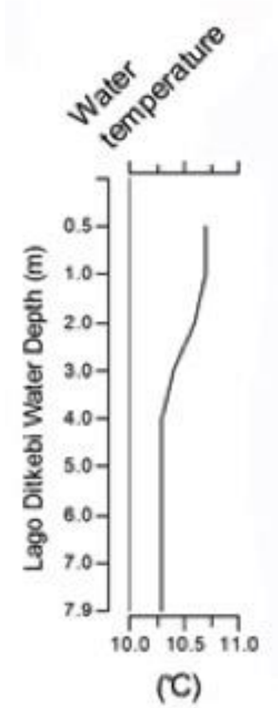


Figure 2.2 Temperature profile of Lago Ditkebi. Measured July 17th, 2014.

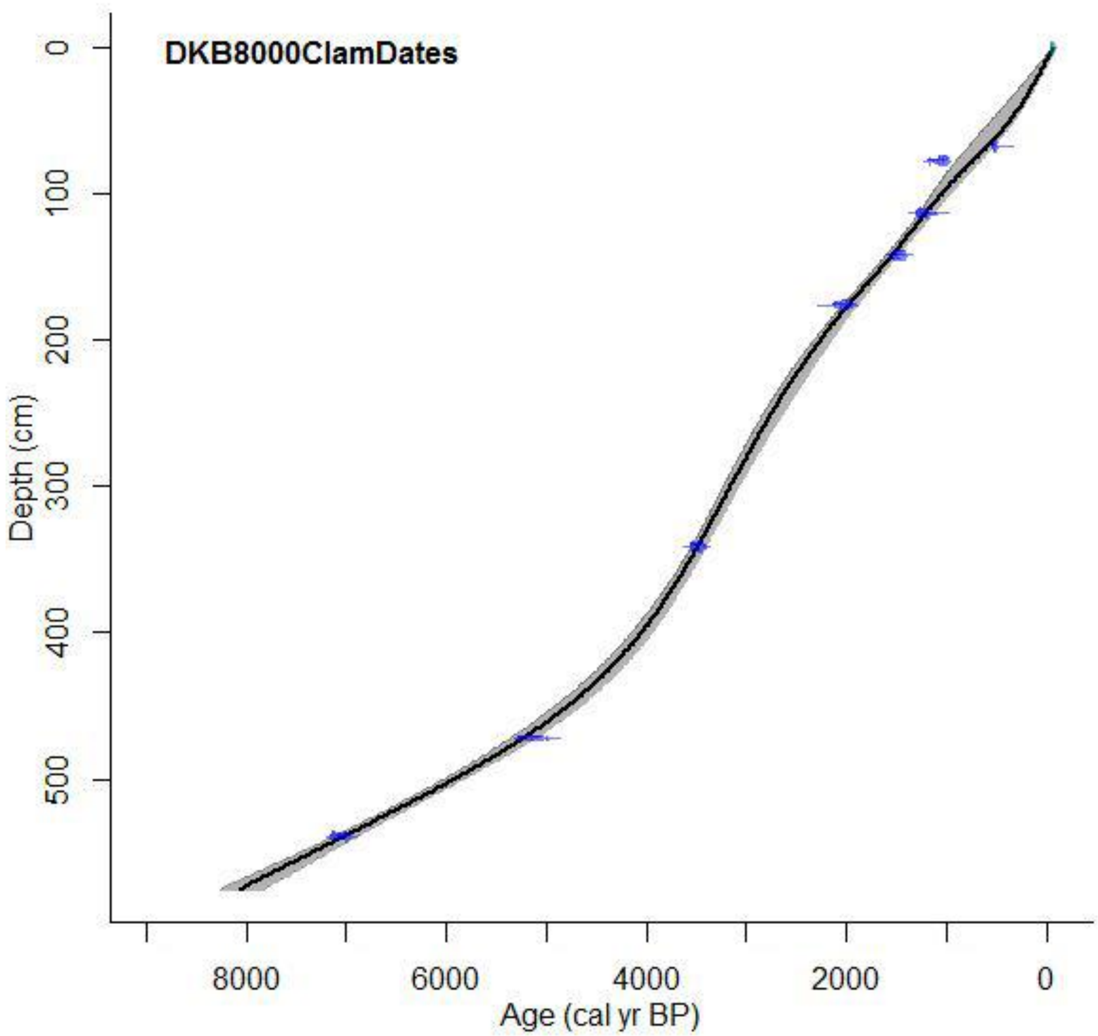


Figure 2.3 Age-depth model developed using Clam for Lago Ditkebi. The calibrated distributions of individual dates are indicated in blue with the gray band depicting the 95% probability intervals established using Clam (http://www.chrono.qub.ac.uk/blaauw/clam.html, Blaauw, 2010).

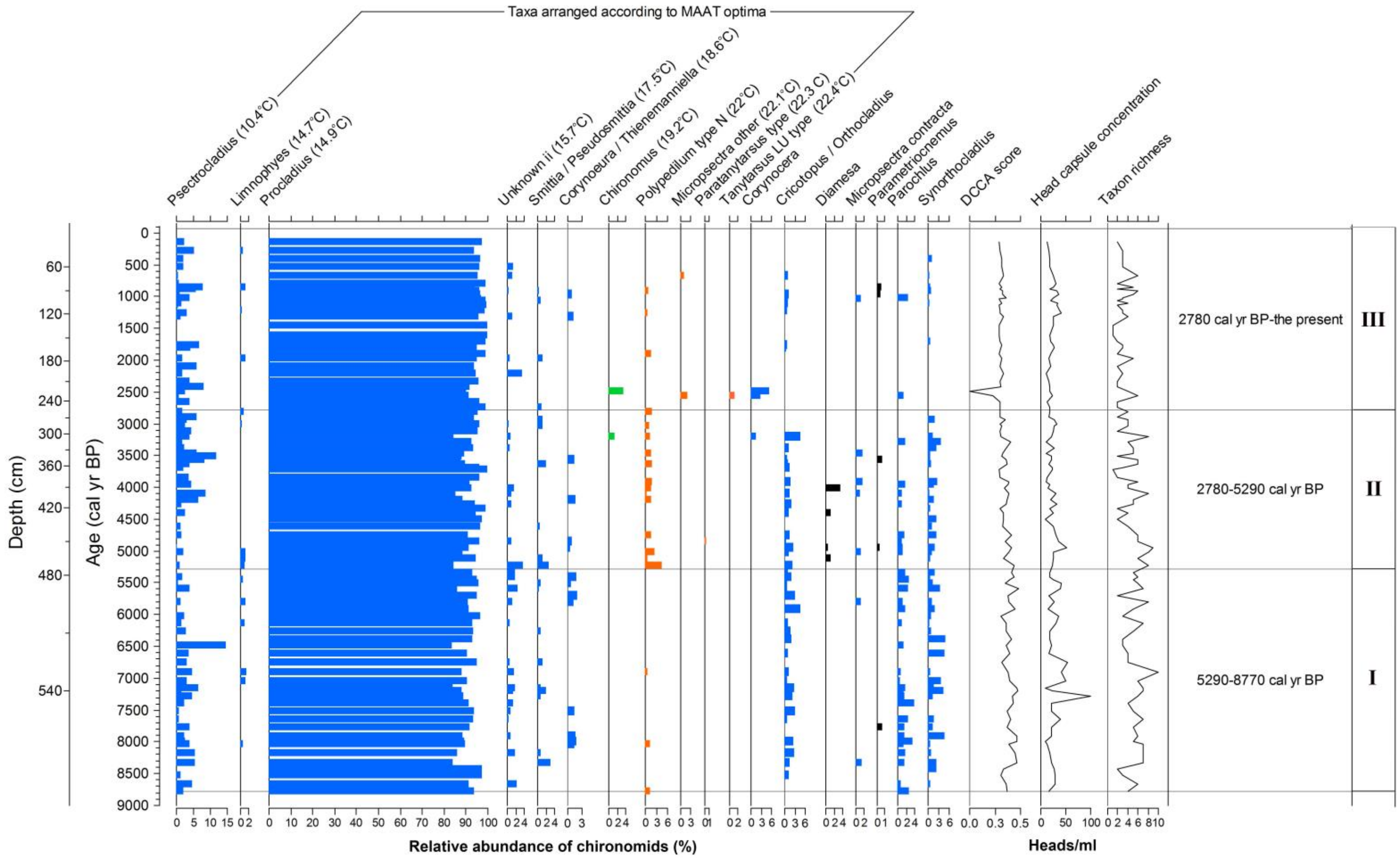


Figure 2.4 Relative abundance diagram for the sub-fossil chironomids from Lago Ditkebi. Chironomid taxa have been arranged according to their MAAT optima (Wu et al., 2015), with temperature optima increasing from left to right. Taxa with MAAT optima <19 °C, or reported as common constituents of high-elevation lakes (Wu et al., 2015, Spies et al., 2009) are colored in blue. Taxa with MAAT optima >20°C, or associated with low-elevation lakes (Wu et al., 2015) are colored in orange. *Chironomus*, a taxon with a MAAT optimum of 19.2 °C (Wu et al., 2015), which is most abundant in mid-elevation lakes is colored in green. Taxa with no specific habitat preference or unknown MAAT optima are plotted in black.

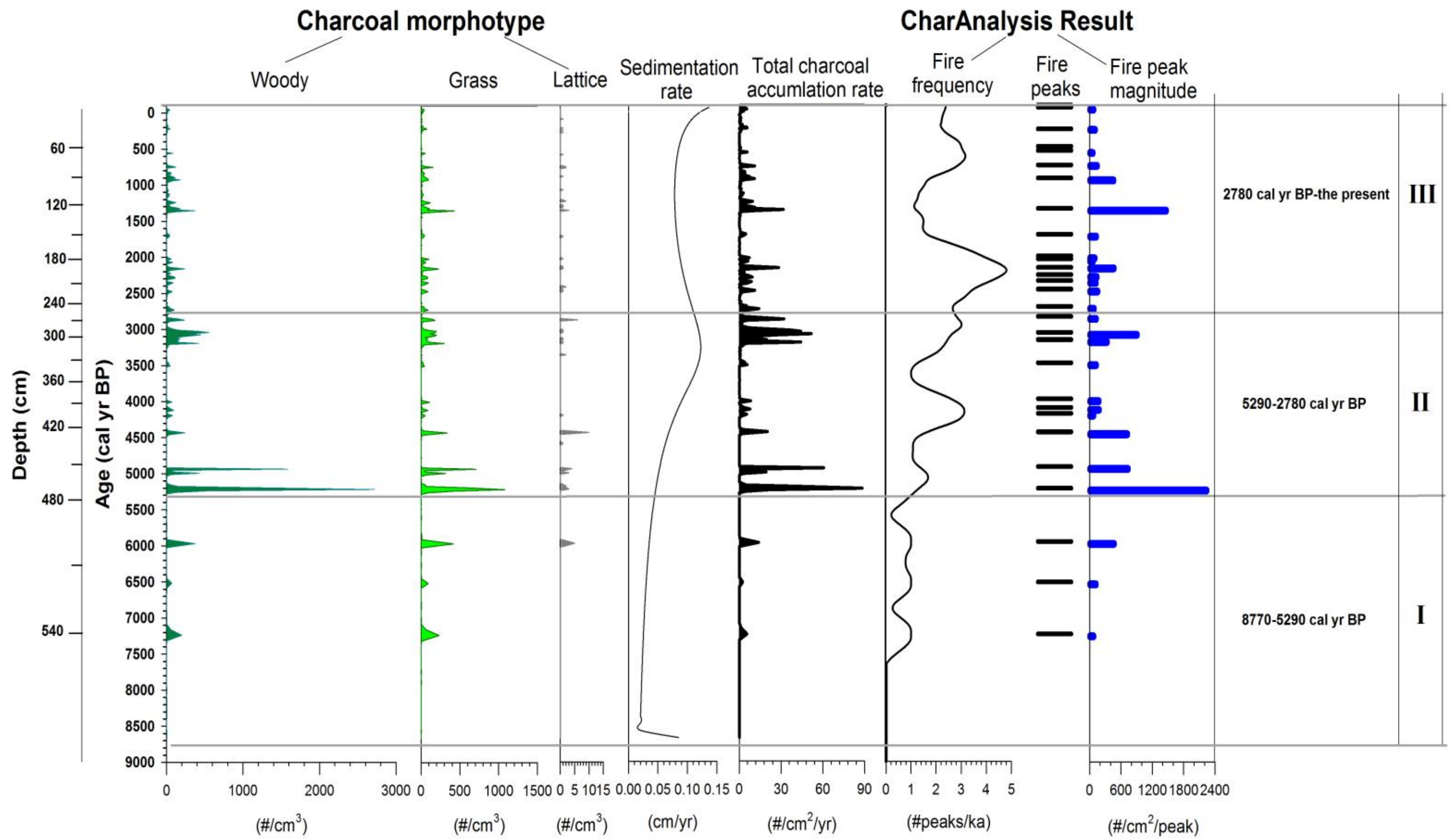


Figure 2.5 Charcoal concentration, charcoal accumulation rate (CHAR), sedimentation rate and CharAnalysis results (Higuera et al., 2009) for Lago Ditkebi. Charcoal concentration is calculated for each of the morphotypes. CHAR is based on the sum of all charcoal morphotypes (>125μm). Chironomid assemblage-based zones are also indicated.

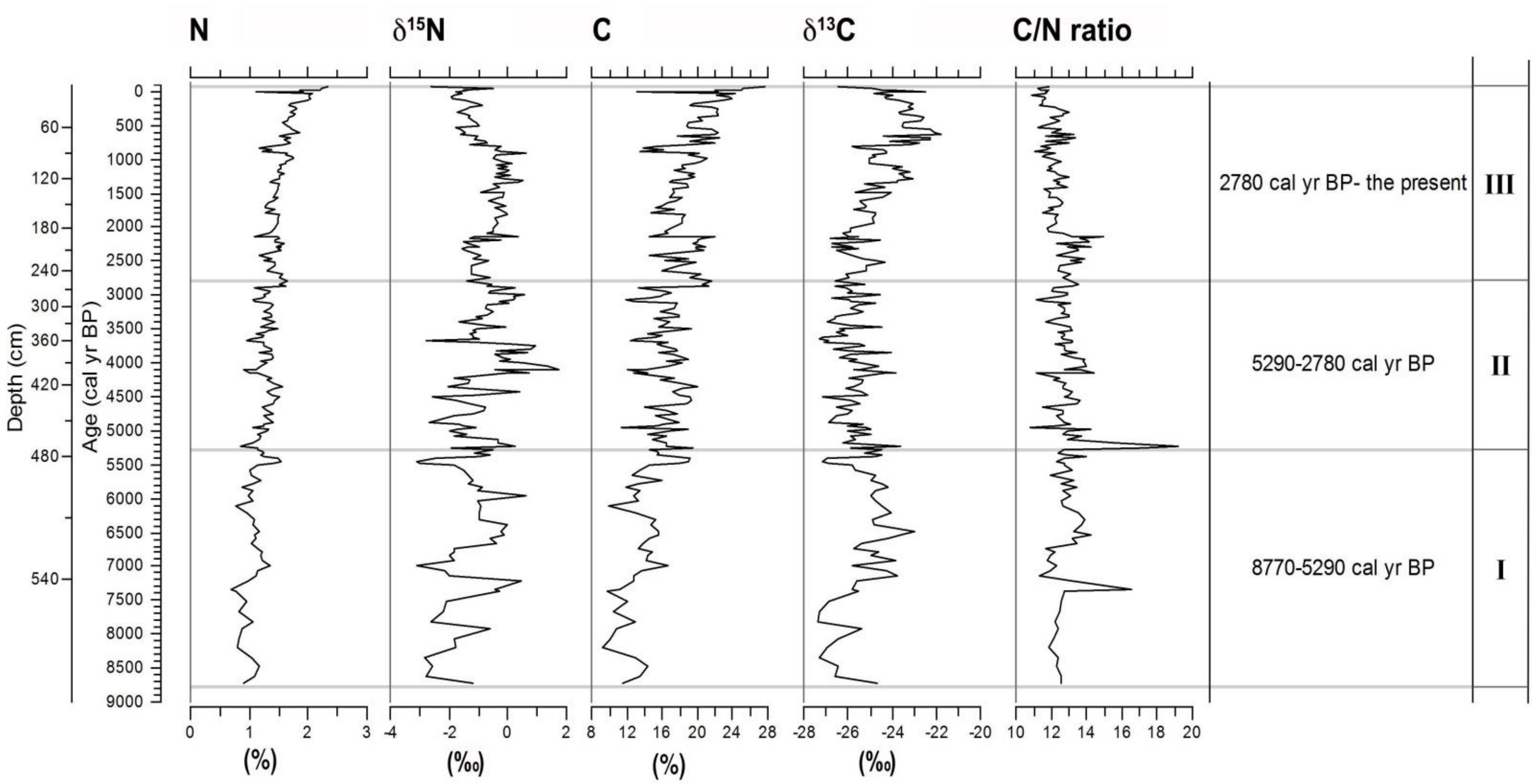


Figure 2.6 Sediment geochemistry records developed for Lago Ditkebi. Chironomid assemblage-based zones are also indicated.

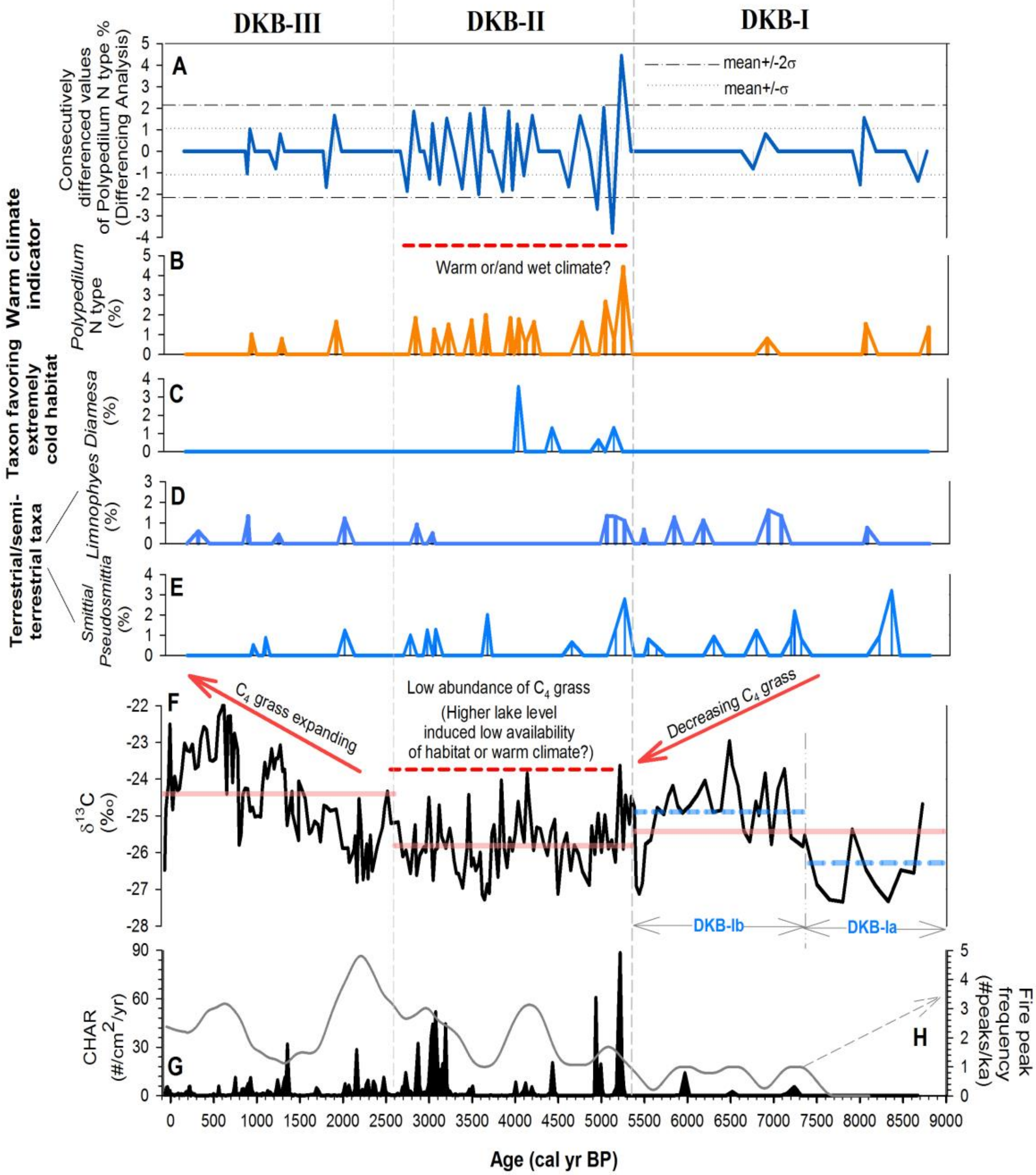


Figure 2.7 Summary diagram of select proxies from Lago Ditkebi, reflecting Holocene hydroclimate and paleoenvironmental change. The pink horizontal lines in (F) represent the mean values of $\delta^{13}C$ for DKB I-III zones, and blue dashlines represent the mean values of $\delta^{13}C$ in DKB-Ia and DKB-Ib.

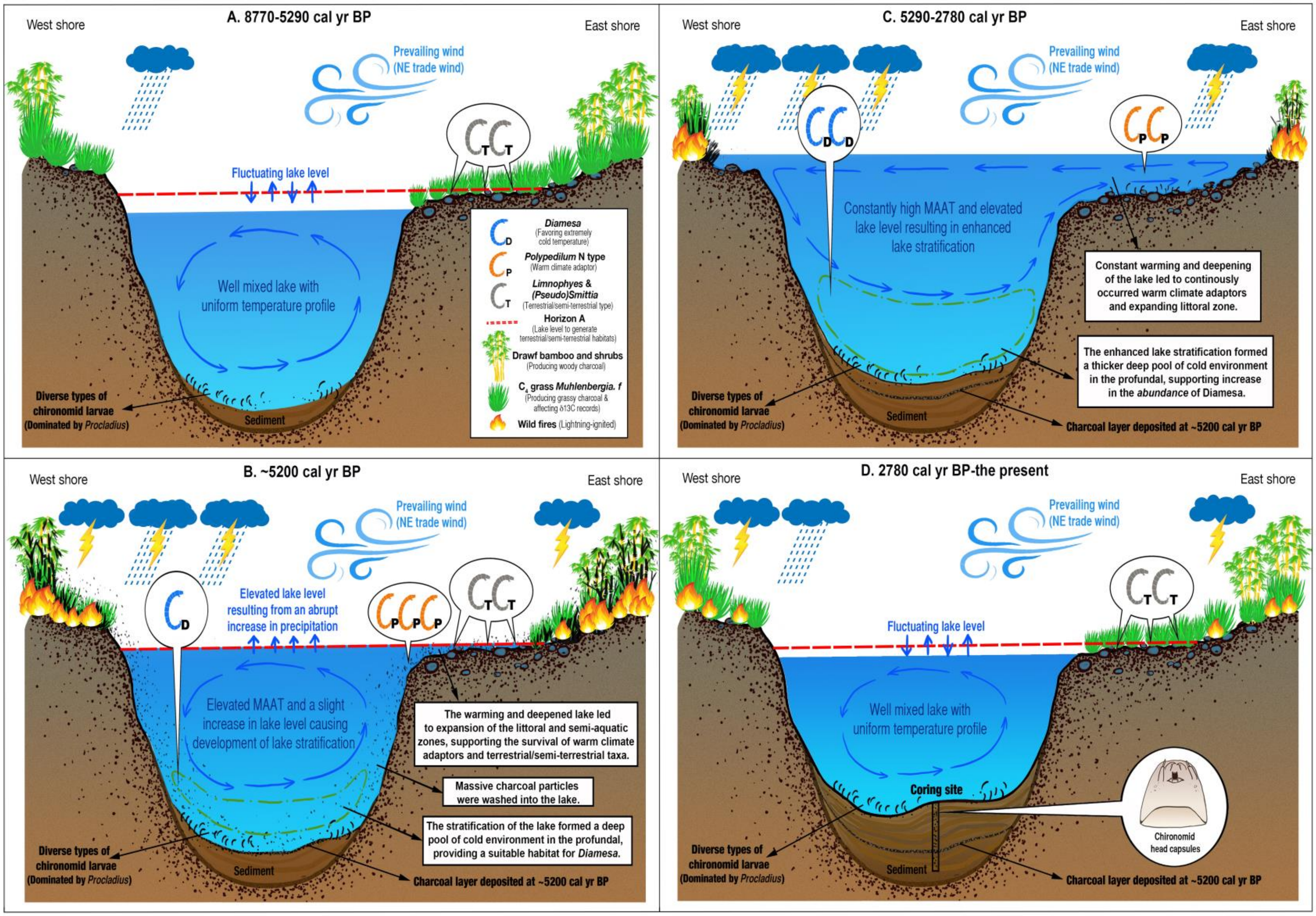


Figure 2.8 Scenarios of Holocene hydroclimate and environmental change at Lago Ditkebi for: A) DKB-I (~8770-5290 cal yr BP); B) at ~5200 cal yr BP; C) DKB-II (5290 – 2780 cal yr BP); and D) DKB-III (2780 cal yr BP-present).

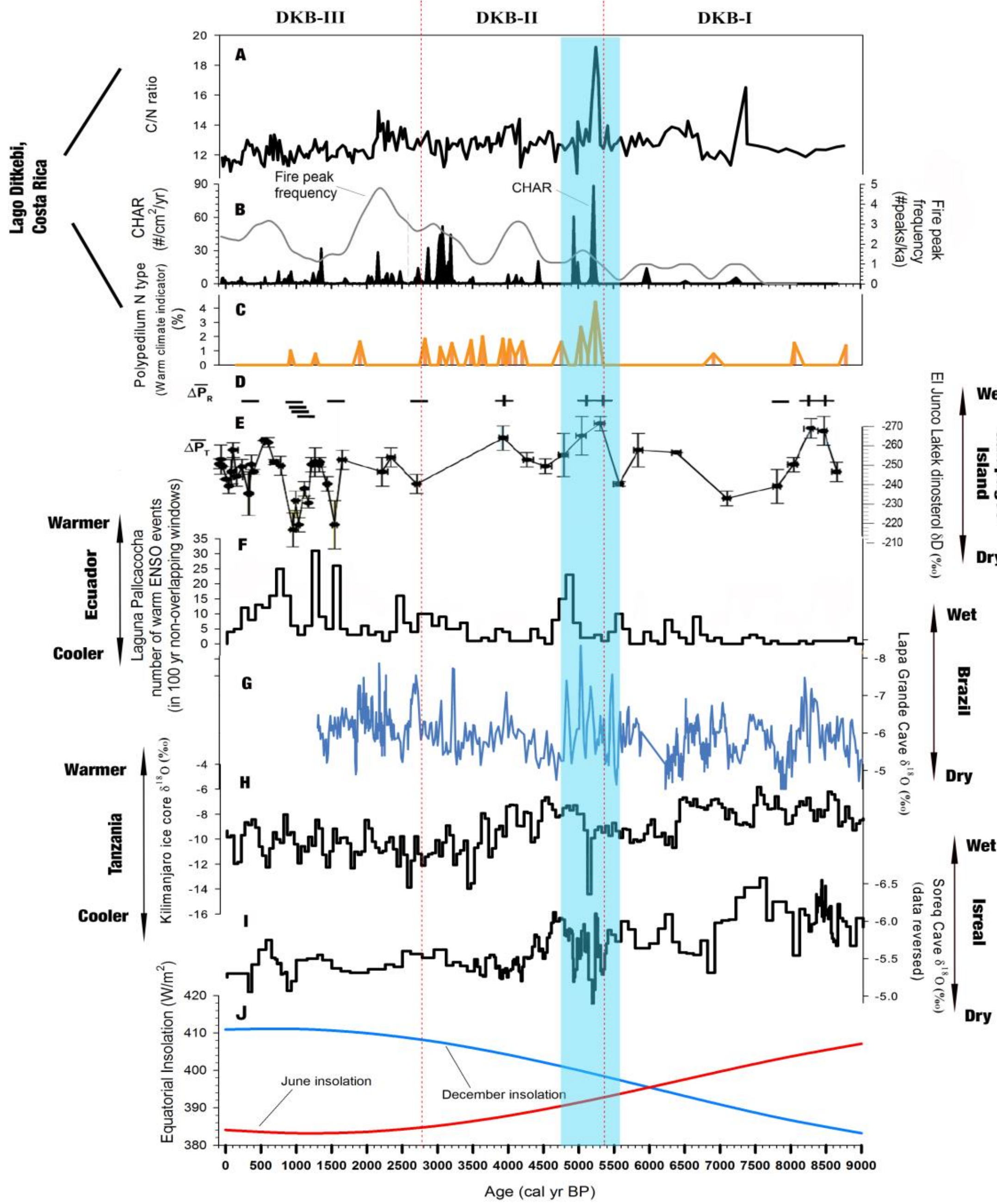


Figure 2.9 Summary diagram of select proxy data documenting the occurrence of the 5200 cal yr BP climate event in the tropics. A-C) C/N, charcoal concentration and the abundance of *Polypedium* N type in Lago Ditkebi (this study); D-E) Estimated rainfall (ΔP) associated without ENSO activities and dinosterol δD in El Junco Lake, Galapagos Island (Atwood, 2015); F) ENSO reconstruction from Laguna Pallcacocha, Ecuador (Moy et al., 2002), G) Speleothem $\delta^{18}O$ from Lapa Grande Cave, Brazil (Strikis et al., 2011); H) Ice core $\delta^{18}O$ from Mount Kilimanjaro, Tanzania (Thompson et al., 2002); I) Speleothem $\delta^{18}O$ from Soreq Cave, Israel (Bar-Matthews et al., 1997 and 1999). Blue bar highlights the 5200 cal yr BP event; J) June and December insolation at 0° N (Berger and Loutre, 1991).

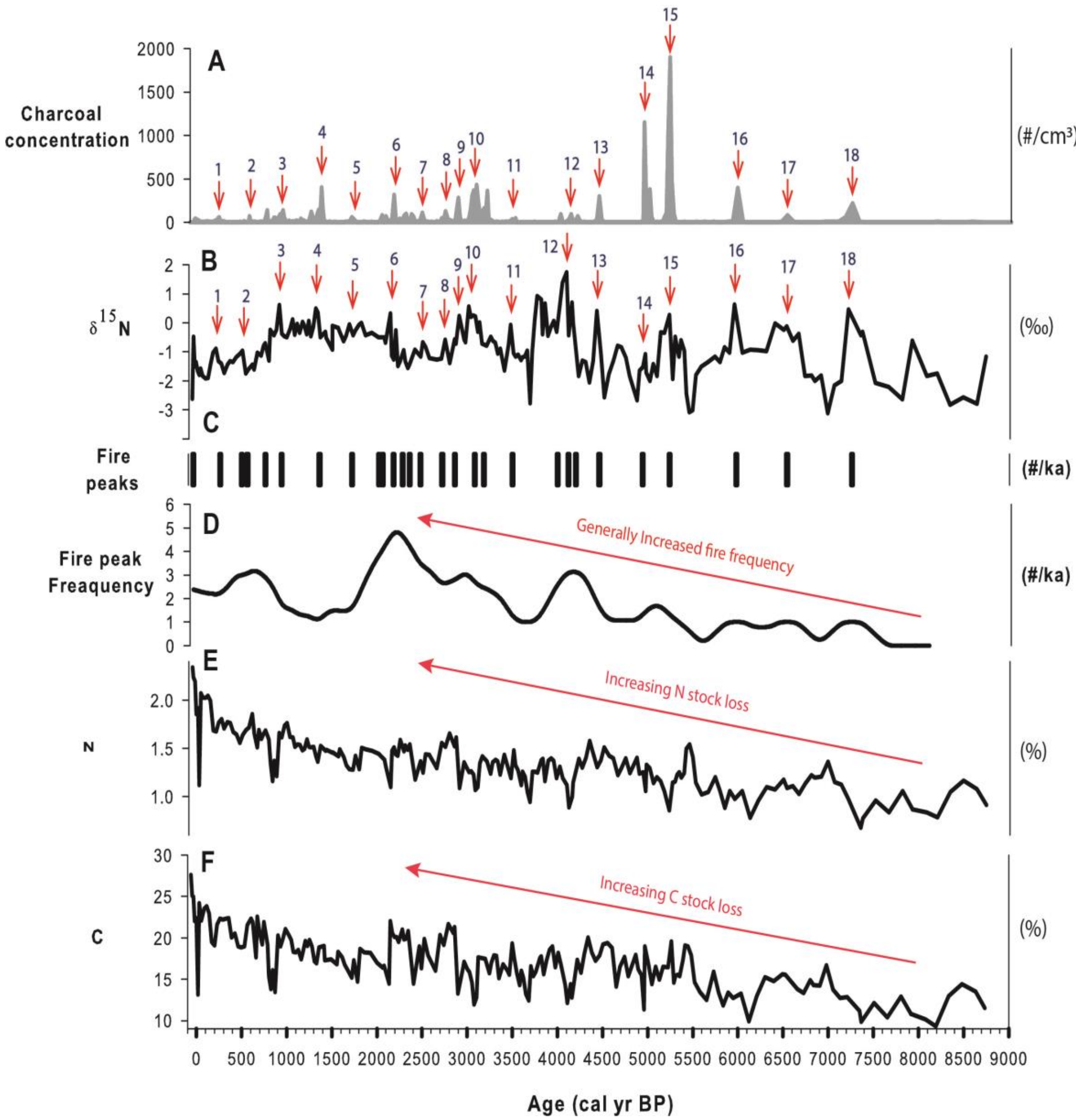


Figure 2.10 Select geochemical and charcoal records from the Ditkebi core documenting the relationship between fire activity and sediment geochemistry.

CHAPTER 3

A HIGH-RESOLUTION RECONSTRUCTION OF LATE HOLOCENE FIRE REGIMES IN THE PÁRAMO OF CHIRRIPÓ NATIONAL PARK, COSTA RICA: EVIDENCE FROM CHARCOAL AND SEDIMENT GEOCHEMISTRY[2]

[2] Wu, J., and Porinchu, D.F. To be submitted to *Quaternary Research*

3.1 ABSTRACT

Multi-proxy analysis of two sediment cores recovered from Lagos Morrenas 3C and Ditkebi, located in the páramo of Costa Rica's Chirripó National Park, was undertaken to develop multi-decadal scale reconstructions of the late Holocene fire regimes for the region. Analysis of macroscopic charcoal and sediment geochemistry (N%, C%, $\delta^{13}C$, $\delta^{15}N$ and C/N ratios) documents periodic burning of the páramo in Chirripó National Park during the last two millennia. The charcoal records developed for the two study sites provide evidence of elevated fire frequency between ~550 and 730 CE and between 980 and 1230 CE. Severe fire episodes are reflected by a rapid increase in the flux of carbon (C) and nitrogen (N) from the surrounding catchment due to the volatilization of elements in vegetation of páramo. In addition, stable isotopes, particularly $\delta^{15}N$, which sharply increase following local fire events, capture post-fire changes in nutrient loading and likely, the decadal-scale rate of post-fire recovery of páramo vegetation. The consistently elevated $\delta^{13}C$ values and high C/N ratios observed between ~750 and 1100 CE is inferred to reflect the expansion of *Muhlenbergia*, a native grass utilizing the C4 pathway, suggesting that the interval between ~750 and 1100 CE was characterized by a decrease in effective moisture and reduced temperature.

3.2 INRODUCTION AND LITERATURE REVIEW

Páramo, an ecosystem located at the high elevations in the Neotropics (tropical Americas), extends from southern Central America to northern South America (Luteyn, 1999; Fig. 3.1A). Páramo in Costa Rica consists of a diverse, mixed shrub, grass, and perennial herbaceous vegetation composed of vascular plant taxa originating in the Andean region (Kappelle and Horn, 2016). Páramo is considered to be an evolutionary and biodiversity hotspot with up to 60% of its approximately 3000-4000 species of vascular plants considered endemic (Luteyn, 1999; Madriñán et al., 2013). The páramo located within Chirripó National Park (N.P.), Costa Rica (Fig. 3.1C) is at the northern limit of its geographical distribution in the tropical Americas (Fig. 3.1A). Ecologically, the páramo is a fragile system that is slow to recover after disturbances such as wildfire (Chaverri-Polini et al., 1976). According to a vegetation survey conducted following a large fire that occurred in Chirripó N.P. in 1976, vegetation took more than 10 years to grow back to pre-fire status (Horn, 1990). Analysis of both macroscopic and microscopic charcoal preserved in lake sediments revealed that the páramo in Chirripó N.P. experienced episodic fires during the Holocene, with the highest fire frequency observed from ~4200 cal yr BP to the present (Horn, 1992 and 1993; League and Horn, 2000; Chapter 2 in this dissertation). However, limited chronological control, insufficient sampling resolution, and absence of paired stable carbon ($\delta^{13}C$) and nitrogen isotope ($\delta^{15}N$) data in the previous charcoal studies precluded a description of the pattern of post-fire nutrient loading and recovery and fire-induced landscape change within the Chirripó páramo ecosystem.

During the dry season, the high elevations of Chirripó N.P. are susceptible to fire. The most recent fire events occurred in 1953, 1958, 1976, 1977, 1981 and 1992 (Horn and Kappelle, 2009). The 1992 fire event affected over 20 km^2 and forced park administration to close the park for four months. Evidence of Holocene fire history in the páramo derives from studies of sediment cores recovered from glacial lakes within the park (e.g. Horn, 1989; Horn, 1993; League and Horn, 2000). In 1985, two short cores were raised from Lago Chirripó (3520 m a.s.l.), the largest lake in a chain of three glacially formed lakes within Valle de los Lagos (Horn, 1989). The charcoal stratigraphy developed for Lago Chirripó revealed two distinct layers (~2400 and 1180 cal yr BP) of macroscopic charcoal (fragments >125 μm, visible to the unaided eye) and abundant microscopic charcoal throughout the core (Horn, 1989 and 1993). An additional charcoal stratigraphy developed for Lago Morrenas 1, a glacial lake located in adjacent catchment, confirmed and extended the fire history developed for Lago Chirripó reaching back to deglaciation, 11,000 cal yr BP. Fires repeatedly burned the Chirripó páramo during the Holocene with greater fire activity during the late Holocene (last ~4200 ^{14}C years) (Horn, 1993; League and Horn, 2000). The highest macroscopic charcoal at the size of >500 μm influx is observed during the late Holocene, when human population density was higher and when the circum-Caribbean was characterized by lower effective moisture, particularly after about 3000 ^{14}C yr BP (Hodell et al., 2000; League and Horn, 2000). The lowest charcoal influx is found between 6800 and 4200 ^{14}C yr BP, an interval that overlaps with a circum-Caribbean wet interval (Hodell et al., 2000; League and Horn, 2000). With the exception of the present study, the macroscopic charcoal record from Lago de las Morrenas 1 (League and Horn, 2000) is the only high-resolution sedimentary charcoal record (multi-decadal resolution) of local fires presently available from the Chirripó páramo.

Wildfire-mediated environmental disturbance can be reflected in pollen-inferred vegetation composition change (e.g. Horn, 1993; Kennedy et al., 2006; Morris et al., 2014), and can also be documented in records of sedimentary geochemical variation that can capture the signature of burning-induced vegetation dynamics and alteration of soil nutrient loading in the catchment (Knicker, 2007; Walsh et al., 2008; Morris et al., 2015). Surface fires often consume above ground vegetation and the litter layer, with high temperatures also influencing mineral soil and soil organisms. During this process, elemental nutrients (e.g. N%) and biomass (e.g. C%) assimilated in vegetation and preserved in soil can be volatized when temperature is generally above 200°C (Knicker, 2007). Further isotopic fractionation, mediated by the heat, may also occur because the volatilization of lighter stable isotopes (e.g. ^{12}C and ^{14}N) is likely greater than that experienced by the heavier stable isotopes (e.g. ^{13}C and ^{15}N) (Morris et al., 2015). Most available studies providing detailed interpretation of fire-geochemistry correlations have been conducted in the forests of the western United States (e.g. Walsh et al., 2008; Morris et al., 2015). These existing studies have found robust correlations between sediment geochemistry and fire-related disturbance. However, limited research has been conducted in the tropical Americas on the response of sediment geochemistry to wildfire during the Holocene. Such research could greatly contribute to our understanding of post-fire nutrient loading to aquatic ecosystems.

The goal of this study is to develop sub-decadal to multi-decadal-scale fire histories spanning the late Holocene in Chirripó N.P. Macroscopic charcoal and the sediment geochemisty (C%, N%, $\delta^{13}C$, $\delta^{15}N$ and C/N ratios) of sediment cores recovered from Lagos Morrenas 3C and Ditkebi were examined with the objectives of: 1) characterizing the late Holocene fire frequency and intensity in the high-elevation watersheds in Chirripó N.P.; 2) assessing if fire events are reflected in lake sediment geochemistry; and 3) integrating charcoal and sediment geochemistry to derive a record of the late Holocene climate and environmental change. The results from this study will improve our understanding of late Holocene fire history and the impact of fire on sediment geochemistry in the Chirripó páramo, thereby providing additional insights relevant for the management and conservation of páramo ecosystems in light of projected climate change.

3.3 STUDY AREA

3.3.1 Climate

Lago Morrenas and Lago Ditkebi are located immediately adjacent to the crest of the Cordillera Talamanca, in Chirripó N.P., Costa Rica (Fig. 3.1A). Long-term meteorological data are not available for Chirripó N.P. but records from the Cerro Páramo station (3,466 m; 9°33’41’’ N, 83°45’18’’W) in the Buenavista páramo located ~30 km west of the study area, provide broadly representative climate data for the high-elevation portions of Chirripó N.P. (Lane et al., 2011). Mean annual temperature and mean annual precipitation for the interval 1971-2000 at the Cerro Páramo station was 8.5 ^{o}C and 2581 mm, respectively (Kappelle and Horn, 2016). The precipitation regime in Chirripó N.P. is characterized by a distinct wet and dry season, with ~90% of the precipitation falling between May and November (Kappelle and Horn, 2016). The annual pattern of precipitation at Cerro Chirripó is strongly correlated to the migration of the ITCZ (Lane et al., 2011). When the Intertropical Convergence Zone (ITCZ) is in its southernmost position during the boreal winter (dry season), convective activity over Cerro Chirripó is reduced, leading to intensification of the trade wind inversion in the lower troposphere and dissipation of cloud formation and precipitation on the summit of Cerro Chirripó (Lane et al., 2011). During the dry season (December-April), the intervals of cloud-free weather associated with the trade wind inversion reduce humidity sufficiently to support fire (Horn, 1993). The ITCZ's migration to its northernmost position in the boreal spring and summer enhances convective activity over Cerro Chirripó and weakens the trade wind inversion, resulting in increased cloud formation and precipitation (Lane et al., 2011).

3.3.2 Vegetation

Lago Morrenas 3C and Lago Ditkebi are surrounded by páramo (Fig. 3.1AC), a high-elevation ecosystem dominated by a diverse, mixed shrub, grass and perennial herbaceous plant assemblage of Andean origin (Kappelle and Horn, 2016). Páramo is considered to be an evolutionary and biodiversity hotspot (Madriñán et al., 2013). The páramo ecosystem within Chirripó, N.P. which extends from ~ 3300 to 3819 m a.s.l., is dominated by dwarf bamboo (*Chusquea subtessellata)*. This dwarf bamboo species comprises approximately 60% of the vegetation cover and co-occurs with other shrubs (all < 10% cover), such as *Hypericum strictum*, *Hypericum irazuense*, *Vaccinium consanguineum*, and an evergreen species, *Escallonia myrtillioides* (Kappelle and Horn, 2016; Kerr et al., 2018). A diversity of tussock grasses, sedges, dicotyledonous herbs, prostrate shrubs, pteridophytes, and mosses grow beneath the shrub canopy and in more open areas (Horn, 1993). In addition, C_4 grasses belonging to the genus *Muhlenbergia* (Sage et al., 1999a) are also present (Pohl, 1980). Three species of *Muhlenbergia* occur in the Chirripó páramo (Vargas and Sánchez, 2005). *Muhlenbergia flabellate*, the most common species, is abundant in cirque at the head of Valle de las Morrenas, where Lago

Morrenas 3C is located (Lane et al., 2011) and present near the shore of Lago Ditkebi (personal observation). Grasses belonging to the genus *Muhlenbergia* can tolerate low temperatures, which enable them to be widely distributed in sub-arctic and alpine settings (Schwarz and Redmann, 1988; Sage et al., 1999b), including in the boreal forest of Canada and high-elevation sites (4000 m a.s.l.) in the Rocky Mountains (Sage et al., 1999b). In the Chirripó páramo, dry microhabitats with a coarse substrate and relatively low moisture availability (e.g. glacial till) are the locations where *M. flabellata* flourishes (Lane et al., 2011).

3.3.4 Study Lakes

Lago Morrenas 3C (3492 m a.s.l.; Horn et al., 2005) is a small (0.75 ha), shallow lake (depth = 2m) located among the glacial lake group found in Valle de las Morrenas (Fig. 3.1B), which is situated on the north side of the Chirripó massif. Valle de las Morrenas is a well-developed alpine glacial trough containing a compound cirque headwall, numerous lakes and ponds, rock thresholds and moraines (Orvis and Horn, 2000). The bedrock underlying Morrenas 3C consists principally of granodiorite and other plutonic rocks of the Miocene-age Talamancan intrusive series (Haberyan et al., 2003). Lago Morrenas 3C is ~110 m long and 80 m wide with a maximum depth of 2 m (measured in July 2014), with water temperature of 8.8°C (Table 3.1). Lake water was neutrual and dilute with a pH = 7.18 and conductivity = 0.003 S/cm. An inflow is located along the northeast margin of the lake and an outflow, located along the southwest margin, connects Lago Morrenas 3C to an adjacent small lake. The lake is surrounded by typical páramo vegetation with scattered glacial deposits present throughout the upper valley.

Lago Ditkebi (3493 m a.s.l.; Horn et al., 2005) is an oval-shaped glacial lake with a maximum depth of 8 m (measured in July 2014) and a surface area of 1.67 ha (Fig. 3.1B). The bedrock underlying Lago Ditkebi is composed of pyroclastic deposits (Haberyan et al., 2003). An inflowing stream is located along the western margin of the lake, with a secondary inflow located to the east. An outflow connects Lago Ditkebi to a small river, Rio Ditkebi, which flows to the Atlantic coast (Horn et al., 2005). Gravel deposits are located in the shallow water along the east and west shore of Lago Ditkebi (Haberyan et al., 2003; Horn et al., 2005). Sorted rings, associated with (possible) periglacial activity, are found along the eastern margin of the lake. Surface water temperature, measured in July 2014, was 10.7°C. The lake is characterized by dilute, near circum-neutral water, as reflected by conductivity and pH (Table 3.1). Lago Ditkebi is surrounded by páramo vegetation, dominated by the dwarf bamboo *Chusquea subtessellata* (Kappelle, 1990).

3.4 METHODS

3.4.1. Late Holocene Sediment Core Recovery

A 40.5 cm long sediment core was recovered from center of Lago Morrenas 3C, using a DeGrand maxi-corer deployed from an inflatable raft in July 2014. The DeGrand maxi-corer is a gravity corer that allows recovery of lake surface sediment with minimum disturbance of the mud-water interface. A 575 cm sediment core was recovered from the center of Lago Ditkebi using a modified Livingstone piston-corer at a water depth of 8.0 m in July 2014. A plastic tube attached to the Livingstone corer was used to recover the upper 84 cm of sediment from Lago Ditkebi. The Livingstone corer was deployed from a platform established on two inflatable rafts. The mud-water interface for both cores was stabilized using Zorbitrol®. Observations regarding the stratigraphy and color of the cores were described in a field notebook before the cores were sectioned. The uppermost sediment from Lago Morrenas 3C (0-40.5 cm) and Lago Ditkebi (0-84 cm) were sectioned at a 0.25 cm interval in the field and were stored in Whirl-paks and transported back to the Environmental Change Lab (ECL), Department of Geography, University of Georgia. The stratigraphy of DKB core was well preserved, but a depth adjustment was undertaken following sectioning to account for core compression.

3.4.2 Laboratory Analyses

Chronological control for the lake sediment cores from Lago Morrenas 3C (MOR3C) and Lago Ditkebi (DKB) is based on seven and eight AMS radiocarbon dates, respectively, obtained on charcoal and aquatic moss (Table 3.2). The radiocarbon dates were converted to calendar years using the most recent IntCal13 calibration curve (CALIB 7.10: calib.org/calib/calib.html; Reimer et al., 2013) except the uppermost sample, which provided a modern date (pMC=100.68%, error=1.03). This modern date was calibrated using Bomb CALIB (http://calib.org/CALIBomb/). All relative areas of ±2σ age ranges and the corresponding median probability ages for the reminder samples are reported relative to CE or cal yr BP. Age-depth models of MOR3C core are based on a probability sampling method implemented using Clam 2.2 (Fig. 3.2AB; Blaauw, 2010). The calibrated ±2σ age range with >95% possibility area (71 cal yr BP ± 77 yrs) of the modern date was used as input data in Clam age depth model. Samples located at 10.375 cm (mid-point) and 14.25 cm (mid-point) in the MOR3C core were not included in the final Clam age-depth model. The date of 990 ^{14}C yr ± 25 yrs obtained at 10.375 cm is considered anomalously old, likely reflecting the persistence of the charcoal fragment, utilized in ^{14}C analysis, on the landscape for a period of time following a fire event. The date of 60 ^{14}C yr ± 25 yrs obtained on charcoal from 14.25 cm is likely related to low sample mass and possible contamination (the mass of the charcoal dated was ~300 μg, and it was based on microscopic fragments collected from eight adjacent sample bags). The eight radiocarbon dates obtained from the DKB core were utilized in the Clam age-depth model (type=4, smooth=0.3), resulting in a basal age of ~8770 cal yr BP. The upper 152 cm of the DKB core, which spans the past ~1700 years, is discussed in this study (Frame in red box in Fig. 3.2B and Table 3.1). All radiocarbon analyses were conducted at the Center for Applied Isotope Studies (CAIS) at the University of Georgia.

Macroscopic charcoal fragments were analyzed following the protocol available from the Limnological Research Center at the University of Minnesota (http://lrc.geo.umn.edu/laccore/procedures.html). Specifically, contiguous samples consisting of 1 cm^3 of sediment was sampled at 0.25 cm resolution from the MOR3C core between 0 cm and 40.5 cm. Sub-sampling of the DKB core varied, with contiguous samples consisting of 2 cm^3 of sediment sampled at 1.0 cm resolution between 0 cm and 84 cm and contiguous samples consisting of 1.5-2 cm^3 of sediment sampled at 1.1-2.2 cm intervals between 84 cm and 152 cm to account for core compaction. Samples were washed into beakers using distilled water. Samples were treated with a 30 ml solution of 6% hydrogen peroxide (H_2O_2) to bleach organic matter. Beakers were sealed with aluminum foil to avoid contamination and placed in a drying oven and heated at 50°C for ~24 hours to amplify bleaching. Samples were washed through 250 µm and 125 µm sieves; the material retained by the sieves was transferred into labeled petri dishes. Approximately 2 ml of 0.5% sodium hexametaphosphate was added to each petri dish to disperse the charcoal and make counting easier. Charcoal fragments were tallied using a gridded counting sheet at 100x magnification after the water in the petri dishes evaporated. Charcoal belonging to each size fraction (125-250 µm and >250 µm) were tallied and used to determine charcoal accumulation rates (CHAR). Charcoal belonging to the large size fraction is typically transported no more than a few kilometers from the fire source and can provide evidence of local, catchment-scale fire events (Whitlock and Larsen, 2002; Walsh et al., 2008 and 2010). The charcoal was classified as either woody, herbaceous, or lattice-type based on appearance. Woody charcoal, produced by trees and shrubs, can be identified by its sheen, and thick, layered and prismatic structure; grass charcoal, derived from grasses, is usually thin, flat and characterized by stomata in the epidermal walls (Walsh et al., 2008 and 2014); charcoal associated with the burning of thin leaves is characterized by a flat, single-layered, lattice pattern (Jensen et al., 2007; Walsh et al., 2008 and 2014).

Charcoal concentration and CHAR were calculated and further analyzed using CharAnalysis (Higuera, 2009; http://charanalysis.googlepages.com/). CharAnalysis identifies individual fire episodes, characterized by elevated CHAR relative to the charcoal background component ($C_{background}$) making use of peak thresholds. Threshold type in this research is locally defined based on the available charcoal records from the two study lakes. Three types of threshold values (thresholds 1-3) are calculated using percentile cut-off (0.90, 0.95 and 0.99) on the Gaussian mixture model-based noise distribution (C_{noise}) (Higuera, 2009). Concentration values were interpolated to constant 10-year time steps, and 100 years was used to smooth the $C_{background}$ record. A fire peak event is identified when CHAR exceeds fire peak threshold 3. The level of fire severity in this study is determined based on the amount of woody charcoal concentration for both the 125-250 μm and >250 μm categories observed during a fire peak event, because the burning of shrubs in páramo can produce more, large woody charcoal pieces and may have required much higher heat than the burning of grass páramo (Horn and Kappelle, 2009). In addition, a severe fire was identified to be close to shore if >250 μm woody charcoal pieces were observed during a fire peak episode, otherwise, the severe fire would be considered as occurring some distance from the lake margin.

Geochemical analyses of the sediment recovered from Lago Morrenas 3C and Lago Ditkebi, included total organic carbon (C%), total organic nitrogen (N%) and stable carbon ($\delta^{13}C$) and nitrogen ($\delta^{15}N$). The C% and N% values were used to calculate C/N. Approximately 3-4 mg of freeze-dried sediment was weighed out using a high-precision digital scale and placed in silver capsules. These samples were pretreated with 10-50 μm^3 of diluted hydrochloric acid (5% HCl), prior to combustion, to remove carbonate. The sediment samples were not milled following freeze-drying due to the fine-grain nature of the sediment. For the few samples that contained coarser-grained material, we ran three replicate samples and calculated the average value for the geochemical analyses of these samples. All geochemical analyses were conducted at the Center for Applied Isotope Studies (CAIS) at the University of Georgia.

3.5 RESULTS

3.5.1 Charcoal Analysis

The late Holocene is characterized by the occurrence of periodic fires in the catchment of Lago Morrenas 3C, with three major fire episodes observed during the past ~1700 years (Fig. 3.3A). Charcoal concentration and CHAR remained low and stable until approximately 600 CE, at which time they began to increase. A gradually increasing sedimentation rate is observed following the peak in charcoal concentration and CHAR at ~680 CE. The increase in charcoal concentration and CHAR is consistent across all charcoal types (woody, grass and lattice) and both size classes (125-250 μm and > 250 μm) except for the fire event at ~1160 CE. A second fire episode, characterized primarily by elevated charcoal concentrations and CHAR belong to the 125-250 μm size class, occurred at ~1160 CE. The elevated concentration and CHAR of the smaller size class at ~1160 CE may reflect the occurrence of a severe fire outside the Lago Morrenas 3C catchment or a less intensive local fire near Lago Morrenas 3C. The sedimentation rate reached a maximum at approximately 950 CE and then slowly decreased throughout the remainder of the MOR3C core. Charcoal concentration and CHAR (all size classes) remained stable and relatively low from ~1160 CE until approximately 1780 CE. The fire events observed at ~680 CE and 1780 CE are likely very severe and occurred near the shore based on the high concentration of >250 μm woody charcoal. The interval between 1780 and 1900 CE, is characterized by a large increase in charcoal concentration and CHAR across both size classes. The peak values in charcoal concentration and CHAR in the upper part of MOR3C core largely reflect the contribution of grass type charcoal (both size classes), which reached a maximum at approximately 1880 CE. The sedimentation rate shows little response to this fire event which peaked at ~1880 CE.

The low amount of large woody charcoal suggests that the fire regime at Lago Ditkebi is characterized by more frequent, lower severity wildfires relative to Morrenas 3C during the late Holocene (Fig. 3.3B). Charcoal concentration and CHAR were relatively low until approximately 560 CE when woody and grass charcoal belonging to the small size class (125-250 μm) and lesser amounts of woody charcoal belong to large size class (>250 μm) began to increase, peaking at ~ 600 CE. The elevated amounts of the small size class charcoal at 600 CE may indicate the occurrence of an extra-local fire or a severe fire that occurred within catchment but at some distance from the shore. The sedimentation rate did not change in response to this fire event. A second fire event, which occurred at approximately 700 CE, is also characterized by elevated woody and grass charcoal (125-250 μm) and lesser amounts of woody charcoal (>250 μm). The relatively quiescent fire regime which characterizes the interval between 720 and 980 CE was followed by a more active fire regime between ~980 and 1230 CE. The elevated fire activity observed between ~980 and 1230 CE at Lago Ditkebi is characterized by increased charcoal concentration and CHAR for 125-250 μm particles of all types (woody, grass and lattice). These elevated charcoal concentrations and CHAR likely reflect the potential influence of a severe fire event that occurred some distance from the lake margin at approximately at 1020 CE. The occurrence of four additional fire events is evidenced by high values in charcoal concentration and CHAR at ~1200 CE, ~1400 CE, ~1730 CE and ~2000 CE. The fire episode identified at ~1200 CE (CHAR=11.2 particles/cm^2/yr) is associated with elevated amounts of all charcoal types in the smaller size class and woody charcoal in the larger size class. The fire episode at ~1400 CE (CHAR=5.8 particles/cm^2/yr) is characterized by elevated amounts of all types of charcoal associated with the large size class. The increase in charcoal concentration and CHAR at ~1730 CE, is comprised nearly exclusively of charcoal belonging to the smaller size class, indicating the occurrence of a low-intensity fire at some distance from the lake margin. The most recent fire event is captured by the elevated CHAR values at ~2000 CE. The sedimentation rate, which increased throughout the late Holocene, reached 0.103 cm/yr at ~1795 CE. The sedimentation rate continued to increase to the present, rising to its maximum value of 0.136 cm/yr at ~2010 CE.

CharAnalysis identifies the occurrence of three major fire peak episodes at Lago Morrenas 3C, centered at ~660 CE, 1140 CE, and ~1850 CE (Fig. 3.5a). Among these major fire peak episodes, the fire peak (M2) at ~1160 CE, which is characterized by abundant charcoal belonging to smaller size class, limited amounts of >250 μm charcoal and CHAR residuals that greatly exceed the highest fire peak threshold, appears to represent a severe fire some distance from the lake margin (Fig. 3.3a). The intervals (280-580 CE, 780-1040 CE, and 1240-1700 CE) sandwiched between these three major fire episodes were quiescent, characterized by limited fire and low fire frequency. Lago Ditkebi experienced more frequent wildfires during the past ~1700 years with six fire peaks (D1-D6) identified. These fire episodes are centered at ~590 CE, 710 CE, 1020 CE, 1200 CE, 1390 CE, and 1740 CE (Fig. 3.5c). As evidenced by synchronous changes in both size classes of charcoal, five of the fire episodes (D1-4, D6) appear to represent both catchment scale burning. The extremely low abundance of charcoal belonging to the small size class suggests that the fire peak event (D5) centered at 1390 CE possibly represents a small fire close to the lake or an extra-local fire. The post-1200 CE interval is characterized by greatly reduced fire frequency and severity as evidenced by the low CHAR residuals with the CHAR residuals exceeding the peak fire threshold twice in DKB core and once in MOR3C core post-1200 CE. The reduced fire frequency at Lago Ditkebi during the last 800 years corresponds to a similar reduction in fire frequency at Lago Morrenas 3C during the same interval. It is important to note that discrepancies exist between the CharAnalysis results and the record of historic fire events in Chirripó National Park. Severe fires burned Chirripó National Park in 1953, 1958, 1976, 1977, 1981 and 1992 CE, with the most recent fire, which burned 20 $km^2$of páramo vegetation, resulting in a closure of the park for four months (http://www.sinaccr.net/aclap_chirripo_general.php). However, these severe historic fire events are not identified as discrete fire peak episodes by CharAnaylsis.

3.5.2 Geochemistry

Limited change in N%, C%, $\delta^{13}C$ and $\delta^{15}N$ values characterized MOR3C core between 500 CE and ~ 600 CE. At 600 CE, N%, C%, C/N and $\delta^{13}C$ values began to decrease, but $\delta^{15}N$ values rapidly increased. N%, C%, and $\delta^{13}C$ continued to drop until ~680 CE, when their values quickly rose to reach their core maxima at ~880 CE. The trend in $\delta^{15}N$ is opposite to that of N%, C%, C/N and $\delta^{13}C$ between 580 CE and 900 CE; $\delta^{15}N$ values peaked at ~680 CE and quickly declined to a core minimum (-1.1 ‰) at ~900 CE. The $\delta^{15}N$ values generally stayed at or near 0‰ between ~400 and 600 CE and between ~800 and 1000 CE. The C/N ratios increased at ~680 CE and reached a local maximum at ~1000 CE, potentially reflecting an increase in the relative contribution of terrestrial organic matter to the lake. At ~1150 CE, a synchronous reduction in the values of C%, $\delta^{13}C$ and C/N, along with an increase in $\delta^{15}N$, is observed. The interval from ~1300 CE to the present is characterized by limited change in lake sediment geochemistry, with the exception of the late 20th century when increases in $\delta^{15}N$ and C/N and a decrease in N% are observed. A trend of decreasing $\delta^{13}C$ beginning at approximately 1750 CE is also documented in the Morrenas 3C core.

Changes in sediment geochemistry at DKB are muted relative to MOR3C (Fig 3.4B). The core is characterized by limited variation in N%. Brief departures in N% occurred at approximately 680 CE, between 1050 and 1150 CE, and at approximately 1940 CE. Each of these brief departures in N% corresponded to negative excursions in C%, $\delta^{13}C$ and C/N. A simultaneous decrease in N%, C%, $\delta^{13}C$ and C/N and an increase in $\delta^{15}N$ occurred between ~1050 and 1150 CE, with a core maxima of $\delta^{15}N$ occurring at ~1050 CE. Variation in $\delta^{15}N$ is characterized by notable sample-to-sample variability between ~280 and 1050 CE. The value of N% remained nearly unchanged from ~1150 to 1850 CE; however, during this interval the remaining geochemical parameters experienced notable fluctuations, particularly between ~1150 and 1380 CE. A synchronous decrease in C%, $\delta^{13}C$ and C/N is observed between approximately 1400 and 1700 CE. A core maximum in C/N is observed at approximately 1530 CE. Relatively depleted $\delta^{15}N$ characterized the interval between 1300 and 1420 CE. The uppermost portion of the core (~1850 CE to the present) is characterized by several abrupt changes in sediment geochemistry including a notable reduction in C% and N% and an increase in $\delta^{13}C$ at approximately 1935 CE, enriched $\delta^{15}N$ at ~2000 CE, and depleted $\delta^{15}N$ values in the most recently deposited sediment.

3.6 DISCUSSION

3.6.1 Late Holocene fire regimes in the páramo of Chirripó National Park

The occurrence of multiple fire episodes in the Chirripó páramo during the past 1700 years is evident in the charcoal records developed for Lago Morrenas 3C and Lago Ditkebi. The broad correspondence of the fire events' timing at Lago Ditkebi (~550-730 CE and ~980-1230 CE) and at Lago Morrenas 3C (620-720 CE and 1120-1200 CE), suggest that wildfires were widespread within the Chirripó páramo during these two intervals. This finding is generally consistent with results from previous studies reporting intensive fire activity from ~1200 to 600 ^{14}C yr BP at Lago Morrenas 1 (League and Horn, 2000) and from ~1200 to 1000 ^{14}C yr BP at Lago Chirripó (Horn, 1993). Limited age control and the sample resolution of these earlier studies prevent a direct comparison of the timing of the fire events identified at Lago Morrenas 1 and Lago Chirripó with the fire events identified in this study. However, this study provides further support that the highlands in Chirripó N.P. were characterized by severe fires and a higher fire frequency between ~ 600 and 1250 CE. It is notable that the timing of the two broad intervals of elevated fire frequency at Lago Morrenas 3C and Lago Ditkebi bracket the interval of Terminal Classic Drought (TCD: ~770-1100 CE) defined in Hodell et al., (2005) and the period of Medieval Climate Anomaly (MCA: ~950-1250 CE) defined in Mann et al., (2009). The ignition source for these fires is likely climate-related rather than human activity since the Chirripó páramo is relatively isolated (Horn and Kappelle, 2009) with no evidence of human occupation or presence documented until relatively recently when Chirripó N.P. was opened to the public in 1975 (Horn, 1990). Whether these fires were caused by decreased relative humidity, increased convective activity (intensity/frequency)-related lightning or a combination of these factors requires additional investigation.

The presence of both size classes of charcoal for the three major fire events observed at Lago Morrenas 3C suggests that the fire events at ~660 CE, 1160 CE and 1850 CE were widespread; not only within the catchment of the lake, but also in the vicinity of Lago Morrenas 3C. A similar pattern is evident at Lago Ditkebi with the wildfires found at ~590 CE, 710 CE, 1020 CE, 1200 CE and 1740 CE reflecting the occurrence of both local and extra-local scale burning. Interestingly, the fire episode in DKB core at 1390 CE (D5 in Fig. 5.5), evidenced solely by charcoal belonging to the large size class, appears to reflect a local event, suggesting that not all fires are driven by regional-scale hydroclimate variability. If a low-severity fire occurred close to the shore of Lago Ditkebi and did not spread to the Valle de las Morrenas, it may account for the absence of charcoal belonging to the small size class in the MOR3C core at 1390 CE. However, the issue pertaining to the discrepancy between between the CharAnalysis results and historic fire events recorded since 1900 CE is worth noting. The failure of CharAnalysis to capture the severe fire events during the mid- to late 20th century suggests that caution must be taken in using the CharAnalysis results to establish and characterize fire frequencies for the region.

3.6.2 Response of sediment geochemistry to fire events

In the MOR3C core, a clear relationship exists between variations in sediment geochemistry and fire episodes, specifically fire events M1 and M2 (Fig. 3.6). The M1 fire event was characterized by an initial increase in charcoal particles belonging to the small and large size classes at ~ 580 CE and an abrupt increase in charcoal belonging to the large size class at ~640 CE. The response of the sediment geochemistry to the initial increase in charcoal is evident in the C% and N% values, which decreased; and the $\delta^{15}N$ values, which were increasingly enriched beginning at ~580 CE. The trend in C%, N% and $\delta^{15}N$ was reversed at ~ 740 CE, corresponding to the abrupt decrease in charcoal concentration and accumulation rates. A similar response of the sediment geochemistry to fire event M2 is detected at ~1140 CE, with a concurrent decrease in N% and C%, and an increase in $\delta^{15}N$, followed by the rapid recovery of N%, C% and $\delta^{15}N$ to their pre-fire levels at ~1180 CE corresponding to the abrupt decrease in charcoal concentration and accumulation rates at this time. A dramatic reorganization of the chironomid (aquatic invertebrate) community at 1230 CE suggests that a notable change in lake conditions occurred following the M2 fire event (Wu, 2018 Dissertation Chapter 4). The limited variation in sediment geochemistry following fire event M2 and the muted response of sediment geochemistry to the 1880 CE fire event may reflect decreased lake sensitivity to catchment conditions in response to the chironomid-inferred changes in lake conditions that occurred at ~1230 CE.

The response of the sediment geochemistry, particularly N% and C%, to the M1 and M2 fire events suggests that the temperatures associated with these fire events were sufficiently high to facilitate the volatilization of C and N in vegetation surrounding Morrenas 3C (Morris et al., 2015; Fig. 3.6ce). Laboratory experiments indicate that the volatilization temperature for N is between 200 °C and 300 °C (Dubreuil and Moore, 1982; Gillon et al., 1995; Uhelski and Miesel,

2017) and as low as 100 °C for C (Raison, 1979). Limited loss of C has been observed when organic matter is heated to <100 °C for 16 hours, whereas, 99% of C will be combusted with 30 minutes at 500°C (Feger and Hawtree, 2013; Raison, 1979). The results of these experimental studies suggest that when fire is light to moderate (<500°C), the loss of C during volatilization will be slightly greater than that of N; however, the loss of C can be significantly greater relative to N during a severe fire (>500°C). The decrease in C/N that occurred during the M1 and M2 fire events may therefore reflect elevated rates of terrestrial C volatilization, resulting in the decreased flux of terrestrial C to the lake during these events. The depleted values of $\delta^{13}C$ that characterized fire episodes in M1 and M2 may reflect the loss of *Muhlenbergia*, a C_4 grass. The increase in $\delta^{15}N$ that characterized fire events M1 and M2, may be accounted for by kinetic fractionation theory, which suggests that lighter N (^{14}N) will be volatilized more easily when plant tissues are exposed to temperatures >180 °C (Turekian et al., 1998). Thus, ^{15}N-enriched organic matter would persist in the catchment and be available for transport to the Lago Morrenas 3C.

In general, the response of sediment geochemistry at Lago Ditkebi is not as strongly coupled to fire events as is evident in the MOR3C core. Variation in sediment geochemistry is muted in much of the DKB record and the coupling of $\delta^{15}N$ with fire events is not strongly expressed at Lago Ditkebi. The occurrence of increasingly elevated $\delta^{15}N$ values with the onset of a fire event, followed by a recovery that corresponds with the decrease in charcoal concentration and accumulation rates was apparent for the fire episodes that occurred during the intervals of 580-660 CE, 680-730 CE, 980-1100 CE and 1180-1240 CE. The coupling of $\delta^{15}N$ with fire events provides support for the use of $\delta^{15}N$ as a potential geochemical proxy indicator of fire (Morris et al., 2015) in the Chirripó páramo. Fluctuations in N% and C% were also broadly associated with fire episodes, particularly the fire events that occurred between ~550 and 730 CE and between ~980 and 1230 CE (Fig. 3.6g-l).

3.6.3 Climate and environmental change inferred from charcoal and sediment geochemistry

Fluctuations in sediment geochemistry at Lago Morrenas 3C, particularly in $\delta^{13}C$, are suggestive of an interval of reduced relative humidity and potentially depressed temperatures between ~750 and 1100 CE. This interval was characterized by the most elevated values of $\delta^{13}C$ during the past 1700 years and a quiescent fire regime. Earlier work has demonstrated the sensitivity of $\delta^{13}C$ in bulk lake sediment to vegetation dynamics in the watershed (e.g. Cerling et al., 1997; Meyer and Lallier-Vergès, 1999; Meyer, 2003; Lane et al., 2011). The ability of C_3 plants to discriminate against the heavier isotope of C (^{13}C) during photosynthesis results in C_3 plant derived bulk organic matter with depleted $\delta^{13}C$ values (-37 and -20 ‰) relative to C_4 plant derived bulk organic matter (-8 and -16 ‰) (Cerling et al., 1997; Meyer, 2003). The vegetation surrounding Morrenas 3C is dominated by shrubs and grasses utilizing the C3 pathway. The notably high values of $\delta^{13}C$ that characterized the interval between 750 and 1100 CE (Fig. 3.7) suggest an expansion of *Muhlenbergia*, the sole grass taxon utilizing the C4 photosynthetic pathway present in the Chirripó páramo (Pohl, 1980; Sage et al., 1999a). *Muhlenbergia flabellata* is the most common *Muhlenbergia* species observed in the Chirripó páramo. *M. flabellata*, surrounds Lago Morrenas 3C, but it is largely restricted to dry microhabitats, characterized by coarse substrate and low moisture availability (Lane et al., 2011). The presence of *M. flabellata* can be an indicator of drier conditions (Lane et al., 2011). Thus, expansion of *M. flabellata* in the catchment of Lago Morrenas 3C would result in increasingly enriched soil organic matter, which could account for the increase in $\delta^{13}C$ that occurred between ~ 750 and 1100 CE.

The increase $\delta^{13}C$ also corresponded to increases in C% and C/N, which suggests that the input of terrestrial organic matter to the lake was contributing to the fluctuations observed in the

$\delta^{13}C$ record during this interval. The sediment record in MOR3C is also characterized by the presence of brown algal nodules that are typically associated with low lake levels (pers. comm. Mark Bush) between 750 and 1100 CE, providing additional support for reduced effective moisture. An increase in the relative abundance of *M. flabellata* in the Morrenas 3C catchment at this time could reflect reduced relative humidity and/or depressed temperatures. *Muhlenbergia*, which is found in the boreal forests of Canada and in alpine settings in the Rocky Mountains (Sage et al., 1999b), is well adapted for cold climates and can tolerate extremely low temperature (Schwarz and Redmann, 1988; Sage et al., 1999b). Thus, expansion in abundance of *Muhlenbergia* may also suggest the occurrence of a colder climate between ~750 and 1100 CE. I hypothesize that lower effective moisture between 750 and 1100 CE resulted in lowered lake levels and an increase in near-shore habitat suitable for colonization by *Muhlenbergia* (Horn, 1993; Lane et al., 2011), which in turn facilitated the delivery of soil organic matter enriched in ^{13}C to the Lago Morrenas 3C basin. However, it is important to note that changes in nutrient loading and trophic conditions may account for the variations in $\delta^{13}C$ observed in MOR3C core (Terranes and Bernasconi, 2005). The $\delta^{13}C$ values, given the composition of bulk lake sediment, can be influenced by many factors including fluctuations in algae abudance-related lake productivity (Meyers and Terranes, 2003).

The sediment geochemistry record for Lago Ditkebi is characterized by relatively muted change between 750 and 1100 CE with no apparent trend identified in $\delta^{13}C$ and C/N values (Fig. 3.7b) and no clear evidence for the existence of lowered lake levels or lower temperatures. The relative complacency of the sediment geochemistry record in DKB core, in relation to that in MOR3C core, likely reflects the differential influence of lake basin characteristics on sediment deposition. Lago Morrenas 3C is a shallow lake with maximum depth of 2 m; whereas, Lago Ditkebi is four times as deep (8 m) and has a surface area nearly twice as large (1.67 ha) as Lago Morrenas 3C (depth=2 m, area=0.75 ha). The geochemical signature associated with fire episodes can be attenuated because the large surface area and volume of Lago Ditkebi that can moderate and reduce the sensitivity of the lake to external disturbances.

3.7 CONCLUSION

This study provides the first multi-decadal scale reconstruction of late Holocene fire regimes in the páramo of Chirripó N.P., Costa Rica. Analyses of macroscopic charcoal and sediment geochemistry provided evidence of periodic burning of páramo in Chirripó N.P. during the last two millennia. Macroscopic charcoal preserved in sediments of Lago Morrenas 3C and Lago Ditkebi indicates that the Chirripó páramo experienced repeated wildfires during the last 1700 years at the two sites. The charcoal records developed for the two study lakes also provide evidence of elevated fire frequency from ~550 to 730 CE and from 980 to 1230 CE. Severe fire episodes are reflected by a rapid increase in the flux of C and N from the surrounding catchment due to the volatilization of elements (e.g. C and N) in páramo plants. In addition, stable isotopes, particularly $\delta^{15}N$, which increases quickly following local fire events, capture post-fire changes in nutrient loading likely reflecting the decadal-scale recovery rate of the vegetation surrounding the study sites. The consistently high level of $\delta^{13}C$ and high C/N ratios observed between ~750 and 1100 CE likely reflects the expansion of *Muhlenbergia*, a native grass utilizing the C_4 pathway, suggesting that this interval was likely characterized by decreases in effective moisture and temperature.

3.8 REFERENCES

Blaauw, M., 2010. Methods and code for 'classical'age-modelling of radiocarbon sequences. Quaternary geochronology 5, 512-518.

Cerling, T E, Harris, J M, MacFadden, B J, Leakey, M G, Quade, J, Eisemann, V, and Ehleringer, J R (1997) Global Vegetation Change Through the Miocene–Pliocene Boundary, *Nature* 389, 153–158.

Chaverri-Polini, A. and Cleef, A.M., 1996. Las comunidades vegetacionales en los páramos de los macizos del Chirripó y Buena Vista, Cordillera de Talamanca, Costa Rica. Vegetation communities in the páramos at the Chirripó and Buena Vista Montains, Cordillera de Talamanca, Costa Rica. *Revista Forestal Centroamericana* 17, 44-49.

Chaverri-Polini, A. and Cleef, A.M., 2005. Comunidades vegetales de los páramos de los macizos de Chirripó y Buenavista, Costa Rica.

Chaverri-Polini, A., Vaughan-Dickhaut, C. and Poveda-Alvarez, L.J., 1976. Informe de la gira efectuada al macizo de Chirripó a raíz del fuego ocurrido en Marzo de 1976. *Revista de Costa Rica*, *11*, 243-279.

Dunnette, P.V., Higuera, P.E., McLauchlan, K.K., Derr, K.M., Briles, C.E. and Keefe, M.H., 2014. Biogeochemical impacts of wildfires over four millennia in a Rocky Mountain subalpine watershed. *New Phytologist 203,* 900-912.

Feger, K.H. and Hawtree, D., 2013. Soil carbon and water security. In *Ecosystem Services and Carbon Sequestration in the Biosphere* (pp. 79-99). Springer Netherlands.

Gillon, D., Gomendy, V., Houssard, C., Marechal, J. and Valette, J.C., 1995. Combustion and nutrient losses during laboratory burns. *International Journal of Wildland Fire 5*,1-12.

Haberyan, K.A., Horn, S.P. and Umaña, V., 2003. Basic limnology of fifty-one lakes in Costa Rica. *Revista de biología tropical* 51, 107-122.

Higuera, P., 2009. CharAnalysis 0.9: diagnostic and analytical tools for sedimentcharcoal analysis. *User's Guide, Montana State University, Bozeman, MT*.

Hodell, D.A., Brenner, M. and Curtis, J.H., 2000. Climate change in the northern American tropics and subtropics since the last ice age. Imperfect Balance: Landscape Transformation in the Precolumbian Americas, pp.14-38.

Horn, S.P. and Kappelle, M., 2009. Fire in the páramo ecosystems of Central and South America. In Tropical fire ecology (pp. 505-539). *Springer Berlin Heidelberg.*

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

Horn, S.P., 1989. Prehistoric fires in the Chirripó highlands of Costa Rica: Sedimentary charcoal evidence. *Revista de Biología Tropical 37*, 139-148.

Horn, S.P., 1990. Vegetation recovery after the 1976 páramo fire in Chirripó National Park, Costa Rica. *Revista de Biologia Tropical 38,* 267-275.

Horn, S.P., 1993, Postglacial vegetation and fire history in Chirripó páramo of Costa Rica. *Quaternary research* 40, 107-116.

Horn, S.P., Orvis, K.H. and Haberyan, K.A., 2005. Limnología de las lagunas glaciales en el páramo del Chirripó, Costa Rica. *Páramos de Costa Rica*, pp.161-81.

IPCC, 2016. http://www.ipcc.ch/ipccreports/tar/wg2/index.php?idp=524

Jensen, K., Lynch, E.A., Calcote, R. and Hotchkiss, S.C., 2007. Interpretation of charcoal morphotypes in sediments from Ferry Lake, Wisconsin, USA: do different plant fuel sources produce distinctive charcoal morphotypes? *The Holocene17,* 907-915.

Juggins, S., 2003. C2 data analysis. *University of Newcastle*, *England*.

Kappelle, M., 1990, June. Altitudinal Zoning of the Chirripó National Park, Talamanca Mountain Range, Costa Rica. In Abstract of paper presented at the V Latin American Congress of Botany. Havana, Cuba

Kappelle, M. and Horn, S.P., 2016. The Páramo ecosystem of Costa Rica's highlands. In *Costa Rican ecosystmes*. University of Chicago Press, pp.492-523.

Kennedy, L.M., Horn, S.P. and Orvis, K.H., 2006. A 4000-year record of fire and forest history from Valle de Bao, Cordillera Central, Dominican Republic. *Palaeogeography, Palaeoclimatology, Palaeoecology*, *231*(3-4), pp.279-290.

Kerr, M.T., Horn, S.P., Grissino-Mayer, H.D. and Stachowiak, L.A., 2018. Annual growth zones in stems of Hypericum irazuense (Guttiferae) in the Costa Rican páramos. *Physical Geography*, *39*(1), pp.38-50.

Knicker, H., 2007. How does fire affect the nature and stability of soil organic nitrogen and carbon? A review. Biogeochemistry, 85(1), pp.91-118.

Lane, C. S., Horn, S. P., Mora, C. I., Orvis, K. H., and Finkelstein, D. B., 2011. Sedimentary stable carbon isotope evidence of late Quaternary vegetation and climate change in highland Costa Rica. *Journal of Paleolimnology* 45, 323-338.

League, B.L. and Horn, S.P., 2000. A 10 000 year record of Páramo fires in Costa Rica. *Journal of Tropical Ecology*, 747-752.

Luteyn, J., 1999. Introduction to the páramo ecosystem. *Páramos: A Checklist of Plant Diversity, Geographical Distribution, and Botanical Literature. The New York Botanical Garden Press. NY*, pp.1-39.

Madriñán, S., Cortés, A.J. and Richardson, J.E., 2013. Páramo is the world's fastest evolving and coolest biodiversity hotspot. *Frontiers in genetics*, 4.

Meyers, P.A. and Lallier-Vergès, E., 1999. Lacustrine sedimentary organic matter records of Late Quaternary paleoclimates. *Journal of Paleolimnology*, *21*(3), pp.345-372.

Meyers, P.A., 2003. Applications of organic geochemistry to paleolimnological reconstructions: a summary of examples from the Laurentian Great Lakes. *Organic geochemistry*, *34*(2), pp.261-289.

Morris, J.L., McLauchlan, K.K. and Higuera, P.E., 2015. Sensitivity and complacency of sedimentary biogeochemical records to climate-mediated forest disturbances. *Earth-Science Reviews148*, 121-133.

Morris, J.L., Mueller, J.R., Nurse, A., Long, C.J. and McLauchlan, K.K., 2014. Holocene fire regimes, vegetation and biogeochemistry of an ecotone site in the Great Lakes Region of North America. *Journal of vegetation science 25*,1450-1464.

Orvis, K.H. and Horn, S.P., 2000. Quaternary glaciers and climate on Cerro Chirripó, Costa Rica. *Quaternary Research* 54, 24-37.

Pohl, R. W. 1980. Flora costaricensis: family number 15, Gramineae. *Fieldiana Bot*. n.s. 4: 1-608.

Polini, C. and A Cleef, AM, 1996. Vegetation communities in the moorlands of the Chirripó and Buenavista massifs, Talamanca mountain range, Costa RicaVegetation communities in the páramos at the Chirripó and Buena Vista Mountains, Cordillera de Talamanca, Costa Rica. *Central American Forest Journal (CATIE) (No. 17) p. 38-43*

Raison, R.J., 1979. Modification of the soil environment by vegetation fires, with particular reference to nitrogen transformations: a review. *Plant and soil* 51, 73-108.

Reimer, P.J., Bard, E., Bayliss, A., Beck, J.W., Blackwell, P.G., Bronk Ramsey, C., Buck, C.E., Cheng, H., Edwards, R.L. and Friedrich, M., 2013. IntCal13 and Marine13 radiocarbon age calibration curves 0-50,000 years cal BP.

Sage, R.F., Li, M., and Monson, R.K., 1999a. The taxonomic distribution of C4 photosynthesis. In: *Sage RF, Monson RK (eds) C4 plant biology. Academic Press, San Diego*, 551–584.

Sage, R.F., Wedin, D.A. and Li, M., 1999b. The biogeography of C4 photosynthesis: patterns and controlling factors. In: *Sage RF, Monson RK (eds) C4 plant biology. Academic Press, San Diego*, 313-374.

Sawyer, J.O. and Lindsey, A.A., 1971. Vegetation of the life zones in Costa Rica. *Vegetation of the Life Zones in Costa Rica*.

Schwarz, A.G. and Redmann, R.E., 1988. C4 grasses from the boreal forest region of northwestern Canada. *Canadian Journal of Botany 66*, 2424-2430.

Teranes, J.L. and Bernasconi, S.M., 2005. Factors controlling δ13C values of sedimentary carbon in hypertrophic Baldeggersee, Switzerland, and implications for interpreting isotope excursions in lake sedimentary records. *Limnology and Oceanography*, *50*(3), pp.914-922.

Turekian, V.C., Macko, S., Ballentine, D., Swap, R.J. and Garstang, M., 1998. Causes of bulk carbon and nitrogen isotopic fractionations in the products of vegetation burns: laboratory studies. *Chemical Geology 152*,181-192.

Uhelski, D. and Miesel, J.R., 2017. Physical location in the tree during forest fire influences element concentrations of bark-derived pyrogenic carbon from charred jack pines (Pinus banksiana Lamb.). *Organic Geochemistry*.

Vargas, G. and Sánchez, J.J., 2005. Plantas con flores de los páramos de Costa Rica y Panamá: el páramo ístmico. *Páramos de Costa Rica*, 397-435.

Walsh, M.K., Prufer, K.M., Culleton, B.J. and Kennett, D.J., 2014. A late Holocene paleoenvironmental reconstruction from Agua Caliente, southern Belize, linked to regional climate variability and cultural change at the Maya polity of Uxbenká. *Quaternary Research 82*,38-50.

Walsh, M.K., Whitlock, C. and Bartlein, P.J., 2008. A 14,300-year-long record of fire–vegetation–climate linkages at Battle Ground Lake, southwestern Washington. *Quaternary Research*, *70*(2), pp.251-264.

Walsh, M.K., Whitlock, C. and Bartlein, P.J., 2010. 1200 years of fire and vegetation history in the Willamette Valley, Oregon and Washington, reconstructed using high-resolution macroscopic charcoal and pollen analysis. *Palaeogeography, Palaeoclimatology, Palaeoecology297*, 273-289.

Whitlock, C. and Larsen, C., 2002. Charcoal as a fire proxy. *Tracking environmental change using lake sediments vol 3*, 75-97.

Table 3.1. Limnology of Lago Morrenas 3C and Lago Ditkebi. Elevation of the study sites is taken from Horn et al. (2005). Lake depth and chemical parameters were measured on July 19th, 2014 for Morrenas 3C and on July 17th, 2014 for Lago Ditkebi. Coordinates and dimension (length, width and area) of the lakes were estimated using Google Earth Pro.

Lake Name	Date Visited (yyyy.mm)	Latitude N. Longitude W.	Elevation m a.s.l.	Depth (m)	Length (m)	Width (m)	Area (ha)	Temperature (°C)	DO (%)	DO (mgl^{-1})	SPC (Scm^{-1})	Conductivity (S^{-1})	pH
Lago Morrenas 3C	2014.07	9°29'44",83°29'06"	3492	2	110	80	0.75	8.8	64.4	4.9	0.003	2.3	7.18
Lago Ditkebi	2014.07	9°28'06",83°28'49"	3493	8	190	116	1.67	10.7	87.6	6.44	0.029	21.3	7.95

Table 3.2 Accelerator Mass Spectrometry (AMS)-based radiocarbon (^{14}C) dates obtained for the MOR3C core (dates not incorporated in the Clam age-depth model are highlighted in red) and the DKB core (the dates bracketed by the red box cover the interval discussed in this study).

Lab code	Core code	Depth in core (cm)	Material	Uncalibrated ^{14}C age (^{14}C yr BP)	±	2σ Age range	Relative area under distribution	Median Probability (CE or cal yr BP)
UGAMS#28489	MOR3C-PT	5.75-7.5	Charcoal	modern	-	1802-1938 CE	0.686	-
						1689-1739 CE	0.252	
						1952-1956 CE	0.036	
						1742-1763 CE	0.026	
UGAMS#23001	MOR3C-PT	10.25-10.5	Charcoal	990	25	991-1050 CE	0.676	1032 CE (918 cal yr BP)
						1083-1126 CE	0.259	
						1136-1151 CE	0.064	
UGAMS#28490	MOR3C-PT	13.25-15.25	Charcoal	60	25	1875-1918 CE	0.566	1871 CE (79 cal yr BP)
						1695-1726 CE	0.22	
						1813-1838 CE	0.158	
						1842-1853 CE	0.031	
						1868-1874 CE	0.015	
						1955-1955 CE	0.01	
UGAMS#21658	MOR3C-PT	17.25-17.75	Charcoal	880	20	1150-1217 CE	0.773	1169 CE (781 cal yr BP)
						1049-1084 CE	0.192	
						1124-1136 CE	0.035	
UGAMS#23002	MOR3C-PT	24-24.5	Charcoal	940	25	1030-1155 CE	1	1097 CE (853 cal yr BP)
UGAMS#21659	MOR3C-PT	33-33.5	Charcoal	1330	20	652-695 CE	1	671 CE (1279 cal yr BP)
UGAMS#20643	MOR3C-PT	39.5-40	Charcoal	1690	20	326-405 CE	0.926	361 CE (1589 cal yr BP)
						260-279 CE	0.074	
UGAMS#21660	DKB-PT	67.5-67.75	Charcoal	460	20	1422-1451 CE	1	1437 CE (513 cal yr BP)
UGAMS#28661	DKB-LC2A	77.3-77.8	Charcoal	1150	20	856-969 CE	0.804	894 CE (1056 cal yr BP)
						804-845 CE	0.126	
						777-792 CE	0.069	
UGAMS#23000	DKB-LC2A	112.6-114.2	Charcoal	1300	45	647-778 CE	0.955	713 CE (1237 cal yr BP)
						840-862 CE	0.02	
						791-805 CE	0.014	
						813-825 CE	0.01	
UGAMS#28662	DKB-LC2A	140.6-143.4	Charcoal	1580	25	418-541 CE	1	482 CE (1468 cal yr BP)
UGAMS#18526	DKB-LCBb	176	Charcoal	2060	25	1967-2114 cal yr BP	0.954	2028 cal yr BP
						1949-1963 cal yr BP	0.046	
UGAMS#18527	DKB-LCEa	340.8	Charcoal	3260	25	3445-3562 cal yr BP	0.958	3487 cal yr BP
						3409-3425 cal yr BP	0.042	
UGAMS#18406	DKB-LCFb	472	Charcoal	4480	30	5152-5289 cal yr BP	0.575	5173 cal yr BP
						5037-5048 cal yr BP	0.379	
						4979-5007 cal yr BP	0.046	
UGAMS#18407	DKB-LCGa	539	Aquatic Moss	6150	20	6976-7158 cal yr BP	1	7069 cal yr BP

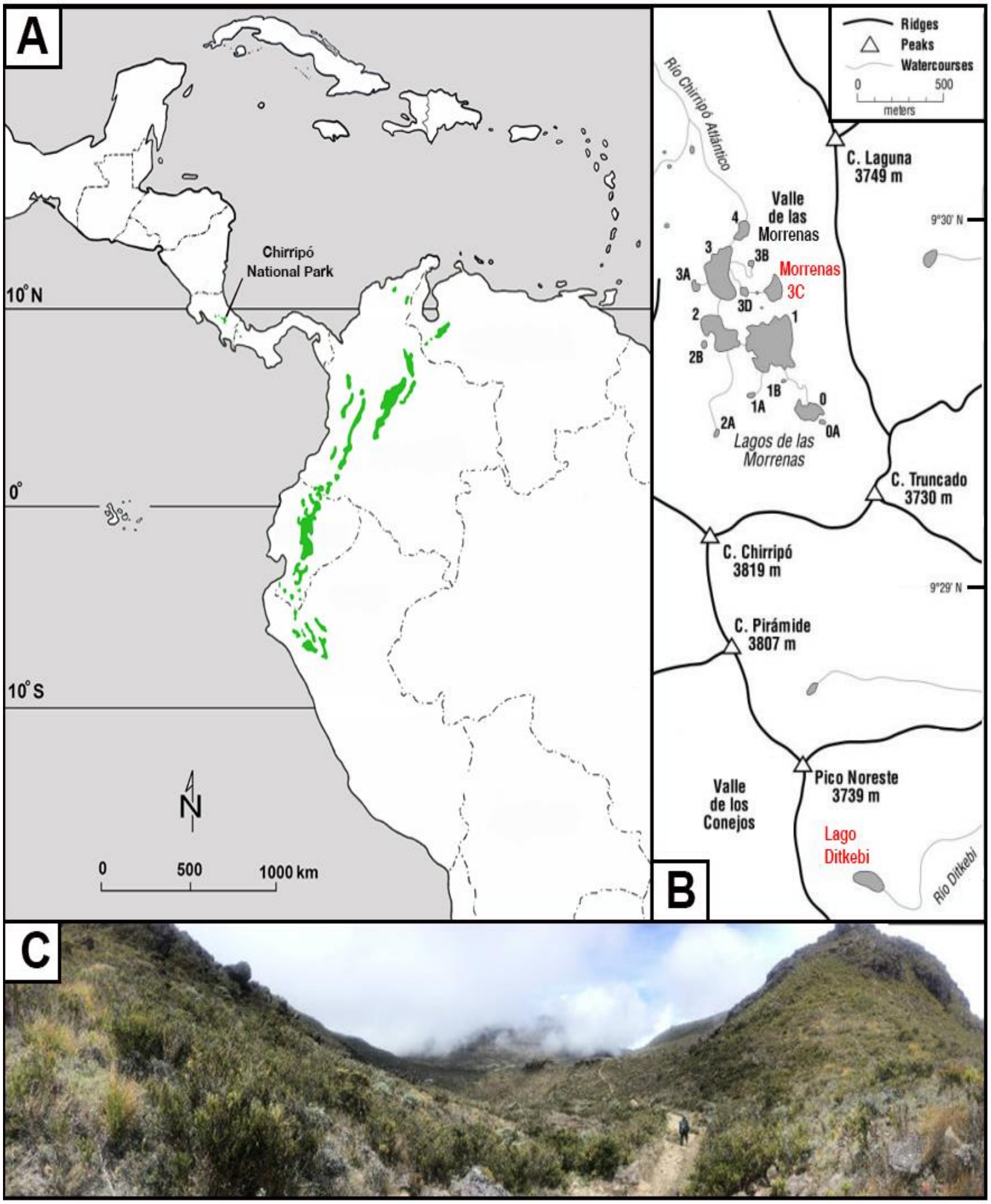


Figure 3.1 (A) Distribution of páramo (shaded in green) in the Neotropics, which extends from Costa Rica to northern Peru (Luteyn, 1999; revised by Jiaying Wu). The location of Chirripó National Park is also indicated; (B) Location of Lago Morrenas 3C and Lago Ditkebi, Chirripó National Park, Costa Rica (Orvis and Horn, 2000; modified by Jiaying Wu); and (C) Páramo vegetation within Chirripó National Park, Costa Rica (Photo: Jiaying Wu).

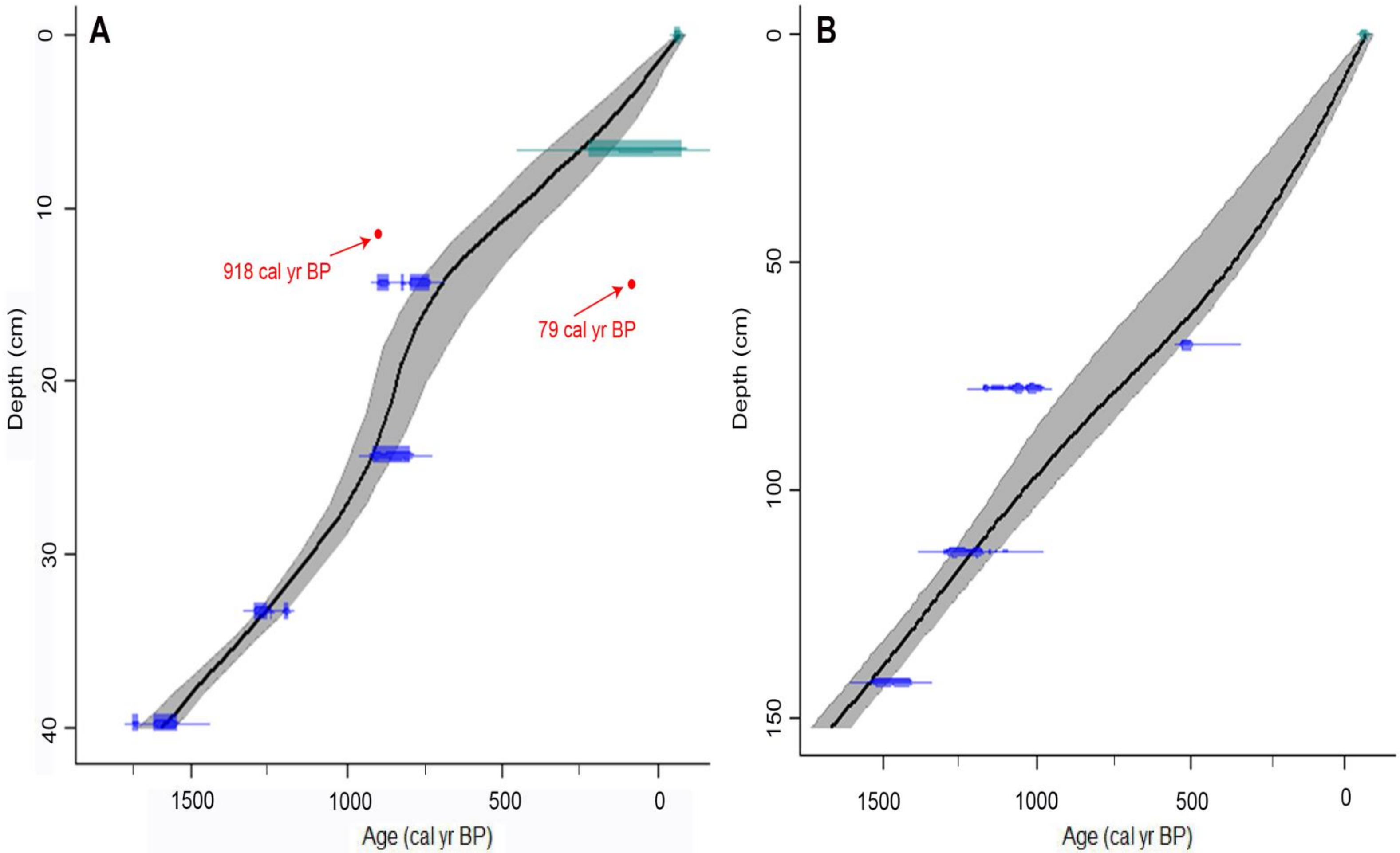


Figure 3.2 Clam-based age-depth models for (A) MOR3C and (B) DKB. Radiocarbon dates not incorporated in the age-depth model for MOR3C are depicted by red dots and labeled with calibrated median age (see Table 3.2 and text for additional details). The chronology for the DKB core capturing the past 1700 years is depicted here. The calibrated distributions of individual dates are depicted in blue and the Clam model's 95% probability intervals are depicted in grey (http://www.chrono.qub.ac.uk/blaauw/clam.html, Blaauw, 2010).

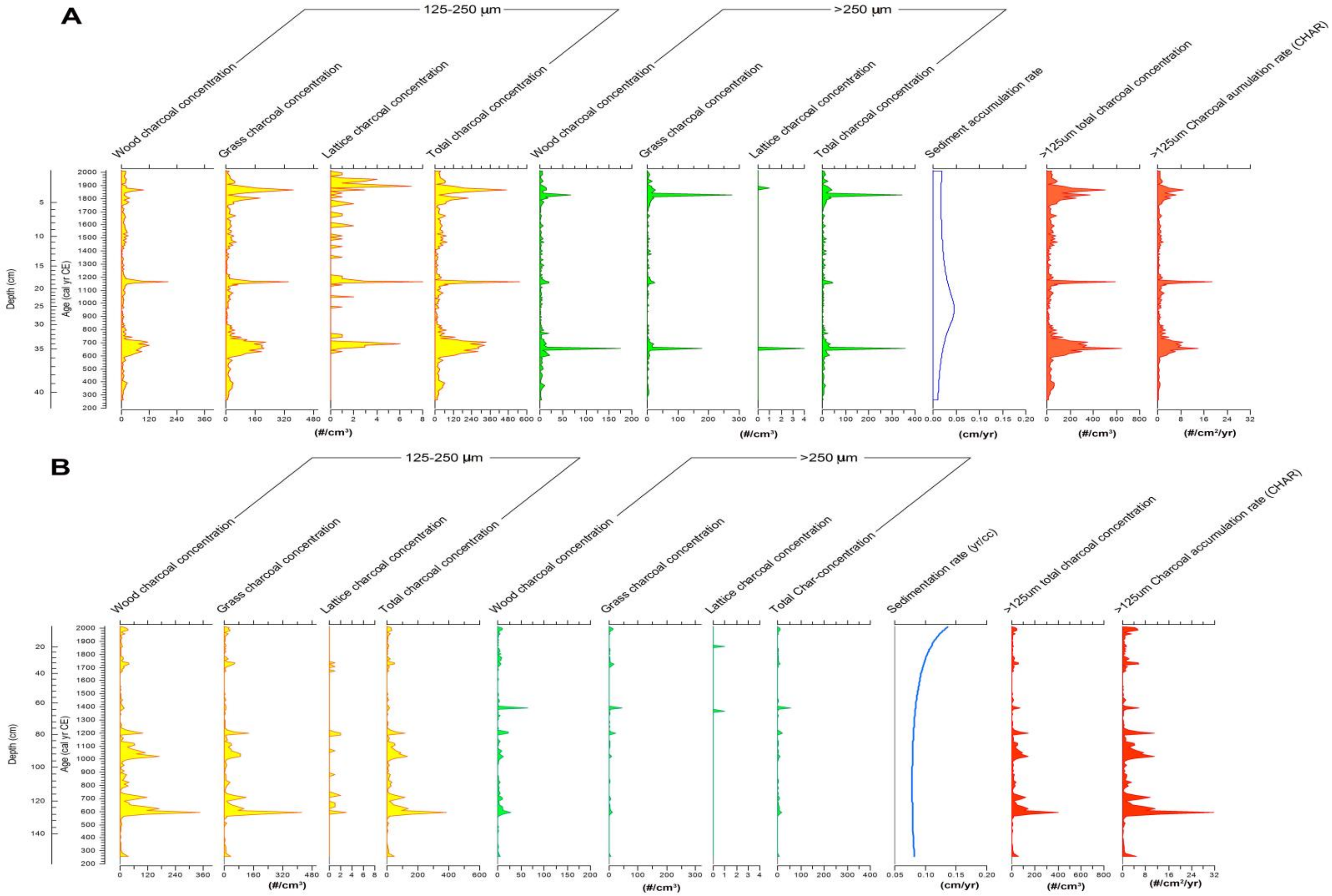


Figure 3.3 Charcoal records and sedimentation rates for (A) MOR3C and (B) DKB spanning the last 1700 years. The scale of the x axes for the charcoal parameters are set consistently for ease of comparison.

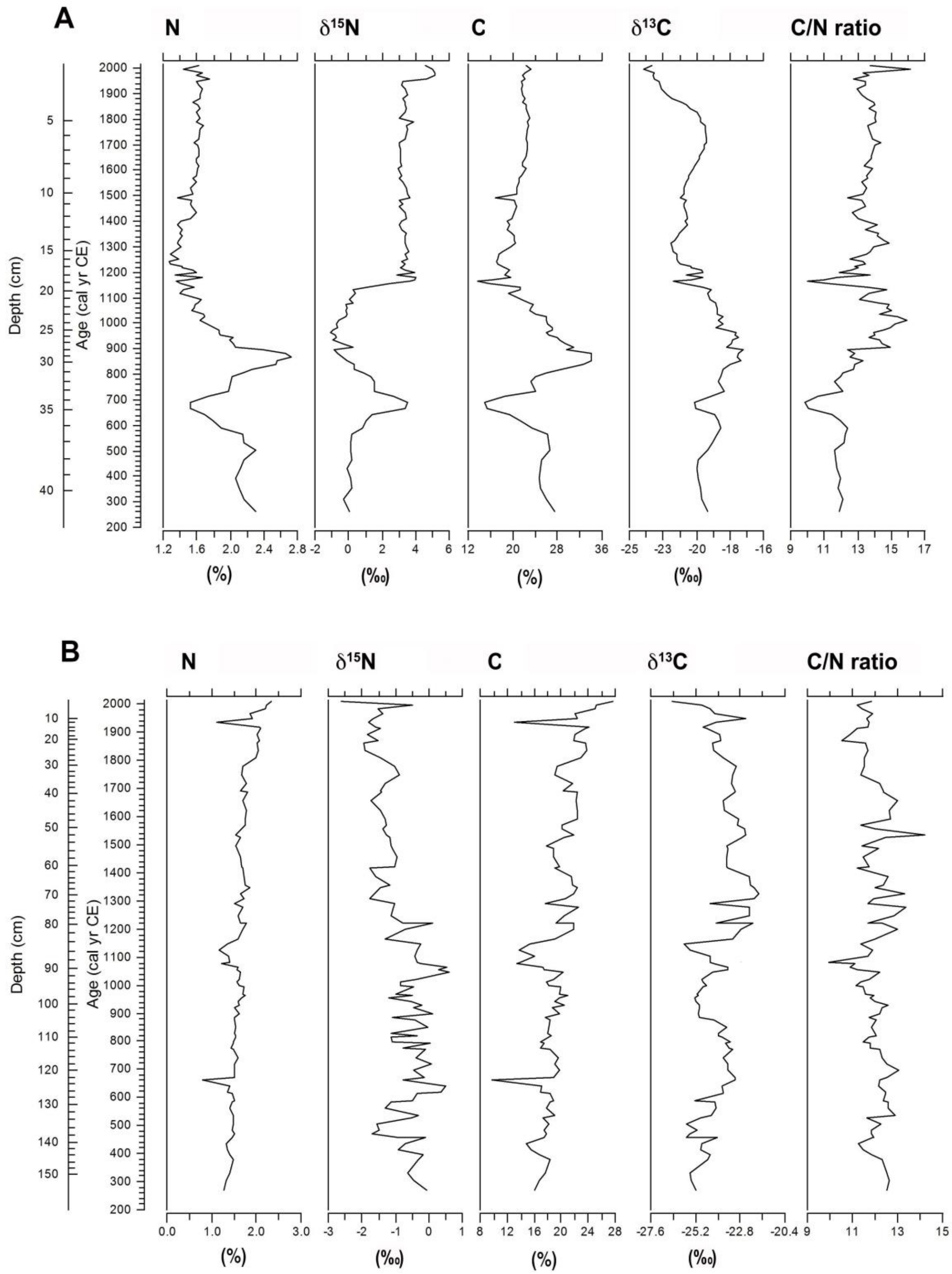


Figure 3.4 Sedimentary geochemistry for (A) MOR3C and (B) DKB spanning the last ~1700 years.

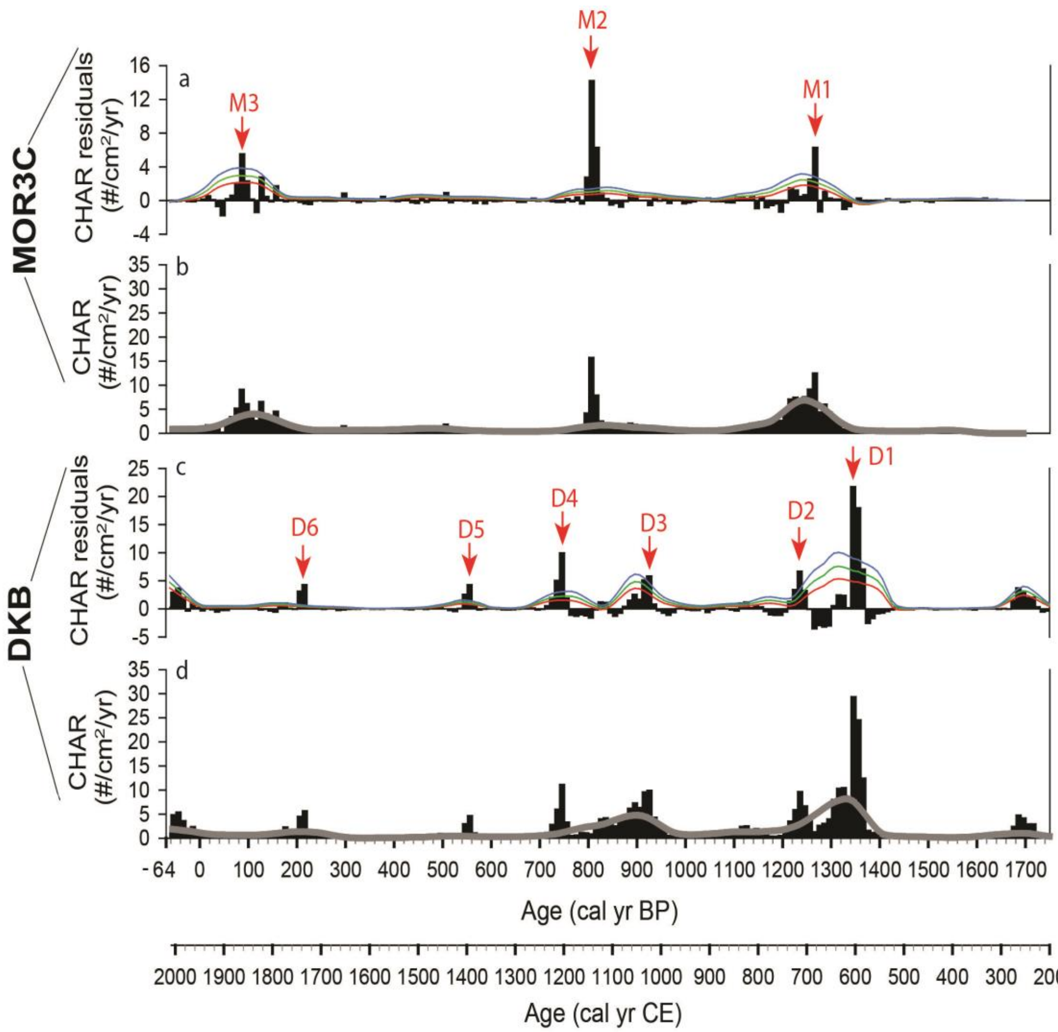


Figure 3.5 Comparison of charcoal (>125 µm) accumulation rate (CHAR) and the associated CharAnalysis result from MOR3C and DKB. The gray curves in b) and d) reflect the background charcoal ($C_{background}$). CHAR residuals = CHAR – $C_{background}$. The red, green and blue lines in a) and c) depict three distinct fire peak thresholds based on 0.90, 0.95 and 0.99 percentile cut-off of the Gaussian mixture model-based noise distribution (C_{noise}), respectively (see text for further details). Fire events with CHAR residuals exceeding the highest thresholds (blue curve) are identified as fire peaks in this study, and labeled with lake code and a fire peak number (e.g. D1 = first fire peak observed in the DKB core).

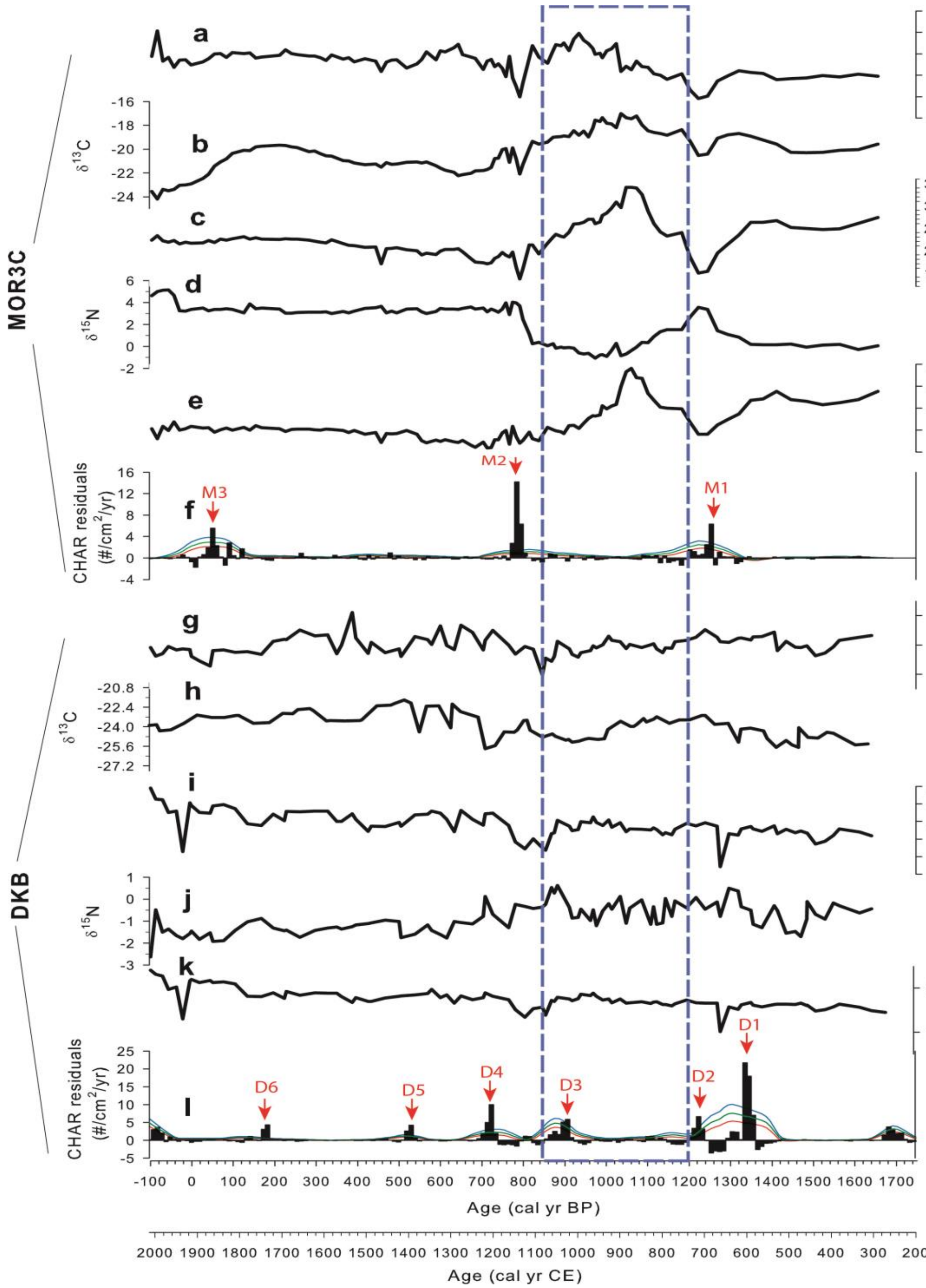


Figure 3.6 Plot of charcoal-based fire peaks and sediment geochemistry for MOR3C and DKB cores spanning the last ~1700 years. The interval characterized by notable variance in sediment geochemistry (~750-1100 CE) is framed in the blue box.

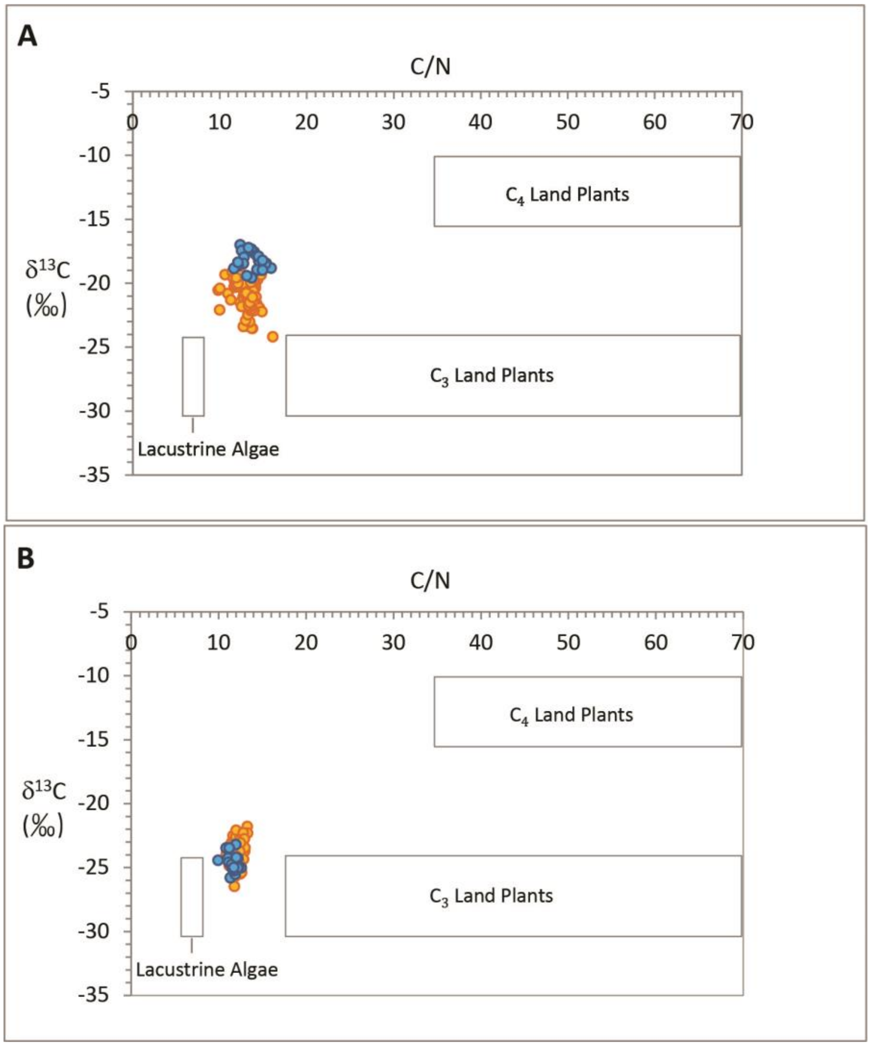


Figure 3.7 Stable carbon isotope ($\delta^{13}C$) and C/N values for A) MOR3C and B) DKB cores plotted against generalized $\delta^{13}C$ and C/N values of major sources of plant organic matter to lake sediments (taken from Meyers, 2003). Stable carbon isotope ($\delta^{13}C$) and C/N values observed during the interval ~750 to 1100 CE are depicted in blue.

CHAPTER 4

HYDROCLIMATE VARIABILITY IN COSTA RICA COEVAL WITH THE TERMINAL CLASSIC DROUGHT AND THE MEDIEVAL CLIMATE ANOMALY: LINKAGES WITH THE TROPICAL NORTH ATLANTIC[3]

[3] Wu, J., Porinchu, D.F., and Horn, S.P. To be submitted to *The Holocene*

4.1 ABSTRACT

In the northern tropical Americas, the interval between 800 and 1200 CE (~1150-750 cal yr BP) was characterized by a series of severe, spatially extensive droughts. However, there remains a paucity of paleoclimate records that can provide reliable estimates of terrestrial thermal variability during this period. Here, I present chironomid stratigraphies developed from sediment cores from two lakes: (1) Lago Morrenas 3C, a high-elevation lake (3492 m a.s.l.) located in glacial highlands on the Atlantic slope of central Costa Rica and (2) Laguna Zoncho, a mid-elevation lake (1190 m a.s.l.) located in the southern Pacific slope of Costa Rica. Distinctive shifts in the chironomid assemblages occurred at both sites between ~640 and 1230 CE (1310-720 cal yr BP). The results generated in this research indicate that chironomid taxa with low temperature optima largely replaced the thermophilous chironomid taxa at Lago Morrenas 3C between 640 and 1230 CE, reflecting an ~600-year interval of depressed temperatures. A more positive stable carbon isotope ($\delta^{13}C$) value between ~750 and 1100 CE (1200-850 cal yr BP), inferred to reflect the expansion of *Muhlenbergia*, a C_4 grass associated with cold, dry habitats, suggest that the high elevations of Costa Rica were likely characterized by decreased effective moisture and temperature during this interval. The absence of chironomid remains in Laguna Zoncho between ~730 and ~ 1110 CE (1220-840 cal yr BP) provides additional evidence of decreased effective moisture and lake drawdown. Taken together, evidence from these two lakes suggests that a mid-elevation site on the Pacific slope and the high-elevations on the Atlantic slope of Costa Rica experienced an interval of sustained drought coeval with the Terminal Classic Drought (TCD) and the onset of the Medieval Climate Anomaly (MCA). The timing of the hydroclimate variability evident in these records provides support for the hypothesis that cooling and drought in the northern tropical Americas during the TCD and early MCA interval are linked to the thermal conditions in the tropical North Atlantic.

4.2 INTRODUCTION AND LITERATURE REVIEW

A substantial and increasing number of paleoclimate and paleoenvironmental studies have documented the existence of notable climate variability during the last two millennia, particularly between ~500 and 1500 CE (e.g. Mann et al., 2008 and 2009; Graham et al., 2011; Douglas et al., 2016). A synthesis of high-resolution paleoclimate records provides evidence of elevated surface temperatures in the mid- and high latitude regions of the Northern Hemisphere between ~950 and 1250 CE. The Medieval Climate Anomaly (MCA) (~950-1250 CE) was likely marked by extended and persistent La Nina-like conditions, with depressed sea surface temperatures (SSTs) and reduced precipitation in the eastern tropical Pacific (Seager et al., 2007; Mann et al., 2008 and 2009; Graham et al., 2011). In the tropical Americas, the MCA interval overlaps with the termination of an event that is known regionally as the Terminal Classic Drought (TCD) (Hodell et al., 2005a). The TCD is characterized by a series of moderate to severe dry events which occurred between ~770 and 1100 CE (Hodell et al., 2005a). Evidence for these drought events are observed in other regional records from the northern tropical Americas (e.g. Curtis et al., 1996; Medina-Elizalde et al., 2010; Kennett et al., 2012; Lane et al., 2014). Among these studies, the highly resolved stalagmite $\delta^{18}O$ records from Yok Balum Cave, Belize indicated a drying trend between 660 and 1000 CE, followed by an extended severe drought from 1020 to 1100 CE (Kennett et al., 2012). These droughts have been considered as a crucial trigger for the socioeconomic “collapse” of Classic Maya civilization at ~ 1000 CE (Weiss and Bradley, 2001; Kennett et al., 2012; Medina-Elizalde and Rohling, 2012; Lane and Horn, 2013; Douglas et al., 2016), although, it is likely that the “collapse” of the Maya was a complex process involving a multitude of human-environment interactions (Aimers and Hodell, 2011; Luzzadder-Beach et al., 2012; Turner and Sabloff, 2012; Douglas et al., 2016).

Many of the high-resolution reconstructions of hydroclimate that identify the existence of severe and persistent drought during the TCD were conducted in the northern tropical Americas, with a particular focus on the Yucatan Peninsula (Curtis et al., 1996; Hodell et al., 2001; Rosenmeier et al., 2002; Haug et al., 2003; Hodell et al., 2005a; Webster et al., 2007; Medina-Elizalde et al., 2010; Kennett et al., 2012; Wahl et al., 2014; Douglas et al., 2015). Studies from elsewhere in the northern tropical Americas including southern Central America (Lachniet et al., 2004b) and northern South America (Haug et al., 2003; Moy et al., 2002), documented the existence of an extended drought interval that more closely matches the timing of the MCA. In addition, the hydroclimate fluctuations that characterize the interval between ~770 and 1250 CE in the tropical Americas appear to be highly spatially and temporally variable. For example, records from the Dominican Republic provide evidence of a dry TCD (Lane et al., 2014) and a wet MCA (Lane et al., 2011b). Moreover, there is a paucity of records documenting thermal variability between 500 and 1500 CE in the tropical Americas. Therefore, the relative influence of changing thermal conditions on hydroclimate in this region during the TCD and the MCA is poorly known. The heterogeneous response of the climate system to the forcings driving the changes observed during the TCD and MCA in the tropical Americas provides an outstanding research opportunity. The development of new high-resolution records of hydroclimate change in Costa Rica in Central America, will improve our understanding of regional climate dynamics and the mechanisms responsible for the observed changes in hydroclimate between ~500 and 1500 CE.

Existing paleoenvironmental research in Costa Rica has primarily focused on glacial history (Orvis and Horn, 2000; Lachniet and Seltzer, 2002) and documenting changes in vegetation, fire regimes, anthropogenic activity and hydrology during the late Quaternary (e.g. Horn 1989a and 1993; League and Horn, 2000; Clement and Horn, 2001; Lachniet et al., 2004; Lane et al., 2011a; Lane and Horn, 2013; Taylor et al., 2013ab; Horn and Haberyan, 2016; Wu et al., 2017). Highly resolved records of late Holocene paleoenvironmental change, specifically studies focusing on developing thermal reconstructions in Costa Rica remain limited. A recent study developed a quantitative reconstruction of late Holocene mean annual air temperature using sub-fossil chironomid assemblages preserved in a sediment core recovered from Laguna Zoncho, in southern Costa Rica (Wu et al., 2017). The paucity of sub-fossil chironomid remains in the Laguna Zoncho sediment core during the TCD and the MCA intervals precluded application of the chironomid-based temperature inference model established for Costa Rica (Wu et al., 2015). However, this study documented the occurrence of an interval of possible low lake level and reduced effective moisture between ~730 and 1110 CE (1220-840 cal yr BP), likely reflecting the influence of the TCD on regional hydroclimate.

To fill the gap in thermal reconstructions spanning the late Holocene in Costa Rica, particularly during the TCD and MCA intervals, I make use of the modern chironomid-environment relationship established in Costa Rica (Wu et al., 2015), and the results of the multi-proxy analysis of sediment cores, recovered from two lakes in Costa Rica, spanning an elevation range of 2311 m, to develop high-resolution hydroclimate reconstructions extending back to ~280 CE. These records are used to: 1) characterize the nature of hydroclimate and paleoenvironmental change along an elevation gradient in Costa Rica during the late Holocene, with specific attention paid to the TCD-MCA interval; 2) document the correspondence between the records developed in this study and existing paleoclimate and paleoenvironmental studies from the tropical Americas; and 3) assess the relationship between proposed driver(s) of hydroclimate variability and paleoenvironmental change in Costa Rica during the TCD-MCA interval. This study suggests that the TCD was characterized by depressed temperatures in southern Central America, and provides support for the hypothesis that changes in the thermal conditions in the tropical Atlantic can account for the extensive droughts observed during the turn of the 1st millennium in the northern tropical Americas.

4.3 STUDY SITE

Lago Morrenas 3C (9°29’44’’ N, 83°29’06’’ W; 3492 m a.s.l.; Horn et al., 2005) is a small, relatively shallow lake (depth = 2m), located in Valle de las Morrenas in Chirripó National Park (N.P.) (Fig. 4.1; Table 4.1). The bedrock underlying Morrenas 3C consists principally of granodiorite and other plutonic rocks of the Miocene-age Talamancan intrusive series (Haberyan et al., 2003). Lago Morrenas 3C is surrounded by typical páramo vegetation, which is a diverse and endemic mixed shrub, grass, and perennial herbaceous vascular plant assemblage of Andean origin (Luteyn, 1999; Kappelle and Horn, 2016). The páramo ecosystem in Chirripó N.P. extends from 3300 to 3819 m a.s.l. and is dominated by the dwarf bamboo *Chusquea subtessellata*, which covers up to 60% of the páramo in Costa Rica (Kappelle, 1991; Kappelle and Horn, 2016). *Muhlenbergia*, is the only C_4 native grass present in the páramo (Lane et al., 2011), with *M. flabellata*, the most common species, abundantly growing at the margin of Lago Morrenas 3C. *Muhlenbergia* is largely associated with microhabitats characterized by coarse substrate and relatively low moisture availability (Lane et al., 2011). *Muhlenbergia* can tolerate low temperatures (Schwarz and Redmann, 1988; Sage et al., 1999b) and is widely distributed in cold environments, including the boreal forest of Canada and in alpine settings in the Rocky Mountains (Sage et al., 1999b).

The meteorological data for Chirripó N.P. is available from the Cerro Páramo station (3,466 m a.s.l.; 9°33’41’’ N, 83°45’18’’W; Horn et al., 2005), which is located ~30 km west of Cerro Chirripó in the Buenavista páramo. This station provides meteorological data that is broadly representative for Chirripó N.P. (Horn, 1993). The mean annual air temperature (MAAT) and mean annual precipitation at Cerro Páramo between 1971 and 2000 was 8.5 °C and 2581 mm, respectively (Lane et al., 2011). The precipitation record from the Cerro Páramo station documents a distinct dry and wet season, with ~90% of the precipitation falling during the wet season, which occurs between May and November (Kappelle and Horn, 2016). The annual pattern of precipitation at Chirripó páramo is highly linked to the seasonal migration of the Intertropical Convergence Zone (ITCZ). Strong convective activity over Cerro Chirripó is observed when ITCZ moves to its northernmost position in the boreal spring and summer (Coen, 1983; Lane et al., 2011a). The Atlantic slope experiences intense rainfall between November and January; whereas, the Pacific slope experiences a dry season during the boreal winter, when the ITCZ is located in its southernmost position (Coen, 1983). The intense rainfall on the Atlantic side in December and January is generated by the extension of the polar trough southward and the associated intensification of cold fronts that result in cold air from the higher latitudes being pushed as far south as 10˚N. This cold air is forced upward along the windward slope of Cordillera Talamanca by the northeast trade winds, resulting in heavy orographic precipitation on the Atlantic slope with slightly less precipitation along the ridges (Coen, 1983). Therefore, the intensity of the dry season at the crest of the Cordillera Talamanca is tempered relative to lower elevations due to the elevated precipitation falling at the high-elevations along the Atlantic slope and at the crest, where Lago Morrenas 3C is located. However, intervals of cloud-free weather associated with the trade wind inversion during the dry season could lower humidity sufficiently to support fires (Horn, 1993; Horn and Kappelle, 2009).

4.4 METHODS

In July 2014, a 40.5 cm sediment core was recovered from the center of Lago Morrenas 3C (MOR3C) using a DeGrand maxi-corer. The sediment was sectioned at 0.25 cm intervals in the field, stored in Whirl-paks and transported back to the Environmental Change Lab (ECL) in the Department of Geography at the University of Georgia. The sediment samples were stored in a refrigerator at 4 °C in the ECL. Surface water temperature, pH, conductivity and dissolved oxygen were measured during fieldwork.

Chronological control for the lake sediment core from Lago Morrenas 3C (MOR3C) is based on seven AMS radiocarbon dates obtained on charcoal fragments (Table 4.1). The radiocarbon dates were converted to calendar years using the IntCal13 calibration curve (CALIB 7.10: calib.org/calib/calib.html; Reimer et al., 2013), with the exception of the "modern" date (pMC=100.68%, error=1.03) sampled between 5.75 and 7.5 cm, which was calibrated using Bomb CALIB (http://calib.org/CALIBomb/). The relative area of the ± 2σ age range and the corresponding median probability age is reported relative to CE or cal yr BP for each radiocarbon date. The age-depth model for MOR3C core is based on a probability sampling method implemented using Clam 2.2 (Fig. 4.2; Blaauw, 2010). A median age of 71 cal yr BP ±77 yr was utilized for the "modern" date in the Clam age-depth model. Two radiocarbon dates (UGAMS#23001, UGAMS#28490; marked in red in Table 4.2) were not incorporated in the final Clam age-depth model for MOR3C (red dots with calibrated median age labeled in Fig. 4.2). The date of 990 ^{14}C yr ± 25 yr obtained on the charcoal sample dated at 10.375 cm is considered anomalously old. This sample likely persisted on the landscape following a fire episode and was transported to the lake hundres of years later. The anomalously young date obtained on a charcoal fragment at 14.25 cm is likely related to the potentially large influence of young carbon when dating a sample based on eight merged sample bags with relatively low mass (~300 μg). Radiocarbon analyses were conducted at the Center for Applied Isotope Studies (CAIS) at the University of Georgia.

Chironomids are sensitive to temperature (Porinchu and McDonald, 2003), and the existence of a strong relationship between chironomid distribution and air and water temperature has been documented in the low, mid- and high latitudes of the Northern Hemisphere (e.g. Fortin et al., 2015; Porinchu et al., 2010; Wu et al., 2015). Sub-fossil chironomids were processed and analyzed following standard procedures (Walker, 2001). A known volume of sediment (3-5 ml) was placed in a beaker with 50 ml of 5% KOH and heated at 50°C for approximately 30 minutes.

The KOH treatment facilitates the break-up of colloidal matter. The deflocculated sediment was washed through a 95μm mesh and rinsed using distilled water. The material retained on the mesh was backwashed into beaker. A dissection microscope at 50X and a Bogorov plankton counting tray were used to separate the chironomid head capsules from the sediment matrix. The chironomid head capsules were permanently mounted on slides in Entellan® for identification. A minimum of 50 chironomid head capsules was identified from each sample (Heiri and Lotter, 2001). Taxonomic identification was conducted at 400X, typically to genus, relying primarily on Wu et al. (2015) and larval keys for Florida and North and South Carolina (Epler, 1995 and 2001), with Brooks et al. (2007), Cranston (2010), Eggermont et al. (2008) and Spies et al. (2009) providing additional diagnostic information. Chironomid percentage diagrams, plotted using C2 (Juggins, 2003), were based on the relative abundance of all identifiable chironomid remains. Sub-fossil chironomid remains were analyzed at sub-decadal to multi-decadal resolution (~25 yr/sample). Constrained cluster analysis, implemented using the rioja package in R, was used to derive zones for the sub-fossil chironomid stratigraphy (Juggins, 2017; http://cran.r-project.org/package=rioja). Shifts in the composition of the sub-fossil chironomid assemblages were assessed using detrended canonical correspondence analysis (DCCA).

4.5. RESULTS

A total of 14 chironomid taxa were identified in 62 samples in MOR3C core (Fig. 4.3), with all of the taxa present in MOR3C found in the modern training set (Wu et al., 2015). The sub-fossil chironomid remains, which were well preserved in the MOR3C sediment core, varied in concentration between 2.7 and 81 head capsules/cm^3. The taxonomic richness of the chironomid assemblages ranged between 3 and 7 during the last 1700 years. The greatest variation in taxon richness occurred between ~1200 and 1500 CE, and limited change in richness is observed between ~280 and 800 CE. The chironomid stratigraphy is divided into three statistically significant zones (MOR3C-1 to 3). The chironomid assemblage in MOR3C core is dominated by four taxa: *Paratanytarsus*, *Tanytarsus* type LU, *Procladius* and *Psectrocladius.*

In MOR3C-1 (280 - 640 CE; 40.5-34.5 cm) the chironomid assemblage is dominated by three taxa, *Paratanytarsus*, *Tanytarsus* type LU and *Procladius*. *Paratanytarsus* comprises approximately half of the identifiable chironomids in this zone, reaching a core maximum of 65% at ~ 570 CE. *Tanytarsus* type LU and *Procladius* comprise ~20% and 15% of the chironomid assemblage, respectively. *Psectrocladius* is also present throughout this zone, albeit with a relatively low abundance, averaging ~ 5% of the identifiable remains. Other chironomid taxa, e.g. *Cricotopus/Orthocladius* and *Limnophyes,* are intermittently present, increasing in relative abundance at the termination of MOR3C-1. Head capsule concentration fluctuates notably in MOR3C-1, ranging from 16.3 to 66.8 head capsules/ml. The DCCA scores indicate that the rate of faunal turnover gradually increases through this zone, with taxon richness experiencing limited variability in MOR3C-1.

MOR3C-2 (640 - 1230 CE; 34.5-16.25 cm) is characterized by a large increase in relative abundance of *Psectrocladius* and *Procladius* and an accompanying reduction in the relative abundance of *Paratanytarsus* and *Tanytarsus* type LU. *Psectrocladius* and *Procladius* comprise ~ 25% and 45% of the chironomid assemblages in MOR3C-2, respectively. The relative abundance of *Paratanytarsus* and *Tanytarsus* type LU decreases to ~20% in this zone. Seven additional taxa, *Polypedilum* N type, *Micropsectra contracta* type, *Smittia/Pseudosmittia*, *Cricotopus/Orthocladius*, *Corynoneura/Thienemanniella*, *Synorthocladius* and Unknown ii are present in MOR3C, albeit at low levels. Of these taxa, only *Cricotopus/Orthocladius*, is present consistently throughout this zone. Head capsule concentration varies from 10.6 to 81 head capsules/ml (average = 26.6 head capsules/ml) in this zone. DCCA scores increase at the beginning of MOR3C-2, indicating an increase in faunal turnover at approximately 640 CE; the remainder of this zone is characterized by muted faunal change. Taxon richness increases in MOR3C-2, with a maximum richness of seven occurring at 900 CE and 1100 CE.

Notable turnover in the chironomid assemblages is detected in MOR3C-3 (1230 CE-the present; 16.25-0 cm). The relative abundance of *Psectrocladius* abruptly decreases at ~1230 CE, along with a large increase in *Paratanytarsus*, followed by an increase in *Tanytarsus* type LU at 1400 CE. The relative abundance of *Psectrocladius* drops from ~25% in MOR3C-2 to ~1% in MOR3C-3. *Paratanytarsus* and *Tanytarsus* type LU increase, comprising ~30% and 20% of the chironomid assemblage in MOR3C-3. However, the relative abundance of both taxa begins decreasing following 1500 CE. The amount of *Procladius*, which gradually decreases after the termination of MOR3C-2, begins to progressively increase from ~40% to 60% of the identifiable chironomid remains in the uppermost portion of the core. The increase in *Procladius* is coincides with decreases in *Paratanytarsus and Tanytarsus type LU*. *Chironomus* appears for the first time in this zone. *Smittia/Pseudosmittia*, *Cricotopus/Orthocladius*, *Thienemannella/Corynoneura*, *Synorthocladius* and Unknown ii, present in MOR3C-2, remain extant in MOR3C-3, although the relative abundance of *Cricotopus/Orthocladius* is greatly reduced. Head capsule concentration is lower than MOR3C-1 and MOR3C-2 with an average of ~16 head capsules/ml and a maximum of 55 head capsules/ml, observed at ~1470 CE. The DCCA documents notable compositional turnover at ~1230 CE, with the remainder of MOR3C-3 characterized by limited faunal turnover. Taxonomic richness varies between three and seven in this zone, with high variability in taxonomic richness occurring between 1300 and 1450 CE.

4.6 DISCUSSION

4.6.1 Chironomid-based reconstruction of late Holocene thermal conditions at Lago Morrenas 3C

The chironomid assemblage observed in MOR3C-1 (280-640 CE) is dominated by three taxa, *Paratanytarsus*, *Tanytarsus* type LU and *Procladius* (Fig. 4.3). In Costa Rica, *Paratanytarsus* and *Tanytarsus* type LU are restricted to low and mid-elevation lakes characterized by moderate to high MAAT and conductivity (Wu et al., 2015). The MAAT optima for *Paratanytarsus* and *Tanytarsus* type *LU* are 22.3 °C and 22.4 °C, respectively. The MAAT optima for these two taxa are amongst the highest of all the taxa present in the training set (Wu et al., 2015). *Procladius* is considered an indicator of cold conditions, with an MAAT optimum of 14.9 °C (Wu et al., 2015). *Psectrocladius*, which is present in MOR3C-1, is also associated with a very low MAAT optimum (10.4°C) (Wu et al., 2015). The predominance of thermophilous chironomid taxa in MOR3C-1 suggests that the interval between ~280 and 640 CE was characterized by relatively high temperature. The increase in the relative abundance of *Psectrocladius* and *Procladius* at ~640 CE is inferred to represent the onset of an extended interval of low temperatures. Today, *Psectrocladius* and *Procladius* are most abundant in cold, high-elevation lakes, and largely restricted to the glacial lakes located in the Chirripó páramo (>3400 m a.s.l.), with an average MAAT of 7.7°C (Wu et al., 2015). *Psectrocladius* inhabits the littoral zone and is often associated with aquatic macrophytes (Brook et al., 2007). *Procladius*, a benthic taxon most often found in the profundal of lakes (Brooks et al., 2007; Cranston, 2010; Epler, 1995 and 2001; Spies et al., 2009), is very abundant (>60%) in the glacial lakes of varied depth (0.3-22 m) that have been sampled in Chirripó N.P. (Wu et al., 2015). Six additional cold indicator taxa, *Smittia/Pseudosmittia*, *Corynoneura/Thienemanniella*, Unknown ii, *Cricotopus/Orthocladius*, and *Synorthocladius*, associated with high-elevation lakes and low

MAAT in Costa Rican modern training set, are also found in MOC3C-2 (Wu et al., 2015). *Cricotopus*/*Orthocladius* and *Synorthocladius* are most common in the littoral zone, with *Cricotopus*/*Orthocladius* favoring macrophytes (Cranston, 2010). *Smittia/Pseudosmittia* is primarily associated with terrestrial/semi-terrestrial habitats (Spies et al., 2009) and Unknown ii is only found in relatively shallow lakes (<3 m) (Wu et al., 2015). The high relative abundance and diversity of cold-indicator chironomid taxa together with the notable decrease in thermophilous taxa is inferred to reflect the influence of cooler conditions between ~640 and 1230 CE. The presence of taxa associated with shallow lakes, the littoral zone and macrophytes, including terrestrial/semi-terrestrial taxa, implies the occurrence of lower lake levels, with a possible expansion of aquatic macrophytes during this interval. Taken together, MOR3C-2 (~640-1230 CE) appears to represent a cold and relatively dry interval, with the maximum drought occurring between ~900 to 1050 CE. The increase in the thermophilous taxa, *Paratanytarsus* and *Tanytarsus* type LU, and the decrease in the cold-indicator taxa, *Procladius* and *Psectrocladius*, is inferred to reflect the onset of warmer conditions, initially beginning at ~1230 CE and peaking at ~1500 CE. The increase in *Procladius* at ~1550 CE signals the re-arrival of cooler conditions. The decrease and/or absence of many of the littoral and terrestrial/semi-terrestrial chironomid taxa, between ~1230 and 1750 CE, suggests Lago Morrenas 3C experienced an increase in effective moisture, resulting in higher lake levels and greater volume.

4.6.2 Late Holocene hydroclimate variability along an elevation gradient in Costa Rica

Similar patterns of climate and environmental change are found at Lago Morrenas 3C and Laguna Zoncho for the past 2000 years (Fig. 4.4AB). For example, the composition of the chironomid assemblage in MOR3C core suggests that the interval from 280 to 640 CE (1670-1310 cal yr BP) is characterized by elevated temperature. This interval is also characterized by low $\delta^{13}C$ value, extremely reduced charcoal accumulation rates (CHAR) and no significant fire events (Fig. 4.4A). The chironomid, $\delta^{13}C$ value and charcoal data, together suggest that the interval between 280 and 640 CE in the high elevations of Chirripó N.P. was relatively warm and wet. The mean of chironomid-inferred MAAT at Laguna Zoncho between 280 and 640 CE is 0.4 ºC above the late Holocene average (21.3°C) (Fig. 4.4B; Wu et al., 2017). The limited abundance of the benthic diatom, *Aulacoseira sp* 3, implies a lowering lake level of Laguna Zoncho during the same interval (Haberyan and Horn, 2005). The more positive $\delta^{13}C$ values in Laguna Zoncho core occurring coincidently with the reduction in *Aulacoseira* sp 3, are inferred to reflect the increasing abundance of C_4 plants and grasses, such as *Zea mays* and *Poaceae* which favor drier habitats (Lane et al., 2004). However, there appears to be little correspondence between the charcoal records at two sites; the elevated charcoal concentration during this time at Laguna Zoncho is likely related to anthropogenic activities, i.e. land clearance (Clement and Horn, 2001).

Notable changes in climate and environmental conditions are evident at both Lago Morrenas 3C and Laguna Zoncho between 640 and 1230 CE (~1310 -720 cal yr BP). Cool climate indicators at high abundance dominate the chironomid assemblage in MOR3C core during this interval, with concurrent presence of littoral and terrestrial/semi-terrestrial types. This likely reflects the onset of rapid cooling and lower lake levels (Fig. 4.4A). The relatively high abundance of *Smittia/Pseudosmittia* and Unknown ii suggests that lake drawdown was greatest at ~950 CE (1000 cal yr BP). Increased $\delta^{13}C$ values observed between 750 and 1100 CE (1200 and 850 yr BP) is inferred to represent the expansion of the C_4 grass, *Muhlenbergia,* in response to cool, dry conditions at this time. The severe fires documented at 680 CE and 1150 CE, which broadly bracket the TCD-MCA, also occur during this cool, dry period. At Laguna Zoncho, the chironomid-inferred estimate of thermal conditions (Wu et al., 2017) indicates that MAAT decreased ~1.9°C, relative to the late Holocene average, sometime between ~550 CE (1400 cal yr BP) and ~650 CE (1300 cal yr BP). The lack of quantitative chironomid-based estimates of MAAT for the interval from 730 to 1110 CE (1220-840 cal yr BP) is due to the near absence of well-preserved chironomid head capsules during this interval. The lack of sub-fossil chironomid remains, together with the limited abundance of *Aulacoseira sp* 3 (a benthic diatom type), suggest Laguna Zoncho was characterized by a notable drop in lake level, resulting in a greatly reduced pool of standing water between 730 to 1110 CE (1220-840 cal yr BP) (Wu et al., 2017).

The chironomid stratigraphy from MOR3C-3, suggests that the interval between 1230 and 1550 CE was characterized by rising temperature, with MAAT initially beginning to rise at ~1230 CE and peaking at ~1550 CE. Together with co-occurred moderate level of *Procladius*, a cold climate indicator, it suggests the climate was moderate to warm from 1230 to 1550 CE. The absence and/or relatively low abundance of littoral and terrestrial/semi-terrestrial chironomids likely reflect the influence of increasing effective moisture and lake level. Wildfires, which are effectively absent during this interval, support the chironomid-based inference of wetter conditions (i.e. fuel was too wet to ignite). A decreasing MAAT trend starting at ~1550 CE at Lago Morrenas 3C is inferred by the concurrent increase in *Procladius* and decrease in *Paratanytarsus* and *Tanytarsus* LU type. At Laguna Zoncho, chironomid-inferred MAAT indicates an interval of moderate MAAT between ~1200 and 1550 CE, followed by an extended interval of below average MAAT beginning at ~1550 CE. The increase in the benthic diatom, *Aulacoseira sp* 3, that begins at 1550 CE likely reflects the onset of an interval characterized by increased effective moisture (Clement and Horn, 2001; Haberyan and Horn, 2005; Wu et al., 2017). The reduction in MAAT and increase in effective moisture that is inferred to have occurred at Laguna Zoncho and Morrenas 3C between ~1550 CE and the present provides evidence of the manifestation of the Little Ice Age (LIA) in the southern Central America.

The patterns of response at Laguna Zoncho and Lago Morrenas between ~750 and 1100 CE are similar, although these two study sites span an elevation range of ~2300 m. The interval between ~640 and 1230 CE (1310-720 cal yr BP) is characterized by a notable cold condition in the high-elevation páramo of Chirripó N.P. and depressed MAAT or low head capsule recovery of chironomids at the mid-elevations in southern Costa Rica. In addition, it appears that mid- and high-elevation regions in Costa Rica respond to climate forcing in a similar way during the last ~1700 years: relatively high temperatures between ~280 and 640 CE (1670-1310 cal yr BP), moderate temperatures between ~1230 and 1550 CE (720 to 400 cal yr BP), and the onset of cooling at ~1550 CE (400 cal yr BP). The multi-proxy records developed for both lakes provide a relatively consistent picture of hydroclimate variability during the TCD and the early interval of MCA. The composition of the chironomid community and the $\delta^{13}C$ values provide evidence for a reduction in effective moisture and low lake level between ~750 and 1100 CE (1200 and 850 cal yr BP) at Lago Morrenas 3C, which corresponds to the drought at Laguna Zoncho between ~730 and 1110 CE (Wu et al., 2017).

The basin features and geographic location of these two lakes may explain their sensitivity to climate and environmental change during the late Holocene. Laguna Zoncho and Lago Morrenas 3C are both small (area < 1 ha), shallow lakes (depth ~ 2 m; Horn and Haberyan, 2016)(Table 4.1; Fig. 4.1). The drought that characterized the interval spanned by the TCD and the MCA at Laguna Zoncho appears to be more severe than the hydroclimate change observed at Lago Morrenas 3C. The near absence of sub-fossil chironomid head capsules between ~730 and 1110 CE (1220-840 cal yr BP) is inferred to reflect the near desiccation of the Laguna Zoncho basin (Wu et al., 2017). The timing and amount of precipitation in Costa Rica is driven by the 1) equatorial low-pressure trough (seasonal migration and geographic extent of ITCZ), 2) strength of the trade winds, and 3) the southward penetration of the polar front during boreal winter (Coen 1983; Bunndschul and Alvarado, 2007). The interaction of these three factors results in the length and intensity of the wet season in Costa Rica being greater along the Atlantic side of the Cordillera, relative to the Pacific slope (Coen, 1983). In general, the mid- to low elevation sites located on the leeward slope or the Pacific slope of the Cordillera are drier relative to sites located at the ridges and on the windward side or the Atlantic side (Coen, 1983). The Atlantic slope experiences intense precipitation from November to January, which is related to the arrival of the polar front, increased frontal activity and enhanced orographic precipitation during northern winters (Coen, 1983). The cold air masses, which are entrained by the prevailing northeast trade winds and forced over the Talamanca range, produce little rainfall on the Pacific slope from December to January when ITCZ is located in Southern Hemisphere (Coen, 1983). However, the difference in precipitation regimes is minimized along the crest of the Cordillera. The dry season at Lago Morrenas is less pronounced relative to the middle-elevations of the Pacific side of the crest of the Cordillera, where Laguna Zoncho is located, because of the elevated amounts of precipitation that occur along the windward slope in response to the polar trough and orographic-induced precipitation (Coen, 1983). Additionally, high cloud cover limits evaporation during most much of the year could contribute to retain moisture at Lago Morrenas 3C site during dry seasons.

4.6.4 Signature of the hydroclimate change in the northern tropical Americas between ~500 and 1500 CE

Existing proxy-based reconstructions of late Holocene hydroclimate records generally support occurrence of climate-mediated paleoenvironmental disturbance between ~500 and 1500 CE in the northern tropical Americas (e.g. Curtis et al., 1996; Huag et al., 2003; Lachniet et al., 2004; Hodell et al., 2005; Lane et al., 2011b; Kennett et al., 2012; Douglas et al., 2016; see Table 4.3 for more details). Earlier research focusing on reconstructing vegetation dynamics and the fire history of the páramo in Chirripó N.P. documented the occurrence of severe drought, lower lake levels and intense wildfire at approximately 1100 CE (Horn, 1989a; Horn, 1993). The timing of the more positive $\delta^{13}C$ values evidenced in MOR3C core, which could reflect the expansion of the C_4 grass, *Muhlenbergia flabellate*, closer to the core site due to a reduction in lake level, is coeval with the changes reported in Horn (1989a and 1993). However, recent studies using the

$\delta^{13}C_{C27-C33}$ and δD_{25-33} of n-alkanes from Lago Morrenas 1 suggest that Valle de las Morrenas was characterized by mesic conditions between ~550 and 1150 CE (1400-850 yr BP) (Lane et al., 2011a; Lane and Horn, 2013). Limited chronological control and low sampling resolution of the late Holocene portion of the core precludes a direct comparison of the Lago Morrenas 1 and Lago Morrenas 3C records. Taylor et al. (2013a) analyzed $\delta^{13}C$ and organic carbon content of sediment core recovered from Laguna Zoncho and identified a notable decline in agricultural activities in southern Costa Rica between ~1100 and 1310 CE (850 to 640 cal yr BP). This decline, which predates the arrival of the Spanish by approximately 200 years, was inferred to reflect the influence of regional drought on agriculture.

Though relatively limited in Costa Rica, a number of well dated, high-resolution proxy-based paleoenvironmental and paleoclimate studies spanning the TCD and MCA have been conducted elsewhere in the northern tropical Americas, particularly in Mexico and Belize. Bhattacharya et al. (2017) synthesize the results of existing paleoenvironmental studies and provides robust evidence for severe drying in Mesoamerica between ~800 and 1200 CE, with the sites experiencing severe drought clustered in southern Central America. The majority of these studies, which make use of speleothems and lake and marine sediments, and various proxies including, stable isotopes, sediment geochemistry, biomarkers and flora and faunal remains, focus on exploring the relationship between hydroclimate variability and cultural phases of Maya civilization during the TCD and MCA (Table 4.3). The results of these existing studies have been synthesized and plotted to illustrate the spatiotemporal pattern of hydroclimate variability for the interval between 500 and 1500 CE (1450 and 450 cal yr BP) (Fig. 4.5). Notable drought is identified as occurring between 500 and 1300 CE (1450 to 650 cal yr BP) in central and southern Mexico, Belize, Guatemala, Nicaragua, Costa Rica, Panama and the western Dominican Republic. The precise timing of drought and environmental change that occurred during the termination of the 1st millennium is temporally variable. However, the majority of sites in the northern tropical Americas record a drought interval centered between ~750 and 1200 CE (1200 and 750 cal yr BP) (Fig. 4.5B). The dry interval identified in Costa Rica between 750 and 1100 CE (1200-850 cal yr BP), coincides well with dry conditions at Punta Laguna in Mexico (Curtis et al., 1996), Lake Chichancanab in Mexico (Hodell et al., 2005) and Yok Balum Cave in Belize (Kennett et al., 2012). Proxy and model based reconstructions have identified that existence of persistent La Niña-like conditions, characterized by lowered SSTs and concurrent drought in the eastern tropical Pacific and Mesoamerica between ~950 and 1250 CE (Seager et al., 2007; Mann et al., 2008 and 2009; Graham et al., 2011). However, hydroclimate conditions during this interval are spatially heterogeneous with studies from western Cuba (Fensterer et al., 2012), the Dominican Republic (Lane et al., 2011b), Barbardos (Ouellette, 2013), Cariaco Basin (Huag et al., 2003) and Panama (Lachniet et al., 2004), suggesting the existence of wetter conditions, or alternating wet/dry cycles (e.g. Cariaco Basin, Haug et al., 2003; Panama, Lachniet et al., 2004). In addition to the observed changes in hydroclimate, notable changes in SSTs and terrestrial MAATs are also documented during this interval. A decrease in SSTs is observed in the western and southeastern Caribbean from 900 to 1200 CE (1050-750 cal yr BP) (Site 12 in Fig. 4.5; Sorey, 2014) and from 800 to 1200 CE (Site 22 in Fig. 4.5; Tedesco and Thundell, 2003), respectively. Terrestrial cooling is detected in the páramo of Chirripó N.P., Costa Rica from 640 to 1230 CE (1310-720 cal yr BP) (Site 27 in Fig. 4.5; this study).

4.6.5 Drivers of hydroclimate change in Costa Rica during the TCD and MCA

The TCD-MCA interval (~770-1250 CE) was characterized by a spatially heterogeneous response, although it is generally associated with warmer conditions in the Northern Hemisphere (Hughes and Diaz, 1994; Mann et al., 2008). Global climate conditions at the turn of the 1st millennium are believed to reflect the influence of enhanced solar activity and reduced volcanic activity (Mann et al., 2005; Haltia-Hovi et al., 2007; Cook et al., 2010). However, the forcing of regional climate during the TCD-MCA interval is still not fully understood, with the cause(s) of the observed hydroclimate anomalies in the northern tropical Americas between ~500 and 1500 CE debated for decades (e.g. Jones et al., 1999; Goosse et al., 2004; Diaz et al., 2011). The general trends highlighted in global-scale synthesis (e.g. Mann et al., 2009) often mask the heterogeneous response of the climate system at finer spatial scales (Giorgi and Avissar, 1997). Consequently, these studies are not sufficient for describing possible future conditions at regional and sub-regional scales. Improving our understanding of regional climate dynamics, as well as recognizing the importance of spatial variability in controlling regional patterns, will significantly improve our ability to model regional response to future climate forces (Cubasch et al., 2001; Giorgi et al., 2001; Radić et al., 2014). Comparing the late Holocene proxy records of hydroclimate change from Costa Rica developed in this study to existing research provides the opportunity to assess the various mechanisms that have been invoked to account for climate and environmental change in Mesoamerica between ~500 and 1500 CE.

A link between variations in the strength of Atlantic Meridional Overturning Circulation (AMOC) and hydroclimate variability in Mesoamerica has been proposed (Enfield and Alfaro, 1999; Giannini et al., 2000). A glacial-melt water mediated decrease in the density of North Atlantic water, in response to ice-rafted debris events, such as the Bond events (Fig. 4.6f), would reduce the strength of AMOC due to increased freshwater input at the loci of North Atlantic Deep Water (NADW) formation (Bond et al., 1997; Bianchi and McCave, 1999; Keigwin and Boyle, 2000). A reduction in the strength of AMOC would result in the decreased northward transport of warm tropical water in the Atlantic, facilitate the development of an anomalously warm pool in the Caribbean and change the sea temperature gradient in the Atlantic (Bond et al., 1997; Bianchi and McCave, 1999; Keigwin and Boyle, 2000; Bond et al., 2001). The resulting increase in SST gradient would indirectly force the ITCZ to migrate southward, resulting in drought in the northern tropical Americas and Caribbean (Enfield and Alfaro, 1999; Giannini et al., 2000).

However, the timing of the ice drifting events in the North Atlantic appear to have limited overlap with the dry intervals (~750-1100 CE) identified in Costa Rica and elsewhere in the northern tropical Americas, and these ice drifting events occurred during an interval of anomalously low SSTs in the Caribbean (Table 4.3 and Fig. 4.5; site 22: Tedesco and Thundell, 2003; site 12: Sorey, 2014), suggesting that variability of AMOC strength may not be the primary driver of drought in the northern tropical Americas between ~750 and 1100 CE.

The existence of an interoceanic temperature gradient between the eastern tropical Pacific and the tropical North Atlantic has also been invoked to explain the observed hydroclimate variability broadly between ~600 and 1200 CE in the northern tropical Americas (Enfield and Alfaro, 1999; Giannini et al., 2000; Taylor et al., 2002; Wahl et al., 2014). Meteorological data indicates that summer precipitation in the Caribbean and in Central America decreases when the tropical Atlantic is anomalously cool and the eastern tropical Pacific is anomalously warm (Enfield and Alfaro, 1999; Giannini et al., 2000). Douglas et al. (2015 and 2016) and Lachniet et al. (2017) hypothesize that a SST gradient, associated with El Nino-like conditions, between the Atlantic and the Pacific basins could result in the hydroclimate anomalies observed in Mesoamerica during the TCD and MCA. However, proxy-based reconstructions of late Holocene ENSO activities in the Galapagos Island (Fig. 4.6g; Conroy et al., 2008) and Ecuador (Fig. 4.6h; Moy et al., 2002) do not provide support for an increase in the number of El Niño events (warm anomalies) in the eastern tropical Pacific during the TCD-MCA interval. In addition, climate model simulations utilizing paleoclimate proxy data suggest the existence of La Niña-like conditions characterized by depressed SSTs in the eastern tropical Pacific, between ~950 and 1250 CE (Seager et al., 2007; Mann et al., 2008 and 2009). Unfortunately, the limited number of high-resolution SST reconstructions for the eastern tropical Pacific inhibits a thorough test of the hypothesis that droughts between ~600 and 1200 CE in Mesoamerica are driven by the existence of an interoceanic temperature gradient between the eastern tropical Pacific and the tropical North

Atlantic.

Recently, Bhattacharya et al. (2017) identified a mechanism that can account for the spatiotemporal pattern of widespread drought observed in the northern tropical Americas and the anomalous cooling in the tropical North Atlantic between ~600 and 1200 CE. Bhattacharya et al. (2017) identified two intervals that were characterized by a statistically significant probability of widespread drought in the northern tropical Americas: 400-600 CE and 800-1200 CE. General circulation model (GCM) simulations highlight the influence of SSTs in the tropical North Atlantic on the spatial pattern of hydroclimate variability during these two drought intervals. Anomalously low SSTs in the tropical North Atlantic lead to decreased evaporation and reduced boundary layer moisture over the Caribbean. Stronger easterly trade winds would further contribute to cooling as a result of a positive wind-evaporation-SST feedback (Xie and Carton, 2004). Stronger easterly winds together with reduced boundary layer moisture would facilitate stronger moisture divergence, with moisture transport increasing towards the northern Gulf of Mexico but decreasing in the circum-Caribbean. The effect of depressed SSTs in the tropical North Atlantic on the North Atlantic Subtropical High (NASH), trade wind strength and boundary layer moisture transport coupled with wind-evaporation-SST feedback led to a distinct dipole pattern with northern Mexico getting wetter and southern central America getting drier generally from 600 to 1200 CE (Bhattacharya et al., 2017).

Analysis of the instrumental record identifies the existence of a dipole pattern in precipitation in this region associated with the negative phase of the Atlantic Multidecadal Oscillation (AMO) and the positive phase of the North Atlantic Oscillation (NAO) (Fig. 4.7; Bhattacharya et al., 2017). The negative phase of the AMO, defined by negative SST anomalies (SST cooling) in the tropical North Atlantic and intra-America seas, results in reduced evaporation, a decrease in boundary layer moisture and suppresses convection and tropical storm formation in over southern Central America and northern South America (Mestas-Nuñez et al., 2007). The positive phase of NAO, which is characterized by an enhanced sea-level pressure (SLP) gradient between the Icelandic Low and the North Atlantic Subtropical High (NASH), results in a stronger NASH and easterly tradewinds, lower SSTs and reduced atmospheric humidity, leading to drying over the intra-America seas and southern Central America (Giannini et al., 2000; Hurrell and Deser, 2010). The suggestion that the interval between ~600 and 1200 CE was characterized by a positive NAO is supported by a study documenting that NAO values ranged from 1 to 2.5 between 600 and 840 CE and 900-1050 CE (Fig 4.6i; Olsen et al. 2012). This hypothesis is also supported by model simulations, suggesting that lower SSTs, a stronger NASH, and stronger easterly winds and reduced boundary layer moisture transport can account for the dry conditions observed in southern Central America during the last two millennia (Bhattacharya et al., 2017).

Another mechanism proposed to explain the severe droughts generally between 500 and 1500 CE in the northern tropical Americas relates to the migration of the ITCZ. Typically, today a more southerly (northerly) positioned ITCZ is associated with drier (wetter) conditions in southern Central America (Coen, 1983; Martinson, 1993; Clawson, 1997; Lane et al., 2011a). The mean position of the ITCZ is tightly linked to the inter-hemispheric gradient of SSTs (Wagner et al., 1996; Xie and Carton, 2004; Broccoli et al., 2006; Chiang and Friedman, 2012; Schneider et al., 2014). Anomalous cooling of the Northern Hemisphere, including the tropical North Atlantic, results in the ITCZ migrating southward, which in turn results in reduced rainfall and enhanced drought in the northern tropics (Fig. 4.7; Xie and Carton, 2004; Chiang and Friedman, 2012; Schneider et al., 2014; Bhattacharya et al., 2017). A positive feedback may occur with the southward migration of the ITCZ leading to strengthened easterly winds and decreased cloud cover in the tropical Northern Hemisphere, allowing more long-wave radiation to escape to the atmosphere, further contributing to a decrease in SSTs in the tropical North Atlantic (Fig. 4.7; Xie and Carton, 2004). In fact, evidence of negative SST anomalies is documented in marine sediment cores from the Cariaco Basin between 750 and 1150 CE (Site 22 in Fig. 4.6; Tedesco and Thundell, 2003) and from the northwest Caribbean between 900 and 1200 CE (site 12 in Fig. 4.6; Sorey, 2014). Therefore, in addition to the influence of SSTs the tropical North Atlantic, a southward shift in the mean position of ITCZ may have also played an important role in enhancing the drought that characterizes the TCD-MCA interval in Central America.

The chironomid-inferred cooling observed at Lago Morrenas 3C between 640 and 1230 CE (1310-720 cal yr BP) may reflect the influence of the tropical North Atlantic and Pacific on terrestrial climate in southern Central America during this interval. Pounds et al. (2006) document that variations in tropical SSTs and adjacent terrestrial air temperature, between 30 °S and 30 °N, are positively correlated based on instrumental data from 1950 to 2000 CE. A model-based study determined that anomalies in land surface (air) temperature (LST) in southern Central America, including Costa Rica, match in sign with SST anomalies in the surrounding ocean (Los et al., 2001). Additional support for coupling of LST in southern Central America and SSTs in the tropical Atlantic can be found in Smith et al. (2008). A simulation of low frequency and inter-decadal scale anomalies of global temperature, including SST and LST, for the interval between 1860 and 2000 CE, provides evidence for the existence of positive correlation between LST temperature anomalies in southern Central America and SST in tropical North Atlantic and Pacific during the test period (Smith et al., 2008). The chironomid-inferred cooling at Lago Morrenas 3C, which begins at ~640 CE, tracks the increasingly positive NAO index, which would drive decreasing SSTs in the western and southeastern Caribbean during this time (Fig. 4.6 and 4.7).

The paleoenvironmental record developed for Lago Morrenas 3C, together with the record previously developed for Laguna Zoncho, identify the existence of cool, dry conditions in mid- and high- elevation regions in Costa Rica between 640 and 1230 CE. The absence of sub-fossil chironomid remains in Laguna Zoncho during this interval suggests that the negative precipitation anomaly was greater at lower elevation and with distance from the Atlantic coast. Although depressed SSTs in the tropical Atlantic and a more southerly positioned ITCZ during the TCD-MCA interval would reduce precipitation across southern Central America, mid- and low elevation sites on the Pacific slope can be more greatly affected because precipitation during boreal winter would also be highly reduced. Additionally, if the southward penetration of the polar trough and associated cold fronts are limited during the dry season, the intensity of the dry season would be more amplified and strongly expressed at low to mid- elevations along the Pacific slope in Costa Rica; however, the internsity of the dry season would be less severe along the crest of the Cordillera and along the Atlantic slope. This may imply a higher vulnerability of hydrologic systems located at mid- to low elevations on the Pacific slope of Costa Rica during intervals of severe drought when the mean annual position of ITCZ and/or the northernmost position of the ITCZ is located further south. This assertion is supported by IPCC reports (2016) that identify that precipitation along the Pacific slope in Costa Rica is expected to be reduced by ~25% by 2100 CE; whereas, precipitation on the Atlantic slope will increase slightly. Therefore, serious attention and effective action are imperative for improving the water use and management in Costa Rica along the Pacific slope, particularly for hydrologic systems found between mid-elevations and the coast.

4.7 CONCLUSION

This study pioneers the use of sub-fossil chironomid assemblages to develop high-resolution records of late Holocene hydroclimate variability in Central America. Analysis of sub-fossil chironomid remains from a sediment core recovered from Lago Morrenas 3C, a high-elevation glacial lake located in Chirripó N.P., documents the occurrence of notable faunal turnover between 640 and 1230 CE. This interval is characterized by a large increase in chironomid taxa adapted to cool climate conditions, including *Psectrocladius* and *Procladius*, and an increase in the abundance of taxa associated with littoral and terrestrial/semi-terrestrial habitats. The change in the chironomid assemblage between 640 and 1230 CE is inferred to reflect the onset of pronounced cooling and a decrease in effective moisture. The existence of more positive $\delta^{13}C$ values between 750 and 1100 CE at Lago Morreans 3C, which is inferred to reflect the expansion of *Muhlenbergia*, a C_4 grass with preference of cold and dry habitats, supports the chironomid-based interpretation. Evidence for an even more severe drought is also documented at Laguna Zoncho, a mid-elevation lake located on the Pacific slope of southern Costa Rica. These records suggest that southern Central America was characterized by a warm, wet climate from 280 to 640 CE, temperate conditions from ~1230 to 1550 CE, and cold and wet conditions from 1550 CE to the present. The timing and the hydroclimate climate conditions existing in southern Central America during the MCA-TCD interval supports the hypothesis that depressed SSTs in the tropical North Atlantic together with and a stronger NASH and southward shifted ITCZ could account for the severe drought evidenced in tropical Americas from 750 to 1100 CE.

4.7 REFERENCES

Agar Cetin, A., 2014. *Last 2000 Year Climate Sediment Record from the Belize Central Shelf Lagoon: A detailed Archive of Droughts and Floods Linked to the Collapse of the Mayan Civilization and Caribbean Historical Famines* (Doctoral dissertation, Rice University).

Aimers, J. and Hodell, D., 2011. Societal collapse: Drought and the Maya. *Nature* 479, 44-45.

Bhattacharya, T., Byrne, R., Böhnel, H., Wogau, K., Kienel, U., Ingram, B. L., Zimmerman, S., 2015. Cultural implications of late holocene climate change in the cuenca oriental, Mexico. *Proceedings of the National Academy of Sciences* 112, 1693-1698.

Bhattacharya, T., Chiang, J.C. and Cheng, W., 2017. Ocean-atmosphere dynamics linked to 800–1050 CE drying in mesoamerica. *Quaternary Science Reviews*, *169*, pp.263-277.

Bianchi, G.G. and McCave, I.N., 1999. Holocene periodicity in North Atlantic climate and deep-ocean flow south of Iceland. *Nature*, *397*(6719), p.515.

Blaauw, M., 2010. Methods and code for 'classical'age-modelling of radiocarbon sequences. Quaternary geochronology 5, 512-518.

Bond, G., Kromer, B., Beer, J., Muscheler, R., Evans, M.N., Showers, W., Hoffmann, S., Lotti-

Bond, R., Hajdas, I. and Bonani, G., 2001. Persistent solar influence on North Atlantic climate during the Holocene. *Science*, *294*(5549), pp.2130-2136.

Bond, G., Showers, W., Cheseby, M., Lotti, R., Almasi, P., Priore, P., Cullen, H., Hajdas, I. and Bonani, G., 1997. A pervasive millennial-scale cycle in North Atlantic Holocene and glacial climates. *science*, *278*(5341), pp.1257-1266.

Broccoli, A.J., Dahl, K.A. and Stouffer, R.J., 2006. Response of the ITCZ to Northern Hemisphere cooling. *Geophysical Research Letters*, *33*(1).

Brooks, S.J., Langdon, P.G., Heiri, O., and Quaternary Research Association, 2007. *The Identification and Use of Palaearctic Chironomidae Larvae in Palaeoecology*. Quaternary Research Association.

Bundschuh, J. and Alvarado, G.E. eds., 2007. *Central America, Two-Volume Set: Geology, Resources and Hazards*. CRC Press.

Chaverri-Polini, A. and Cleef, A.M., 2005. Comunidades vegetales de los páramos de los macizos de Chirripó y Buenavista, Costa Rica.

Chiang, J. C. and Friedman, A. R., 2012. Extratropical cooling, interhemispheric thermal gradients, and tropical climate change. *Annual Review of Earth and Planetary Sciences* 40, 383-412.

Clawson, D.L., 1997. *Latin America and the Caribbean*. Wm. C. Brown Publishers.

Clement, R.M. and Horn, S.P., 2001. Pre-Columbian land-use history in Costa Rica: a 3000-year record of forest clearance, agriculture and fires from Laguna Zoncho. *The Holocene* 11, 419-426.

Coen, E., 1983. The climate of Costa Rica. *Chapter III of Costa Rica Natural History, University of Chicago*, Illinois, USA.

Conroy, J.L., Overpeck, J.T., Cole, J.E., Shanahan, T.M. and Steinitz-Kannan, M., 2008. Holocene changes in eastern tropical Pacific climate inferred from a Galápagos lake sediment record. *Quaternary Science Reviews*, *27*(11-12), pp.1166-1180.

Cook, E.R., Anchukaitis, K.J., Buckley, B.M., D'Arrigo, R.D., Jacoby, G.C. and Wright, W.E., 2010. Asian monsoon failure and megadrought during the last millennium. *Science*, *328*(5977), pp.486-489.

Cranston, P., 2010. http://chirokey.skullisland.info/

Cubasch, U., Meehl, G.A., Boer, G.J., Stouffer, R.J., Dix, M., Noda, A., Senior, C.A., Raper, S. and Yap, K.S., 2001. Projections of future climate change. *, in: JT Houghton, Y. Ding, DJ Griggs, M. Noguer, PJ Van der Linden, X. Dai, K. Maskell, and CA Johnson (eds.): Climate Change 2001: The Scientific Basis: Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel*, pp.526-582.

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

Diaz, H.F., Grosjean, M. and Graumlich, L., 2003. Climate variability and change in high-elevation regions: past, present and future. *Climatic change*, *59*(1-2), pp.1-4.

Diaz, H.F., Trigo, R., Hughes, M.K., Mann, M.E., Xoplaki, E. and Barriopedro, D., 2011. Spatial and temporal characteristics of climate in medieval times revisited. *Bulletin of the American Meteorological Society*, *92*(11), pp.1487-1500.

Douglas, P. M., Pagani, M., Canuto, M. A., Brenner, M., Hodell, D. A., Eglinton, T. I., Curtis, J. H., 2015. Drought, agricultural adaptation, and sociopolitical collapse in the maya lowlands. *Proceedings of the National Academy of Sciences* 112, 5607-5612.

Douglas, P.M., Demarest, A.A., Brenner, M. and Canuto, M.A., 2016. Impacts of climate change on the collapse of lowland Maya civilization. *Annual Review of Earth and Planetary Sciences*, *44*, pp.613-645.

Eggermont, H., Kennedy, D., Hasiotis, S.T., Verschuren, D. and Cohen, A., 2008. Distribution of living larval Chironomidae (Insecta: Diptera) along a depth transect at Kigoma Bay, Lake Tanganyika: implications for palaeoenvironmental reconstruction. *African Entomology* 16, 162–184.

Enfield, D.B. and Alfaro, E.J., 1999. The dependence of Caribbean rainfall on the interaction of the tropical Atlantic and Pacific Oceans. *Journal of Climate*, *12*(7), pp.2093-2103.

Epler, J., 1995. Identification manual for the larval Chironomidae (Diptera) of Florida. Identification Manual for the Larval Chironomidae (Diptera) of Florida.

Epler, J., 2001. A guide to the taxonomy of the midges of the southeastern united states, including Florida.

Fensterer, C., Scholz, D., Hoffmann, D., Spötl, C., Pajo_n, J. M., Mangini, A., 2012. Cuban stalagmite suggests relationship between caribbean precipitation and the atlantic multidecadal oscillation during the past 1.3 ka. *The Holocene* 22, 1405-1412.

Figueroa-Rangel, B.L., Willis, K.J. and Olvera-Vargas, M., 2008. 4200 Years of Pine-Dominated Upland Forest Dynamics in West-Central Mexico: Human or Natural Legacy? *Ecology* 89, 1893-1907.

Fortin, M.C., Medeiros, A.S., Gajewski, K., Barley, E.M., Larocque-Tobler, I., Porinchu, D.F. and Wilson, S.E., 2015. Chironomid-environment relations in northern North America. *Journal of paleolimnology*, *54*(2-3), pp.223-237.

Giannini, A., Kushnir, Y. and Cane, M.A., 2000. Interannual variability of Caribbean rainfall, ENSO, and the Atlantic Ocean. *Journal of Climate*, *13*(2), pp.297-311.

Giorgi, F. and Avissar, R., 1997. Representation of heterogeneity effects in earth system modeling: Experience from land surface modeling. *Reviews of Geophysics*, *35*(4), pp.413-437.

Giorgi, F., Hewitson, B., Christensen, J., Hulme, M., Von Storch, H., Whetton, P., Jones, R., Mearns, L., Fu, C., Arritt, R. and Bates, B., 2001. Regional climate information—evaluation and projections.

Goosse, H., Masson- Delmotte, V., Renssen, H., Delmotte, M., Fichefet, T., Morgan, V., Van Ommen, T., Khim, B.K. and Stenni, B., 2004. A late medieval warm period in the Southern Ocean as a delayed response to external forcing?. *Geophysical Research Letters*, *31*(6).

Graham, N., Ammann, C., Fleitmann, D., Cobb, K., and Luterbacher, J., 2011. Support for global climate reorganization during the 'medieval climate anomaly'. *Climate Dynamics* 37, 1217-1245.

Haberyan, K.A., Horn, S.P. and Umaña, V., 2003. Basic limnology of fifty-one lakes in Costa Rica. *Revista de biología tropical* 51, 107-122.

Haberyan, K.A. and Horn, S.P., 2005. Diatom paleoecology of Laguna Zoncho, Costa Rica. *Journal of Paleolimnology*, *33*(3), pp.361-369.

Haltia-Hovi, E., Saarinen, T. and Kukkonen, M., 2007. A 2000-year record of solar forcing on varved lake sediment in eastern Finland. *Quaternary Science Reviews*, *26*(5-6), pp.678-689.

Haug, G. H., Günther, D., Peterson, L. C., Sigman, D. M., Hughen, K. A., Aeschlimann, B., 2003. Climate and the collapse of Maya civilization. *Science* 299 (5613), 1731-1735.

Haug, G.H., Günther, D., Peterson, L.C., Sigman, D.M., Hughen, K.A. and Aeschlimann, B., 2003. Climate and the collapse of Maya civilization. *Science*, *299*(5613), pp.1731-1735.

Heiri, O. and Lotter, A.F., 2001. Effect of low count sums on quantitative environmental reconstructions: an example using sub-fossil chironomids. *Journal of Paleolimnology* 26(3), pp. 343-350.

Hodell, D.A., Brenner, M., Curtis, J.H. and Guilderson, T., 2001. Solar forcing of drought frequency in the Maya lowlands. *Science*, *292*(5520), pp.1367-1370.

Hodell, D. A., Brenner, M., Curtis, J. H., 2005a. Terminal classic drought in the northern Maya lowlands inferred from multiple sediment cores in Lake Chichancanab (Mexico). *Quaternary Science Reviews* 24 (12-13), pp.1413-1427.

Hodell, D. A., Brenner, M., Curtis, J. H., Medina-González, R., Can, E. I.-C., Albornaz-Pat, A., Guilderson, T. P., 2005. Climate change on the Yucatan peninsula during the little ice age. *Quaternary Research* 63, 109-121.

Horn, S.P., 1989a. Prehistoric fires in the Chirripó highlands of Costa Rica: Sedimentary charcoal evidence. *Revista de Biología Tropical* 37(2), pp.139-148.

Horn, S.P., 1989b, January. The Inter-American highway and human disturbance of páramo vegetation in Costa Rica. In Yearbook. Conference of Latin Americanist Geographers (pp. 13-22). Louisiana State University.

Horn, S.P., 1993, Postglacial vegetation and fire history in Chirripó páramo of Costa Rica. *Quaternary research* 40(1), pp.107-116.

Horn, S.P., Orvis, K.H. and Haberyan, K.A., 2005. Limnología de las lagunas glaciales en el páramo del Chirripó, Costa Rica. *Páramos de Costa Rica*, pp.161-81.

Horn, S.P. and Kappelle, M., 2009. Fire in the páramo ecosystems of Central and South America. In Tropical fire ecology (pp. 505-539). *Springer Berlin Heidelberg.*Hughes, M.K. and

Horn, S.P. and Haberyan, K.A., 2016. Lakes of Costa Rica. *Costa Rican Ecosystems. University of Chicago Press, Chicago*, pp.656-682.

Diaz, H.F., 1994. Was there a 'Medieval Warm Period', and if so, where and when?. *Climatic change*, *26*(2-3), pp.109-142.

Hurrell, J.W. and Deser, C., 2010. North Atlantic climate variability: the role of the North Atlantic Oscillation. *Journal of Marine Systems*, *79*(3-4), pp.231-244.

IPCC, 2016. http://www.ipcc.ch/ipccreports/tar/wg2/index.php?idp=524

Jones, T.L., Brown, G.M., Raab, L.M., McVickar, J.L., Spaulding, W.G., Kennett, D.J., York, A. and Walker, P.L., 1999. Environmental imperatives reconsidered: demographic crises in western North America during the medieval climatic anomaly. *Current anthropology*, *40*(2), pp.137-170.

Juggins, S., 2003. C2 Program Version 1.4. *Department of Geology, University of Newcastle: Newcastle upon Tyne, UK.*

Kappelle, M., 1991. Distribución altitudinal de la vegetación del Parque Nacional Chirripó, Costa Rica. Altitudinal distribution of vegetation at the Chirripo National Park, Costa Rica. *Brenesia.*, (36), pp.1-14.

Kappelle, M. and Horn, S.P., 2016. The Páramo ecosystem of Costa Rica's highlands. In *Costa Rican ecosystmes*. University of Chicago Press, pp.492-523.

Keigwin, L.D. and Boyle, E.A., 2000. Detecting Holocene changes in thermohaline circulation. *Proceedings of the National Academy of Sciences*, *97*(4), pp.1343-1346.

Kennett, D. J., Breitenbach, S. F., Aquino, V. V., Asmerom, Y., Awe, J., Baldini,J. U., Bartlein, P., Culleton, B. J., Ebert, C., Jazwa, C., et al., 2012. Development and disintegration of Maya political systems in response to climate change. *Science* 338, 788-791.

Lachniet, M.S. and Seltzer, G.O., 2002. Late Quaternary glaciation of Costa Rica. *Geological Society of America Bulletin*, *114*(5), pp.547-558.

Lachniet, M. S., Asmerom, Y., Polyak, V., Bernal, J. P., 2017. Two millennia of Mesoamerican monsoon variability driven by pacific and Atlantic synergistic forcing. *Quaternary Science Reviews* 155, 100-113.

Lachniet, M. S., Bernal, J. P., Asmerom, Y., Polyak, V., Piperno, D., 2012. A 2400 yr Mesoamerican rainfall reconstruction links climate and cultural change. *Geology* 40 (3), 259-262.

Lachniet, M. S., Burns, S. J., Piperno, D. R., Asmerom, Y., Polyak, V. J., Moy, C. M., Christenson, K., 2004. A 1500-year El Ninõ Southern Oscillation and rainfall history for the Isthmus of Panama from speleothem calcite. *Journal of Geophysical Research*: Atmospheres 109 (D20).

Lane, C. S., Horn, S. P., Kerr, M. T., 2014. Beyond the Mayan lowlands: impacts of the terminal classic drought in the Caribbean Antilles. *Quaternary Science Reviews* 86, 89-98.

Lane, C. S., Horn, S. P., Mora, C. I., Orvis, K. H., and Finkelstein, D. B., 2011a. Sedimentary stable carbon isotope evidence of late Quaternary vegetation and climate change in highland Costa Rica. *Journal of Paleolimnology* 45, 323-338.

Lane, C.S. and Horn, S.P., 2013. Terrestrially derived n-alkane δD evidence of shifting Holocene paleohydrology in highland Costa Rica. Arctic, Antarctic, and Alpine Research, 45, 342-349.

Lane, C.S., Horn, S.P. and Mora, C.I., 2004. Stable carbon isotope ratios in lake and swamp sediments as a proxy for prehistoric forest clearance and crop cultivation in the Neotropics. *Journal of Paleolimnology* 32, 375-381.

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

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

League, B.L. and Horn, S.P., 2000. A 10 000 year record of Páramo fires in Costa Rica. *Journal of Tropical Ecology*, 747-752.

Los, S.O., Collatz, G.J., Bounoua, L., Sellers, P.J. and Tucker, C.J., 2001. Global interannual variations in sea surface temperature and land surface vegetation, air temperature, and precipitation. *Journal of Climate* 14, 1535-1549.

Luteyn, J., 1999. Introduction to the páramo ecosystem. Páramos: A Checklist of Plant Diversity, Geographical Distribution, and Botanical Literature. The New York Botanical Garden Press. NY, pp.1-39.

Luzzadder-Beach, S., Beach, T.P., and Dunning, N.P., 2012. Wetland fields as mirrors of drought and the Maya abandonment. *PNAS* 109, 3646-3651.

Mann, M. E.; Zhang, Z.; Rutherford, S.; et al., 2009. Global Signatures and Dynamical Origins of the Little Ice Age and Medieval Climate Anomaly. *Science* 326, 1256–60.

Mann, M.E., Cane, M.A., Zebiak, S.E. and Clement, A., 2005. Volcanic and solar forcing of the tropical Pacific over the past 1000 years. *Journal of Climate*, *18*(3), pp.447-456.

Mann, M.E., Zhang, Z., Hughes, M.K., Bradley, R.S., Miller, S.K., Rutherford, S. and Ni, F., 2008. Proxy-based reconstructions of hemispheric and global surface temperature variations over the past two millennia. *Proceedings of the National Academy of Sciences* 105, 13252-13257.

Martinson, T.L., 1993. Physical Environments of Latin America. *Latin America and the Caribbean. John Wiley & Sons, New York*, pp.1-33.

Medina-Elizalde and M., Rohling, E. J., 2012. Collapse of classic Maya civilization related to modest reduction in precipitation. *Science* 335 (6071), 956-959.

Medina-Elizalde, M., Burns, S.J., Lea, D.W., Asmerom, Y., von Gunten, L., Polyak, V., Vuille, M. and Karmalkar, A., 2010. High-resolution stalagmite climate record from the Yucatan peninsula spanning the Maya terminal classic period. *Earth and Planetary Science Letters* 298, 255-262.

Mestas-Nuñez, A. M., Enfield, D. B., Zhang, C., 2007. Water vapor fluxes over the intra-

Americas sea: seasonal and inter-annual variability and associations with rainfall. *Journal of Climate* 20, 1910-1922.

Moy, C.M., Seltzer, G.O., Rodbell, D.T. and Anderson, D.M., 2002. Variability of El Niño/Southern Oscillation activity at millennial timescales during the Holocene epoch. *Nature*, *420*(6912), p.162.

Olsen, J., Anderson, N.J. and Knudsen, M.F., 2012. Variability of the North Atlantic Oscillation over the past 5,200 years. *Nature Geoscience*, *5*(11), p.808.

Orvis, K.H. and Horn, S.P., 2000. Quaternary glaciers and climate on Cerro Chirripó, Costa Rica. *Quaternary Research* 54, 24-37.

Ouellette, G.R., 2013. Late Holocene Paleoenvironmental Reconstruction in Barbados.

Pohl, R.W., 1980. Flora Costaricensis: Family 15: Gramineae.

Porinchu, D.F. and MacDonald, G.M., 2003. The use and application of freshwater midges (Chironomidae: Insecta: Diptera) in geographical research. *Progress in Physical Geography* 27, 378-422.

Porinchu, D.F., Reinemann, S., Mark, B.G., Box, J.E. and Rolland, N., 2010. Application of a midge-based inference model for air temperature reveals evidence of late-20th century warming in sub-alpine lakes in the central Great Basin, United States. *Quaternary International*, *215*(1-2), pp.15-26.

Pounds, J.A., Bustamante, M.R., Coloma, L.A., Consuegra, J.A., Fogden, M.P., Foster, P.N., La Marca, E., Masters, K.L., Merino-Viteri, A., Puschendorf, R. and Ron, S.R., 2006. Widespread amphibian extinctions from epidemic disease driven by global warming. *Nature 439*, 161-167.

Radić, V., Bliss, A., Beedlow, A.C., Hock, R., Miles, E. and Cogley, J.G., 2014. Regional and global projections of twenty-first century glacier mass changes in response to climate scenarios from global climate models. *Climate Dynamics*, *42*(1-2), pp.37-58.

Reimer, P.J., Bard, E., Bayliss, A., Beck, J.W., Blackwell, P.G., Bronk Ramsey, C., Buck, C.E., Cheng, H., Edwards, R.L. and Friedrich, M., 2013. IntCal13 and Marine13 radiocarbon age calibration curves 0-50,000 years cal BP.

Ridley, H., 2014. *Recent Central American and low latitude climate variability revealed using speleothem-based rainfall proxy records from southern Belize* (Doctoral dissertation, Durham University).

Rosenmeier, M. F., Hodell, D. A., Brenner, M., Curtis, J. H., Guilderson, T. P., Mar. 2002. A 4000-Year Lacustrine Record of Environmental Change in the Southern Maya Lowlands, Petn, Guatemala. *Quaternary Research* 57, 183-190.

Sage, R.F., Li, M., and Monson, R.K., 1999a. The taxonomic distribution of C4 photosynthesis. In: *Sage RF, Monson RK (eds) C4 plant biology. Academic Press, San Diego*, 551–584.

Sage, R.F., Wedin, D.A. and Li, M., 1999b. The biogeography of C4 photosynthesis: patterns and controlling factors. In: *Sage RF, Monson RK (eds) C4 plant biology. Academic Press, San Diego*, 313-374.

Sawyer, J.O. and Lindsey, A.A., 1971. Vegetation of the life zones in Costa Rica. *Vegetation of the Life Zones in Costa Rica*.

Schneider, T., Bischo_, T., Haug, G. H., 2014. Migrations and dynamics of the intertropical convergence zone. *Nature* 513, 45-53.

Seager, R., Graham, N., Herweijer, C., Gordon, A.L., Kushnir, Y. and Cook, E., 2007. Blueprints for Medieval hydroclimate. *Quaternary Science Reviews*, *26*(19-21), pp.2322-2336.

Smith, T.M., Reynolds, R.W., Peterson, T.C. and Lawrimore, J., 2008. Improvements to NOAA's historical merged land–ocean surface temperature analysis (1880–2006). *Journal of Climate* 21, 2283-2296.

Sorey, L.C., 2014. Thesis. Paleoclimatology and Paleotempestology Study of Blue Hole, Lighthouse Reef, Belize through Geochemical Proxies.

Spies, M., Andersen, T., Epler, J.H. and Watson Jr, C.N., 2009. Chironomidae (non-biting midges). *Manual of Central American Diptera* 1, 437-480.

Stansell, N. D., Steinman, B. A., Abbott, M. B., Rubinov, M., Roman-Lacayo, M., 2013. Lacustrine stable isotope record of precipitation changes in Nicaragua during the little ice age and medieval climate anomaly. *Geology* 41, 151-154.

Taylor, M.A., Enfield, D.B. and Chen, A.A., 2002. Influence of the tropical Atlantic versus the tropical Pacific on Caribbean rainfall. *Journal of Geophysical Research: Oceans*, *107*(C9).

Taylor, Z.P., Horn, S.P. and Finkelstein, D.B., 2013a. Pre-Hispanic Agricultural Decline Prior to the Spanish Conquest in Southern Central America. *Quaternary Science Reviews* 73, 196-200.

Taylor, Z.P., Horn, S.P. and Finkelstein, D.B., 2013b. Maize pollen concentrations in Neotropical lake sediments as an indicator of the scale of prehistoric agriculture. *The Holocene* 23, 78-84.

Tedesco, K. and Thunell, R., 2003. High-resolution tropical climate record for the last 6,000 years. *Geophysical Research Letters*, *30*(17).

Thompson, L.G., Mosley-Thompson, E., Brecher, H., Davis, M., León, B., Les, D., Lin, P.N., Mashiotta, T. and Mountain, K., 2006. Abrupt tropical climate change: Past and present. *Proceedings of the National Academy of Sciences*, *103*(28), pp.10536-10543.

Thompson, L.G., Mosley-Thompson, E., Davis, M.E., Zagorodnov, V.S., Howat, I.M., Mikhalenko, V.N. and Lin, P.N., 2013. Annually resolved ice core records of tropical climate variability over the past~ 1800 years. Science, 340(6135), pp.945-950.

Turner, B.L. and Sabloff, J.A., 2012. Classic period collapse of the central Maya lowlands: Insights about human—environment relationships for sustainability. *PNAS* 309, 13908-13914.

Wagner, R.G., 1996. Mechanisms controlling variability of the interhemispheric sea surface temperature gradient in the tropical Atlantic. *Journal of Climate 9*, 2010-2019.

Wahl, D., Estrada-Belli, F., Anderson, L., 2013. A 3400 year paleolimnological record of prehispanic human-environment interactions in the Holmul region of the southern Maya lowlands. *Palaeogeography, Palaeoclimatology, Palaeoecology* 379, 17-31.

Walker, I.R., 2001. Midges; Chironomidae and Related Diptera. *Developments in Paleoenvironmental Research* 4, 43-66.

Webster, J. W., Brook, G. A., Railsback, L. B., Cheng, H., Edwards, R. L., Alexander, C., Reeder, P. P., 2007. Stalagmite evidence from Belize indicating significant droughts at the time of pre-classic abandonment, the Maya hiatus, and the classic Maya collapse. *Palaeogeography, Palaeoclimatology, Palaeoecology* 250, 1-17.

Weiss, H. and Bradley, R.S., 2001. What drives societal collapse? *Science* 291, 609-610.

Wu, J., Porinchu, D.F. and Horn, S.P., 2017. A chironomid-based reconstruction of late-Holocene climate and environmental change for southern Pacific Costa Rica. *The Holocene* 27, 73 -84.

Wu, J., Porinchu, D.F., Horn, S.P. and Haberyan, K.A., 2015. The modern distribution of chironomid sub-fossils (Insecta: Diptera) in Costa Rica and the development of a regional chironomid-based temperature inference model. *Hydrobiologia* 742, 107-127.

Xie, S.P. and Carton, J.A., 2004. Tropical Atlantic variability: Patterns, mechanisms, and impacts. *Earth's Climate*, pp.121-142.

Table 4.1 Geographic and limnological information for Lago Morrenas 3C and Laguna Zoncho, Costa Rica.

Lake Name	Date Visited (yyyy.mm)	Latitude N. Longitude W.	Elevation m a.s.l.	Depth (m)	Length (m)	Width (m)	Area (ha)	Temperature (°C)	DO (%)	DO (mgl^{-1})	SPC (Scm^{-1})	Conductivity (S^{-1})	pH
Lago Morrenas 3C	2014.07	9°29'44",83°29'06"	3492	2	110	80	0.75	8.8	64.4	4.9	0.003	2.3	7.2
Lago Zoncho	1997.07	8°48'44", 82°57'38"	1190	2.6	105	62	0.55	20.2		7.1		16	7.4

Table 4.2 AMS radiocarbon dates available for MOR3C (Red crosses identify dates that were not incorporated in the age-depth model).

Lab code	Core code	Depth in core (cm)	Material	Uncalibrated ^{14}C age (^{14}C yr BP)	±	2σ Age range	Relative area under distribution	Median Probability (CE or cal yr BP)
UGAMS#28489	MOR3C-PT	5.75-7.5	Charcoal	modern	-	1802-1938 CE	0.686	-
						1689-1739 CE	0.252	
						1952-1956 CE	0.036	
						1742-1763 CE	0.026	
UGAMS#23001	MOR3C-PT	10.25-10.5	Charcoal	990	25	991-1050 CE	0.676	1032 CE (918 cal yr BP)
						1083-1126 CE	0.259	
						1136-1151 CE	0.064	
UGAMS#28490	MOR3C-PT	13.25-15.25	Charcoal	60	25	1875-1918 CE	0.566	1871 CE (79 cal yr BP)
						1695-1726 CE	0.22	
						1813-1838 CE	0.158	
						1842-1853 CE	0.031	
						1868-1874 CE	0.015	
						1955-1955 CE	0.01	
UGAMS#21658	MOR3C-PT	17.25-17.75	Charcoal	880	20	1150-1217 CE	0.773	1169 CE (781 cal yr BP)
						1049-1084 CE	0.192	
						1124-1136 CE	0.035	
UGAMS#23002	MOR3C-PT	24-24.5	Charcoal	940	25	1030-1155 CE	1	1097 CE (853 cal yr BP)
UGAMS#21659	MOR3C-PT	33-33.5	Charcoal	1330	20	652-695 CE	1	671 CE (1279 cal yr BP)
UGAMS#20643	MOR3C-PT	39.5-40	Charcoal	1690	20	326-405 CE	0.926	361 CE (1589 cal yr BP)
						260-279 CE	0.074	

Table 4.3 Existing paleoenvironmental reconstructions of hydroclimate variability during TCD/MCA phase. Sites are numbered according to latitude with sites correspondingly numbered in Figure 4.5.

(Table 4.3 Part 1/2)

Site No.	Site Location	Proxy	TCD/MCA expression 500-1200 CE	Source
1	Dos Anas Cave, northwestern Cuba	$\delta^{18}O$ in stalagmite	Wetter condition between 950 and 1050 CE is observed, and lower SSTs in the North Atlantic possibly lead to a southward shift of ITCZ	Fensterer et al., 2012
2	Punta Laguna, Mexico	$\delta^{18}O$ of the ostracod and gastropod shells in lake sediments	Relatively dry climate was found from ~280 to 1080 CE Multiple significant dry events identified at ~600 CE, 860 CE	Curtis et al., 1996
3	Tecoh cave, northwest Yucatán Peninsula	$\delta^{18}O$ in stalagmite	Rainfall greatly reduced, eight severe droughts occurred btw 800-950 CE with an even servere one 640-680 CE	Medina-Elizalde et al., 2010
4	Lake Chinchancanab, Mexico	Bulk density, red and blue color reflection in lake sediments	A series of dry events concentred in periods of 770-870 CE, and 920-1100 CE	Hodell et al., 2005
5	The Sierra de Manantlan Biosphere Reserve, west central Mexico	Pollen	Dry interval observed between 750 and 1100 CE	Figueroa-Rangel et al., 2008
6	Lake Aljojuca in Central Mexico	Elemental geochemistry and $\delta^{18}O$ from authigenic calcite	A lont-term drought observed from 500 to 1150 CE may have caused abandonment of Cantona and population collapse in Cantona	Bhattacharya et al., 2015
7	Laguna Castilla, Domincan Republic	Long-chain ($\geq C_{25}$) n-alkane δD, d18O in ostracods, pollen, mineral influx in lake sediments	Increased aridity found during TCD (~750-1100 CE)	Lane et al., 2014; 2009
8	Laguna Felipe, Dominican Republic	$\delta^{18}O$ in ostracods, $\delta^{13}C$ in lacustrine biognic carbonates	Wetter MCA detected from 1000 to 1300 CE based on absence of carbonate material and mineral-rich clay indicates a northward migration of ITCZ	Lane et al. 2011
9	Lake Salpeten, Mexico Lake Chinchancanab, Mexico	Plant wax carbon isotopes in lake sediments	Aridity between ~800 and 1200 CE forced extensive agriculture to shift to intensive, waterconservative maize cultivation	Douglas et al., 2015
10	Belize Centrtal Shelf Lagoon	Particle size and elements (e.g.Ti, K, Ti/Al) in lacustrine (lagoon and channel) sediments	Unusually low Ti counts and Ti/Al inferred low precipitation btw 800 and 900 CE. High Ti, Ti/Al between 900 and 1350 CE inferred more rainfall and wet condition	Agar Cetin, thesis 2014
11	Lake Salpetén, Guatemala	$\delta^{18}O$ on valves of the ostracod, Inorganic carbon in lake sediments	Severe aridity identified between 800 and 900 CE	Rosenmeier et al., 2002
12	Blue hole, western Caribbean Sea near Belize	$\delta^{15}N$ in marine sediments	Intensified upwelling btw 900 and 1200 CE, corresponded strengthening trade wind (Positive NAO)	Sorey, thesis 2014
13	Laguna Yaloch (Holmul region), Guatemala	Magnetic susceptibility, $\delta^{13}C$ C%, N%, pollen, charcoal	Evidence for anomalously dry conditions found from ~680 to 910 CE	Wahl et al., 2013
14	Macal Chasm Cave, Belize	reflectance,color, luminescence, and $\delta^{13}C$ and $\delta^{18}O$ in stalagmites	A series of droughts concentrated from 700 to 1135 CE	Webster et al., 2007

(Table 4.3 Part 2/2)

Site No.	Site Location	Proxy	TCD/MCA expression 500-1200 CE	Source
15	Juxtlahuaca Cave, Mexico	$\delta^{18}O$ in JX-6 stalagmites	Dry condition peaked during period of 600-900 CE and megadrought observed at 770 CE	Lachniet et al., 2012
16	Juxtlahuaca Cave, Mexico	$\delta^{18}O$ in JX-6 and JX-7 stalagmites	Intense dry condition observed from 700 to 850 CE, Five short-lived dry events during period of 930-1300 CE	Lachniet et al., 2017
17	Yok Balum Cave, southern Belize	$\delta^{13}C$ in stalagemites	Notably dry from 850 to 950 CE and 1000 to 1150 CE but with negative NAO observed (short-lived climate shifts related to NH volcanic eruptions)	Ridley, thesis 2014
18	Yok Balum Cave, southern Belize	$\delta^{18}O$ in stalagmite	Drying trend between 660 and 1000 CE triggered collapse of polities, followed by population collapse during an extended drought between 1020 and 1100 CE.	Kennet et al., 2012
19	Harrison's Cave, Barbardos	$\delta^{18}O$ in speleothem	Wet condition observed between 850 and 1150 CE	Gilman, thesis 2013
20	Lago El Gancho, Nicaragua	$\delta^{18}O$ in ostracods	Wetter condition between 950 and 1250 CE inferred from low $\delta^{18}O$, indicating a La Nina-like conditin in the tropical Pacific	Stansell et al., 2012
21	Cariaco Basin, Venezuela	Ti% in marine core riverine sediments	An extended regional dry period is found with more punctuated intense multi-year droughts at approximately 810, 860, and 910 CE	Haug et al., 2003
22	Cariaco Basin, Venezuela	$\delta^{18}O$ in ostracods	Strong upwelling caused SST cooling observed between 800 and 1200 yr BP	Tedesco and Thundell, 2003
23	Lago Morrenas 1 core 2, Costa Rica Lago Chirripo, Costa Rica	Microscopic charcoal and pollen	Charcoal peak identified at 1100 CE and abundant *isoetes* pollen at approximately 900 CE, suggesting dry condition	Horn, 1989 and 1993
24	Lago Morrenas 1 core 1, Costa Rica	δD of long chain alkane in bulk sediment	Low δD inferred reduce in E/P ratio arround 1000 CE, suggesting wetter climate	Lane and Horn, 2013
25	Lago Morrenas 1 core 1, Costa Rica	$\delta^{13}C$ of long chain alkane in bulk sediment	C_4 plants may lightly shrink approximately between from 800 to 1200 CE, indicating wetter condition	Lane et al., 2011
26	Lago Morrenas 3C and Lago Ditkebi, Costa Rica	Charcoal and geochemical (C%, N%, $\delta^{13}C$, $\delta^{15}C$)	Low lake level observed from ~750 to 1100 CE, intense drought may occur between 850 and 1100 CE, severe local fires found during periods of 550-750 CE and 1050-1200 CE	Wu, dissertation chapter 3 2017
27	Lago Morrenas 3C	Subfossil chironomids	Cold phase detected from ~600 to 1150 CE	Wu, dissertation chapter 4 2017
28	Chilibrillo Cave, Canal Zone, Panama	$\delta^{18}O$ in stalagmite	Weakenend monsoon observed from 1100 to 1200 CE, and from 750 to 950 CE, with even drier period during 550-650 CE	Lachniet et al., 2004
29	Laguna Zoncho, Costa Rica	Chironomids-based temperature inferrence model	Extremely low head capsules recovery between 730 and 1110 CE, like indicating low effective moisture in the lake	Wu et al., 2017

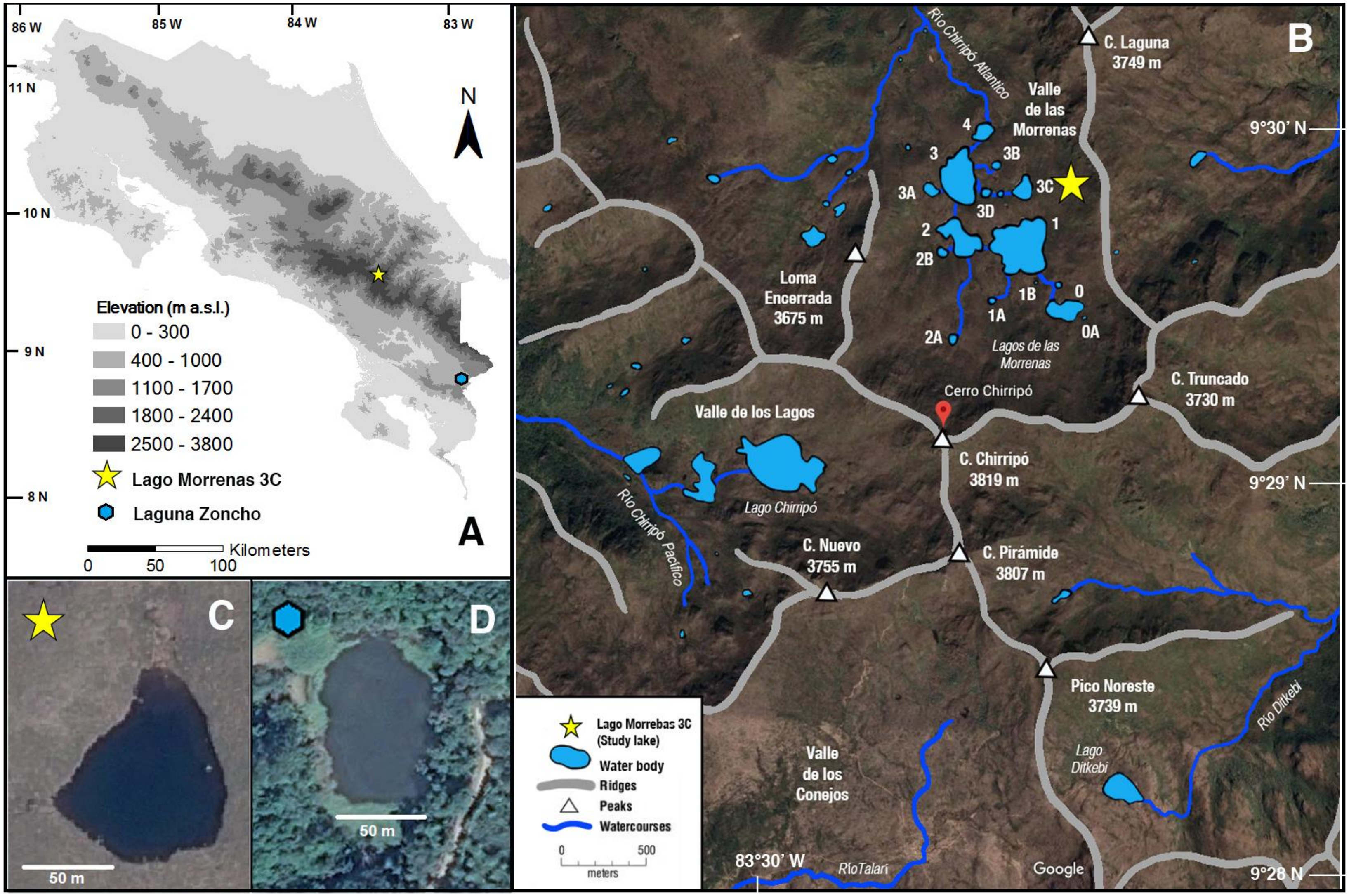


Figure 4.1 A) Location of Lago Morrenas 3C and Laguna Zoncho, Costa Rica; B) Location of Lago Morrenas 3C within Chirripó National Park, Costa Rica (base maps originate from Orvis and Horn, 2000 and Google Earth, modified by Jiaying Wu); C) Aerial photo of Lago Morrenas 3C; and D) Aerial photo of Laguna Zoncho.

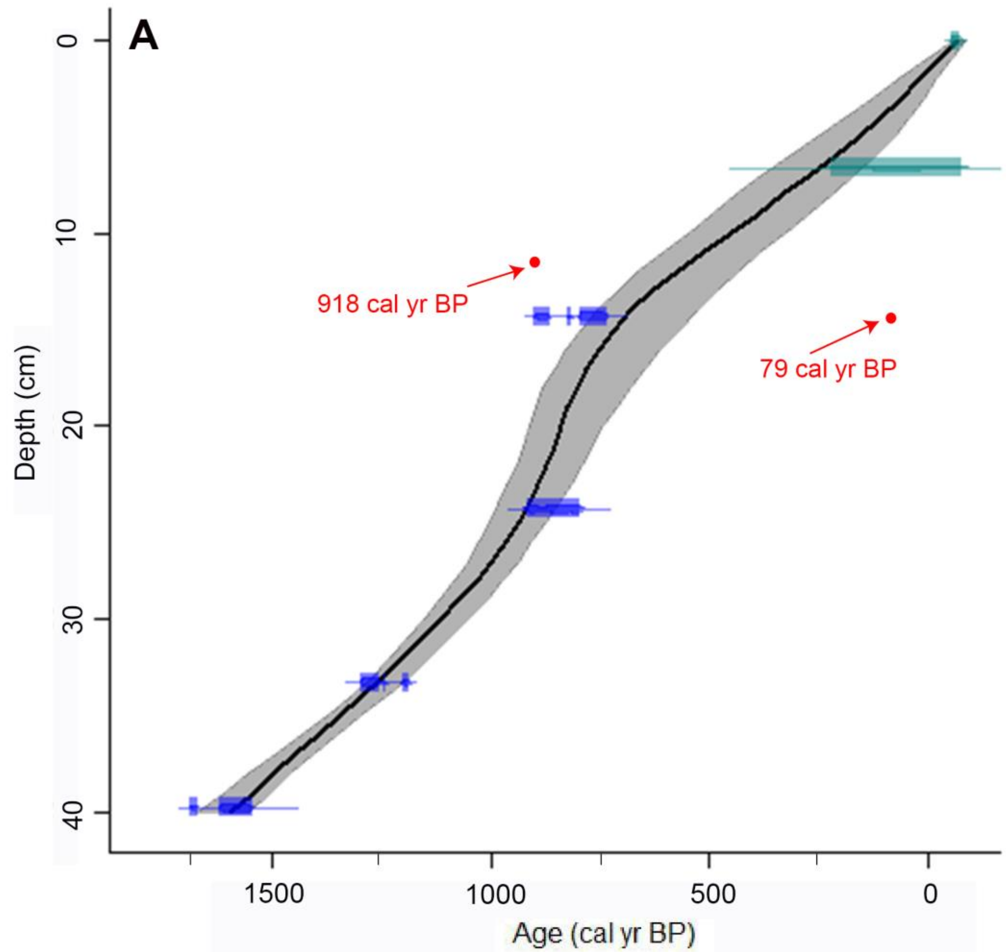


Figure 4.2 Clam-based age-depth model for the MOR3C core. Two AMS ^{14}C dates based on charcoal at 10.25 and 13.25 cm (the calibrated ages are marked as red, Table 4.2) were not incorporated in the age-depth model.

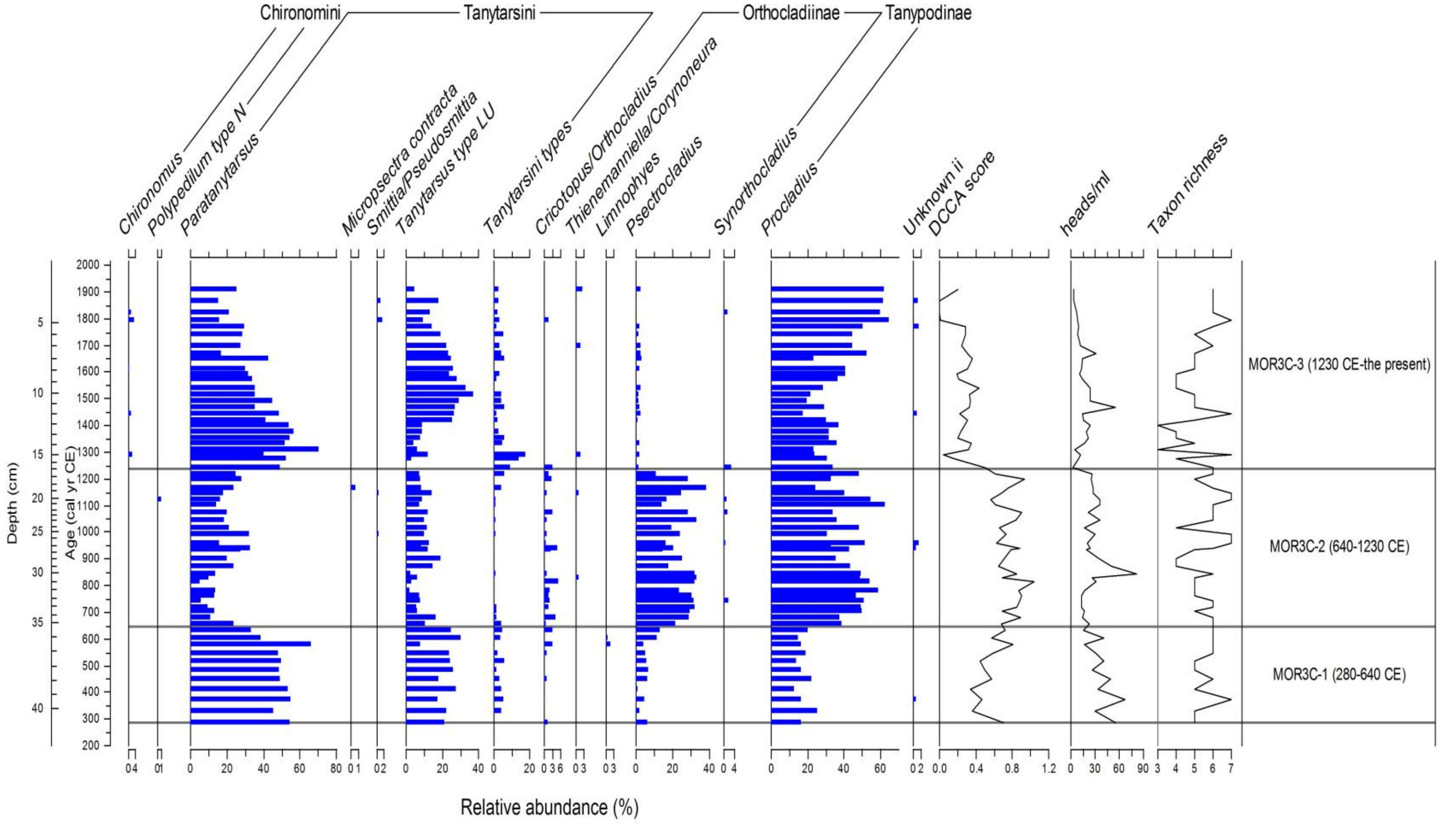


Figure 4.3 Relative abundance of chironomids preserved in MOR3C for the interval from 280 CE to the present.

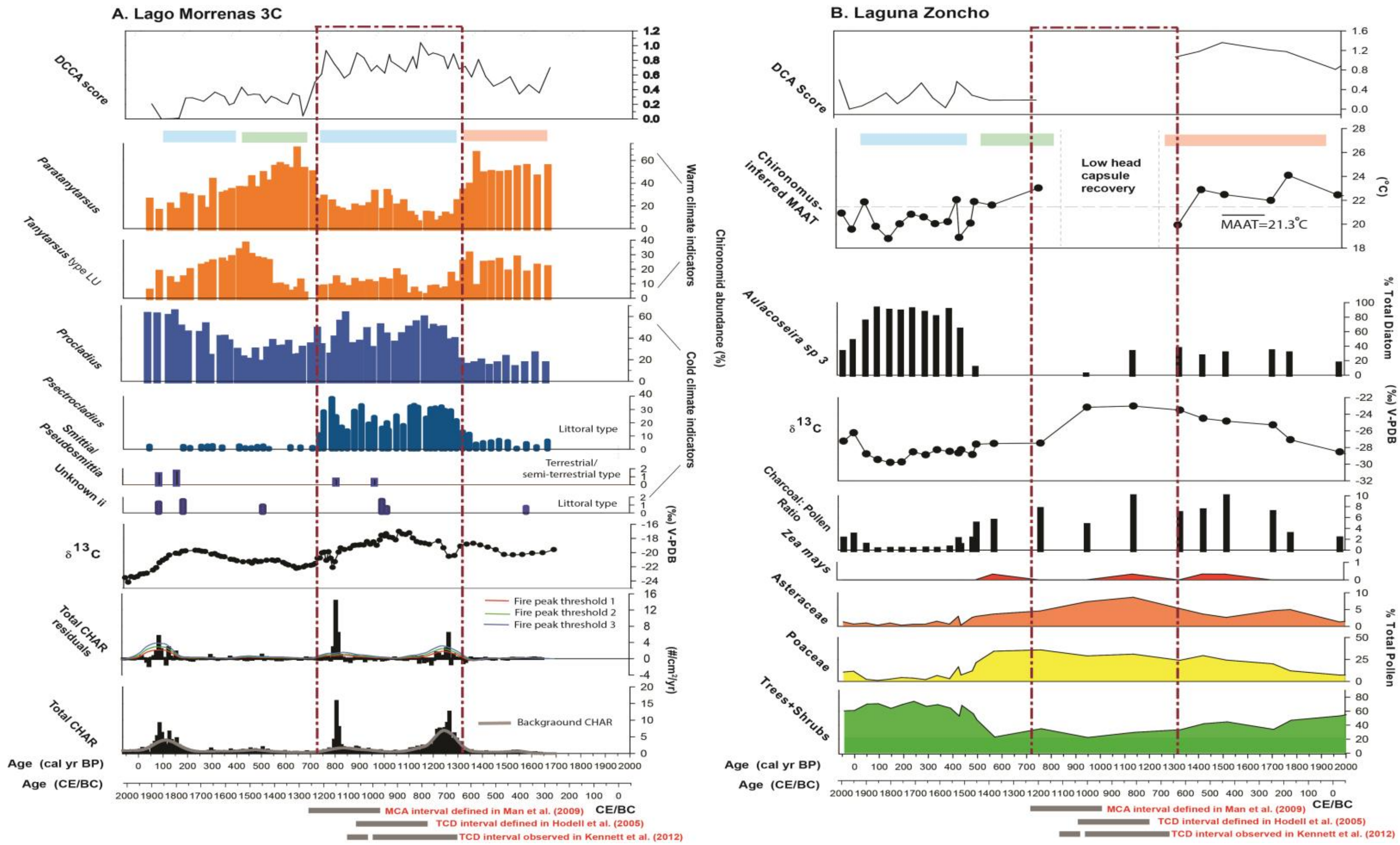


Figure 4.4 Select proxy data from (A) Lago Morrenas 3C and (B) Laguna Zoncho (Wu et al., 2017). The red dashed line frames the interval between 640 and 1230 CE. Grey horizontal bars below the X-axes represent the MCA (950-1250 CE) defined in Mann et al. (2009) and TCD intervals (770-1100 CE) in Hodell et al. (2005a) and TCD intervals (660-1000 CE and 1020-1100 CE) observed in Kennett et al. (2012), respectively. Horizontal bars colored by orange, green and blue bars represent intervals that are characterized by warm, temperate and cool conditions, respectively. Abbreviations: Total CHAR = charcoal accumulation rate for all charcoal >125 μm. Total CHAR residuals are determined by subtracting background CHAR values ($C_{background}$) from Total **CHAR**. Fire episodes are identified when CHAR residuals exceed a fire peak threshold defined as the 0.99 percentile cut-off determined using a Gaussian mixture model-based noise distribution (Higuera, 2009).

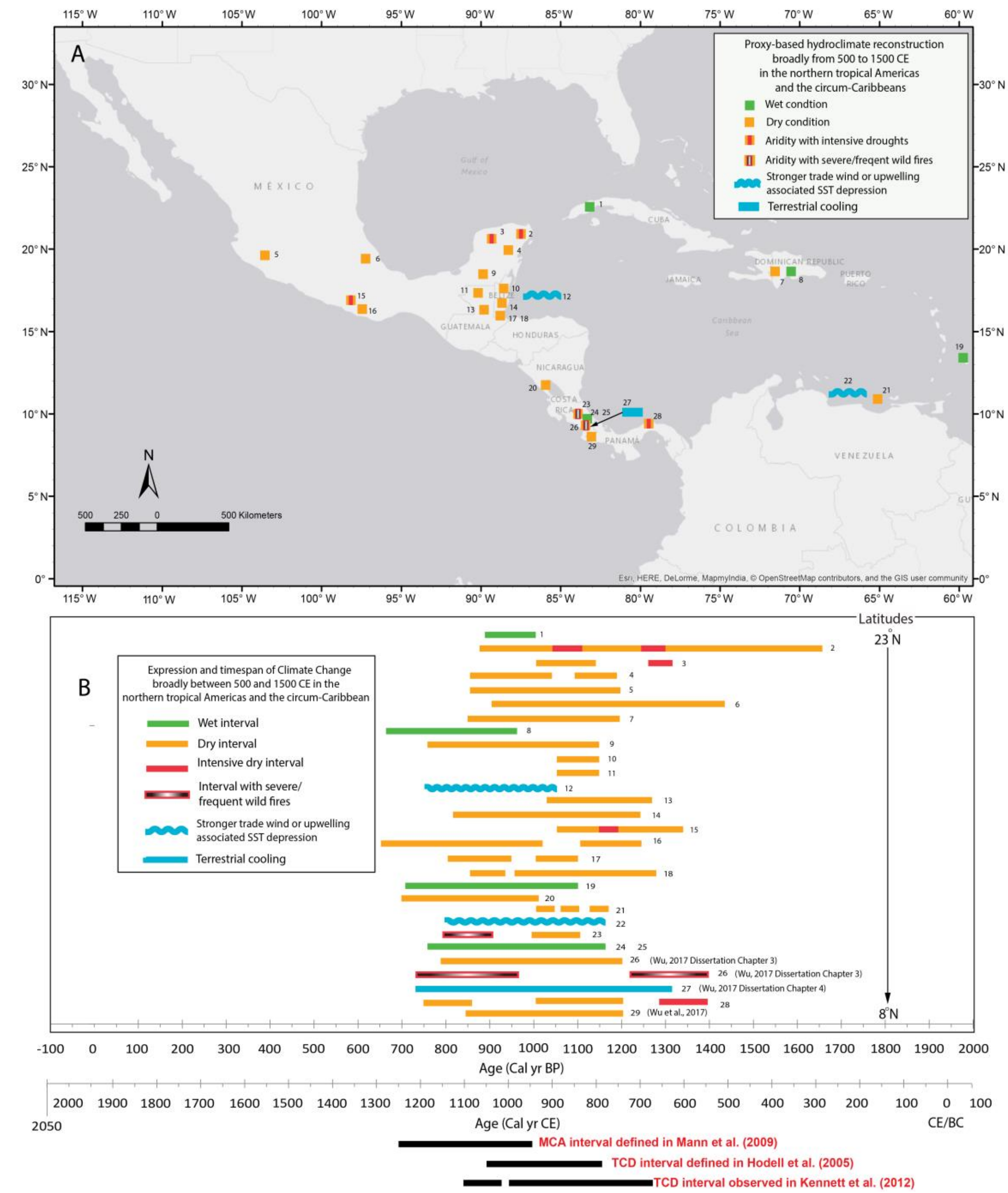


Figure 4.5 Existing research in the northern tropical Americas and Caribbean focusing on reconstructing Holocene paleoclimate and paleoenvironmental change broadly from ~500 to 1500 CE. A) Map of study sites depicting hydroclimate variability and paleoenvironmental change between ~500 and 1500 CE, with the length of anomalous conditions indicated by the length of the bar, shown in B). The study sites are numbered according to latitude, with highest latitude numbered 1. The site numbers in Fig 4.5A and 4.5B correspond to the references in Table 4.3.

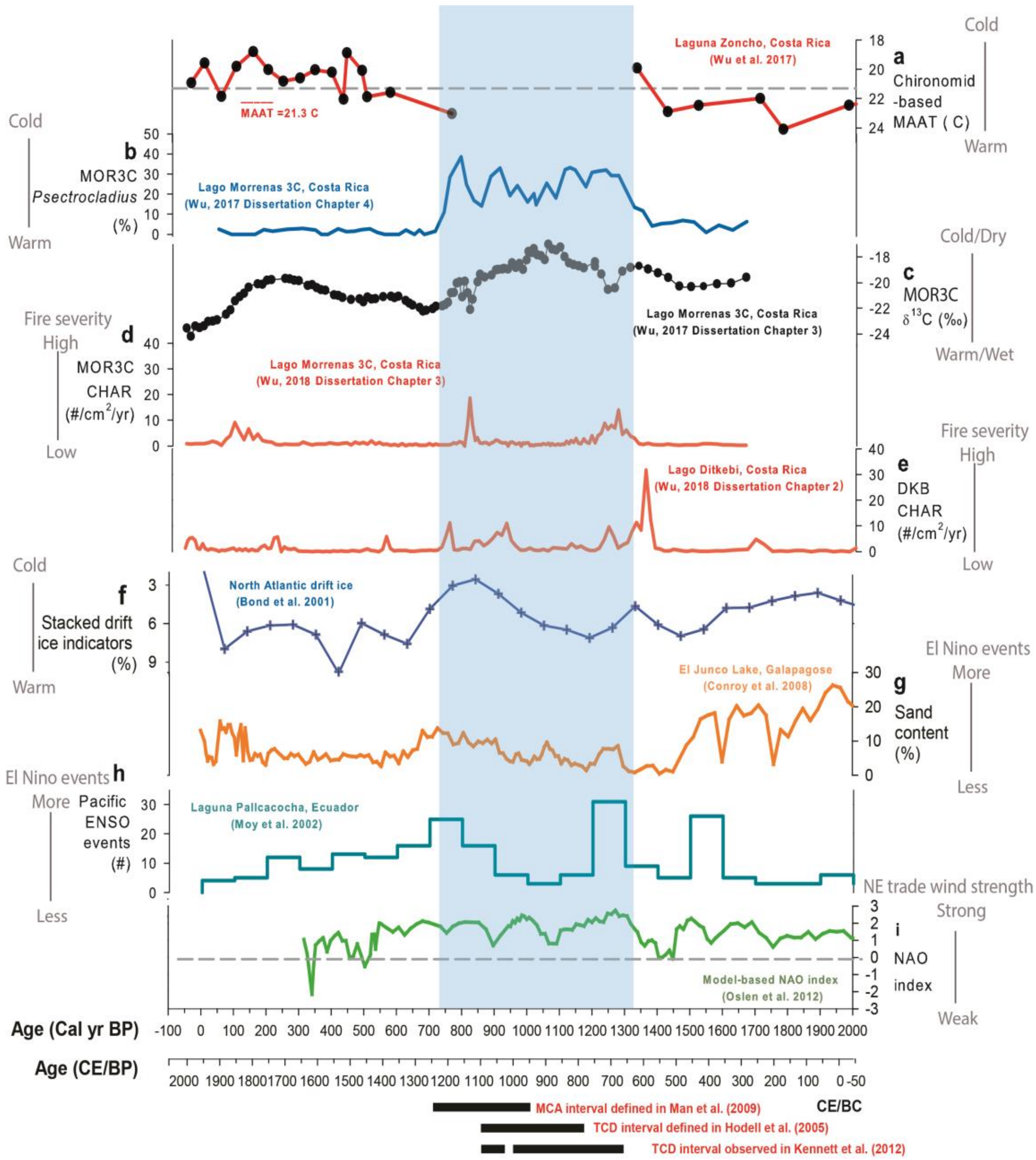


Figure 4.6 Comparison of the proxy records developed in this study and studies from the tropical Americas and the North Atlantic. The black horizontal bar at the bottom of the figure represents the MCA and TCD, as defined and observed in Mann et al. (2009), Hodell et al. (2005) and Kennett et al. (2012), respectively. The MOR3C-2 zone (640-1230 CE) identified in the MOR3C core is highlighted using vertical blue bar.

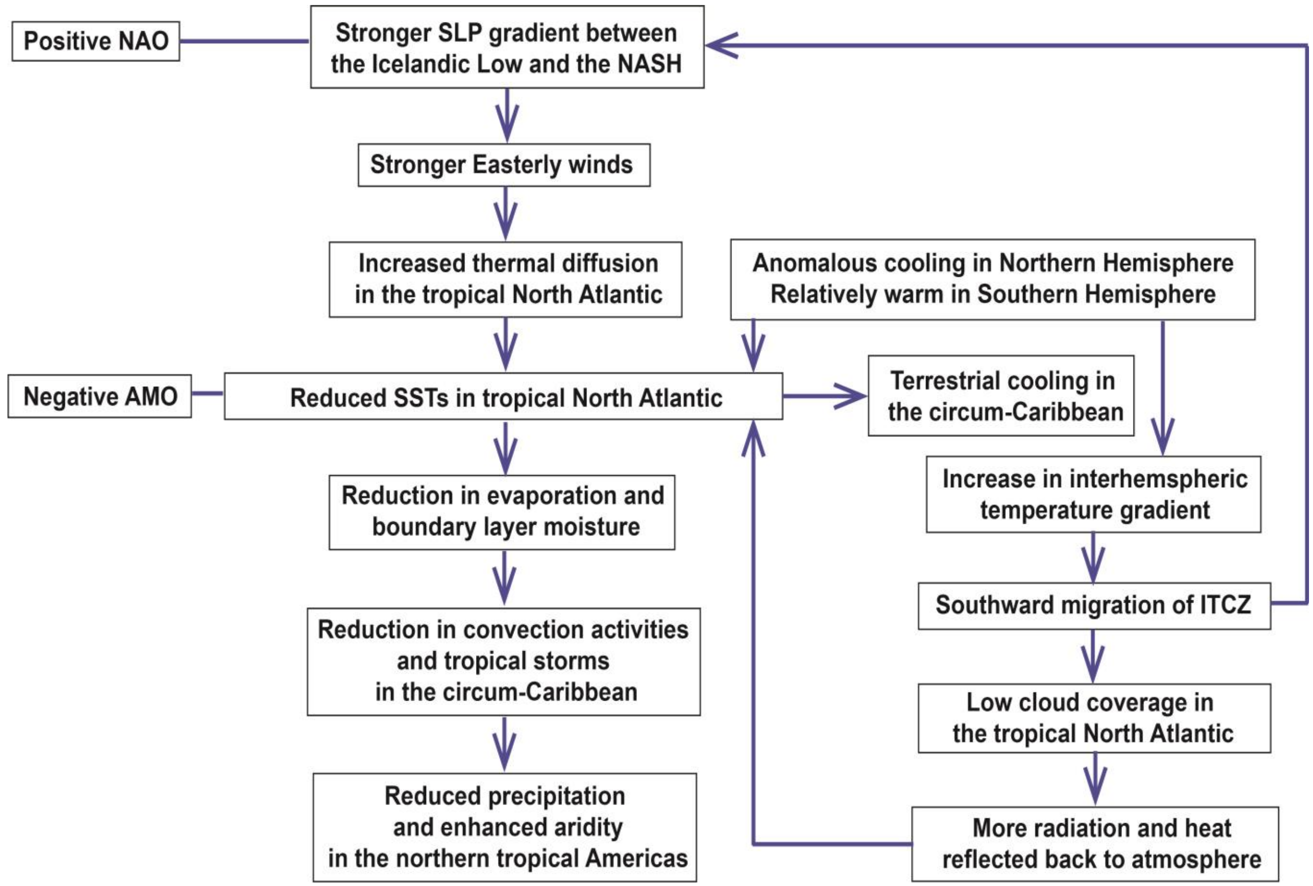


Figure 4.7 Conceptual model of the climatic drivers and the related physical processes that can account for anomalous dry conditions in the northern tropical Americas between 600 and 1200 CE (adapted from Bhattacharya et al., 2017).

CHAPTER 5

CONCLUSIONS

5.1 CONCLUSIONS

Records documenting thermal variability during the Holocene in southern Central America are limited, and obtaining these types of records is imperative. The development of high-resolution reconstructions of Holocene thermal conditions provide an outstanding opportunity to assess the role which thermal changes play in influencing hydrology, fire regimes and vegetation dynamics, and enable an assessment of the potential mechanisms driving the inferred changes in paleoclimate and vegetation in the Chirripó páramo of Costa Rica during the widely observed hydroclimatic anomalies in tropical America between ~600 and 1200 cal yr BP. The main objectives of this dissertation were to: 1) reconstruct Holocene thermal variability at multi-decadal to sub-centennial scale for Chirripó N.P. in Costa Rica using the chironomid-temperature relationship established in a modern regional training set (Wu et al., 2015); 2) analyze sedimentary charcoal and geochemistry to improve our understanding of Holocene fire regimes and the relationship between fire events, vegetation response and the nutrient flux to aquatic systems; and 3) assess the linkages between thermal variability and paleoenvironmental change in Costa Rica and adjacent areas during the TCD and MCA intervals. These objectives are addressed in three separate but interrelated chapters:

Sub-fossil chironomids, sedimentary charcoal and geochemistry extracted from a lake sediment core recovered from Lago Morrenas 3C were analyzed in **Chapter 2** to develop records of Holocene thermal and paleoenvironmental change for the páramo ecosystem in Chirripó N.P. The results of this study indicate that this region was characterized: 1) relatively cool, dry conditions, low lake level, and very limited fire activity between ~8770 and 5290 cal yr BP; 2) a persistent interval of elevated MAAT, increased effective moisture and frequent, moderate to high-severity fires between ~5290 and 2780 cal yr BP; 3) cool, dry conditions and frequent, low-severity fires from 2780 cal yr BP and present. In addition, macroscopic charcoal analysis indicates that although wildfires periodically occurred throughout the Holocene, the interval between ~3300 and 1500 cal yr BP was characterized by the highest fire frequency during the Holocene. An abrupt increase in fire frequency and severity occurred at ~5290 cal yr BP. The concurrent maxima in C/N, charcoal accumulation rates and the abundance of *Polypedilum* N type observed at ~5200 cal yr BP, suggests an abrupt climate change event characterized by warmer conditions, increased effective moisture and severe fires. The evidence of an abrupt climate event at ~5200 cal yr BP corresponds well with existing records from elsewhere in the tropics and provides additional support for the existence of a global-scale event at ~5200 cal yr BP. The Holocene record of climate and environmental change developed here provides important insights of multi-decadal to centennial-scale hydroclimate variability and the associated response of vegetation and fire regimes, and offers a valuable reference for park staff to anticipate the potential impacts associated with projected climate change in the páramo ecosystem found in Chirripó N.P.

In **Chapter 3**, analyses of macroscopic charcoal and sediment geochemistry (N%, C%, $\delta^{13}C$, $\delta^{15}N$ and C/N ratio) was undertaken on sediment cores recovered from Lagos Morrenas 3C and Lago Ditkebi, two high-elevation glacial lakes located in Costa Rica's Chirripó N.P., to develop sub-to multi-decadal scale reconstructions of late Holocene fire regime for the region. The results generated in this chapter indicate that the páramo in Chirripó N.P. periodically burned during the last two millennia, with synchronous intervals of elevated fire frequency occurring at Lago Morrenas 3C and Lago Ditkebi from ~550 to 730 CE and from ~980 to 1230 CE. The results also indicate that evidence of individual severe fire events are well reflected in the fluctuations of sediment geochemistry. Severe fire episodes are associated with a rapid increase:

1) in the flux of C and N from the surrounding catchment, likely reflecting the volatilization of páramo vegetation; and 2) the stable isotope of N ($\delta^{15}N$), reflecting post-fire changes in nutrient loading in response to the recovery of the páramo vegetation in the catchment. In addition, the concurrent increase in $\delta^{13}C$ ratios and C/N ratios observed between ~750 and 1100 CE is inferred to reflect the expansion of *Muhlenbergia*, a native grass utilizing the C4 pathway with a preference of cold and low-humid habitats, which may suggest a decrease in effective moisture and lower temperature during this interval. The results from this study improve our understanding of the late Holocene fire history and the impact of fire on soil nutrient loading in the Chirripó páramo, thereby providing additional insights relevant to the management and conservation of páramo in light of projected climate change.

In **Chapter 4**, chironomid stratigraphies and hydroclimate reconstructions from two lakes: 1) Lago Morrenas 3C, a high-elevation lake (3492 m a.s.l.) located in glacial highlands of Chirripó N.P.; and 2) Laguno Zoncho, a mid-elevation lake (1190 m a.s.l.) located in the southern Pacific region of Costa Rica document that the mid- and high-elevation regions in Costa Rica responded to hydroclimate forcing in similar ways during the last 2000 years. Costa Rica was characterized by elevated temperature between 280 and 640 CE (1670-1310 cal yr BP), moderate temperatures between 1230 and 1550 CE (720-400 cal yr BP), and the re-occurrence of cooling starting from ~1600 CE (350 cal yr BP). Distinctive shifts in the chironomid assemblages occurred at both sites between 640 and 1230 CE (1310-720 cal yr BP). Lago Morrenas 3C is characterized by a large increase in chironomid taxa adapted to cool climate, including *Psectrocladius* and *Procladius*, an increase in the abundance of taxa associated with littoral and terrestrial/semi-terrestrial habitats near ~640 and 1230 CE, and an increase of stable carbon isotope ($\delta^{13}C$) values from ~750 to 1100 CE (1200-850 cal yr BP). The elevated $\delta^{13}C$ values, reflecting the expansion of *Muhlenbergia,* a native C_4 grass associated with cold and relatively dry environments, together with the shift in the chironomid assemblages, suggest that glacial highlands were likely characterized by enhanced aridity and depressed temperatures during this interval. The absence of chironomid remains in Laguna Zoncho between ~730 and 1110 CE (1220-840 cal yr BP) provides evidence for the occurrence of an even more severe drought at the mid-elevations during the TCD and early MCA intervals. The timing and the hydroclimate climate conditions existing in southern Central America during the TCD and early MCA supports the hypothesis that depressed sea surface temperatures in the tropical North Atlantic, in conjunction with a stronger North Atlantic Subtropical High and southward shifted ITCZ, account for the expansive droughts that occurred during the turn period of the 1st millennium in the northern tropical Americas. In addition, the reduction in MAAT and increase in effective moisture that are inferred to have occurred at Laguna Zoncho and Lago Morrenas 3C between ~1600 CE and the present may provide potential evidence for the Little Ice Age in the southern Central America.

Taken together, the results generated in this dissertation provide a broad understanding of Holocene hydroclimate and paleoenvironmental change in Costa Rica. Chironomid-inferred hydroclimate variations are tightly correlated with fire regimes, vegetation dynamics and nutrient fluxes in the glacial highlands of Chirripó N.P. These studies also document that local fire activity is very complex in the Chirripó páramo, with spatial and temporal variability in fire episodes also observed. The spatial and temporal variability in fire events may not directly relate to the thermal conditions in the Chirripó páramo, but rather reflect the localized influence of convective thunderstorms and lightning - this hypothesis requires further investigation. Additionally, the evidence of the Holocene hydroclimate variation derived in Lago Ditkebi can be refined by analyzing a Holocene sediment core recovered from a shallow glacial lake, such as Lago Morrenas 3C, which will likely be more sensitive to the climate and environmental disturbances that have occurred within its catchment. Lastly, given that the composition of the chironomid assemblages (dominated by a single taxon-*Procladius*) preserved in the glacial lakes in Chirripó N.P. precluded the development of quantitative temperature reconstructions, incorporation of stable oxygen isotope ($\delta^{18}O$) analysis of chironomid head capsules extracted from sediment cores recovered from lower elevation lakes may provide a means to derive independent estimates of past changes in temperature variability through pairing chironomid assemblage-inferred thermal condition with chironomid-$\delta^{18}O$-based temperature reconstructions.

5.2 REFERENCES

Wu, J., Porinchu, D.F., Horn, S.P. and Haberyan, K.A., 2015. The modern distribution of chironomid sub-fossils (Insecta: Diptera) in Costa Rica and the development of a regional chironomid-based temperature inference model. *Hydrobiologia* 742, 107-127.