Providing Paleoenvironmental Baselines to Inform Prescribed Fire Application in Central Florida

by

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A thesis submitted to the Graduate Faculty of
Auburn University in
partial fulfillment of the
requirements for the Degree of
Geology, Master of Science

Auburn, Alabama
December 14, 2024

Keywords: paleofire, paleoclimate, macrocharcoal

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Abstract

Prescribed fire (Rx-Fire) is widely applied in the United States of America (U.S.A.) as a land management tool to promote ecosystem health and mitigate the risk of wildfires by removing excess fuels from landscapes. Rx-Fire use is particularly pronounced in the southeastern U.S.A. Rx-Fire was first developed in this region to restore ecosystems lost to logging, human land use, and Euro-American colonization. However, owing to the relative lack of tree ring records in the area, there is little empirical constraint for this region's pre-modern, long-term fire regimes. In this research, we leverage a lake sediment record of charcoal deposition to establish the natural and early anthropogenic baselines of fire in central Florida. By measuring macroscopic charcoal accumulation rates and characterizing charcoal morphological and morphometric changes through time, we provide paleoenvironmental context for modern Rx-Fire application in this region. Further, we compare the paleofire record with archeological and historical perspectives to understand the pre-colonization impacts of Indigenous people on the natural fire regimes in the Holocene. This thesis highlights the complex relationships between anthropogenic fire influence, climate, and vegetation. Overall, we found that the modern Rx-Fire application is likely overapplied relative to the Holocene baseline of fire activity. Further, we discovered a high variance between all morphometrics from 6.5 to 5.5 cal kyr BP, which can be indicative of the fuel source change from oak to pine dominance, as supported by neighboring proxies.

Acknowledgments

First, I would like to thank my advisor Dr. Richard Vachula for teaching me, helping me, and inspiring me with my research. Without you, I would have never understood the vast world of charcoal. I would also like to thank my committee members, Dr. Richard Vachula, Dr. Matt Waters, and Dr. Thomas Cullen for their support and help throughout my academic career.

Secondly, I would like to thank my parents for always being there for me. I dedicate this thesis to them for being my rock throughout some of the hardest years of my life. Without them, I would not be the woman I am today.

Thirdly, I would like to thank my friends and colleagues. Alexandra Tsalickis, thank you for your willingness to help with this project and for the friendship we have developed outside of it. Savvas Paradeisis-Stathis, thank you for sitting down with me to talk science over a cup of coffee and for helping me with this project. Ashleigh Bright, thank you for teaching me the geography side of the department and for encouraging me to get more involved.

Lastly, I would like to thank Auburn University for being my home for the last five years. The person who first stepped foot on this campus is not the same person who will be leaving it. I have had some of my hardest times, and greatest memories, and have met some of my best friends and colleagues here.

War Eagle!

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List of Abbreviations

CHAR	Charcoal Accumulation Rate
U.S.A.	United States of America
FL	Florida
FWCC	State of Florida Fish and Wildlife Conservation Commission
a.s.l.	above sea level
L:W	Length to Width (Aspect Ratio)
AR	Aspect Ratio
A:P	Area to Perimeter
cal kyr BP	calibrated kiloyears Before Present
CE	Common Era
c.a.	circa

1. Introduction

Fire plays a crucial role in terrestrial ecosystems by altering structure, facilitating nutrient cycling, and creating habitats for diverse flora and fauna (Bond & Keeley, 2005; Debano, 1990; Pausas & Parr, 2018). However, human development has disrupted natural wildfire patterns, leading to widespread fire suppression policies in recent centuries (Bowman et al., 2011; Marlon et al., 2008). To counteract the human impacts of fire suppression, prescribed burning has emerged as a vital management tool, particularly in restoring fire-dependent ecosystems like those in the Southeast, United States of America (U.S.A.) (Ryan et al., 2013; Mitchell et al., 2014).

In the Southeast U.S.A., prescribed burns are pivotal for maintaining biodiversity and resilience to environmental stressors (Keesing & Ostfeld, 2021; Kelly, 2019). Both historical and contemporary fire practices demonstrate their ecological significance and effectiveness in ecosystem management (Johnson & Hale, 2002; Stephanotis, 2003). Special attention has been given to fire-tolerant native longleaf pine ecosystems, which have declined due to land-use changes (Barlow et al., 2015). However, modern anthropogenic fire return intervals in these ecosystems often focus on removing non-native species (Boone et al., 2024). Considering climate change, current fire practices must be carefully considered as they are also the most cost-effective method for reducing concerns of fuel buildup (Bowman et al., 2011; Pollock et al., 2016) and mitigating the cost of wildfire destruction (Hesseln, 2000).

Long-term records of wildfire activity are essential for understanding how fire regimes have varied in response to changes in climate, vegetation, and human land use (Bowman et al.,

2011). Charcoal particles preserved in lake sediments serve as proxies for assessing fire regimes, offering insights into how these regimes have responded to both climate and anthropogenic influences over centuries and millennia (Marlon et al., 2008, 2016; Power et al., 2010). By analyzing the morphology and morphometrics of charcoal particles, it is possible to reconstruct past fire events and determine the types of fuels burned (Feurdean, 2021; Feurdean et al., 2023; Hennebelle et al., 2020; Vachula et al., 2021, 2024; Umbanhowar & McGrath, 1998).

This study aims to explore the complex relationships among people, vegetation, and fire in southeast Florida by analyzing charcoal particles preserved in the sediment archive of Lake Marian, which spans the last 8,000 years. Located near agricultural areas and subject to modern prescribed burning practices, Lake Marian provides a unique opportunity to reconstruct fire activity and investigate the impact of early human populations, Indigenous communities, and modern Euro-American land use. A central research question is whether modern prescribed burns accurately replicate prehistoric fire activity, and the types of fuels burned, shedding light on the effectiveness of contemporary forest management practices (Whitlock & Larsen, 2002). Due to the increased application of fire as a land management technique, many studies showed an increase in CHAR in the modern (Krause et al., 2019; Jones et al., 2014; Clark & Royall, 1995; Ishman et al.,1998) and altered nutrient intake for lake systems (Kenney et al., 2016; Waters et al., 2015; Waters et al., 2018; Waters et al., 2023). It is hypothesized that modern fire application will be significantly different from the observed Holocene baseline of charcoal production at Lake Marian due to the over-application of prescribed fire. If this hypothesis stands true, it is predicted that our current land management practices will cause a vegetation shift to fast-growing terrestrial vascular cryptogam as they are coined a pioneer species (Skutch, 1929). As human environmental influence increased during the Woodland period, the charcoal

accumulation rate significantly differed from the prior period due to the increased utilization of fire by indigenous peoples. The hypotheses will be tested by analyzing the accumulation rate of charcoal during each anthropogenic period, examining the variance of the morphometrics and morphologies throughout time, and comparing the data to neighboring pollen and diatom records.

Additionally, we ask whether charcoal morphometrics from Lake Marian's sediment record can reveal the Holocene shift between oak and pine dominance, providing insights into climate shifts in central Florida. The charcoal preserved in Lake Marian's sediment record is predicted to show the oak-to-pine change between 6.5 to 4.5 cal kyr BP, as shown in previous literature (Grimm et al., 1993; Watts & Hansen, 1988), through shifts in the morphometric data (Feurdean et al., 2023; Vachula et al., 2024; Vachula et al., 2021). This research is critical for developing strategies to predict, prepare for, and mitigate future wildfires in fire-dependent ecosystems increasingly affected by climate change.

2. Methods

2.1 Study Site

Located in the southeastern U.S.A., Lake Marian (27.8870701°N, 81.1228334°W, 18 m a.s.l.; 4.6 m depth; Fig. 1) is a hypereutrophic shallow waterbody within the Three Lakes Wildlife Management Area, managed by the State of Florida Fish and Wildlife Conservation Commission (FWCC). The FWCC has prescribed burns in the management area near Lake Marian for decades. Lake Marian is also surrounded by several archeological markers, making this lake an ideal location to capture charcoal produced through modern and indigenous practices.

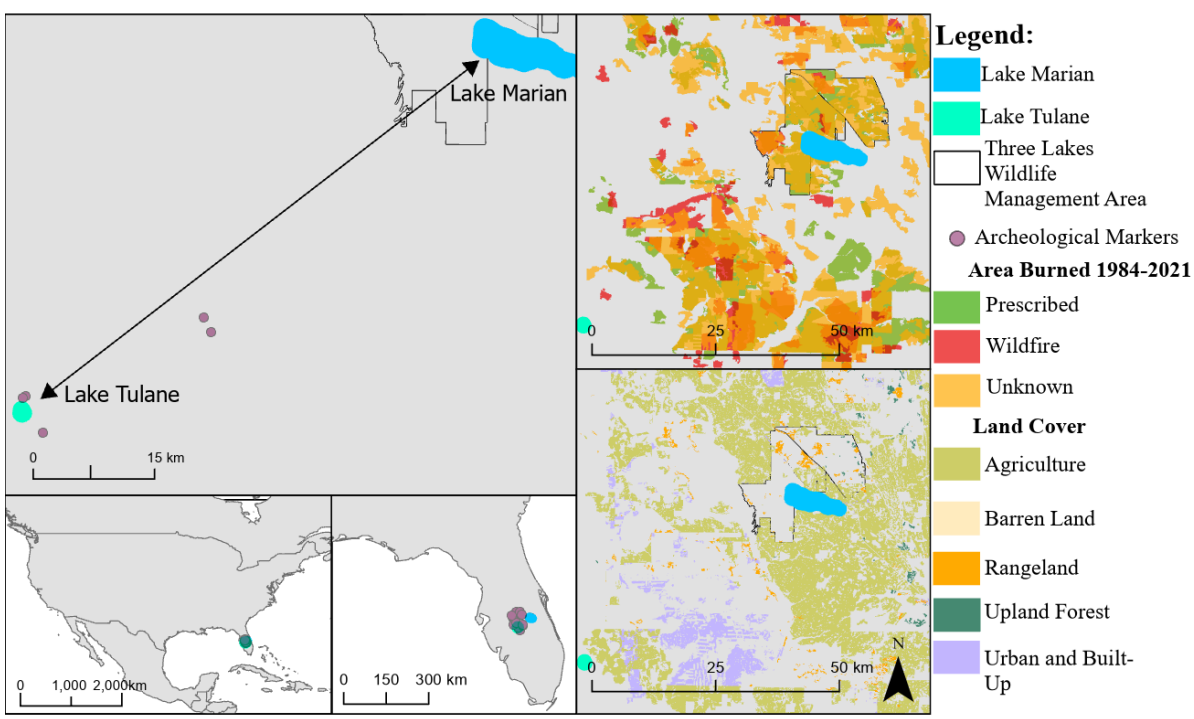


Figure 1: Our study site Lake Marian is in the state of Florida, U.S.A., in an area with active prescribed burning and wildfires (area burned from 1984-2021; (USDA, 2019)). The dots represent archeological findings between Lake Marian and Lake Tulane from the Florida Department of Environmental Protection (2023). Much of the landscape surrounding Lake Marian is used for agriculture (Florida Fish and Wildlife Conservation Commission (FWC), Land Cover Data, 2023) (Lake Tulane; "Florida Department of Environmental Protection Geospatial Open Data," 2024).

2.2 Sediment Collection

The Lake Marian sediment core was collected on January 7, 2022. To identify the coring location, the team relied on previous surveys and locally inspected the bathymetry and soft sediment yield (Whitmore et al., 1996; Waters et al., 2010). A piston corer (7 cm diameter tubes) was used to collect undisturbed mud/water interface sediments, and deeper sediments were extracted using a modified Livingstone corer (5.5 cm diameter tubes) (Fig. 2; Fisher et al., 1992). Each subsequent drive was collected with a 20 cm overlap with the previous drive. The mudwater interface cores were subsampled in 4 cm sections in the field and packed in labeled Whirlpak bags (VWR, USA #11216-092), whereas more consolidated sections were kept in their labeled polycarbonate core barrels. All samples were transported in iced coolers to facilities at Auburn University. Cores were split in half lengthwise, photographed, and described. One half of each core was stored as an archive and the other half was subsampled.

For charcoal analysis, cubic centimeter subsamples were placed in labeled plastic centrifuge tubes (VWR, USA #470150-966). Sample tubes were kept under refrigeration until processed.

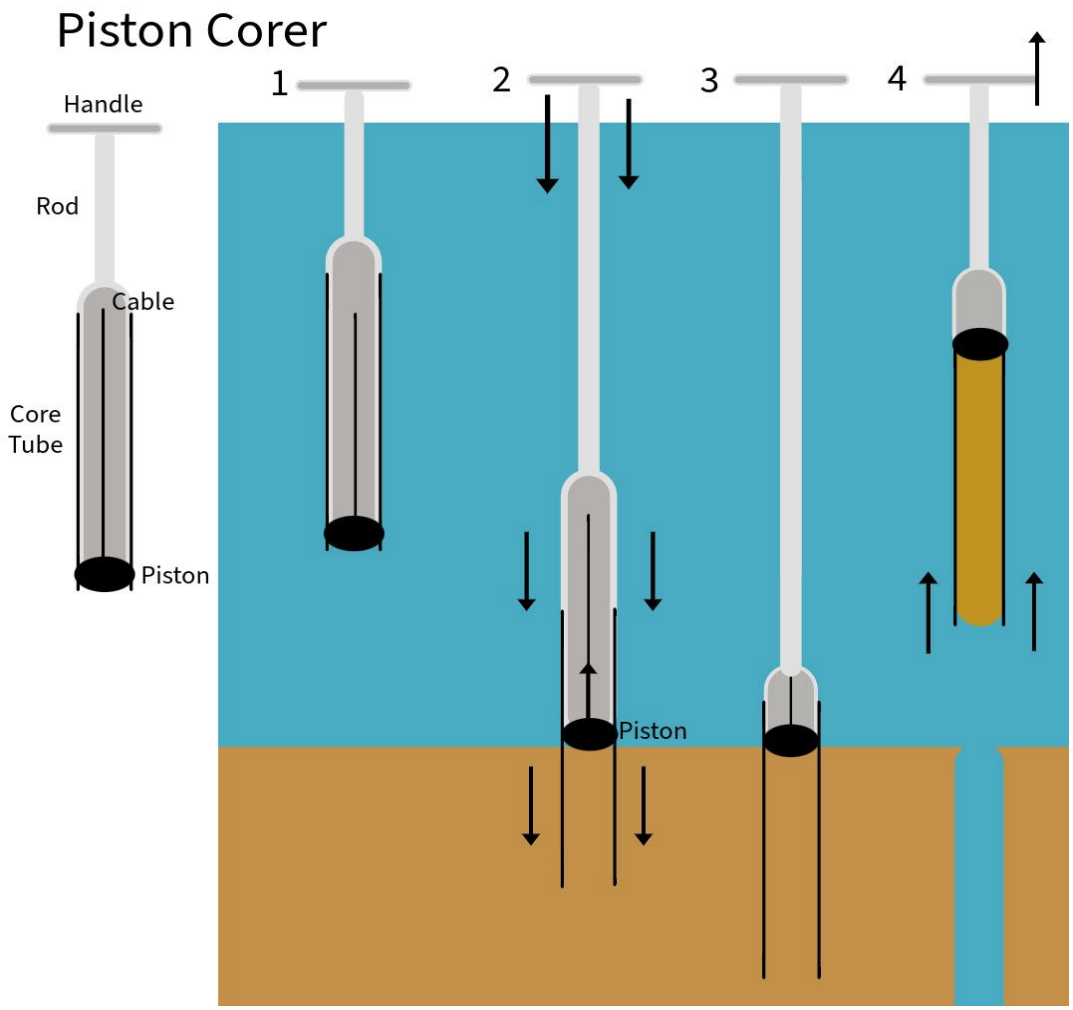


Figure 2: Diagram of the Piston/Livingston Corer used to collect the Lake Marian Sediment Samples. We used a piston corer (7 cm diameter tubes) to collect the uppermost ~2 meters of undisturbed mud/water interface sediments (Fisher et al. 1992). The deeper sediments were extruded using a modified Livingstone corer (5.5 cm diameter tubes), starting at ~1 meter, and taken in three drives to a depth of 3.2 meters. Each sediment core aimed to have a 20 cm overlapping section with the previous.

2.3 Sediment Core Chronology

The age-depth relationship was established using ^{210}Pb dating, radiocarbon dating, and the BACON age modeling package in R statistical software (Blaauw & Christen, 2011; R Core Team, 2024). Subsequently, these dates were employed to calculate charcoal accumulation rates (CHARs). The ^{210}Pb dating was used for the top 50 cm to date the last 100 years due to its half-life of 22 years (Shackley, 2001). After 50 cm we shifted to ^{14}C since it has a half-life of 5,730 ± 70 years and a steady decay rate, the residual radiocarbon can be measured to estimate the age (Shackley, 2001). The dates were then applied to the depth to acquire a sediment accumulation rate using the rBACON age modeling software (Blaauw & Christen, 2011; R Core Team, 2024). Sediment ages are reported in kiloyear units calibrated before the present (cal kyr BP), with 0 cal kyr BP = 1950 CE. The year 1950 represents 0 in cal yr BP because of the widespread use of nuclear warfare which altered the amount of ^{14}C in the atmosphere impacting carbon dating accuracy (Shackley, 2001). Therefore, ^{14}C can only be used to date sediments older than 1950.

2.4 Charcoal Analysis

Each sample was treated with 5mL of 1 M sodium hexametaphosphate and 5mL of 3.75% bleach for 24 hours. The samples were then wet-sieved using a 125 µm mesh and deionized water and the residual was transferred to lined counting trays (Vachula et al., 2019).

The trays were placed under a microscope to identify charcoal particles and photos were taken manually using a Nikon DS-Fi3 microscope camera. CharTool, a free open-source program in ImageJ (Snitker, 2020), was used to quantify and classify charcoal. The morphotypes identified using Chartool followed the charcoal classification key by Enache and Cumming, 2006: M, F, S/B, D, P, and C (Fig. 3). The morphotypes S and B were combined in this study due to their similarities and represent "S/B", following the modified classification scheme as used in CharTool (Snitker, 2020).

For this paper, we focus on the following morphometric parameters collected in CharTool: rectangularity (ranges from 0 to 1, with 1 being the perfect rectangle), circularity ($4\pi \times \text{area} \div \text{perimeter}^2$, ranges from 0 to 1, with 1 being a perfect circle), A:P (area divided by perimeter), and Aspect Ratio (equivalent to and referred to as L:W, as it is defined in the literature (Vachula et al., 2021)) calculated as the principal (primary) axis / minor (secondary) axis of the best fitting ellipse) (Snitker, 2020). The averages and standard deviations of each sample's charcoal morphometrics stated (area, min, max, perimeter, circularity, length to width ((L:W) or aspect ratio), area to perimeter (A:P), and rectangularity) were calculated to detect any long-term vegetation trends. The morphometric parameters can be related to the vegetation burned and the intensity of the fire. As charcoal becomes more rectangular it is more likely to be a wood or grass fuel type (Enache & Cumming, 2006; Mustaphi & Pisaric, 2014). As charcoal is more circular it can indicate leaf material or the particle traveled before being deposited (Crawford & Belcher, 2014). The area-to-perimeter ratio (A:P) increases with irregular surfaces of charcoal and decreases with increased fire temperature (Feurdean et al., 2023). As length-to width ratios increase with increased fire temperatures (Feurdean et al.,

2023). The length-to-width ratio also indicates the fuel source with grasses, palmettos, dicot wood, and gymnosperm needles sharing the highest values (Vachula et al., 2024).

The charcoal accumulation rates (CHARs) for each sample were calculated using the volumetric concentration and age-depth model following Vachula et al. (2019):

$$(1)\ CHAR = \left(\frac{charcoal\ count}{sample\ volume}\right) \times \frac{(bottom\ composite\ depth - top\ composite\ depth)}{(bottom\ age - top\ age)} = \frac{\#}{cm^2 yr}$$

Due to the variability of charcoal measurements (Anderson et al., 2023), replicate measurements of charcoal were taken. We undertook duplicate sampling of 14 samples and one triple sample (14.7% of all 102 samples were repeated). The duplicate samples were averaged in our results.

2.5 Statistical Analysis

Due to the CHAR values' non-normal distribution, a Kruskal-Wallis rank sum test was performed on the three periods' CHAR values to determine the significance between the groups. The Kruskal-Wallis rank sum test was conducted using R statistical software (R Core Team, 2024).

2.6 Comparison to Published Data

We compare the paleofire data to pollen from Lake Tulane (Grimm et al., 1993), which was downloaded from the Neotoma Paleoecology Database (Nelson et al., 2023). Lake Tulane is 51 km southwest of Lake Marian (Fig. 1), and pollen can travel by wind over 100 km, making Lake Tulane's record a plausible representation of Lake Marian's surrounding vegetation throughout time (Frisk et al., 2023; Robledo-Arnuncio & Gil, 2005).

To consider possible human impacts on our paleofire and paleoecological data, we delineated Holocene archeologic history following Delcourt and Delcourt (2004). These periods were then divided into three groups for clarity and possible human influence: (1) the Archaic period including the early, middle, and late Archaic (8.5 to 3 cal kyr BP), (2) the Woodland and Mississippian periods (3 to 0.5 cal kyr BP), (3) the Modern (0.5 cal kyr BP to the present) (Table 1).

Table 1: Time periods with corresponding anthropogenic influences (Delcourt & Delcourt, 2004)

Time-Period	**Archaic**	**Woodland & Mississippian**	**Modern**
	(8.5 to 3 cal kyr BP)	(3 to 0.5 cal kyr BP)	(0.5 cal kyr BP to present)

hunter-gatherers migration climate & vegetation shift oak to pine shift?	anthropogenic environmental influence, sedentism, increased crop cultivation, population growth	complex Indigenous communities, European conquest, deforestation, total fire suppression, and increased land management practices like prescribed burning (Delcourt & Delcourt, 2004; Fowler & Konopik, 2007; Ryan et al., 2013)

2. Results

3.1 Lake Marian Chronology

Radiocarbon dates for four samples from the Lake Marian (LMA22) core are presented in Table 1. The BACON age-depth model was used to estimate ages at undated depths. The ^{210}Pb record for the last ~100 years of Lake Marian reaches a depth of 50cm. After 50 cm, ^{14}C dating

was used due to its longer half-life. The top of the Lake Marian core was estimated at -72 cal yr BP. The age at the base of the Lake Marian core (329cm) was estimated at 8270 cal yr BP.

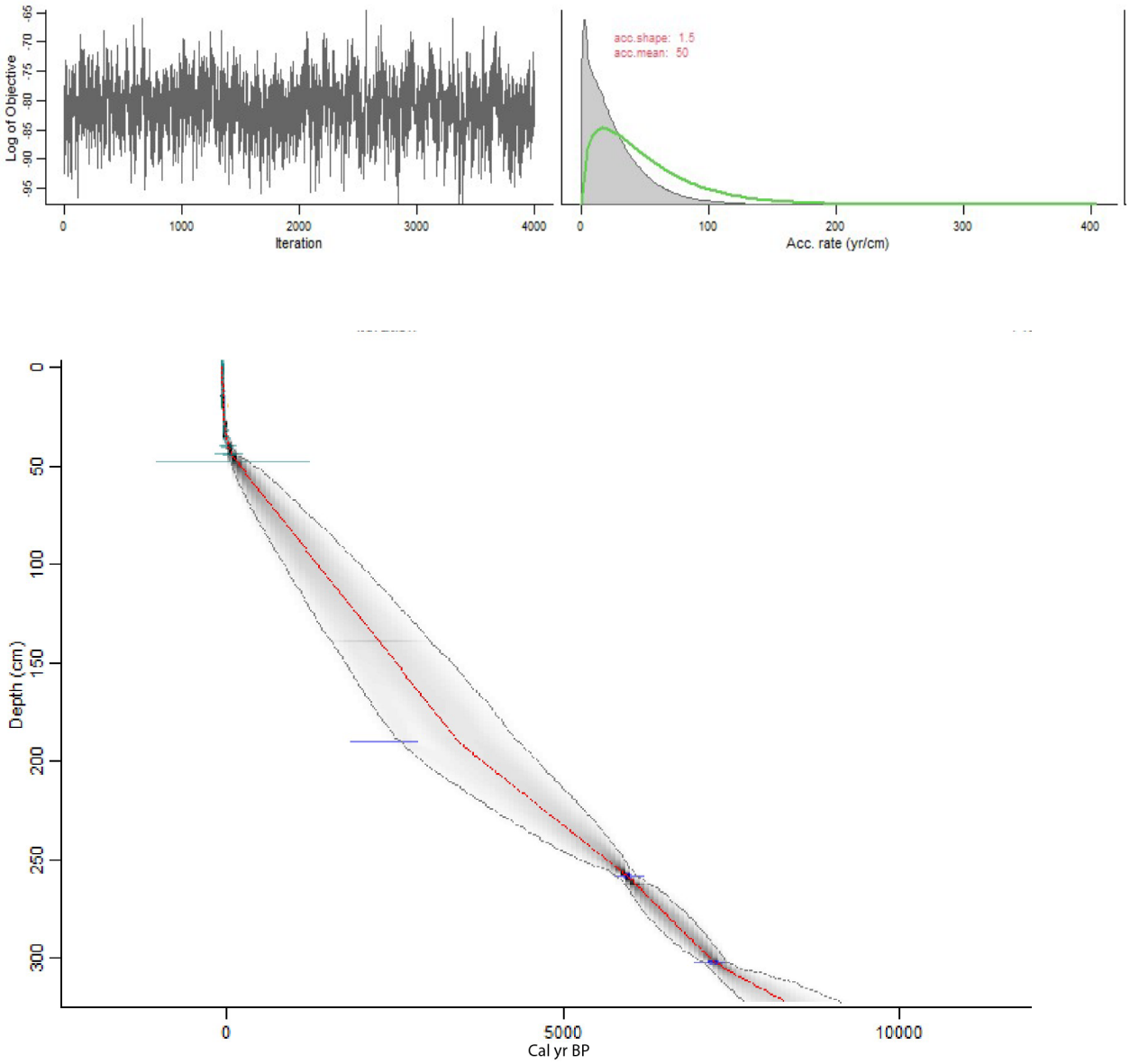


Figure 3: Bacon age-depth model for Lake Marian. The main bottom plot shows the age-depth relationship for the core. The blue violin plots show the probability density function for each calibrated radiocarbon age estimate. The fine black dotted lines represent 95% confidence intervals and bound the grayscale cloud representing the age-model probability. Confidence intervals are wider at depths farther from the radiocarbon-dated samples. The red line represents the weighted averages of all fitted chronologies. The top left graph shows the

Markov Chain Monte Carlo (MCMC) iteration history. The simulation ran at a minimized objective function, and the iterations were run 4000 times until the best solution was found. The top right graph represents the accumulation rate or sedimentation time. The green line represents the gamma distribution or prior density with the two parameters of accumulation shape and accumulation mean. The grey shape is the posterior distribution for the mean accumulation rate.

Table 2: Radiocarbon (^{14}C) and ^{210}Pb dates from Lake Marian, Florida.

Depth (cm)	**^{210}Pb cal yr BP**	**Depth (cm)**	**^{14}C yrs**	**14C error (yrs)**
0	-72	190	2347	± 85
4	-69	258	5947	± 25
8	-65	302	7240	± 50
12	-62			
16	-59			
20	-54			
24	-48			
28	-39			
32	-25			
36	-6			
40	24			
44	67			

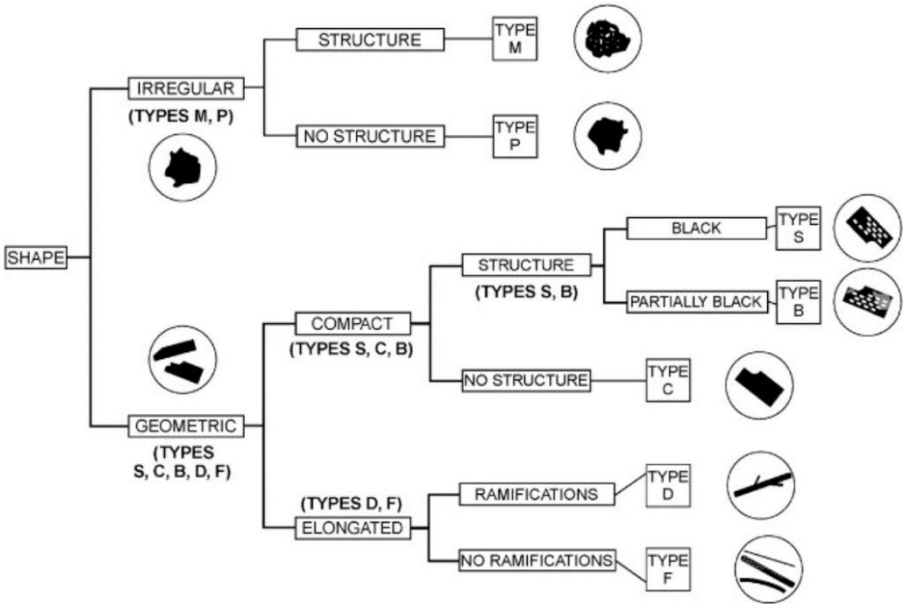


Figure 4: Morphological charcoal key from Enache & Cumming, 2006. To categorize the charcoal's shape, start from the left and decide whether it is irregular (rounded) or geometric (polygonal). An irregular shape can be further classified if there is structure (wall porosity) from the plant tissue or not. If geometric, it is either compact, representing more rectangular shapes, or elongated longer and thinner shapes. The compact shapes can then be divided into structure or no structure. If structure is present the morphotype would be “S/B” following the modified classification scheme used in CharTool (Snitker, 2020). The elongated can be further classified according to any branch-like ramifications present.

3.2 Charcoal Morphometric and Morphological Analysis

We identified, classified, and measured a total of 2,643 charcoal particles >125 µm (standard deviation (σ) =28.1) preserved in the Lake Marian sediment core. Out of the 102 samples, there were 14 duplicate samples. The duplicate samples provided confidence in our measurements, with an average CHAR difference of ± 0.3058 cm $^{-2}$ yr $^{-1}$. The average age of 6.125 cal kyr BP had three samples, with a CHAR average of 0.4 cm $^{-2}$ yr $^{-1}$. Charcoal accumulation rates (CHAR) of the samples varied through time (Fig. 5). CHARs increased around 7.0 cal kyr BP and then decreased around 6.5 cal kyr BP. CHARs were relatively low from ~3.0 to ~ 6.0 cal kyr BP. Then the CHARs begin to rise from ~3.0 to the present.

The morphotypes S/B, D, F, C, M, and P were observed throughout the core with varying percentages throughout time (Fig. 7,11). Percent type P was consistent at around 30% throughout the Holocene. However, between 6.0 and 5.5 cal kyr BP and between ~8.3 cal kyr BP morphotype P increased to maxima of ~90% (Fig. 11). Type M had a relatively consistent percentage (average (μ) = 6.5 standard deviation (σ) = 7.2) from 8.0 to 2.0 cal kyr BP, followed by elevated values (μ =23.1, σ = 9.9) from 2.0 to 0.5 cal kyr BP. Type M had generally low values (μ =11.2, σ =13.5) from 0.5 cal kyr BP to the present, with an elevated value centered at 0.2 cal kyr BP (μ = 26.3, σ =9.1). Type C was highly variable throughout time with the highest percentage at around 60% and the lowest at 0% (μ =20.4, σ =13.4). Type F was relatively constant at 30% with a 90% peak in the last 0.5 cal kyr BP (μ = 21.3, σ =25.7). Type P was typically low throughout time with a high at 8.0 cal kyr BP (μ =13.9, σ =18.1). Type D was stable throughout the Holocene and increased at 5.0 and 2.0 cal kyr BP (μ =10.1, σ =9.9). Type

S/B was elevated from 4.0 to 2.0 cal kyr BP (μ =14.8, σ =10.5). Type S/B increased from 0.5 cal kyr BP to present (μ =15.9, σ =13.9).

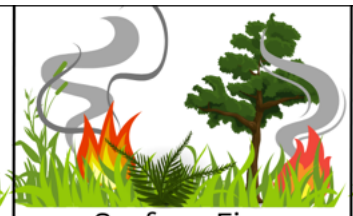
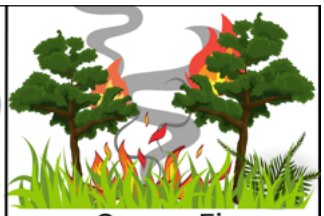
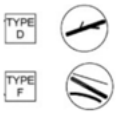
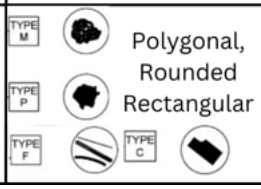
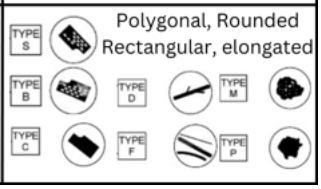
Fire Type	Ground Fire	 Surface Fire	 Crown Fire
Fuel Type	wiregrass, palmettos, needles	leaves, wood, needles, forbs	live tree leaves, wood, needles
Charcoal Production	Low	High	Moderate
Aspect Ratio (L:W) & Area to Perimeter (A:P)	L:W High (>~2.5) A:P High	L:W Moderate (~1.9-~4.6) A:P High to Moderate	L:W Low to Moderate (<~1.9-~4.6) A:P Low to Moderate
Morphologies	 Elongated	 Polygonal, Rounded Rectangular	 Polygonal, Rounded Rectangular, elongated

Table 3: Connections between fire type, fuels, charcoal production, Aspect ratio, Area to Perimeter, and morphologies (Adapted from: Feurdean, 2021; L/W values from: Vachula et al., 2024).

4. Discussion

4.1 Interpreting Charcoal Morphologies and Morphometrics of Lake Marian

The charcoal preserved in Lake Marian's sediment recorded fire over the last ~8.5 cal kyr BP (Fig. 5). While the data span most of the Holocene, we sub-divide this record into three periods for clarity, which correspond to archaeological periods outlined by Delcourt and Delcourt (2004), characterized by similar CHAR data trends: 1) the Archaic period (8.5 to 3 cal kyr BP), 2) the Woodland and Mississippian periods (3 to 0.5 cal kyr BP), and 3) the Modern period (0.5 cal kyr to the present). Fire activity was relatively low in the Archaic period (8.5 to 3 cal kyr BP) (Table 1). In the Woodland and Mississippian periods (3 to 0.5 cal kyr BP), fire activity began to increase into the Modern period (0.5 cal kyr BP to present), characterized by the highest fire activity.

We interpret the Charcoal Accumulation Rate (CHAR) of the macroscopic charcoal size fraction of >125 µm to reflect regional fire history (~30km) (Hennebelle et al., 2020; Vachula et al., 2018; Vachula, 2021; Whitlock & Larsen, 2002). The modern-time Lake Marian CHAR exceeded the Holocene CHAR baseline. We infer this signal to indicate higher severity fires, lower fire return intervals, and increased area burned (Hennebelle et al., 2020).

The morphometrics and morphotypes provide potential fuel types and fire conditions. The morphologies of the charcoal particles are representative of the fuel type (Enache & Cumming, 2006; Mustaphi & Pisaric 2014), however, Enache & Cummings morphotypes are representative of fuels in British Columbia, Canada. While this morphological key is still used in other regions, biome-specific morphological qualification keys, created by using native vegetation for experimental burns as seen in Vachula et al., 2024, would solidify the interpretation of charcoal archives and help resolve many uncertainties when studying other ecosystems.

Since the morphotypes may not be calibrated to the study site, morphometrics can aid in determining the fuel sources. The morphometrics can provide the fuel type and burn conditions (Enache & Cumming, 2006; Feurdean et al., 2023; Mustaphi & Pisaric, 2014; Snitker, 2020). Previous research has tied high L:W (Aspect Ratio) values to high temperatures, grass, and nonwoody fuels (> 3.5) and lower values to woody fuels and lower temperatures (< 2.5) (Feurdean et al., 2023; Umbanhowar & Mcgrath, 1998; Vachula et al., 2021; Vachula et al., 2024).

However, a recent paper experimenting with native Southeast U.S.A. fuels showed that a high L:W value represents grass fuels and possibly dicot wood and gymnosperm needles (Vachula et al., 2024). Additional research on morphometric relationships between fuel types and fire temperatures is necessary to enhance the understanding of this region's fire regime. A high circularity indicates a more rounded particle and could suggest the charcoal was transported far before being deposited (Crawford & Belcher, 2014; Frank-DePue et al., 2023). High rectangularity values indicate an irregular charcoal shape (Snitker, 2020) representing woody fuels (Enache & Cumming, 2006; Mustaphi & Pisaric, 2014). The area-to-perimeter ratio (A:P) increases with irregular surfaces of charcoal and decreases with increased fire temperature (Table 3; Feurdean et al., 2023). The charcoal size, shape, and density can determine the particles' dispersion and incorporation into sediments, with particles carrying more biomasses being deposited closer to the fire source (Clark & Hussey, 1996; Vachula & Richter, 2018; Vachula & Rehn, 2023). Thus, the macrocharcoal analyzed in this study likely represents regional fire activity.

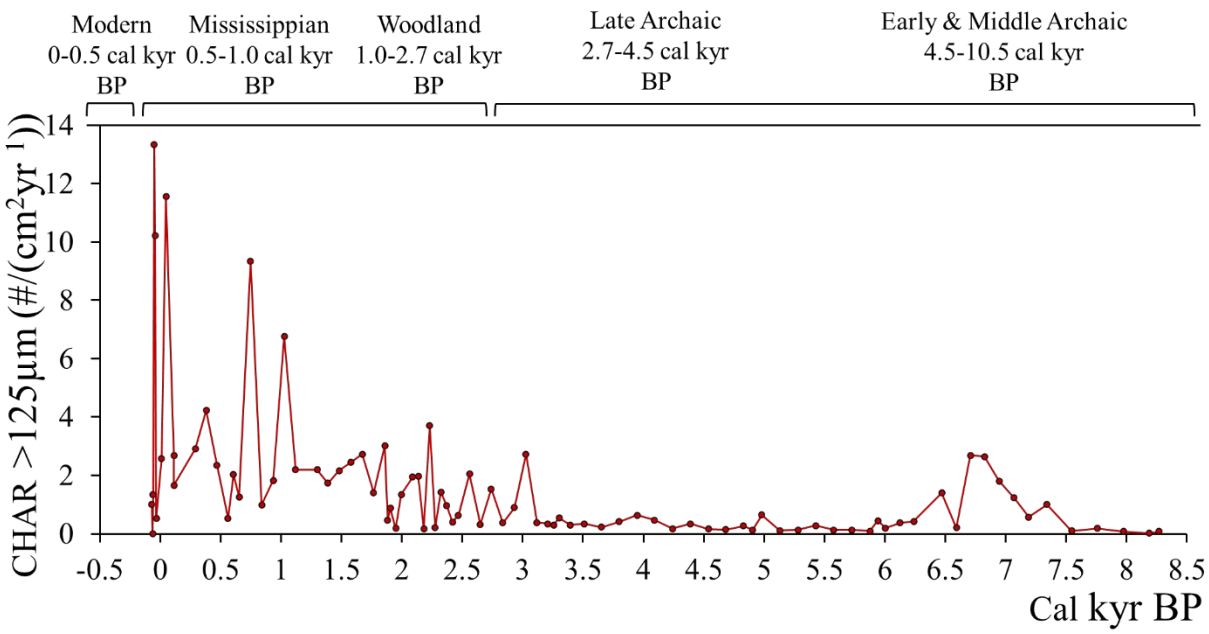


Figure 5: Variations of Charcoal Accumulation Rate (CHAR) correspond with historical land use changes and human utilization of fire. The cultural periods were derived from Delcourt and Delcourt (2004). Around the end of the Late Archaic and into the Woodland, CHAR values began to increase with the highest values coinciding with increased anthropogenic influence in the modern.

Table 4: Literature CHAR comparison.

Study Site	**Distance from Lake Marian**	**CHAR Similarities**	**Reference**
Marl Prairie, FL	286 km	Highest Values in the Modern Peak around 0.5 cal kyr BP	Jones et al., 2014
Lochloosa Lake, FL	207 km	Peak ~7 cal kyr BP	Mendieta et al., 2018
Ocala National Forest Wetlands, FL	158 km	Increase from ~3 cal kyr BP into the Modern	Tanner et al., 2018
Ditch Pond, AL; Manatee Bay, FL	636 km; 177 km	Peak at ~0 cal kyr BP	Waters et al., 2023; Ishman et al.,1998
Ocean Pond, FL	291 km	Highest Values in the Modern Peak ~7 cal kyr BP	Waters et al., 2018

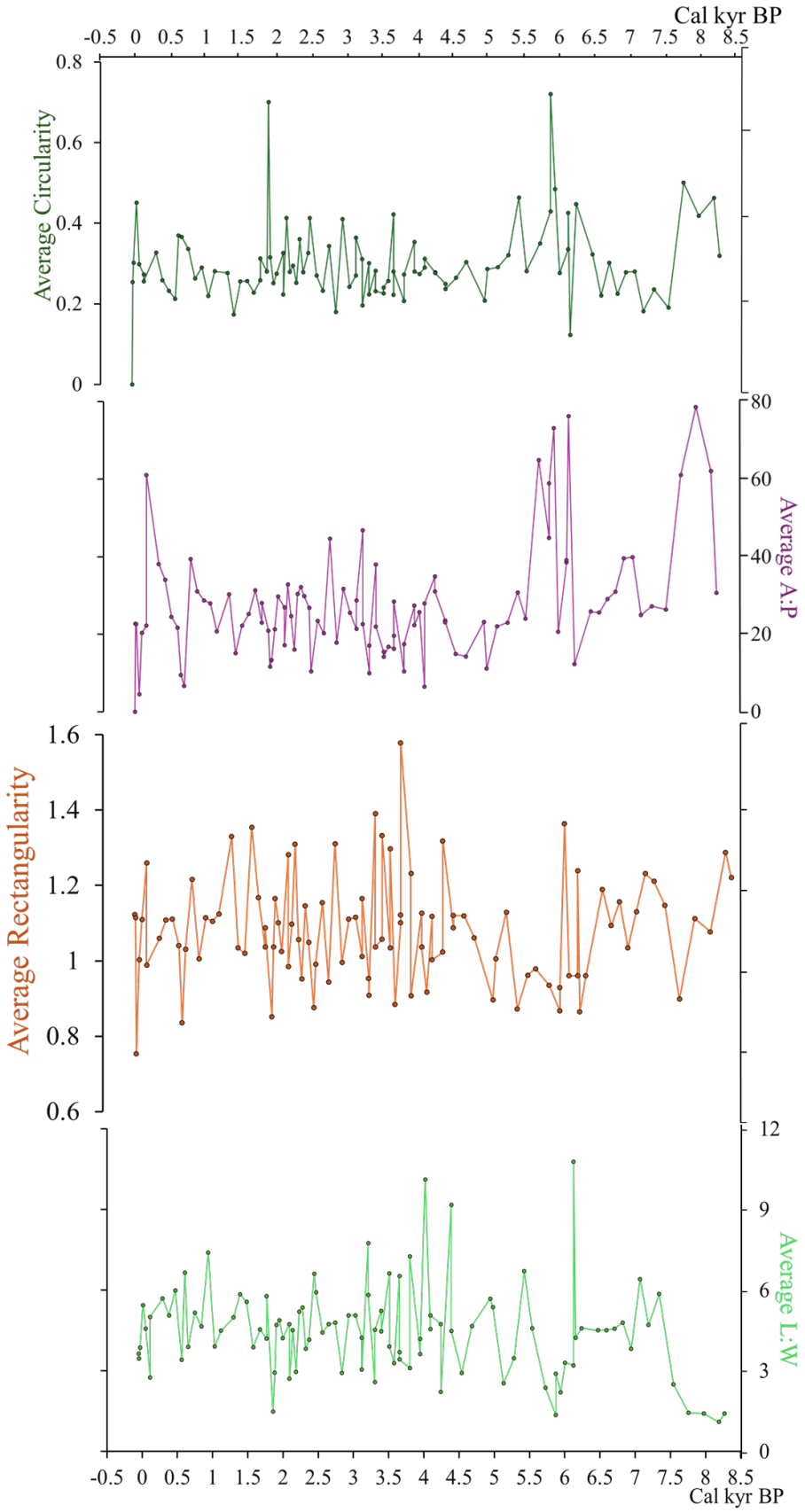

Cal kyr BP
-0.5 0 0.5 1 1.5 2 2.5 3 3.5 4 4.5 5 5.5 6 6.5 7 7.5 8 8.5
Average Circularity
0.8
0.6
0.4
0.2
0
Average A:P
80
60
40
20
0
Average Rectangularity
1.6
1.4
1.2
1
0.8
0.6
Average L:W
12
9
6
3
0
-0.5 0 0.5 1 1.5 2 2.5 3 3.5 4 4.5 5 5.5 6 6.5 7 7.5 8 8.5
Cal kyr BP

Figure 6: The average circularity, rectangularity, Area to Perimeter (A:P), and Length to Width ((L:W) or Aspect Ratio (AR)) from Lake Marian throughout time. Noted irregularities appear across all morphometrics during a 1,000-year interval (5.5 to 6.5 Cal kyr BP).

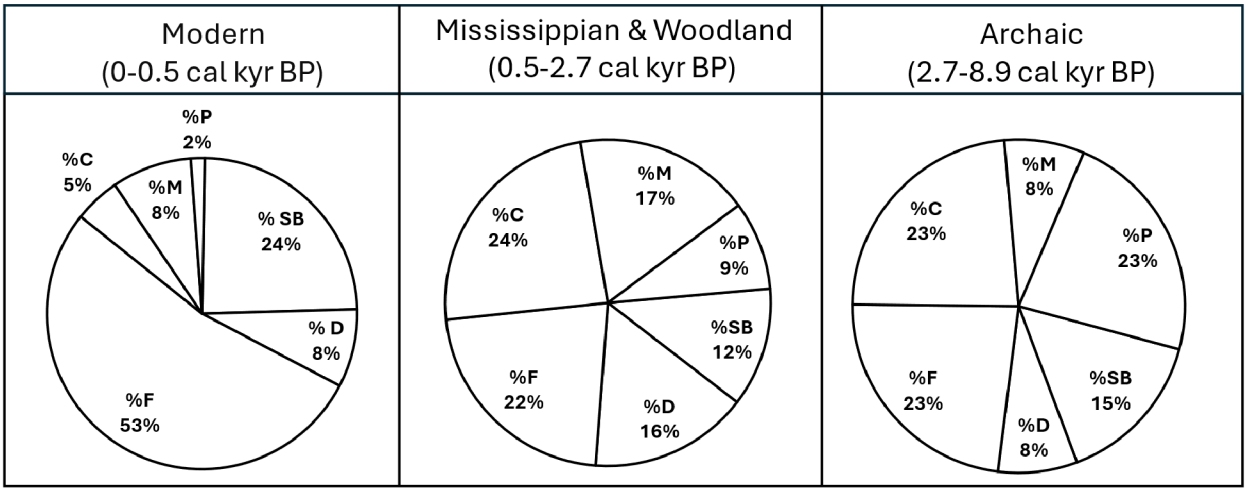


Figure 7: The average morphologies (Enache & Cumming, 2007) recorded during the periods. % P is the highest during the Archaic (23%) and decreases to 2% in the Modern. % F and % SB doubled in the Modern compared to the Mississippian Woodland, and the Archaic periods. % C decreased in the Modern by 18.5%. The fuel types have changed with the increased use of fire as a land management tool.

4.1.1 The Archaic Period (8.5 to 2.7 cal kyr BP)

The Archaic Period (8.5 to 2.7 cal kyr BP) marks the beginning of a seasonally warmer and wetter climate in Florida due to the stabilization of post-glacial sea level rise (Hine et al., 2017). As the climate warmed and sea levels began to rise during the early Archaic, Florida's wetlands began to fill creating shallow lake systems around 9.0 cal kyr BP further changing the terrestrial environment (Brenner et al. 1990; Hine et al., 2017; Waters et al., 2015). A diatom record from the nearby Lake Apopka supports an early Holocene shift from shallow wetland systems to the shallow lakes seen today (Donar et al., 2009; Donders et al., 2011; Waters et al., 2015). This hydrologic change would support vegetation growth by creating moister soils.

The Archaic period was dominated by morphotypes C, F, and P, mostly representing woody fuels (Fig. 6; Enache & Cumming, 2006; Mustaphi & Pisaric, 2014). Moreover, morphotype P could also be leaf material (Feurdean et al., 2023). The CHAR values remained low compared to the other periods as confirmed by the Kruskal-Wallis rank sum test as the CHAR values were significantly different between the Archaic to Mississippian (P=0.003) and the Archaic to Modern (P=0.000002) ($\chi^2 = 26.94$, df = 2, $P = 0.000001$). The CHAR values showed small peaks around 7 and 6.5 cal kyr BP (Fig. 5) also noted by Mendieta et al., (2018) at Lochloosa Lake, Florida, and by Waters et al., (2018) at Ocean Pond, Florida (Table 4). These similar peaks could have resulted from increased vegetation from groundwater shoaling, keeping the fuel relatively dry and more easily flammable.

Following the fire events around 7 and 6.5 cal kyr BP, between 6.5 and 5.5 cal kyr BP, we observed high variability for all recorded morphometrics (circularity, rectangularity, A:P, and L:W) as they drastically increase then decrease within a 1.0 kyr timeframe (Fig. 6). Notably within this shift, at 6 cal kyr BP, morphotypes M, and S/B (non-grass herbaceous fuels) increased while the remaining morphotypes decreased (Enache & Cumming, 2006; Mustaphi & Pisaric,

2014). Frank-DePue et al., (2023) reasoned that M and S/B morphotypes became more prominent during known periods of agricultural intensity, likely herbaceous fuels produced by agrarian burning. The Archaic is not known to share these characteristics; however, we can suppose that herbaceous understory burning increased during this time, possibly from human-induced brush fires for hunting and from a change in the climate and hydrology (Fig. 5; Fowler & Konopik, 2007; Hine et al., 2017; Waters et al., 2015).

A nearby sediment core from Lake Tulane, Florida, shows that early Holocene pollen assemblages were dominated by oak; then around 5.5 cal kyr BP, transitioned to pine dominance (Grimm et al., 1993; Mendieta et al., 2018; Watts 1969; 1971; 1980; Watts & Hansen 1988). This vegetation shift may be represented by jagged increases and decreases of morphometric data, from 6.5 to 5.5 cal kyr BP. The L:W ratios from 6.5 to 6 cal kyr BP, resemble the experimental dicot (oak) wood and monocot L:W values from Vachula et al., 2024. A time of more woody fuels (possibly the start of oak dying off) is also supported by the A:P, and rectangularity peaks from 6.5 to 6.0 cal kyr BP (Fig. 6). A shift in the L:W values to dicot wood and leaf matter possibly even gymnosperm (pine) wood and needles (Vachula et al., 2024), happened between 6.0 to 5.5 cal kyr BP, from the continuous decrease of oak and the emergence of pine as noted in neighboring pollen reconstructions (Grimm et al., 1993; Fig. 8) and the A:P and circularity peaks. After 5.5 cal kyr BP, the L:W values continued to show grasses, dicot wood, and gymnosperm needles (Vachula et al., 2024). A decrease in A:P and circularity also support the presence of woody dicot fuels from the remaining decaying oak and gymnosperm needles from the regeneration of pine (Fig. 6; Table 5; Enache & Cumming, 2006; Feurdean et al., 2023; Mustaphi & Pisaric, 2014; Umbanhowar & Mcgrath, 1998). As mentioned, the pollen assemblages from the neighboring Lake Tulane recorded the oak-to-pine shift during this 1.0 cal

kyr BP interval further supporting the discrepancies in the preserved charcoal to be indicative of this vegetation shift (Fig. 8; Table 5; Grimm et al., 2006).

The oak-to-pine shift is reasoned to have happened around 5 cal kyr BP across Florida (Table 6; Grimm et al., 1993; Mendieta et al., 2018; Watts 1969; 1971; 1980; Watts & Hansen 1988), causing these noted irregularities. Around the shift timing, a small increase in CHAR is seen at Lake Marian and Ocean Pond (Waters et al., 2018; Table 3). The changing climate and possible Indigenous presence could have aided the low-intensity ground fires (L:W peak at 6 cal kyr BP) (Feurdean et al., 2023) by providing more ground fuel from less-fire-tolerant taxa. During this time the morphotypes represent leaves and woody vegetation (M and S/B), however, grass-like fuels tend to ignite faster than other fuel types leaving behind little to no charcoal, resulting in grass fuels being underrepresented in charcoal reconstructions (Feurdean et al., 2023). Therefore, this seems to have been a period of low-intensity fires burning the understory of plants that may not have survived the warmer wetter climate further allowing the expansion of pine (Grimm et al., 1993; Donders et al., 2011). The rise in fires could have contributed to the ~5 cal kyr BP oak-to-pine shift in certain areas (Table 6).

Mendieta et al., (2018), failed to find a correspondence between CHAR values and pollen records during the oak-to-pine shift. However, Lake Marian's charcoal record suggests that there may be a correspondence between morphometric values and pollen records. Based on the abrupt shifts in the data coinciding with the reasoned timeframe of the oak-to-pine shift (~6 to ~5 Cal kyr BP) (Table 6; Brown, 1981; Grimm et al., 1993; Mendieta et al., 2018; Watts & Hansen, 1988; Watts, 1969; 1971; 1975) and Lake Tulane's pollen record, it is reasonable to believe that sedimentary charcoal can record vegetation shifts through the morphometric data.

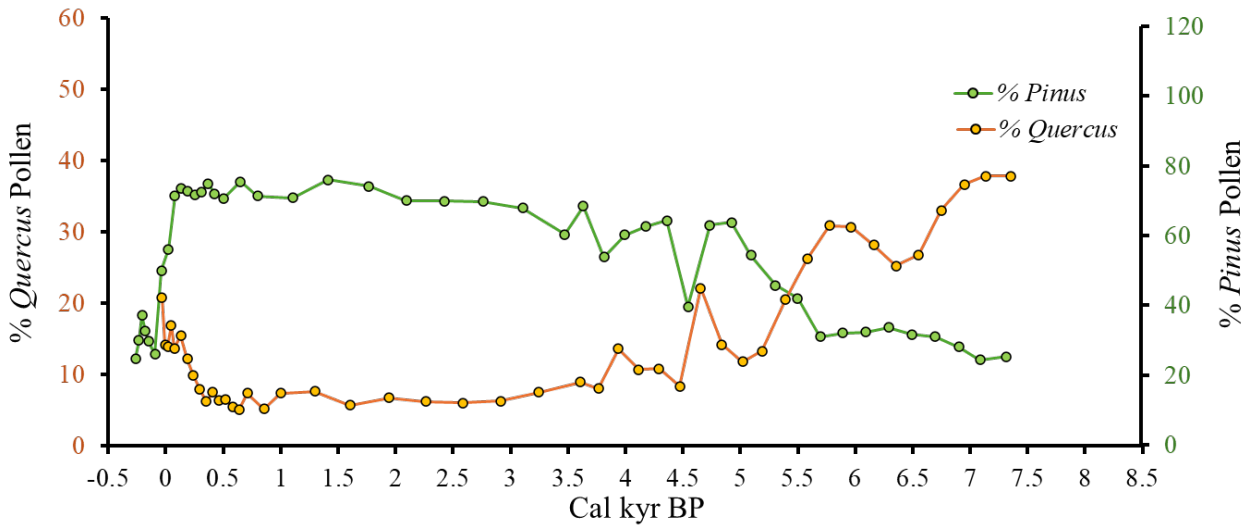


Figure 8: *Pinus* and *Quercus* pollen data from Lake Tulane, FL (Grimm et al., 1993)

Table 5: Oak-to-Pine Overview, comparing with L:W ratios from Vachula et al., (2024).

Timing	**6.5 to 6 cal kyr BP**	**6 to 5.5 cal kyr BP**	**After 5.5 cal kyr BP**
L:W	experimental dicot wood (oak wood) and monocot	dicot wood and leaf matter possibly even gymnosperm (pine) wood and needles	grasses, dicot wood, and gymnosperm needles
Others	A:P and rectangularity peaks (woody fuels)	A:P and circularity peaks (woody and leafy fuels)	decrease in A:P and circularity (grasses, needles, and woody fuels)
Interpretation	possibly the start of oak decline	decrease in oak and the beginning of the increase in pine	woody dicot fuels from the remaining decaying oak and gymnosperm needles from the regeneration of pine

Table 6: Oak-to-Pine Literature Comparison with Florida Lakes.

Data Location	**Distance from Lake Marian**	**Proxy**	**Oak-to-Pine?**	**Literature**
Lake Tulane	51.2 km	Pollen, Charcoal	~5.5 cal kyr BP	Grimm et al., 1993; Watts & Hansen, 1988
Lake Annie	51.7 km	Pollen	~4.7 cal kyr BP	Watts, 1975
Mud Lake	80.1 km	Pollen	~5.5 cal kyr BP	Watts, 1969; 1971
Little Salt Spring	143.2 km	Pollen	~5 cal kyr BP	Brown, 1981
Scott Lake	166.8 km	Pollen	~4.5 cal kyr BP	Watts, 1971

4.1.2 The Woodland and Mississippian Periods (2.7 to 0.5 cal kyr BP)

The Woodland and Mississippian periods (2.7 to 0.5 cal kyr BP) marked sedentism, increased crop cultivation, population growth, and thus anthropogenic environmental influence (Anderson & Mainfort, 2002; Delcourt & Delcourt, 2004; Denevan, 1992). The climate shifted

around 2.2 cal kyr BP to drier fire-prone conditions (van Beynen et al., 2008). Around 2.25 cal kyr BP, CHAR reached a high of 4, further supporting increased fire activity and conditions, as Tanner et al., (2018) documented (Table 4). These increases could also be from human presence and their land management practices as shown by the markers in Figure 1. The markers before European influence mainly showed possible community or temple frames made from logs and stones, pottery, and tools (Krogman, 1948). Nearby shell mounds to the Northeast and West of Lake Marian are estimated to be made around ~1.15 cal kyr BP, the oldest markers in this area (Krogman, 1948). These archeological findings show the complexity and societal advancements during this period further supporting indigenous presence and influence.

These periods reveal increases in morphotypes D and M (Fig. 7). Morphotype D is elongated with ramifications said to be from leaf veins and stems, and roots (Enache & Cumming, 2006; Type C in Mustaphi & Pisaric, 2014), while morphotype M indicates grass or leaf stoma (Type M in Mustaphi & Pisaric, 2014). The morphotypes could be interpreted to indicate crown fires (Enache & Cumming, 2006), possibly due to climatic warming (Marquardt & Walker, 2012). However, the A:P and L:W values fluctuate (Fig. 6), showing a time of both high and low-temperature fires (Feurdean et al., 2023). These discrepancies appear to be an anthropogenic indicator of fire influence.

The increase in woody and leafy fuels with ranging fire temperatures could further support this as an anthropogenic indicator of the broadening use of fire as a tool (Delcourt & Delcourt, 2004; Fowler & Konopik, 2007; Luer et al., 2014). This is also apparent with the high circularity (Fig. 6), suggesting the charcoal was transported far before being deposited; a regional indicator of increased fire activity as supported by the rises in CHAR (Fig. 5; Crawford

& Belcher, 2014; Feurdean et al., 2023; Mustaphi et al., 2015; Umbanhowar & Mcgrath, 1998). The morphotypes and morphometrics reflect the frequent use of low-intensity fires burning leaves and woody fuels; this marks the start of anthropogenic ecosystem disturbance.

4.1.3 The Modern Period (0.5 cal kyr to present)

The third period represents modern times (0.5 cal kyr to present), spanning complex Indigenous communities (Delcourt & Delcourt, 2004), European conquest (Ryan et al., 2013), deforestation (Ryan et al., 2013), total fire suppression (Fowler & Konopik, 2007), and increased land management practices like prescribed burning (Ryan et al., 2013). Westernization increased land use, which converted old-growth pine forests into urban and agricultural areas (Fowler & Konopik, 2007; Mitchell et al., 2014; Ryan et al., 2013). This period coincides with Florida's temperate and subtropical climate (Hine et al., 2017) and increased anthropogenic impacts from Westernization and industrialization (Mitchell et al., 2014; Ryan et al., 2013).

Modern influence has marked the highest CHAR values at Lake Marian (Fig. 5), as documented throughout Florida (Table 3; Jones et al., 2014; Clark & Royall, 1995; Ishman et al.,1998; Waters et al., 2018; 2023). CHAR values began to increase from the late 1800s to the 1900s (~0.1 cal kyr BP), during the total fire suppression ban causing denser forests and heightened competition among native vegetation, increasing fire spread potential (Ali et al., 2012). During this time, there were significant increases in L/W values, along with a decrease in A:P (Fig. 6), which suggests more intense fires likely due to the fuel buildup thought to be

caused by the total fire suppression policy (Bond & Keeley, 2005). Ditch Pond, Alabama recorded increased fire activity during the end of this ban likely due to the available fuel from the lack of fires (Waters et al., 2023), further proving the impacts of this national ban.

The lifting of the total fire suppression ban around 1950 (~0 cal kyr BP) likely contributed to the highest peaks in CHAR, S/B, and F (woody materials, herbaceous, and grass fuels) (Fig. 5, 7; Enache & Cumming, 2006; Mustaphi & Pisaric, 2014), as prescribed burns became a key land management tool to improve forest health and mitigate wildfires (Mitchell et al., 2014; Ryan et al., 2013). This is also thought to be reflected by the peaks in A:P and rectangularity with a decrease in L:W (Fig. 6), indicating decreased fire temperatures, grass, needles, leaves, and woody fuels (Feurdean et al., 2023; Enache & Cumming, 2006; Mustaphi & Pisaric, 2014; Vachula et al., 2024). Waters et al., 2023 and Ishman et al., 1998 also recorded CHAR peaks at Ditch Pond, Alabama, and Manatee Bay, Florida, marking the beginning of frequent prescribed burning practices throughout the southeast.

The last 50 years show the lowest area-to-perimeter ratio (A:P), circularity, and rectangularity values, interpreted as stems, leaves, and grasses with increased fire temperatures (Fig. 6; Feurdean et al., 2023). The land around Lake Marian was cleared for agricultural development (Fig. 1). Following land clearance, unwanted organic materials would be burned, this practice was coined as “slash-and-burn”, highly influencing the fuels burned and recorded (low A:P, circularity, and rectangularity) (Frank-DePue et al., 2023).

As coal and wood were common household fuel sources during this period, this is expected to be reflected in the archive. Frank-DePue et al., (2023), reasoned that morphotype P could be from the combustion of coal products due to its power-like appearance (Enache &

Cumming, 2006); however, increases in type P during the modern era are not observed at Lake Marian. Instead, type F represents more than half of the morphotypes shown during the contemporary, while the percentage of P is at its lowest (Fig. 7). The changing proportion infers a change in fuel source as morphotype F represents woody material, needles, and grasses (as represented in the L:W values during this time (Vachula, et al., 2024)) compared to type P being leaf matter (Enache & Cumming, 2006; Mustaphi & Pisaric, 2014). The rise in F shows changed fuel sources in the modern period, inferred from the increased agricultural activity and development surrounding Lake Marian (Fig. 1). As the land use changes, vegetation is removed and anthropogenically burned, resulting in this noted fuel source change.

The particle morphotypes and morphometrics indicate the fuel types and conditions during these periods. The data presented reconstructs a detailed baseline of Lake Marian's fire ecology. By comparing the past CHAR values to the present, we discovered that our current fire practices are overapplied compared to the recorded fire activity in this area, as hypothesized. Land managers and policymakers should reconsider this ecosystem's suggested fire return intervals. This change would support the regeneration and success rates of native species, and save the unnecessary use of time, money, and resources wasted on the overapplication of prescribed burns.

4.2 Human-fire Influence

Prescribed burns in North America were first introduced by the ancestors of modern Native Americans (Johnson & Hale, 2002), and at least five Native American tribes resided

near Lake Marian before colonization (Fig. 1; Fowler & Konopik, 2007; Krogman, 1948; Ryan et al., 2013). Their presence coincides with the CHAR peaks during the Archaic period (8.5 to 2.7 cal kyr BP), which supports the idea that fire activity at this time may be related to low-intensity human brush fires (Fig. 5; Fowler & Konopik, 2007). During this period, the prominence of fuel types F, C, and P- indicating woody material and leaves (Fig. 7; Enache & Cumming, 2006; Frank-DePue et al., 2023; Umbanhowar & Mcgrath, 1998)- suggests the intentional use of fire for hunting (Chapman et al., 1982; Fowler & Konopik, 2007; Hammett, 1992; Johnson & Hale, 2002). The high A:P ratio seen during the Archaic period (Fig. 6) further supports this, as it points to the occurrence of controlled low-temperature fires (Feurdean et al., 2023), consistent with Archaic Native American fire management practices. By 4.5 cal kyr BP, native plant domestication had begun (Delcourt & Delcourt, 2004), influencing the types of fuels burned and suggesting that agricultural and forest-type vegetation would be evident in Lake Marian's records as early as the Late Archaic. The evidence of Native American burning practices, combined with the data shifts seen in the sediment record (Fig. 9), strongly suggests the presence of environmental management activities of Archaic Native Americans.

During the Mississippian and Woodland periods (2.7 to 0.5 cal kyr BP), maize cultivation began, accompanied by increased burning practices (Fowler & Konopik, 2007; Fig. 9). This period also coincides with a drier climate shift in Florida around 1.8 cal kyr BP (van Beynen et al., 2008). The timing corresponds with peaks in circularity and the appearance of morphotype D (leaf stems/veins) (Enache & Cumming, 2006; Fig. 4). This may indicate crown fires (Enache & Cumming, 2006), potentially due to enhanced fire use in a more fire-prone environment. By 1 cal kyr BP, most settlements had established intensive agriculture (Delcourt & Delcourt, 2004),

and regular burning practices (Fagan, 1991). This cultural shift after 1 cal kyr BP is reflected in the rising CHAR values in the Woodland & Mississippian (μ =3.17, σ =3.15, σ^2=10.97), compared to the CHAR before regular burning practices (μ =1.77, σ =1.5, σ^2=2.2) (Fig. 5, 9; Luer et al., 2014). The increase in CHAR and fuels burned during this period suggests the increased use of fire by Native Americans for agricultural practices resulting in frequent low-intensity fires changing the vegetation to fire-adapted taxa (Delcourt & Delcourt, 2004; Fagan, 1991). However, once Native Americans were removed from their ancestral lands and the federal government implemented fire suppression policies, the fire-adapted taxa were deprived of the benefits of the fire cycle, diminishing the native species (Anderson & Moratto, 1996; Pinkoski et al., 2003).

Modern human activity has further influenced and altered the fire regime (Fig. 9). This period shows an increase in CHAR during and after the historic presence of Native Americans. Fire continues to be used for land clearing, hunting, and gardening (Luer et al., 2014). The primary fuels during this time included wood, grasses, needles, and stems, as evidenced by the rise in morphotypes S/B and F and the L:W values (Fig. 6, 7; Enache & Cumming, 2006; Vachula et al., 2024). The use of fire as a land management tool has promoted the native firetolerant species creating a need for fire in these ecosystems.

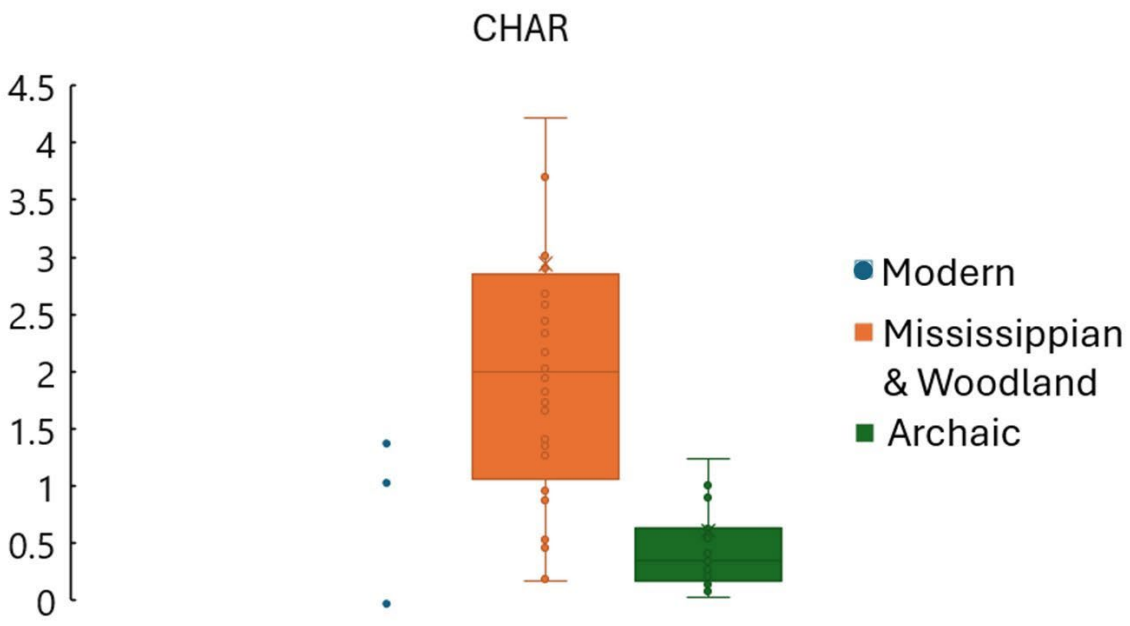


Figure 9: CHAR averages are grouped by periods. The fire regime shifted with increased human influence.

4.3 Modern Fire Use

During the Modern period, there were significant increases in CHAR (Fig. 5) and L/W values, along with a decrease in A:P (Fig. 6), which suggests more intense fires due to fuel buildup thought to be caused by the total fire suppression policy from the late 1800s to the late 1900s (Bond & Keeley, 2005). From the late 1800s to the 1900s, total fire suppression caused denser forests and heightened competition among native vegetation, increasing fire spread potential (Ali et al., 2012). Post-1950, low A:P values indicate higher fire temperatures, likely due to fuel accumulation, the ban's removal, and rising temperatures.

The lifting of the total fire suppression ban around 1950 (~0 cal kyr BP) likely contributed to the highest peaks in S/B and F (woody materials and grasses) (Fig. 5, 7; Enache & Cumming, 2006; Mustaphi & Pisaric, 2014), as prescribed burns became a key land management tool to improve forest health and mitigate wildfires (Mitchell et al., 2014; Ryan et al., 2013). This shift increased fire activity, favoring fire-tolerant vegetation while reducing fire-intolerant species (Clark et al., 1996). The effects of fire suppression are reflected in increased CHAR and fire intensity at Lake Marian (Fig. 5, 10).

The reapplication of fire to these ecosystems can be beneficial if executed accurately. However, the extent and frequency of our prescribed burning practices seem over-applied in this region (Fig. 5, 10). As shown in Figure 10, in the last 100 years fire in this area has become more intense with higher fire temperatures and lower charcoal area (Feurdean et al., 2023; Hennebelle et al., 2020). As increased byproducts of fire enter the surroundings, it can further influence the ecosystem's nutrient deposits.

Nearby diatom records showed that increased prescribed burning practices influenced the biogeochemical stoichiometry in shallow lake systems by increasing the total phosphorous (Kenney et al., 2016; Waters et al., 2015; Waters et al., 2018; Waters et al., 2023). Following Rxburns, nutrient deposition increases in the surrounding areas, with phosphorous being the primary input due to its biogeochemistry having no gaseous component (Waters et al., 2023). An increase in phosphorus due to burning increases primary producers like cyanobacteria, resulting in pyroeutrophication (Waters et al., 2023). As stated in Waters et al., 2023, increased charcoal inputs cause high turbidity and dissolved organic carbon decreasing light flux (Waters et al., 2018) and favoring cyanobacteria species. Cyanobacteria can outcompete other primary producers by consuming nutrients at the bottom and then filling their gas vesicles allowing

them to float to the surface for photosynthesis (Paerl et al., 2011; Waters et al., 2010). After receiving light at the top of the lake, they float down to the bottom and start the process over, allowing them to infest the water. Once the nutrients become limited nitrogen-fixing cyanobacteria take over, keeping the lake in a green unpleasant hypereutrophic state (Paerl et al., 2011). Although a diatom record has not been excavated from Lake Marian, it would likely show similarities to the other shallow lakes in Florida that document the influx of cyanobacteria and phosphorus after prescribed burns.

The current fire practices exceed the Holocene baseline of fire activity (Fig. 5), intensity (Fig. 10), and aquatic nutrient intake. Land managers and policymakers should reevaluate the frequency and the extent of these practices to ensure successful reimplementation in a time of climate-related concerns. By understanding the effects of prescribed burns on all surrounding ecosystems we can ensure healthy aquatic and terrestrial environments.

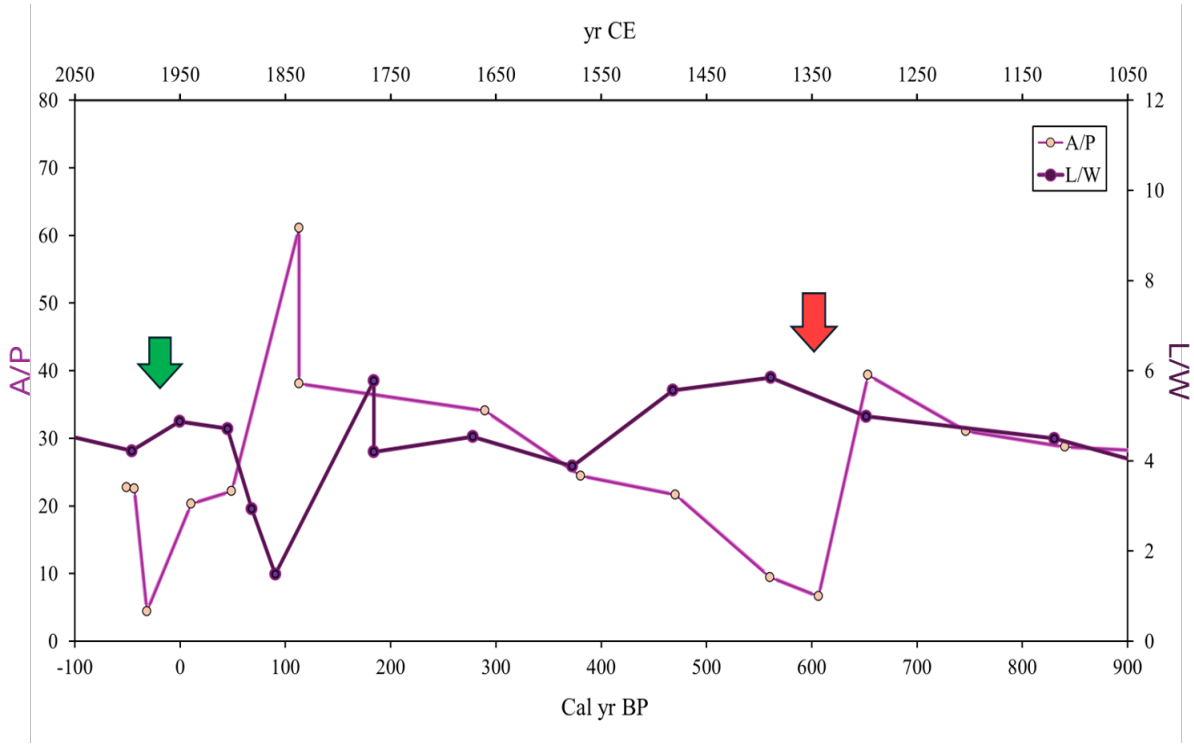


Figure 10: The last 1,000 years of A:P and L:W ratios. The green arrow represents the most recent shift of A:P and L:W ratios indicating an increased fire temperature, grass, and needle fuels (Feurdean et al., 2023; Vachula et al., 2024) possibly due to prescribed burning practices.

4.4 Morphometrics Determine Fire-Vegetation Dynamics

Lake Marian's charcoal record combined with the reconstructed pollen from the neighboring Lake Tulane can aid in clarifying fuel sources (Whitlock et al., 2004; Higuera et al., 2005; Crawford & Belcher, 2014; Fig. 11). Based on the Lake Tulane pollen record, oak (*Quercus*) species were dominant during the Early Archaic, providing evidence for a cooler and wetter environment that coincided with the relatively low CHAR (highest peak for morphotype P, (Fig. 7,8)). Around 5.5 cal kyr BP, Lake Tulane, and three other central Florida records show the oak to pine shift (Grimm et al., 2006; Mendieta et al., 2018; Watts & Hensen, 1994). It is thought that this vegetation shift is shown in Lake Marian around 6 cal kyr BP (Fig. 8), with the morphotypes and morphometrics pointing to a fire fuel change (Fig. 6, 7, refer to section 4.1.1). This concludes a warmer and wetter period in central Florida due to its geographic location (Watts & Hansen, 1994), which aided in the shift to *Pinus* dominance (Krause et al., 2019).

A recent vegetation shift to vascular cryptogam pollen (VACR) around 0.75 cal kyr BP (Fig. 11) likely reflects a significant change in the fire regime, driven by a combination of land management practices and climate change. The increase in VACR pollen, spore-reproducing plants like ferns and mosses known to regrow quickly after a fire (Skutch, 1929), and the decrease in tree-shrub (TRSH) pollen suggests that the landscape became less favorable for

woody vegetation and more supportive of the understory pioneer species. This shift coincides with evidence of more frequent, high-intensity fires, as indicated by lower charcoal particle circularity and an aspect ratio (L:W) around 4 (Fig. 6, 10), which represents increased burning of grasses, needles, and wood (Vachula et al., 2024) (types F and S/B, Fig. 4, 11), likely tied to land management and drier and warmer conditions (van Beynen et al., 2008). Krause et al., 2019, found similar results in the modern, high CHAR values and increased grass fuels.

Several factors likely contributed to this shift. Warmer and wetter climates would have increased fire frequency and intensity, further stressed tree and shrub species, and made it harder to regenerate after fires. Human activities, such as increased logging and land clearance, could have amplified these effects by removing fire-adapted vegetation and wood fuels thus promoting grass-dominated landscapes. The expansion of prescribed burning practices during the Modern period likely exacerbated this by creating a fire return interval that exceeds natural historical patterns, further pushing the ecosystem toward a grass-fern dominance. The current land management practices in this area have caused a recent vegetation shift to pioneer species, as hypothesized, further supporting the over-application of fire in this region.

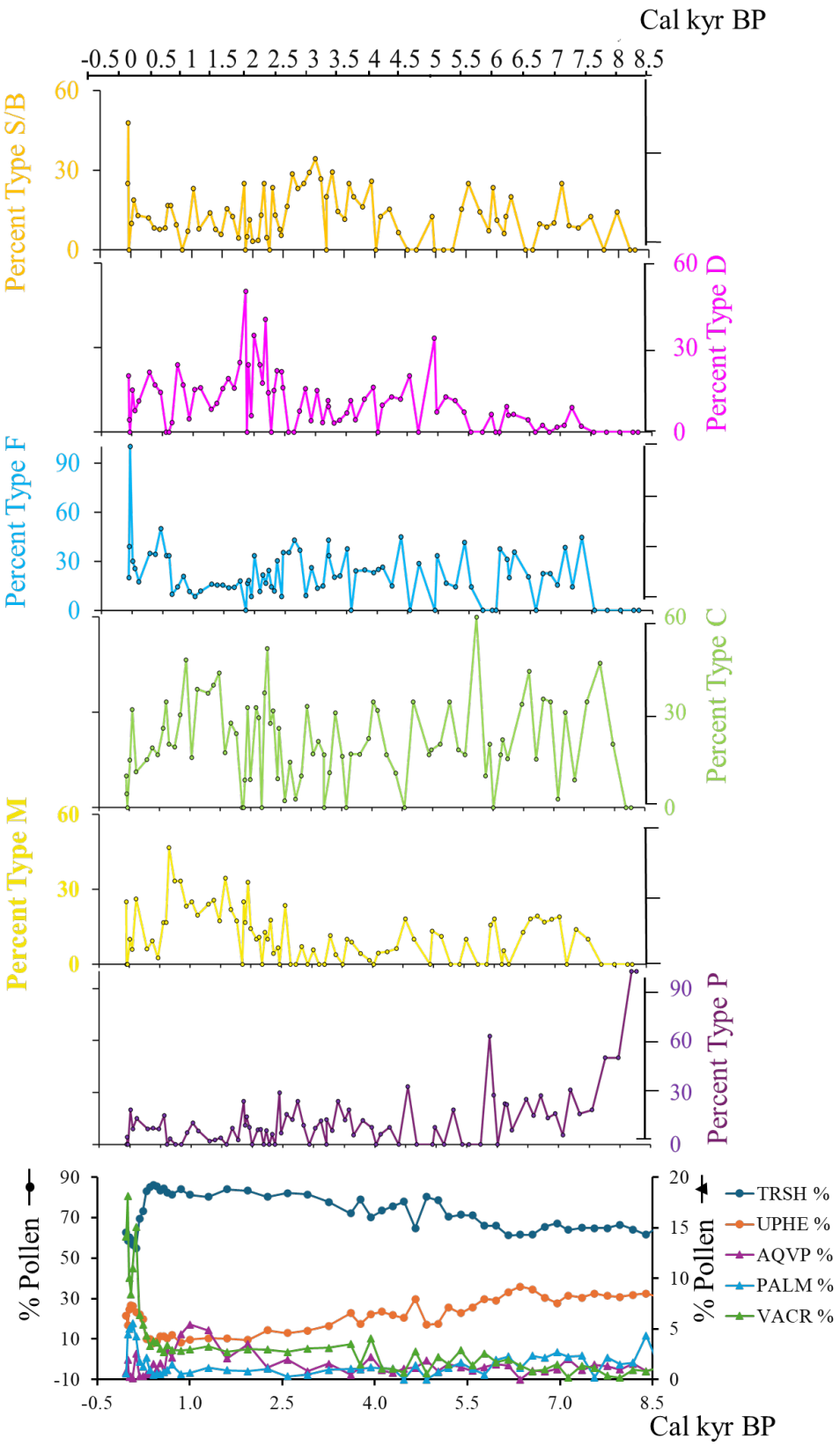

Cal kyr BP
-0.5 0 0.5 1 1.5 2 2.5 3 3.5 4 4.5 5 5.5 6 6.5 7 7.5 8 8.5
Percent Type S/B
Percent Type D
Percent Type F
Percent Type C
Percent Type M
Percent Type P
% Pollen
TRSH %
UPHE %
AQVP %
PALM %
VACR %
-0.5 1.0 2.5 4.0 5.5 7.0 8.5
Cal kyr BP

Figure 11: Morphotypes of charcoal from Lake Marian compared to the pollen record from Lake Tulane Florida (Grimm et al.,1993). The morphotypes varied throughout time with noted changes in the modern vegetation shift. The pollen percentages with triangle markers are plotted on the secondary axis. The pollen acronyms are defined as: TRSH= Trees/Shrubs, UPHE= Upland Herbs, AQVP= Aquatic Vascular Plants, PALM= Palms, VACR= Terrestrial Vascular Cryptogams.

5. Conclusion

The charcoal record from Lake Marian, Florida, revealed the fire regime and vegetation dynamics over the last 8.5 thousand years. We divided the charcoal record into three distinct periods—the Archaic period, the Woodland and Mississippian periods, and the Modern—which revealed varying levels of fire activity and corresponding fire fuels. Little fire activity occurred during the Archaic Period (8.5 to 3 cal kyr BP). However, the morphometrics within this period show high variance (between 6.5 to 5.5 cal kyr BP) with L:W values coinciding with the Lake Tulane pollen record, documenting the increase of oak wood fuels with decreasing oak pollen and the introduction of needles with increasing pine pollen. The charcoal and neighboring pollen records show the oak-to-pine shift at around 6 cal kyr BP, likely driven by climatic changes towards wetter and warmer conditions. The Woodland and Mississippian Periods (3 to 0.5 cal kyr BP) showed increased fire activity. Fluctuations in the area to the perimeter (A:P) and length to width (L:W or Aspect Ratio (AR)) suggest varying fire temperatures, likely from intensified agricultural practices and fire utilization by Native

Americans. The Modern Period (0.5 cal kyr BP to present) represents the highest recorded fire activity at Lake Marian. This period is characterized by peaks in morphotypes S/B and F (woody vegetation and grasses) and a vegetation shift to terrestrial vascular cryptogams. This could indicate land use changes such as urbanization, agricultural practices, prescribed burning practices, etc. further influencing what is being burned and contributing to a vegetation change from trees and shrubs to terrestrial vascular cryptogams known as the pioneer species. The surrounding aquatic ecosystems have also felt the increased use of prescribed fires as it has altered the biogeochemistry pushing Lake Marian into a hypereutrophic state. Anthropogenic influences have profoundly altered the fire regime and ecology in this area.

In conclusion, the charcoal record from Lake Marian provides valuable insights into the long-term interactions between fire, climate, human impacts, and vegetation changes in Central Florida. To address the knowledge gap, additional research on morphometric relationships between fuel types and fire temperatures is necessary to enhance the understanding of the region's fire regime. Regional-specific morphological qualification keys created for the native vegetation would solidify the interpretation of charcoal archives and help resolve many uncertainties in studying the southeastern U.S.A.. Understanding these dynamics is essential for effective land management strategies to preserve biodiversity, mitigate wildfire risks, and conserve southeastern ecosystems in the face of ongoing environmental changes.

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Appendix 1: Average sample ages, CHAR values, and morphometrics

Average Age	Composite Depth (cm)	CHAR	A/P	Circularity	AR	Rectangularity
-51.0	0-4	1.000	22.7	0.3	3.6	1.1
-43.5	4-8	0.000	22.6	0.3	3.5	1.1
-31.5	8-12	1.333	4.4	0.5	3.9	0.8
10.5	12-16	13.333	20.3	0.3	5.4	1.0
49.0	16-20	10.222	22.2	0.3	4.6	1.1
113.0	20-24	0.533	49.6	0.3	3.9	1.1
289.5	24-28	2.581	34.1	0.3	5.7	1.1
380.5	28-32	11.565	24.5	0.2	5.1	1.1
470.5	32-36	2.683	21.7	0.2	6.0	1.1
560.5	36-40	1.659	9.5	0.4	3.4	1.0
606.5	40-44	2.901	6.6	0.4	6.7	0.8
653.5	44-48	4.220	39.3	0.3	3.9	1.0
746.5	48-52	2.337	31.1	0.3	5.2	1.2
840.5	52-56	0.527	28.7	0.3	4.7	1.0
936.0	56-60	2.022	28.0	0.2	7.4	1.1
1028.0	60-64	1.263	20.7	0.3	3.9	1.1
1119.5	64-68	9.333	30.3	0.3	4.5	1.1
1298.5	68-72	0.990	15.1	0.2	5.0	1.3
1389.0	72-76	1.830	22.2	0.3	5.9	1.0
1482.0	76-80	6.756	25.2	0.3	5.6	1.0
1577.5	80-84	2.194	31.4	0.2	3.9	1.4
1672.0	84-88	2.198	22.9	0.3	4.5	1.2
1766.0	88-92	1.733	24.5	0.3	5.0	1.1
1859.5	92-96	2.167	11.6	0.7	1.5	0.9
1882.0	96-100	2.442	13.3	0.3	2.9	1.0
1905.0	100-104	2.723	21.3	0.3	4.7	1.2
1950.5	104-108	1.408	29.7	0.3	4.9	1.1
1996.0	108-112	3.011	27.0	0.3	4.2	1.0
2089.5	112-116	0.463	25.0	0.3	3.7	1.1
2136.5	116-120	0.870	24.6	0.3	4.5	1.1
2183.5	115-117	0.180	16.0	0.3	3.0	1.3
2229.5	124-128	1.348	30.4	0.3	5.2	1.1
2276.5	127-129	1.939	32.2	0.4	5.4	1.0
2323.5	132-136	1.978	29.8	0.3	3.8	1.1
2371.0	135-137	0.170	26.8	0.3	4.2	1.0

2444.0	139-141	3.699	10.4	0.4	6.6	0.9
2468.0	143-145	0.213	23.5	0.3	5.9	1.0
2561.5	139-141	1.432	20.2	0.2	4.4	1.2
2650.0	143-145	0.958	24.3	0.3	4.7	1.1
2740.5	147-149	0.408	17.8	0.2	4.8	1.3
2836.0	151-153	0.625	31.7	0.4	2.9	1.0
2930.5	155-157	2.044	25.5	0.2	5.1	1.1
3027.5	159-161	0.318	21.3	0.3	5.1	1.1
3118.5	163-165	1.532	37.7	0.3	3.6	1.1
3209.5	167-169	0.375	22.6	0.2	7.7	1.0
3210.7	171-173	0.894	9.9	0.3	5.8	0.9
3303.0	175-177	2.723	27.5	0.3	3.6	1.2
3396.0	179-181	0.378	18.7	0.2	4.9	1.2
3509.5	183-185	0.340	15.5	0.2	5.3	1.2
3578.5	187-189	0.298	16.2	0.4	3.3	0.9
3653.0	191-193	0.543	19.4	0.2	4.5	1.3
3800.5	195-197	0.300	22.4	0.3	5.2	1.1
3947.5	199-201	0.338	24.0	0.3	3.9	1.1
4020.0	203-205	0.230	6.5	0.3	10.1	0.9
4092.5	207-209	0.411	31.4	0.3	4.8	1.1
4241.0	211-213	0.630	27.3	0.3	3.5	1.2
4390.0	215-217	0.466	19.0	0.3	6.8	1.1
4538.5	219-221	0.176	14.3	0.3	2.9	1.1
4682.0	223-225	0.338	23.2	0.2	4.7	1.1
4943.0	227-229	0.164	11.1	0.3	5.7	0.9
4980.5	231-233	0.139	22.0	0.3	5.4	1.0
5129.5	235-237	0.267	23.0	0.3	2.5	1.1
5280.5	239-241	0.132	30.8	0.5	3.5	0.9
5426.5	243-245	0.640	24.0	0.3	6.7	1.0
5537.0	247-249	0.107	64.9	0.4	4.6	1.0
5726.0	251-253	0.133	44.9	0.4	2.4	0.9
5875.5	255-257	0.274	66.0	0.6	2.1	0.9
5941.5	259-261	0.133	20.6	0.3	2.2	1.4
6004.0	261-263	0.132	38.5	0.3	3.3	1.0
6125.0	265-267	0.087	57.7	0.3	7.0	1.1
6154.0	269-271	0.444	12.3	0.4	4.2	0.9
6238.5	273-275	0.194	25.9	0.3	4.6	1.0
6471.0	277-279	0.368	25.6	0.2	4.5	1.2

6592.5	281-283	0.421	29.0	0.3	4.5	1.1
6708.0	281-283	1.400	30.9	0.2	4.6	1.2
6824.5	285-287	0.203	39.5	0.3	4.8	1.0
6945.0	289-291	2.690	39.9	0.3	3.8	1.1
7069.0	293-295	2.644	24.9	0.2	6.4	1.2
7190.0	297-299	1.806	27.2	0.2	4.7	1.2
7342.0	299-301	1.233	26.4	0.2	5.9	1.1
7545.0	303-305	0.576	61.1	0.5	2.5	0.9
7759.0	307-309	1.000	78.7	0.4	1.4	1.1
7975.0	311-313	0.094	62.1	0.5	1.4	1.1
8189.5	315-317	0.185	30.6	0.3	1.1	1.3
8270.0	319-321	0.074	20.0	0.4	1.4	1.2

Appendix 2: Morphological percentages per sample

Avg Age	Composite Depth (cm)	%P	%SB	%D	%F	%C	%M
-51.0	0-4	0	25	20	20	10	25
-43.5	4-8	4.3	47.8	4.3	39.1	4.3	0
-31.5	8-12	0	0	0	100	0	0
10.5	12-16	20	10	15	30	15	10
49.0	16-20	9	18.8	7.5	25.6	30.8	6
113.0	20-24	15	12.9	11	17.5	11.2	26.2
289.5	24-28	9.1	12.1	21.2	34.8	15.2	6.1
380.5	28-32	9.4	8.3	16.7	34.4	18.8	9.4
470.5	32-36	9	7.7	14.1	50	16.7	2.6
560.5	36-40	16.7	8.3	0	33.3	25	16.7
606.5	40-44	0	16.7	0	33.3	33.3	16.7
653.5	44-48	3.3	16.7	3.3	10	20	46.7
746.5	48-52	0	9.5	23.8	14.3	19	33.3
840.5	52-56	0	0	16.7	20.8	29.2	33.3
936.0	56-60	7	7	4.7	11.6	46.5	23.3
1028.0	60-64	12.5	23	15.1	8.6	15.8	25
1119.5	64-68	7.8	7.8	15.7	11.8	37.3	19.6
1298.5	68-72	2	14	8	16	36	24
1389.0	72-76	2.6	7.7	10.3	15.4	38.5	25.6
1482.0	76-80	3.8	5.8	15.4	15.4	42.3	17.3
1577.5	80-84	0	15.5	19	13.8	17.2	34.5

1672.0	84-88	9.4	12.5	15.6	14.1	26.6	21.9
1766.0	88-92	2.6	4.4	24.6	17.9	23.2	17.3
1859.5	92-96	25	25	50	0	0	0
1882.0	96-100	11.1	0	0	16.7	0	25
1905.0	100-104	16	5	23.8	18.2	8.7	16.7
1950.5	104-108	10	11.4	5.7	8.6	31.4	32.9
1996.0	108-112	0	3.2	34.4	33.3	8.8	14.3
2089.5	112-116	8.6	3.6	23.8	11.5	31.5	10.1
2136.5	116-120	8.7	13	17.4	21.7	28.3	10.9
2183.5	115-117	0	25	40	16.7	0	0
2229.5	124-128	8.1	4.7	14	24.4	36	12.8
2276.5	127-129	0	0	0	14.3	50	10
2323.5	132-136	5.9	23.5	14.7	11.8	26.5	17.6
2371.0	135-137	0	13	21.7	30.4	30.4	4.3
2444.0	139-141	30	7.7	21.4	8.3	9.1	6.7
2468.0	143-145	6.7	5.6	15.8	35.3	25	0
2561.5	139-141	17.4	16.3	0	35.4	2.1	23.5
2650.0	143-145	14.3	28.6	0	42.9	14.3	0
2740.5	147-149	25	23.1	7.5	36.8	2.7	0
2836.0	151-153	11.1	25	15.4	9.1	10	7.1
2930.5	155-157	0	29.2	4	26.1	31.8	0
3027.5	159-161	9.4	34.3	14.7	13.6	16.9	5.8
3118.5	163-165	13.6	26.8	3.3	14.8	20.8	0
3209.5	167-169	0	0	11.1	42.9	16.7	0
3210.7	171-173	14.3	20	9.1	33.3	0	0
3303.0	175-177	8	29.4	3.1	20.2	11	11.4
3396.0	179-181	25	14.5	4.2	21.1	29.9	3.8
3509.5	183-185	14.2	11.5	6.7	37.5	16.1	0
3578.5	187-189	20	25	11.1	0	0	10
3653.0	191-193	5.6	20.1	4.3	24.1	16.8	8.9
3800.5	195-197	13.9	16.2	11.6	24.6	16.8	4.3
3947.5	199-201	9.9	25.9	15.8	23.1	21.7	1.6
4020.0	203-205	0	0	0	25	33.3	0
4092.5	207-209	5.9	12.5	9.5	26.3	30.6	4.5
4241.0	211-213	10	15.3	12.5	15	16.7	5
4390.0	215-217	0	6.5	11.7	45	10.8	6.3
4538.5	219-221	33.3	0	20	0	0	18.2
4682.0	223-225	0	0	0	28.6	33.3	10

4943.0	227-229	0	12.5	33.3	0	16.7	0
4980.5	231-233	10	0	7.1	33.3	18.2	13.3
5129.5	235-237	0	0	12.5	16.7	20	11.1
5280.5	239-241	20	0	11.1	14.3	33.3	0
5426.5	243-245	0	15.4	7.1	41.7	18.2	0
5537.0	247-249	0	25	0	14.3	16.7	10
5726.0	251-253	0	14.3	0	0	60	0
5875.5	255-257	62.5	7.1	6.3	0	10	0
5941.5	259-261	28.6	23.5	0	0	20	15.8
6004.0	261-263	0	11.1	0	37.5	0	18.2
6125.0	265-267	23.6	6.3	9.1	31.3	16.7	0
6154.0	269-271	23.1	12.5	5.9	20	21.4	5.6
6238.5	273-275	8.3	20	6.3	35.7	15.4	0
6471.0	277-279	26.2	0	4.3	20.5	32.6	12.8
6592.5	281-283	16.7	0	0	0	42.9	18.2
6708.0	281-283	28.2	9.9	2.4	22.5	15.2	19.3
6824.5	285-287	15.4	8.6	0	22.5	34.2	16.9
6945.0	289-291	17.9	10.2	1.7	15.5	33.3	18
7069.0	293-295	5.4	25	2.4	38.5	2.6	19
7190.0	297-299	31.6	9.1	8.7	14.3	30	0
7342.0	299-301	17.8	8.3	2	44.7	8.7	14
7545.0	303-305	20	12.5	0	0	33.3	10
7759.0	307-309	50	0	0	0	45.5	0
7975.0	311-313	50	14.3	0	0	20	0
8189.5	315-317	100	0	0	0	0	0
8270.0	319-321	100	0	0	0	0	0

Appendix 3: Sediment Core Alignment

Composite Depth (cm)	MWIA	MWIB	Drive 1	Drive 2	Drive 3
0	LMA22 A 0-4cm				
4	LMA22 A 4-8cm				
8	LMA22 A 8-12cm				
	LMA22 A 12-				

12	16cm	
16	LMA22 A 16-20cm	
20	LMA22 A 20-24cm	
24	LMA22 A 24-28cm	
28	LMA22 A 28-32cm	
32	LMA22 A 32-36cm	
36	LMA22 A 36-40cm	
40	LMA22 A 40-44cm	
44	LMA22 A 44-48cm	LMA22 B 0-4cm
48	LMA22 A 48-52cm	LMA22 B 4-8cm
52		LMA22 B 8-12cm
56		LMA22 B 12-16cm
60		LMA22 B 16-20cm
64		LMA22 B 20-24cm
68		LMA22 B 28-32cm
72		LMA22 B 32-36cm
76		LMA22 B 36-40cm
80		LMA22 B 40-44cm
84		LMA22 B 44-48cm
88		LMA22 B 48-52cm
92		LMA22 B 52-56cm

96	LMA22 B 56-60cm		
100	LMA22 B 60-64cm		
104	LMA22 B 64-68cm		
108	LMA22 B 68-72cm		
112	LMA22 B 72-76cm		
116	LMA22 B 76-80cm	LMA22 D1 100-102cm	
120	LMA22 B 80-84cm	LMA22 D1 104-106cm	
124	LMA22 B 84-88cm	LMA22 D1 108-110cm	
128	LMA22 B 88-92cm	LMA22 D1 112-114cm	
132	LMA22 B 92-96cm	LMA22 D1 116-118cm	
136	LMA22 B 96-100cm	LMA22 D1 120-122cm	
140	LMA22 B 100-104cm	LMA22 D1 124-126cm	
144	LMA22 B 104-108cm	LMA22 D1 128-130cm	
148	LMA22 B 108-112cm	LMA22 D1 132-134cm	
152	LMA22 B 112-116cm	LMA22 D1 136-138cm	
156	LMA22 B 116-120cm	LMA22 D1 140-142cm	
160	LMA22 B 120-124cm	LMA22 D1 144-146cm	
164	LMA22 B 124-128cm	LMA22 D1 148-150cm	
168	LMA22 B 128-132cm	LMA22 D1 152-154cm	
172	LMA22 B 132-136cm	LMA22 D1 156-158cm	LMA22 D2 180-182cm
176	LMA22 B 136-140cm	LMA22 D1 160-162cm	LMA22 D2 184-186cm
180	LMA22 B 140-144cm	LMA22 D1 164-166cm	LMA22 D2 188-190cm

184	LMA22 B 144-148cm	LMA22 D1 168-170cm	LMA22 D2 192-194cm	
188	LMA22 B 148-152cm	LMA22 D1 172-174cm	LMA22 D2 196-198cm	
192		LMA22 D1 176-178cm	LMA22 D2 200-202cm	
196		LMA22 D1 180-182cm	LMA22 D2 204-206cm	
200		LMA22 D1 184-186cm	LMA22 D2 208-210cm	
204		LMA22 D1 188-190cm	LMA22 D2 212-214cm	
208		LMA22 D1 192-194cm	LMA22 D2 216-218cm	
212		LMA22 D1 196-198cm	LMA22 D2 220-222cm	
216			LMA22 D2 224-226cm	
220			LMA22 D2 228-230cm	
224			LMA22 D2 232-234cm	
228			LMA22 D2 236-238cm	
232			LMA22 D2 240-242cm	
236			LMA22 D2 244-246cm	
240			LMA22 D2 248-250cm	
244			LMA22 D2 252-254cm	LMA22 D3 250-252cm
248			LMA22 D2 256-258cm	LMA22 D3 254-256cm
252			LMA22 D2 260-262cm	LMA22 D3 258-260cm
256			LMA22 D2 264-266cm	LMA22 D3 262-264cm
260			LMA22 D2 268-270cm	LMA22 D3 266-268cm
262				LMA22 D3 268-270cm
266				LMA22 D3 272-274cm
270				LMA22 D3 276-278cm

					LMA22 D3
274					280-282cm
					LMA22 D3
278					284-286cm
					LMA22 D3
282					287-289cm
					LMA22 D3
286					292-294cm
					LMA22 D3
290					296-298cm
					LMA22 D3
294					300-302cm
					LMA22 D3
298					304-306cm
					LMA22 D3
300					306-308cm
					LMA22 D3
304					310-312cm
					LMA22 D3
308					314-316cm
					LMA22 D3
312					318-320cm
					LMA22 D3
316					322-324cm
					LMA22 D3
320					326-328cm