A late Pleistocene/early Holocene fire record from Appleman Lake, Indiana: The use of charcoal analysis in investigating landscape change

Katherine Lininger

Professor John W. Williams

UW-Madison Department of Geography

December 2007

ABSTRACT

Charcoal analysis was conducted on a sediment core from Appleman Lake, Indiana. Appleman Lake is a kettle lake that was formed as the Laurentide Ice Sheet retreated during the last deglaciation. Macroscopic charcoal (particles >125μm) indicates local fires. Charcoal analysis was connected to other proxies, such as pollen analysis (a proxy for vegetation), the presence of *Sporormiella* spores (a proxy for megafaunal abundance), and magnetic susceptibility (a proxy for erosion), to understand long-term landscape change. The late Pleistocene/early Holocene time period was the focus of the study. During this period, rapid climate change occurred, many megafaunal species became extinct, no-analogue vegetation assemblages were present, and humans arrived. Charcoal concentrations (particles/cm^3) were transferred into charcoal accumulation rate (CHAR, expressed as particles/cm^2/yr) by dividing the charcoal concentrations by the sedimentation rate for the core. Using Charster, a program developed by Dan Gavin, the charcoal record was decomposed into a background component (slowly varying) and a peaks component (used to infer fire events). A threshold value was applied to the peaks component to separate noise from inferred fire events. In the Appleman Lake charcoal record, there are three inferred time periods displaying different fire characteristics. During the late glacial period, from 17,600 to 15,900 cal yr BP, there are few charcoal particles and zero inferred fire events. *Picea* is the dominant vegetation, indicating a cold climate, and megafaunal abundance is high. In the transitional period, from 15,900 to 10,800 cal yr BP, the fire return interval is 1.55/1000yr with 8 inferred fire events. During the transitional period, a fire peak occurs almost simultaneously with the inferred extinction of many megafaunal species, possibly indicating that as megafauna became extinct, fuel load increased and a major fire event occurred. A fire peak occurs contemporaneously with the onset of the Younger Dryas climatic event at 12,900 cal yr BP, supporting the hypothesis of an extraterrestrial impact at that time. In the early Holocene time period, from 10,800 to 7,100 cal yr BP, the background level of CHAR increases significantly, alongside increases in *Quercus* and other deciduous taxa. The fire return interval in the early Holocene is 3.24/1000yr, with 12 inferred fire events. Increased fire activity and more deciduous taxa indicate a warmer climate in the early Holocene. Charcoal analysis and other proxies provide a long-term history of landscape change in northern Indiana during the late Pleistocene/early Holocene time period.

INTRODUCTION

Fire disturbances play an important role on the landscape. As a consumer of vegetation, fire recycles nutrients, creates a mosaic of habitats, and accelerates erosion across a watershed (Noss et al. 2006). Fire can act as an evolutionary agent, selecting for fire-tolerant species and establishing and maintaining ecosystems (Bond & Keeley 2005, Nelson et al. 2006). Thus, in order to determine the causes of landscape change over long time scales, the influence of fire must be taken into account. Lake sediments provide a record of landscape changes over long time scales. As mineral and various organic materials are deposited into lakes, some components of the sediment record can be used to reconstruct long-term fire histories (fossil charcoal) and vegetation assemblages (fossil pollen). In charcoal analysis of lake sediments, local fire events can be reconstructed by counting macroscopic charcoal particles greater than 125µm. A peak in the charcoal record signifies a local fire event (Whitlock & Larsen 2001). The fire regime of a landscape is composed of fire frequency or fire return interval, fire severity, and fire intensity (Whelan 1995). It is not possible to make inferences regarding fire severity and intensity using charcoal analysis, because there is no clear relationship between these variables and the abundance and type of charcoal found in lake sediments. However, variations in fire frequency and return interval can be inferred (Brunelle & Whitlock 2003). Charcoal analysis can be used alongside other proxies to gain greater insight into long-term landscape changes.

For my senior honors thesis, I reconstructed a late glacial/early Holocene fire record from a sediment core from Appleman Lake, Indiana (Figure 1). In addition, I analyzed a portion of a sediment core from Spicer Lake, Indiana. Because the Spicer Lake core has not been dated or analyzed for pollen, my analysis will be confined to Appleman Lake (See Appendix A for the Spicer Lake data). Appleman Lake, in eastern Lagrange County, is a kettle lake that formed as the Laurentide ice sheet retreated during the last deglaciation. Lake area is 21 hectares, and the lake is set in till and outwash substrate. Small, closed, deep lakes are ideal study locations for collecting macroscopic charcoal particles to determine the frequency of local fires (Tolonen, 1986). Because the lake has no inflows or outflows of water, the source of the macroscopic charcoal particles in the lake sediments was from the local watershed. Therefore, the charcoal particles analyzed here are indicators of local fires.

I focused my analysis on the late Pleistocene/Holocene transition, from approximately 17,000 yr BP to 8,000 yr BP. During this time period, climates changed rapidly, some vegetation assemblages were compositionally unlike modern vegetation assemblages, most megafaunal mammalian species became extinct, and humans arrived. The goal of my thesis is to describe the fire regime surrounding Appleman Lake and use this information to provide insights into the interactions between the fire regime, climate, vegetation, megafauna, and human arrival during the late Pleistocene/early Holocene time period. My work contributed to Jacquelyn Gill's Masters Thesis, which delves further into the relationships between vegetation, climate, megafauna and fire in northern Indiana during this time period.

LITERATURE REVIEW

Charcoal Analysis

In 1941, Iverson was the first scientist to use fossil charcoal as a fire proxy, and since then the field of charcoal analysis has greatly expanded (Whitlock & Larsen, 2001). Charcoal is created when organic material is incompletely burned. When fires reach temperatures between 280 and 500º C charcoal is produced (Whitlock & Larsen, 2001). During fire events, thermal buoyancy lofts charcoal particles into the air, and the particles then may be deposited into lakes (Clark, 1988).

Charcoal particles are divided into microscopic and macroscopic charcoal. Microscopic charcoal is characterized as being less than 100 µm in diameter, while macroscopic charcoal is greater than 100µm in diameter (Whitlock & Larsen 2001). Other authors define microscopic charcoal as less than 125µm and macroscopic charcoal as greater than 125µm (Long et al 1998, Nelson et al. 2006, Brunelle & Whitlock 2003*). Larger particles are more easily moved into lakes by erosion because smaller particles are more cohesive to each other (Clark 1988). Smaller charcoal particles from a fire event are not as easily deposited into a nearby lake. Additionally, microscopic charcoal is more easily transported by winds (Clark 1988, Whitlock & Larsen 2001). Microscopic charcoal is transported further from the fire site, while macroscopic charcoal remains within the local area of the fire site. Because of differences in the transport and deposition of microscopic and macroscopic charcoal particles, macroscopic charcoal records identify periods of local fire events, while microscopic charcoal records indicate regional fire characteristics (Figure 2) (Clark 1988, Whitlock & Larsen 2001, Higuera et al. 2007).

A distinction is also made in the literature between primary and secondary charcoal. Primary charcoal is deposited in lakes during or shortly after a fire, while secondary charcoal comes from non-fire year surface runoff or long-term contributions of charcoal particles (Whitlock & Larsen 2001). Secondary charcoal may be deposited into a lake via slopewash, erosional pulses, or long-term accumulation (Figure 2).

In macroscopic charcoal analyses of lake sediments, the initial data recorded is charcoal concentration, or particles/cm^3. This raw data is then transformed into charcoal accumulation rate (CHAR), expressed as particles/cm^2/yr. CHAR is determined by dividing the charcoal concentration by the sediment accumulation rate for the core, which is determined from the radiocarbon dates and other age controls for the core. Separating the charcoal record into background and primary (or peaks) components based on charcoal accumulation rates can provide more insights into fire history (Long et al. 1998, Whitlock & Larsen 2001, Higuera et al. 2007). The background component is a low-frequency charcoal accumulation, while the primary component is a higher frequency and more variable charcoal accumulation (Long et al. 1998).

The background component of the charcoal record is composed of secondary charcoal and charcoal from regional fires (Long et al. 1998). Higuera et al. (2007) compared numerical model results from a Charcoal Simulation Model to fire records from the Alaskan boreal forest to gain a better understanding of the decomposition method. They made a distinction between the background component deposited from more regional fires and the background component resulting from slopewash and erosion into the lake (Higuera et al. 2007). The model supports the expectation that both regional fires and slopewash contribute to the background component (Higuera et al. 2007). Long et al. (1999), in a study of Little Lake in the Pacific Northwest, found that the background component of the charcoal record varied with the magnetic susceptibility (a proxy for erosion into the lake from the surrounding topsoil). They suggest that most of the background charcoal originated from slopewash and erosion from the surrounding landscape. In addition, the background component is associated with the amount of fuel available on the landscape; an increase in the background component indicates an increase in fuel available for burning (Long et al. 1998, Millspaugh et al. 2000, Brunnelle & Whitlock 2003, Power et al. 2006).

The primary component of the charcoal record is also described as the peaks component, and peaks can be attributed to local fire events (Long et al. 1998). While there is usually random "noise" in a charcoal accumulation rate signal, peaks above a threshold value in the primary component of the charcoal accumulation rate separate the "noise" in the peaks component from the fire events (Whitlock & Larsen 2001). When processing for macroscopic charcoal, individual fires cannot necessarily be determined (Whitlock & Larsen 2001). One centimeter of a lake sediment core from a non-laminated lake usually represents 5-20 years, depending on rates of sedimentation. This means that multiple fires can create one fire peak in the charcoal record. Because of the slow deposition of secondary charcoal and the lack of certainty about the timing of individual fires, peaks in the charcoal record are described as fire events, not as distinct fires (Whitlock & Larsen 2001). Despite this, the mean fire interval and fire frequency can be determined using inferred fire events (Whitlock & Larsen 2001).

Additional Proxies and Landscape Influences

Pollen analysis is used to determine the vegetation characteristics of the landscape through time. Found in angiosperms and gymnosperms, pollen is most often dispersed by wind or insects; pollen grains caught in the atmosphere can rain down over a regional area and be deposited in lakes (Bennet & Willis 2001). Pollen grains found in lake sediments can be identified to the genus or family, and the pollen types and percentages indicate the vegetation surrounding the lake. There is not an exact relationship between pollen found in lakes and vegetation on the landscape; different taxa vary in the amount of pollen produced, pollen dispersal method, and pollen preservation. The interpretation of pollen records can be purely descriptive or can attempt to determine the causes of vegetation change or stability. The drivers of vegetation change include climate, ecology of the landscape, human influence, and pathogens. Mostly likely, vegetation assemblages change in response to multiple causes. In order to understand the causes of vegetation change, many different proxies should be used to obtain a comprehensive understanding of past landscape change (Bennet & Willis 2001).

Pollen analysis can be used to determine the presence of no-analogue vegetation assemblages. During the late-glacial/early-Holocene transition, vegetation assemblages that are not analogous to any modern vegetation assemblages existed in the Great Lakes region (Williams et al. 2001). Williams et al. (2001) measured the dissimilarity between modern and late-glacial pollen samples and determined that the time period with the highest dissimilarity (signifying the presence of no-analogue vegetation) occurred between 17,000 and 12,000 yr BP. It is assumed that plant growth and vegetation characteristics in the late glacial and modern time periods are controlled by similar conditions, including soil, fire and climate (Gill 2007). Thus, if vegetation assemblages lack a modern analogue, the vegetation compositions should be caused by a difference in the conditions affecting vegetation. Greater seasonality, meaning there were colder-than-present winters and warmer-than-present summers, characterized the late glacial climate; greater seasonality resulted from the influence of orbital forcings and the resultant more seasonal-than-present insolation (Ruddiman 2001, Williams et al. 2001). Williams et al. (2001) reported a strong correlation between the spatial and temporal distribution of fossil pollen assemblages with no modern analogue and climates with no modern analogues.

Another factor affecting the vegetation was the extinction of many megafaunal species, which also occurred during the late glacial/early Holocene time period. Fifty thousand years ago BP, large mammals with a body mass greater than 44kg lived on the earth (Koch & Barnosky 2006). By 10,000 yr BP, almost all of these large mammals, or megafauna, had become extinct. There are competing explanations for this extinction event, including human overkill, environmental changes, other human influences, and combination hypotheses (Koch & Barnosky 2006). Megaherbivores have a large impact on the composition and structure of present-day plant communities, browsing and disturbing the landscape. Both herbivores and fire are vegetation consumers, and the presence of one or both greatly affects vegetation composition (Bond 2005). If one vegetation consumer (fire or herbivory) disappears from the landscape, the other may take over as the dominant disturbance process (Gill 2007). Spores from the *Sporormiella* fungus found in lake sediments can be used to detect the abundances of megafauna on the landscape (Gill 2007). Counted on pollen slides alongside pollen grains, *Sporormiella* can be identified and quantified. When *Sporormiella* content falls below 2 percent of the pollen total, the extinction of the megafauna is inferred (Gill 2007).

Humans most likely arrived in North America most during the late glacial/early Holocene time period (Waters & Taylor 2007). The Clovis people are thought to have traveled from Asia to North America approximately 11,050 to 10,800 radiocarbon years BP. A Clovis site in Ohio that is relatively close to northern Indiana is dated to 10,920 to 10,600 radiocarbon years BP (Waters & Stafford 2007). Though the exact arrival date of humans is unclear, human impact upon arrival may have had drastic impacts on vegetation, fire, and animal species.

Erosion also plays an important role on the landscape and can be connected to fire regimes. Magnetic susceptibility measurements conducted on lake sediment cores indicate levels of erosion by determining the presence and abundance of iron-bearing minerals within the sediments (Spigel 2006). Surface soils contain more iron-bearing minerals due to "magnetic enhancement," which is caused by burning, fermentation and atmospheric deposition. Magnetic susceptibility will peak during periods of greater sediment influx from the surrounding topsoil (Spigel 2006). Magnetic susceptibility helps to determine whether peaks in the charcoal data are closely correlated to erosional pulses from the surrounding landscape.

Relationships Among Fire, Climate, and Vegetation

The relationships between fire, climate, and vegetation are complex and varied. Climate, vegetation and fuel load, and ignition frequency control fire regimes (Whelan 1995, Gavin 2007). Local factors such as topography and aspect also influence fire (Gavin 2003). Ignition frequency relates to the frequency of lightning and the frequency of human created fires (Whelan 1995). Climate is a regional or global control of fire regimes, while vegetation and fuel load are local controls (Gavin et al. 2007). Even over large spatial and temporal scales, fuel loads affect fire regime; usually the more biomass available for burning, the more burning will occur (Gavin et al. 2007). The spatial scale of study influences what controls appear to affect fire regimes. With an increasing number of sites over a regional area a climatic affect on fire may become evident (Gavin et al. 2006, Gavin et al. 2007). Fire also affects vegetation and helps establish vegetation assemblages. Many studies use pollen, charcoal, and other proxies, to determine the relationships between fire, climate, and vegetation.

Some studies have found that climate was the direct cause of changes in fire regimes. Millspaugh et al. (2000) analyzed a 17,000 yr fire history from Yellowstone Park. They determined that summer insolation was the driver of fire regimes; during periods of high summer insolation, fire was the most frequent because of dry, hot climatic conditions (Millspaugh et al. 2000). Fire regimes in the Northern Rocky Mountains also were most affected by climatic shifts from the late glacial to the late Holocene (Brunelle & Whitlock 2003). The highest fire frequency east of the Continental Divide in the Northern Rocky Mountains occurred in the mid to late Holocene and was connected to a decrease in summer precipitation. West of the continental divide, fire frequency was greatest in the early Holocene when summer insolation was high (Brunelle & Whitlock 2003). In the Canadian boreal forest throughout the Holocene, climate, not vegetation, was the driver of the fire regime (Carcaillet et al. 2001). Similarly, a study of the last 9000 years on the Oregon coast determined that climate change caused the changes in fire return interval (Long et al. 1998). These studies show that climate can be the direct cause of fire regime changes.

Other studies have determined that local factors, such as vegetation, fuel load, and aspect were the most influential in changing fire patterns. Though climate may cause changes in vegetation, vegetation can be the direct cause of changes in fire regime. Brown et al. (2005) found that on the Northern Great Plains in the late Holocene, fuel load influenced fire. Increased grass cover during moister periods increased the fuel load available for fire, and charcoal flux into Kettle Lake, North Dakota increased. Charcoal influx decreased in times of drought, when fuel loads were limited (Brown et al. 2005). Even when wetter conditions dominated, fire occurred more frequently because of fuel loads. In the Alaskan Boreal Forest, the main cause of increased fire frequency in the Holocene was the presence of black spruce, an extremely flammable tree species (Hu et al. 2006). Along with the establishment of black spruce, the climate became cooler and wetter, indicating vegetation type controlled the fire regime (Hu et al. 2006). Local aspect and topography influence the location of fire (Gavin 2003). Gavin et al. (2003) used soil charcoal to determine that southern facing slopes on Vancouver Island, British Colombia were much more likely to burn than northern facing slopes. Local factors such as fuel load, vegetation type, and aspect can directly influence a fire regime.

It may be apparent that climate and vegetation contribute equally to establishing a fire regime. Power et al. (2006) studied fire and vegetation over the last 3800 years in NW Montana. In the earliest part of their record, steppe vegetation and cooler conditions caused less fire activity. Forest was then established in the area, because there was increased moisture available. Fire also increased at this time, indicating that the summers were dry, but the winters were moist enough to support the forest vegetation. The background CHAR increased with the establishment of the forest. Climate and vegetation caused an increase in fire frequency and background CHAR level; drier summers allowed for more burning, and the forest vegetation increased the available fuel load (Power et al. 2006).

Fire also establishes specific vegetation types and characteristics. Nelson et al (2006) studied the role of fire in the establishment of prairie vegetation in the eastern Prairie Peninsula during the Holocene. They found that two different time periods solidified the existence of the Prairie Peninsula. In the early Holocene, aridity increased and fire correspondingly increased. In the following period of decreased aridity, prairie existed alongside fire sensitive trees. Around 6,200 cal yr BP, the prairie became dominant, but aridity was not more severe. Increased ignition frequency, from humans or lightning, most likely caused the re-establishment of the prairie. Even in a period of increased moisture, from 5800 to 5400 cal yr BP, fire maintained the eastern Prairie Peninsula (Nelson et al 2006).

METHODS

Appleman Lake was cored in October 2005 by Professor Jack Williams and Jacquelyn Gill, a graduate student in physical geography. They obtained an 11.5m sediment core from Appleman Lake. The core was split, imaged and scanned for magnetic susceptibility at the National Lacustrine Core Repository at the University of Minnesota's Limnological Research Center. In the lab, the cores were cut at 1cm intervals and placed into labeled bags for sampling.

The Center for Applied Isotope Studies at the University of Georgia conducted Accelerated Mass Spectrometry (AMS) radiocarbon dating on three wood fragments at 631cm, 774cm and 810cm depths. Radiocarbon dates from these wood fragments were converted to calendar ages using CALIB, yielding median ages of 8,110, 11,780 and 13,468 cal yr BP respectively (Table 1). These three dates were used to construct a linear age-depth model for the Appleman Lake core. The equation for the linear regression age model is: Age = -10084.5853 + (28.7186)(Depth). This means that the sediment accumulation rate for the analyzed core is 28.7186yr/cm.

Table 1:

Depth from top of core	*Context*	*Libby Age*	*Corrected Age*	*Median Cal. Age*	*Cal. 2σ Age Around Median*
631cm	silty gyttja	7,283 +/- 50	7,310	**8,110**	**8,065 - 8,156**
774cm	sand/gravel	10,174 +/- 70	10,137	**11,780**	**11,619 - 11, 941**
810cm	silty clay	11,613 +/- 63	11,621	**13,468**	**13,386 - 13,550**

Charcoal analysis was conducted using Lynch & Curran's macroscopic sieving method (Whitlock and Larsen 2001) as modified by Professor Hotchkiss' Lab at UW-Madison. Samples of 1 cm^3 of sediment were taken from the sediment core at 1cm or 2cm intervals. From 597 to 623cm cumulative depth below the sediment/water interface, samples were taken every 2cm down the core. At depths 623 to 824cm, samples were taken at 1cm intervals. The remainder of the analyzed core, from 824 to 968cm, was sampled at 2cm intervals. All samples were treated with 6% hydrogen peroxide and placed in a drying oven overnight; this bleached the organic matter and broke up the sediment, leaving the charcoal particles intact. The samples were then poured through 250µm and 125µm sieves, and each portion was counted at 40X using a binocular microscope. The 250µm portion was counted directly on the sieve and then discarded. The 125-250µm size class was transferred onto plastic Petri dishes. Using a holder with a grid and a corresponding paper grid, the 125-250µm size particles were tallied, and their locations were marked on the corresponding paper grid.

While marking the location and abundance of charcoal particles, I also noted charcoal morphology. Charcoal particles may be classified into types, signifying the types of vegetation that were burned. Members of Professor Hotchkiss' Lab at UW-Madison, mainly Crystal Sutheimer, developed the typing scheme I applied. Sutheimer and the Hotchkiss Lab also conducted burning experiments to connect the charcoal particle types with different kinds of vegetation. Charcoal particles were classified into dark, graminoid cellular, porous, spongy, fibrous, branched, lattice, bordered pit and other types (Figure 3). Certain types are more meaningful indicators of the types of vegetation burned. Dark charcoal indicates woody material, graminoid cellular signifies grasses, branched results from deciduous leaf veins, and bordered pit charcoal implies coniferous vegetation. The additional types (spongy, porous, fibrous, lattice, and other) are more ambiguous; I had a more difficult time consistently distinguishing between these types. Under the other charcoal category, I included gall charcoal particles. Galls are formed by insects and are left on oak leaves (Burns & Honkala 1990). The presence of gall charcoal is interpreted to indicate the presence of oak on the landscape.

Once the samples were counted, the 125-250µm and >250µm size classes were summed, and charcoal data was expressed as charcoal particle counts per volume of sediment (particles/cm^3). Using the age model described above, charcoal concentration was then transferred into charcoal accumulation rate (CHAR), expressed at particles/cm^2/year. Samples above 630cm and below 811cm to 968cm are not bracketed by radiocarbon dates, so for these samples, more radiocarbon dates are needed to confirm the estimated sedimentation rate. I used Charster, a program developed by Dan Gavin at the University of Oregon (Gavin 2006), to decompose the fire record into the background and peaks component and to determine fire return intervals.

In order to analyze charcoal data in Charster, I imported a text file containing the estimated ages for the top and base of each sample, the total number of charcoal particles per sample, and sample volumes (1cm^3 for all samples). Charster transforms the data into

CHAR based on the ages of the samples. Various parameters may be changed in the analysis of a charcoal record:

1). The charcoal record must be re-sampled at equal time intervals to encompass the coarsest sampling resolution of the record.

2). Charster can log transform the record, which emphasizes and exaggerates smaller magnitude variations within a record.

3). To determine the background component of CHAR, a LOWESS (locally-weighted regression), a Tricube Filter (center-weighted moving average) or a moving median function is applied to the data using a set background window.

4). The final parameter that can be manipulated is the threshold value applied to the peaks component of the record, in order to filter out noise in the record. The threshold value can be set as a difference between the background level and the peak component or as a ratio above the background level. A difference threshold level means that any peak in the record that is a set amount of CHAR units above the background level is interpreted as a fire event. A ratio threshold means that peaks are identified if the peak is a certain ratio above the background level.

Once peaks in the charcoal record are identified, the fire return interval can be calculated. Fire return interval is expressed as the number of fires per 1,000 years, and is a measure of fire frequency.

Using Charster, I re-sampled the record at 50-year intervals in order to encompass the coarsest sampling resolution of the core. Although the sedimentation rate determined by the three radiocarbon dates is 28yrs/cm, certain sections of the core were sampled at 2cm intervals. I did not log-transform the data. In order to calculate the background component of CHAR, the LOWESS function, a moving locally-weighted average, was applied to the record. A difference threshold level was used for analysis of the peaks component.

The two most subjective parameters to choose were the background window, which the LOWESS function uses to determine the background level of CHAR, and the threshold value, which determines the frequency of peaks in the record (fire events). Many studies use dendrochronological (tree ring) records and historical records of past fires to determine the threshold value (Long et al. 1999, Millspaugh et al. 2000, Brunelle & Whitlock 2003, Power et al. 2006). These studies tune the long-term charcoal record from a site to the known fire record; the threshold value is set so the fire events identified from the charcoal record mirrors the known fire history. This method is particularly useful in the Pacific Northwest, where tree ring records are available. In northern Indiana, tree ring records are not available. Focusing on the late glacial time period also rules out the option of comparing the charcoal record to historical records. For this thesis, I experimented with various settings for the background window and threshold and the sensitivity of the inferred fire events to these settings (see Results). Though setting the background window and threshold value parameters is subjective, the main goal in analysis of the Appleman Lake record is to compare the fire regime across the time period of the core. As long as the same Charster parameters are used for all time periods, this comparison can take place despite uncertainty in the exact number of peaks for the entire record.

Jacquelyn Gill, a PhD student in the UW-Madison Geography Department, conducted pollen analysis on the Appleman Lake core using standard procedures (Faegri & Iverson 1989). Using a x40 magnification, Gill counted up to 300 pollen grains on each slide of processed pollen. Data for each taxa is expressed as a percentage of the total 300 grains, stated as the percent of the upland sum. Gill also analyzed the core for *Sporormiella*. Gill counted *Sporormiella* spores on pollen slides, and expressed the data as a percentage of the 300 pollen grains, without including spores in the 300 grain counting limit. Gill conducted dissimilarity analysis to determine the presence and timing of no-analog vegetation assemblages. Magnetic susceptibility data was obtained from the National Lacustrine Core Repository at the University of Minnesota's Limnological Research Center.

RESULTS AND DISCUSSION

Raw Charcoal Data

The most striking observation about the raw charcoal data (Figure 4) is the appearance of 3 time periods, each with different fire characteristics. In the third time period, from 968cm to 905cm, there are very few charcoal particles. In the second time period, from 905cm to 725cm, the total number of charcoal particles dramatically decreases. There are few peaks during this time period. In the first time period, from 725cm to 600cm, charcoal particles are abundant, and noticeable peaks exist throughout the time period. Background charcoal levels are high, which is interpreted to indicate a large amount of biomass available for burning. These time periods are based upon my visual inspection of the raw charcoal data.

When comparing the 125-250µm size class and the >250µm size class, there is no apparent difference in the pattern of charcoal peaks (Figure 5). Though significantly smaller in particle abundance, the >250µm size class mirrors the 125-250µm size class throughout the record. When the 125-250µm size charcoal particles increased, the >250µm size charcoal particles also increased.

Charcoal Morphology

As indicated above, certain charcoal particle morpho-types may contain additional ecological information. In the third time period, the few charcoal particles present are primarily “other” or dark particles. The prevalence of “other” charcoal particles may be the result of taphonomic processes or because the core in the earlier time periods has more sand content. The oldest charcoal particles were more difficult to identify, possibly because they were more degraded and broken up. In the second time period, “other” charcoal particles compose a substantial proportion of the charcoal. In the first time period, dark and fibrous charcoal are the most abundant (Figure 6). Dark charcoal indicates burned woody vegetation.

When compared to pollen data, certain charcoal types show that charcoal can indicate the type of vegetation burned. For example, gall charcoal appears in the record when *Quercus* (oak) pollen increases to 60% of the upland sum at approximately 715cm depth (Figure 7). Before the presence of gall charcoal, oak pollen levels are low, possibly indicating that oak is present in the regional area versus the local area. An increase in gall charcoal and oak pollen around 715cm indicates that oak became established in the local area surrounding Appleman Lake. The slight lead in the pollen increase of oak pollen prior to the appearance of galls may indicate that oak became regionally widespread before it became abundant in the Appleman Lake watershed. Increases in bordered pit charcoal particles and *Picea* (spruce) and *Pinus* (pine) pollen also occur at similar depths in the core (Figure 8). When *Picea* pollen reaches a maximum of 75% of the upland sum at approximately 860cm, bordered pit charcoal also peaks. Bordered pit charcoal also peaks when *Pinus* peaks at around 775cm depth. Peaks in graminoid cellular charcoal, indicating grass vegetation, do not closely correspond to increases in *Poaceae* (grass) pollen (Figure 9), and may even be anticorrelated. It seems as though peaks in *Poaceae* occur after peaks in fire, and during a charcoal peak, *Poaceae* pollen drops. A possible explanation for this pattern is that directly after a fire, grasses are regenerated and abundant on the landscape. The additional charcoal types not shown here are not correlated any pollen types.

Determining Parameters for Charster (Threshold and Background Window)

When I first analyzed my results in Charster, I analyzed the 125-250µm size class without adding the >250µm size class. I tested both the background window parameter and the threshold value parameter for the data, and found that the data was insensitive to changes in the background window (Tables 2 & 3, Appendix B). Because the 250 year background window appeared to have the best fit for a background level of CHAR, I chose the 250 year background window for the 125-250µm data.

In order to determine the threshold value, I first inspected the raw charcoal data (particles/cm^3) to identify charcoal peaks that I was highly confident represented fires. Any peak in the raw charcoal data that was composed of two samples was counted as a fire event, because it is unlikely to be due to processing error. I tried to conservatively estimate the number of fire events. After inferring the number of fire events for each of the three time periods from the raw charcoal data, I identified the highest possible threshold value that would still include all visually-identified fire events. This CHAR threshold was 0.35 particles/cm^2/yr.

If the >250µm size class is added to the 125-250µm size class, the sensitivity to parameter selection and number of fire peaks in each time period is slightly altered (Tables 4 & 5, Appendix B). Changing the background window parameter had a slightly larger effect on the number of fire peaks in each time period. After visual analysis of the raw charcoal data, I determined that a background window of 250 years and a threshold level of 0.3 CHAR was the best fit for the charcoal record. The number of peaks for each time period with a 250 year background window and 0.3 CHAR threshold value level equaled the number of peaks for each time period inferred by visual analysis of the combined 125-250µm and >250µm size classes (Figure 4). Though the threshold value changed when I added the >250µm size class to the 125-250µm size class, the amount of fire peaks and the relationship between the fire return intervals of each time period remained almost constant.

In summary, based on my analyses of the combined >250µm size and 125-250µm size classes I decided to use a 250 year background window and a 0.3 CHAR threshold value. All subsequent analyses are performed on the combined size fractions. Relative comparisons between different time periods in the record can be made regardless of the exact values of the background window and the threshold value.

Charster Results

The background level of CHAR varies significantly throughout the record (Figure 10). In the third time period, from 17,600 to 15,900 cal yr BP, background CHAR does not exceed 0.3 particles/cm^2/yr. Background CHAR increases in the second time period, from 15,900 to 10,800 cal yr BP, reaching a maximum of 2 particles/cm^2/yr. In first time period, from 10,800 to 7,100 cal yr BP, background CHAR increases drastically, reaching 4.5 particles/cm^2/yr. Based upon the dates for each time period, the third time period is the late glacial period, the second time period is the late glacial/early Holocene transition, and the first time period could be characterized as the early Holocene.

Using a CHAR threshold of 0.3, there are 0 fire events in the late glacial period, 8 fire events in the transitional period, and 12 fire events in the early Holocene period, (Figure 11). The fire return interval for the late glacial and the transitional periods were 0/1000 yr and 1.55/1000 yr respectively (fires per thousand years). The fire return interval for the early Holocene is 3.24/1000 yr. While setting the threshold value at greater than or less than 0.3 CHAR would have changed the fire return intervals for each period, the relationship between each period would have remained relatively constant (Table X). Thus, a comparison between each time period in relative fire frequency can be made. The fire return interval approximately doubled from the transitional period to the early Holocene, while the late glacial period appeared to have no fires.

A fire peak that occurs at the same time as the onset of the Younger Dryas climatic event is evident in the charcoal record (Figure 11). The Younger Dryas was a cold interval that occurred during deglaciation approximately 13,000 to 11,700 years ago (Ruddiman 2001). Warming that was causing deglaciation was interrupted because of this cold period; some believe that the cooling was caused by a meltwater pulse into the North Atlantic that changed ocean chemistry and decreased temperatures (Ruddiman 2001). Firestone et al. (2007) believe that extraterrestrial impacts occurred 12,900 cal yr

BP, and this impact caused the Younger Dryas cooling and contributed to megafauna extinction. They identify a Younger Dryas Boundary (YDB) in 10 Clovis sites and 15 sites in the Atlantic Coastal Plain, and each layer dated to 12,900 cal yr BP. The YDB layers in their core data contain peaks in charcoal, carbon content, and other minerals (Firestone et al. 2007). At 12,900 yr BP, there is a substantial peak in the Appleman Lake charcoal record (Figure 11), which could support the hypothesis presented by Firestone et al. (2007).

Analyses alongside additional proxies

Greater insights into the fire record from Appleman Lake can be made when the record is connected to pollen and *Sporormiella* data (Figure 12). The following will be an analysis of each time period, moving from the late glacial to the early Holocene.

More pollen samples from Appleman Lake are needed from the late glacial time period, but it is evident that *Picea* (spruce) is dominant during this time (Figure 12). Spruce grows in extreme climatic and soil conditions, and is know to populate recently de-glaciated areas (Burns & Honkala 1990). *Sporormiella* is also high during this period, indicating the presence of megafauna. Cold conditions, lack of biomass, and megaherbivore influence on the landscape most likely caused the lack of fire activity during the late glacial period.

In the transitional period, spruce gradually declines and disappears by the end of the time period. This indicates that the climate was become warmer, and conditions were more hospitable to the growth of other taxa, including deciduous taxa. *Quercus* (oak) begins to appear in this period, as does *Ulmus* (elm) and *Carya* (hickory). *Sporormiella* declines during this period as well, and falls below 2% around 850cm depth, which can be inferred as extinction. As *Sporormiella* abundances decrease, palynological dissimilarity increases, signifying the presence of no-analogue vegetation assemblages. *Fraxinus* (ash) and *Ostrya/Carpinus* (hornbeam/hophornbeam) are major constituents of no-analogue vegetation in the late glacial/early Holocene, and these taxa increase along with increases in dissimilarity (Gill 2007). The megafaunal extinction may have helped with the establishment of the anomalous vegetation assemblages. As the megafauna stopped grazing and browsing the landscape, certain taxa such as ash and hornbeam were able to grow (Gill 2007).

The transitional period also marks the first presence of charcoal peaks. A major peak in the charcoal record occurs prior to the onset of the Younger Dryas event and almost contemporaneously with the inferred extinction of the megafauna at 850cm depth (Figure 12). A possible explanation could be that as megaherbivores became extinct, fuel load built up and a fire pulse occurred because of the increased fuel load. Another possibility is that a climatic shift caused this large fire event at 850cm; i.e., a drought may have occurred. Though the date of human arrival is not well known, one or more of the peaks in the transition period may have been caused by human ignitions. The fire event at 850cm does not coincide with a peak in magnetic susceptibility, indicating that the peak is not a result of an erosional event (Figure 13). The peak is most likely an ecological signal, meaning that it was caused by megafaunal extinction, climate shifts, and/or human arrival. The charcoal peaks in the transitional period coincide with peaks in *Ambrosia* (ragweed), which is a disturbance taxa. Also, fire sensitive taxa such as *Salix* (willow) and *Carpinus* (hornbeam) decrease as charcoal particles increase.

The early Holocene period is marked by a dramatic increase in oak, and by then end of this period oak comprises over 60% of the upland sum of pollen (Figure 12). Elm and hickory increase as well, and the no-analogue taxa decrease along with the dissimilarity index. The background level of CHAR and the number of charcoal particles also dramatically increase in the early Holocene. Fires are more frequent; from the transitional period to the early Holocene, the fire return interval increases from 1.55/1000yr to 3.24/1000yr. There is also more biomass available for burning on the landscape. There is a contemporaneous increase in fire and oak. Some species of oak have fire-resistant bark, and oak responds well to open landscapes (Burns & Honkala 1990). Also during this period, ragweed increases with increases in charcoal. The increase in deciduous taxa and fire signifies warming and the beginning of the Holocene period.

In sum, charcoal analysis of Appleman Lake alongside other proxies demonstrates a history of landscape change. In the late glacial period, cold condition and lack of available biomass meant that fire rarely occurred. In the transitional period to the Holocene, fire became more frequent, and fire peaks can be connected to events such as megafaunal extinction, vegetation changes, the Younger Dryas event, and possibly human arrival. Warming continued into the early Holocene. In the early Holocene fire frequency increases along with biomass and background charcoal. The Appleman Lake sediment record contains information about changes in and interactions between fire, vegetation, climate and megafauna.

CONCLUSION

Implications and Significance of Study

Though Cole & Taylor (1995) studied the presence and prevalence of oak savanna in Northern Indiana from 4,000 yr BP to the present, this study is the first analysis of the fire regime for the late glacial/early Holocene time period in Northern Indiana. This present study demonstrates the complex relationships between various aspects of the environment. Studies that span long time scales allow for a holistic interpretation of landscape changes, and paleorecords help to inform present and future environmental interactions. In order to learn what might happen in the future, one must look to the past.

Lessons learned from Honors thesis experience

I learned many lessons from completing this honors thesis. I now understand and appreciate the amount of time and effort needed to accumulate scientific data. I also learned to have patience with the scientific process. I know that persistence and dedication is needed for the production of scientific data. Because of my senior honors thesis, I was able to contribute data to a larger project that is being worked on by Jacquelyn Gill and The Williams Lab. I realize that many individual contributions can help the greater goal of understanding complex environmental relationships.

Acknowledgements

I would like to thank Professor Jack Williams and Jacquelyn Gill for their constant advice, help, and encouragement. I would also like to thank Crystal Sutheimer and the Hotchkiss Lab for their help. Thanks to Dominique Alhambra for help with processing data, and to Leila Gonzales, Karen Russ, and Jeremiah Marsicek for their support and insights.

REFERENCES

Bennet, K.D. & K.J. Willis, 2001. Pollen. In: Tracking Environmental Change Using Lake Sediments: Terrestrial, Algal, and Siliceous Indicators (vol. 3). Smol, J.P., Birks, H.J.B. & Last, W.M. (eds.). Kluwer Academic Publishers, Dordrecht: 5-33.

Bond, W.J. & J.E. Keeley, 2005. Fire as a global 'herbivore': the ecology and evolution of flammable ecosystems. Trends in Ecology and Evolution 20: 387-394.

Brown, K.J., Clark, J.S., Grimm, E.C., Donovan, J.J., Mueller, P.G., Hansen, B.C. & I. Stefanova, 2005. Fire cycles in North American interior grasslands and their relation to prairie drought. PNAS 102: 8865-8870.

Brunelle, A. & C. Whitlock, 2003. Postglacial fire, vegetation, and climate history in the Clearwater Range, Northern Idaho, USA. Quaternary Research 60: 307-318.

Burns, Russell M., and Barbara H. Honkala, tech. cords, 1990. Silvics of North America: 1. Conifers; 2. Hardwoods. Agriculture Handbook 654.
U.S. Department of Agriculture, Forest Service, Washington, DC: vol. 2.

Carcaillet, C., Bergeron, Y., Richard, P.J.H, Frechette, S.G. & Y.T. Prairie, 2001. Change of fire frequency in the eastern Canadian boreal forests during the Holocene: does vegetation composition or climate trigger fire regime? Journal of Ecology 89: 930-946.

Clark, J.S., 1988. Particle motion and the theory of charcoal analysis: source area, transport, deposition, and sampling. Quaternary Research 30: 67-80.

Cole, K.L. & R.S. Taylor, 1995. Past and current trends of change in a dune prairie/oak savanna reconstructed through a multiple-scale history. Journal of Vegetation Science 6: 399-410.

Faegri, K. & J. Iverson, 1989. Textbook of Pollen Analysis, 4th Edition. The Blackburn Press, Caldwell.

Firestone et al., 2007. Evidence for an extraterrestrial impact 12,900 years ago that contributed to the megafaunal extinctions and the Younger Dryas cooling. PNAS 104: 16016-16021.

Gavin, D.G. 2006. CHARSTER version 0.8.3. http://geography.uoregon.edu/gavin/charster/, Last accessed on December 26, 2007.

Gavin, D.G., Brubaker, L.B. & K.P. Lertzman, 2003. An 1800-year record of the spatial and temporal distribution of fire from the west coast of Vancouver Island, Canada. Canadian Journal of Forest Research 33: 573-586.

Gavin, D.G., Hu, F.S., Lertzman, K. & P. Corbett, 2006. Weak climatic control of stand-scale fire history during the late Holocene. Ecology 87: 1722-1732.

Gavin, D.G., Hallet, D.J., Hu, F.S., Lertzman, K.P., Prichard, S.J., Brown, K.J., Lynch, J.A., Bartlein, P. & D.L. Peterson, 2007. Forest fire and climate change in western North America: insights from sediment charcoal records. Frontiers in Ecology and the Environment 5:499-506.

Hu, F.S., Brubaker, L.B., Gavin, D.G., Higuera, P.E., Lynch, J.A., Rupp, T.S. & W. Tinner, 2006. How climate and vegetation influence the fire regime of the Alaskan boreal biome: the Holocene perspective. Mitigation and Adaptation Strategies for Global Change 11: 829-846.

Gill, J. 2007. Investigating biotic drivers of Quaternary landscape change: Late glacial no-analog communities and the North American megafaunal extinction. MS Thesis, University of Wisconsin-Madison, Department of Geography.

Higuera, P.E, Peters, M.E., Brubaker, L.B. & D.G. Gavin, 2007. Understanding the origin and analysis of sediment-charcoal records with a simulation model. Quaternary Science Reviews 26:1790-1809.

Long, C.J., Whitlock, C., Bartlein, P.J. & S.H. Millspaugh, 1998. A 9000-year fire history from the Oregon Coast Range, based on a high-resolution charcoal study. Canadian Journal of Forest Research 28: 774-787.

Millspaugh, S.H., Whitlock, C. & P.J. Bartlein, 2000. Variations in fire frequency and climate over the past 17000 yr in central Yellowstone National Park. Geology 28: 211-214.

Nelson, D., Hu, F.S., Grimm, E.C., Curry, B.B. & J.E. Slate, 2006. The influence of aridity and fire on Holocene prairie communities in the eastern Prairie Peninsula. Ecology 87: 2523-2536.

Noss, R.F., Franklin, J.F., Baker, W.L., Schoennagel, T. & P.B. Moyle, 2006. Managing fire-prone forests in the western United States. Frontiers in Ecology and the Environment 4: 481-487.

Power, M.J., Whitlock, C., Bartlein, P. & L.R. Stevens, 2006. Fire and vegetation history during the last 3800 years in northwestern Montana. Geomorphology 75: 420-436.

Ruddiman, W.F., 2001. Earth’s Climate: Past and Future. W.H. Freeman and Company, New York.

Spigel, K.M, 2006. Erosion and sedimentation history of Emrick Lake, south-central Wisconsin, in response to Holocene environmental change. Ph.D. Dissertation, University of Wisconsin-Madison.

Tolonen, K., 1986. Charred Particle Analysis. In Berglund, B.E. (ed.) Handbook of Holocene Palaeoecology and Palaeohydrology. John Wiley and Sons, Ltd., New York: 485-496.

Waters, M.R. & T.W. Stafford Jr., 2007. Redefining the Age of Clovis: Implications for the Peopling of the Americas. Science 315: 1122-1126.

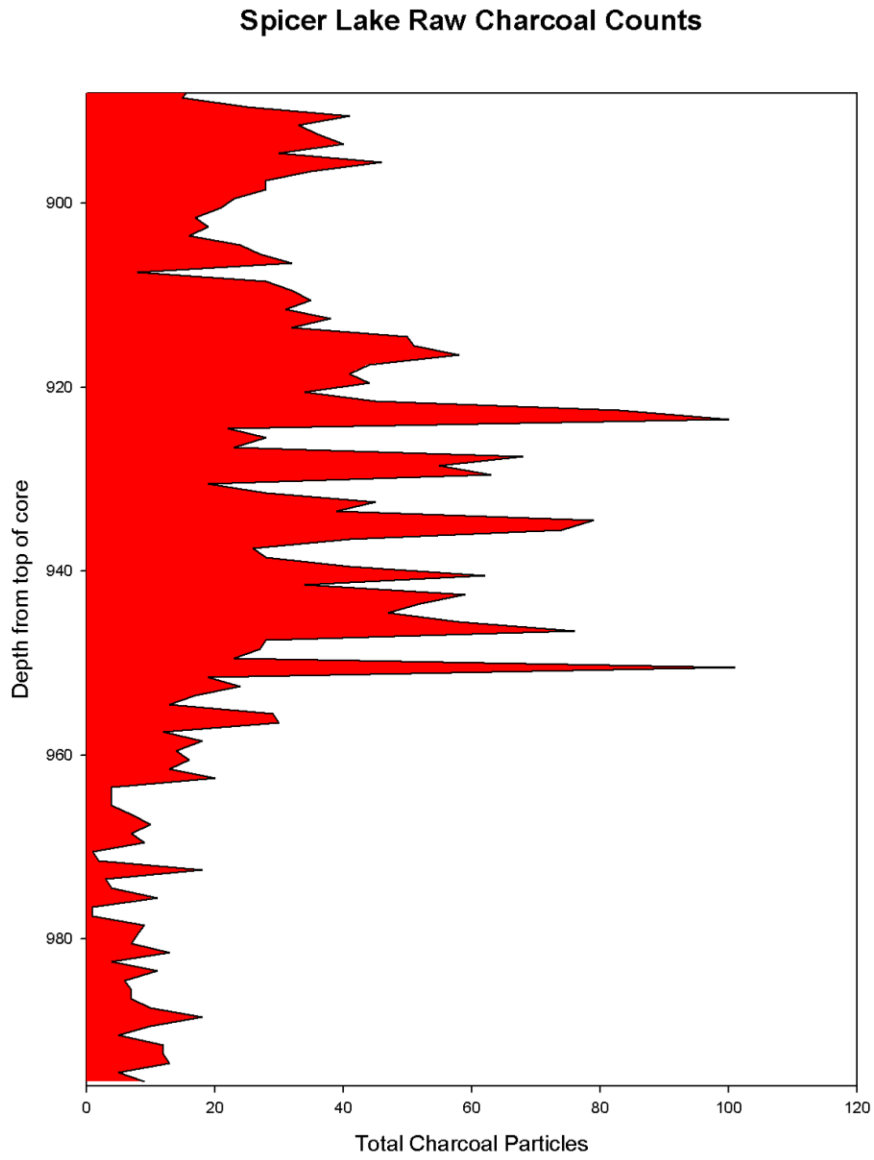
Whelan, R.J., 1995. The Ecology of Fire. Cambridge University Press, Cambridge.

Whitlock, C. & C.P.S. Larsen, 2001. Charcoal as a Fire Proxy. In: Tracking Environmental Change Using Lake Sediments: Terrestrial, Algal, and Siliceous Indicators (vol. 3). Smol, J.P., Birks, H.J.B. & Last, W.M. (eds.). Kluwer Academic Publishers, Dordrecht: 75-97.

Williams, J.W., Shuman, B.N. & T. Webb III, 2001. Dissimilarity analyses of late-Quaternary vegetation and climate in eastern North America. Ecology 82: 3346-3362.

APPENDIX A

For my senior thesis, I began charcoal analysis on a lake sediment core from Spicer Lake, Indiana. Spicer Lake is a kettle lake located in St. Joseph County in north-central Indiana. The lake is 4 hectares, surrounded by marsh, and is set in glacial till. Radiocarbon dates, pollen analysis, and other analyses of the Spicer Lake core will be completed in the near future. Below is the raw charcoal data from Spicer Lake, which will be added to by Luke Straka, an undergraduate research assistant in The Williams Lab.



APPENDIX B

Table 2: Using the data from the 125-250μm size class, I tested the how changing the background window affected the number of interpreted fire events with a set threshold value of 0.35.

Background Window (yr)	Fire Peaks Time Period 3	Fire Peaks Time Period 2	Fire Peaks Time Period 1	Total peaks
150	0	8	11	19
200	0	8	11	19
250	0	7	12	19
300	0	7	12	19
350	0	7	11	18
400	0	7	11	18
450	0	7	11	18
500	0	7	11	18

Table 3: Using the data from the 125-250μm size class, I tested the how changing the threshold value affected the number of interpreted fire events with a set background window of 250 yr.

Threshold Value	Fire Peaks Time Period 3	Fire Peaks Time Period 2	Fire Peaks Time Period 1	Total Peaks
0.1	0	14	18	32
0.12	0	13	17	30
0.15	0	10	17	27
0.2	0	9	14	23
0.25	0	8	14	22
0.27	0	8	14	22
0.3	0	7	12	19
0.35	0	7	12	19
0.37	0	6	12	18
0.4	0	6	9	15
0.45	0	6	8	14
0.5	0	6	8	14
0.55	0	5	7	12

Table 4: Using the combined >250μm size and 125-250μm size classes, I tested how changing the background window affected the number of interpreted fire events with a set threshold value of 0.3.

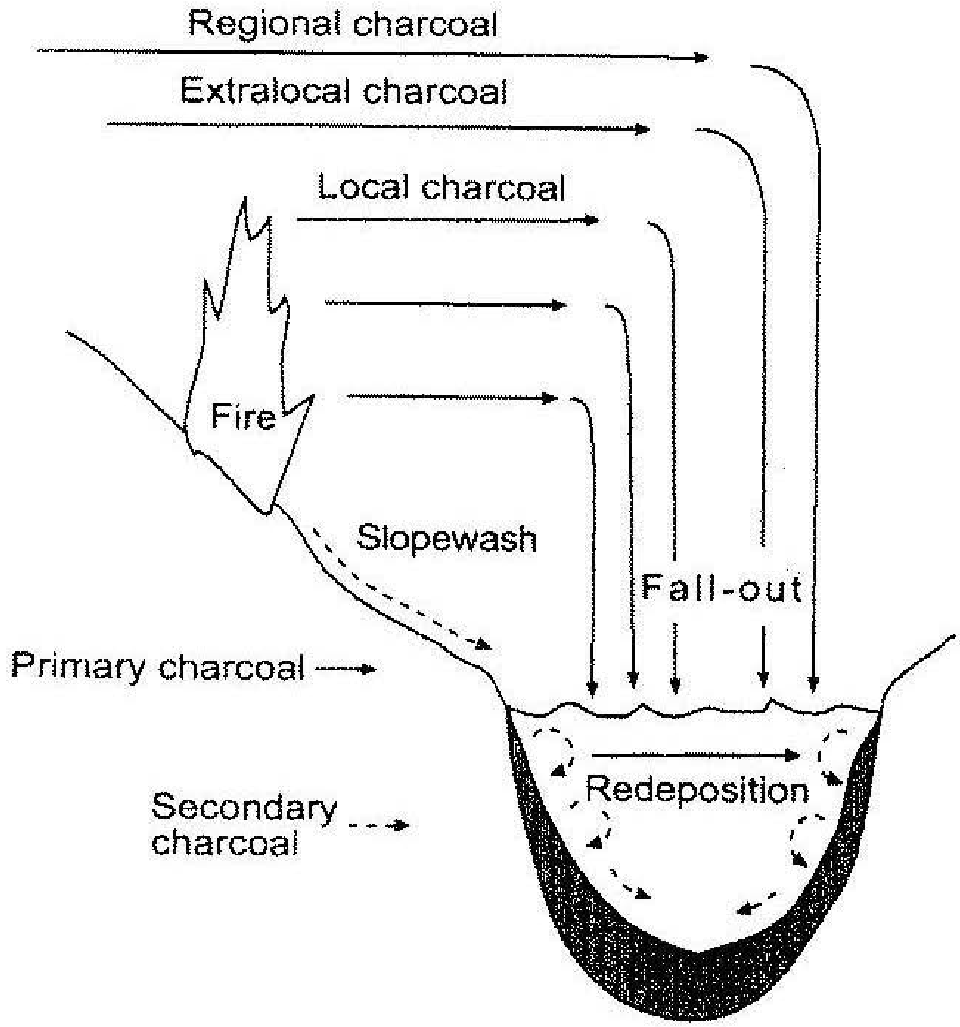
Background Window (yr)	Fire Peaks Time Period 3	Fire Peaks Time Period 2	Fire Peaks Time Period 1	Total peaks
150	0	10	11	21
200	0	10	11	21
250	0	8	12	20
300	0	8	12	20
350	0	7	11	18
400	0	7	11	18
450	0	8	12	20
500	0	8	12	20

Table 5: Using the combined >250μm size and 125-250μm size classes, I tested how changing the threshold value affected the number of interpreted fire events with a set background window of 250 yr.

Threshold Value	Fire Peaks Time Period 3	Fire Peaks Time Period 2	Fire Peaks Time period 1	Total Peaks
0.1	0	17	17	34
0.15	0	12	13	25
0.2	0	10	12	22
0.25	0	9	12	21
0.27	0	8	12	20
0.3	0	8	12	20
0.31	0	6	12	18
0.33	0	6	12	18
0.35	0	6	12	18
0.37	0	6	12	18
0.4	0	6	12	18
0.45	0	6	11	17
0.5	0	6	10	16
0.55	0	6	9	15
0.6	0	6	9	15
0.7	0	4	6	10

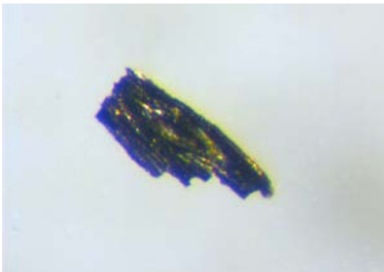
Figures

Figure 1: An areal photo and the location of Appleman Lake, Indiana. Appleman Lake is a kettle lake, with no inlets or outlets, that was formed as the Laurentide Ice Sheet retreated.

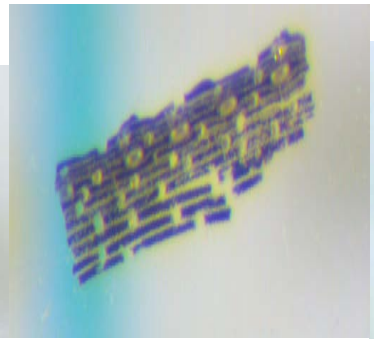


Source: Whitlock & Larsen 2001

Figure 2: This figure illustrates the influx of primary and secondary charcoal, as well as the deposition of microscopic (regional and extralocal) and macroscopic (local) charcoal particles. Primary charcoal is deposited during or directly after a fire occurs, while secondary charcoal gradually accumulates into the lake, mainly as a result of slopewash or erosion. Because of transport processes, macroscopic charcoal (>125µm) indicates local fires, while microscopic charcoal (<125µm) indicates regional fires.

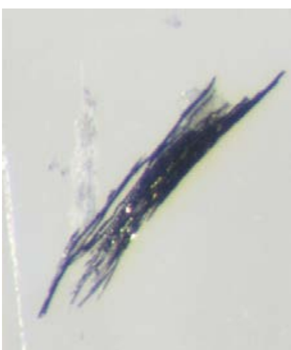


Dark

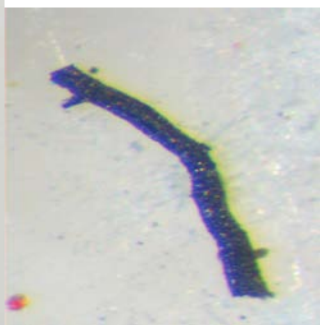


Graminoid Cellular

Spongy

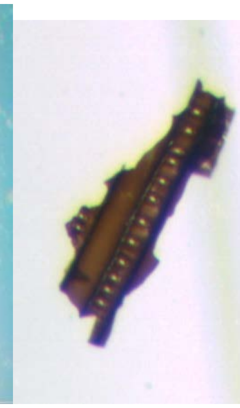


Fibrous



Branched

Lattice



Bordered Pits

Photos by Crystal Sutheimer

Figure 3: The photos above show different types of charcoal particles. Charcoal morphology may provide insight into the types of vegetation burned, such as dark particles indicating woody vegetation, bordered pits signifying conifers, and graminoid cellular indicating grasses.

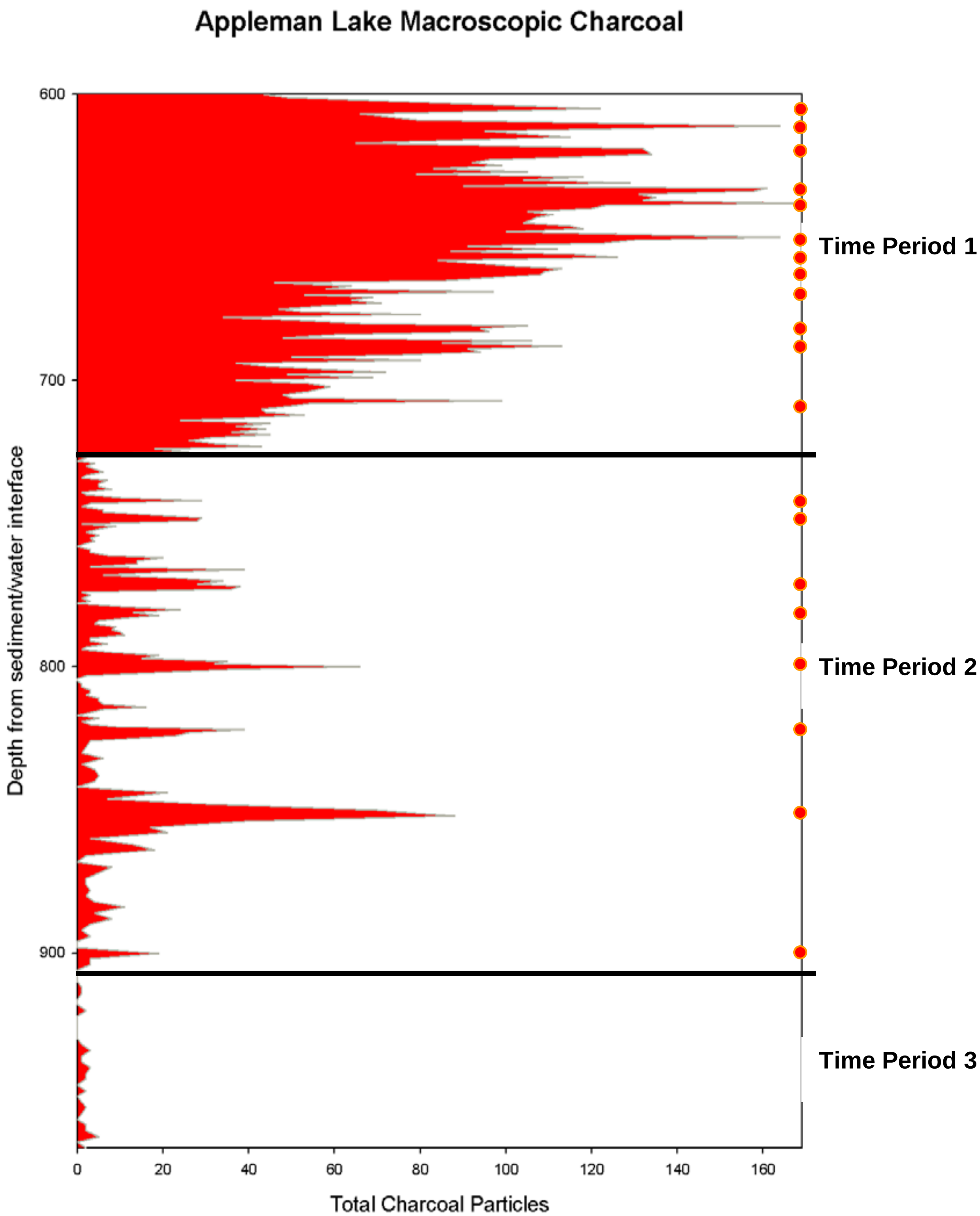


Figure 4: This figure shows the raw counts of charcoal particles for Appleman Lake, from 968 to 600cm (depth below sediment/water interface). Three separate time periods with different fire characteristics are evident in the record. The third period is from 968cm to 905cm depth, the second period is from 905cm to 725cm depth, and the first time period encompasses 725cm to 600cm depth. The red dots along the right side of the figure note fire events inferred by visual analysis of the raw charcoal data (See Results).

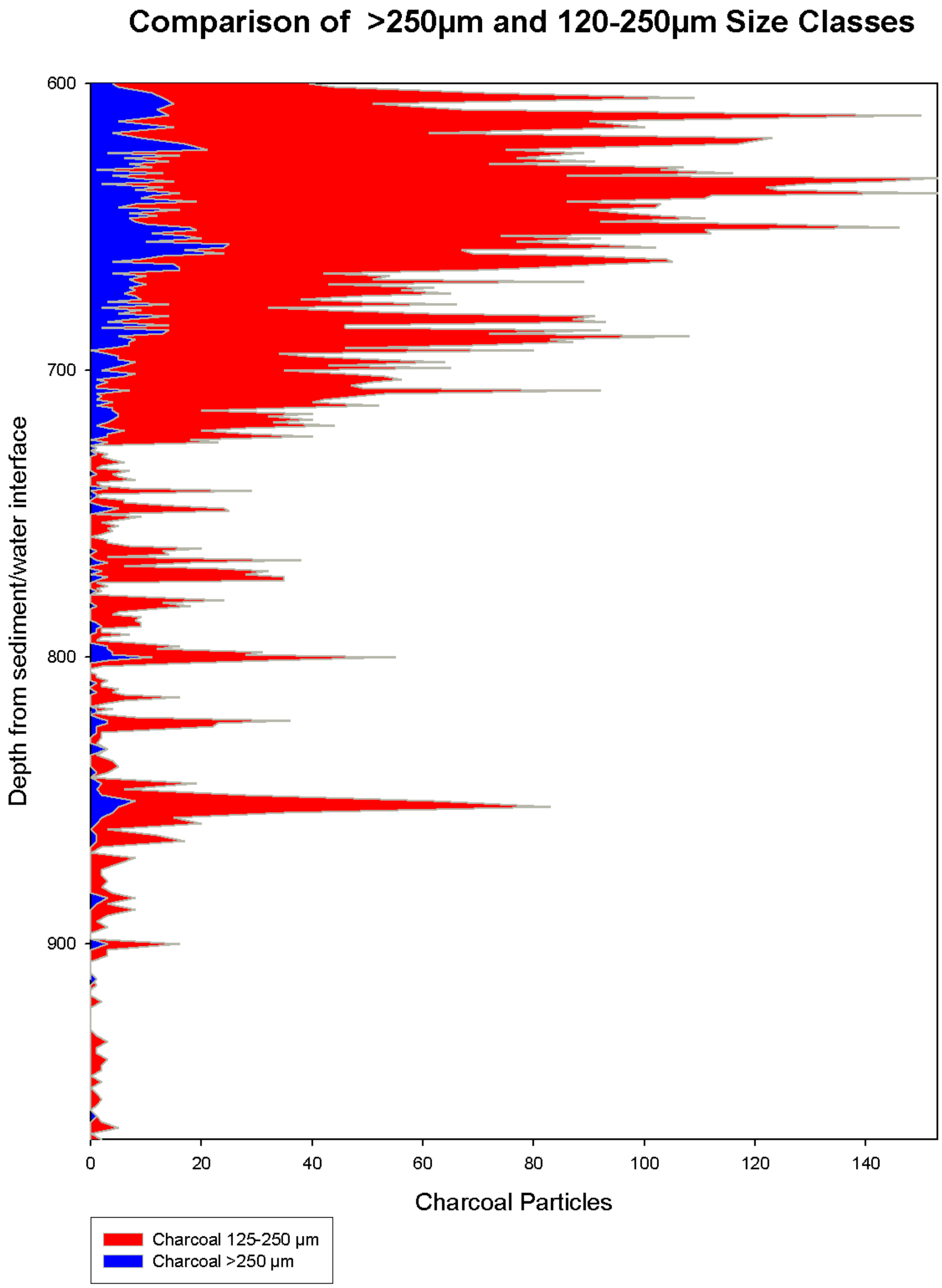


Figure 5: This figure compares the number of charcoal particles in the 125-250µm size class and the >250µm size class. The >250µm size class mirrors the 125-250µm size class throughout the record. Note that the red curve is not a total charcoal sum, but in almost all samples the number of charcoal particles in the 125-250µm size class exceeds the number for the >250µm size class.

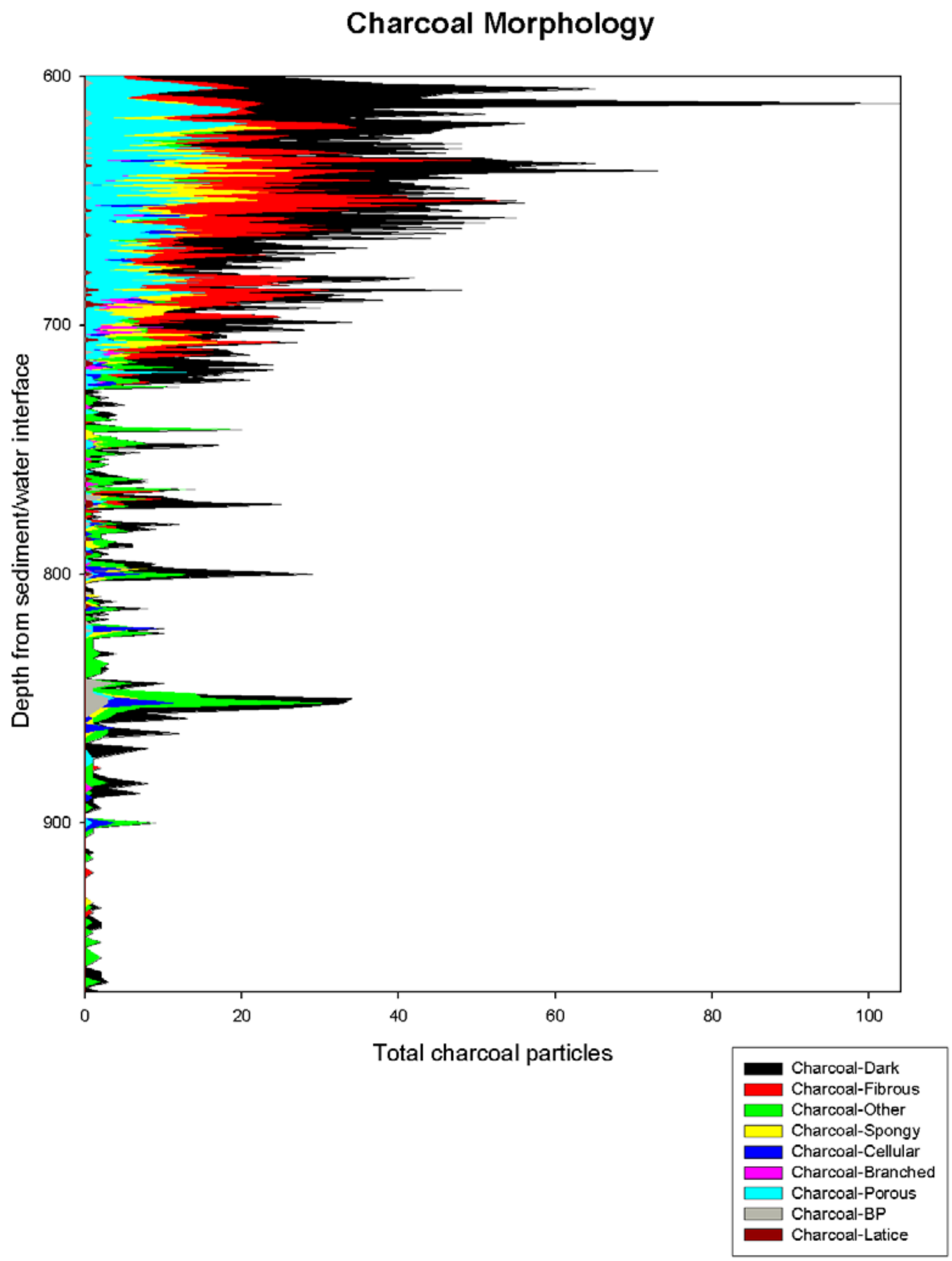


Figure 6: This figure is an area-fill plot that shows amount of each type of charcoal particle throughout the record. There are nine charcoal particle types, and these types provide insight into the type of vegetation burned. In the first part of the record, there are mostly dark charcoal particles, indicating woody vegetation. In the lower portion of the record, "other" charcoal particles become more prevalent. This may be due to particle degradation because of increasing depth.

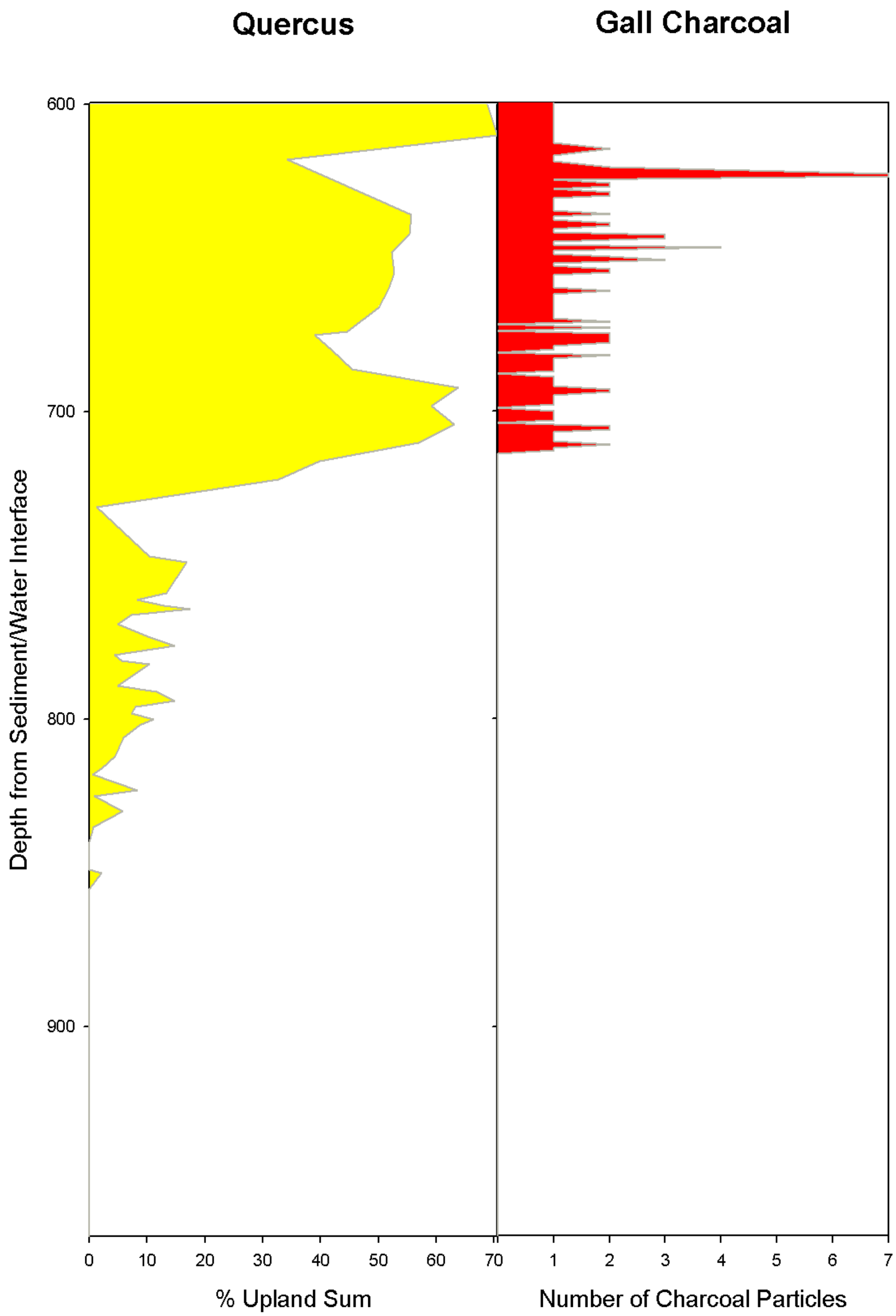


Figure 7: This figure compares gall charcoal with *Quercus* (oak) pollen. Galls are formed by insects and deposited on oak leaves. The presence of gall charcoal and the sharp increase of oak pollen at 715cm depth likely indicate the arrival of oak in the local area.

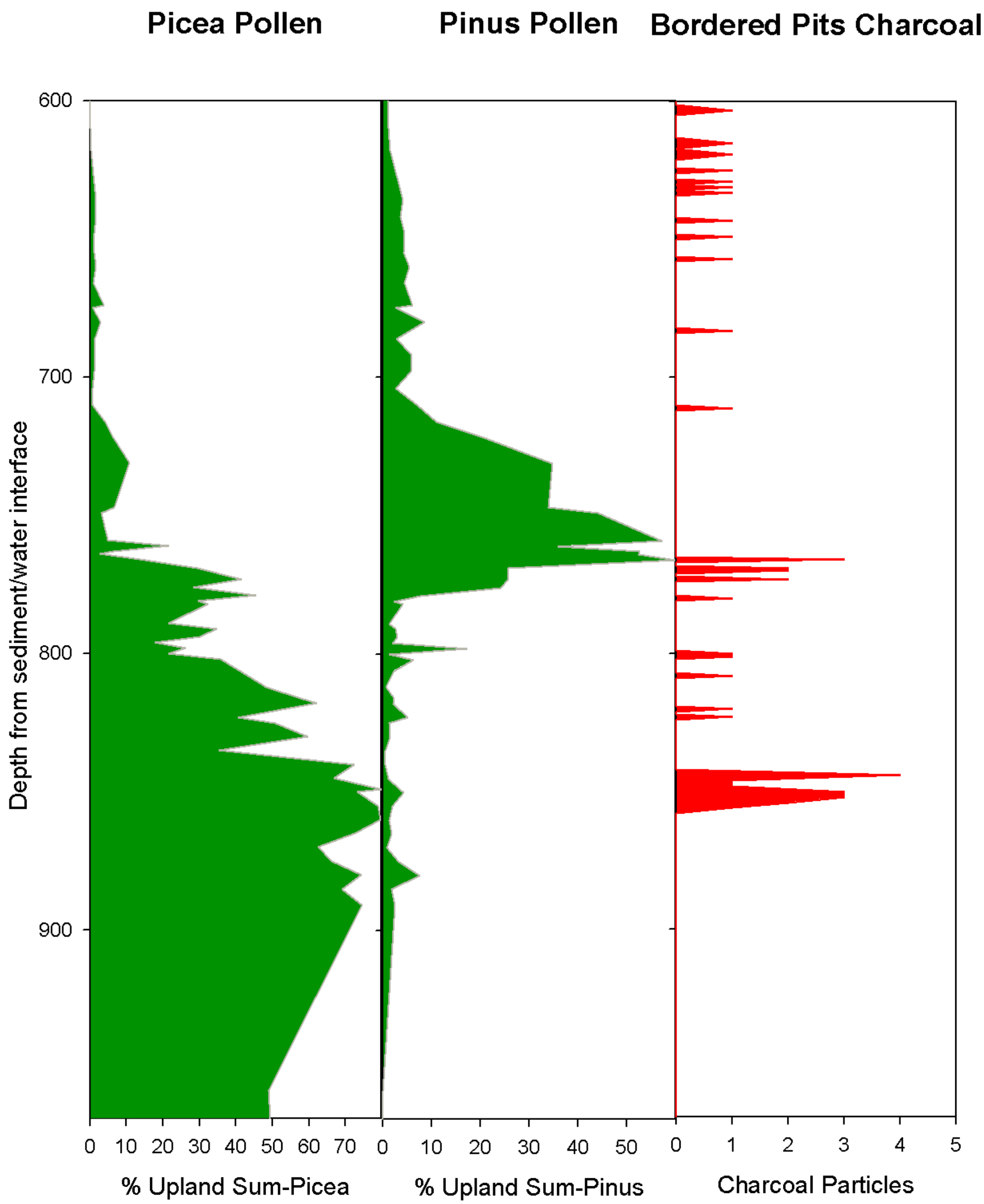


Figure 8: This figure compares bordered pit charcoal with the percent pollen abundances for two conifer tree taxa, *Picea* (spruce) and *Pinus* (pine). Bordered pit charcoal comes from burned conifers, and the peaks in bordered pit charcoal coincide with peaks in spruce and pine.

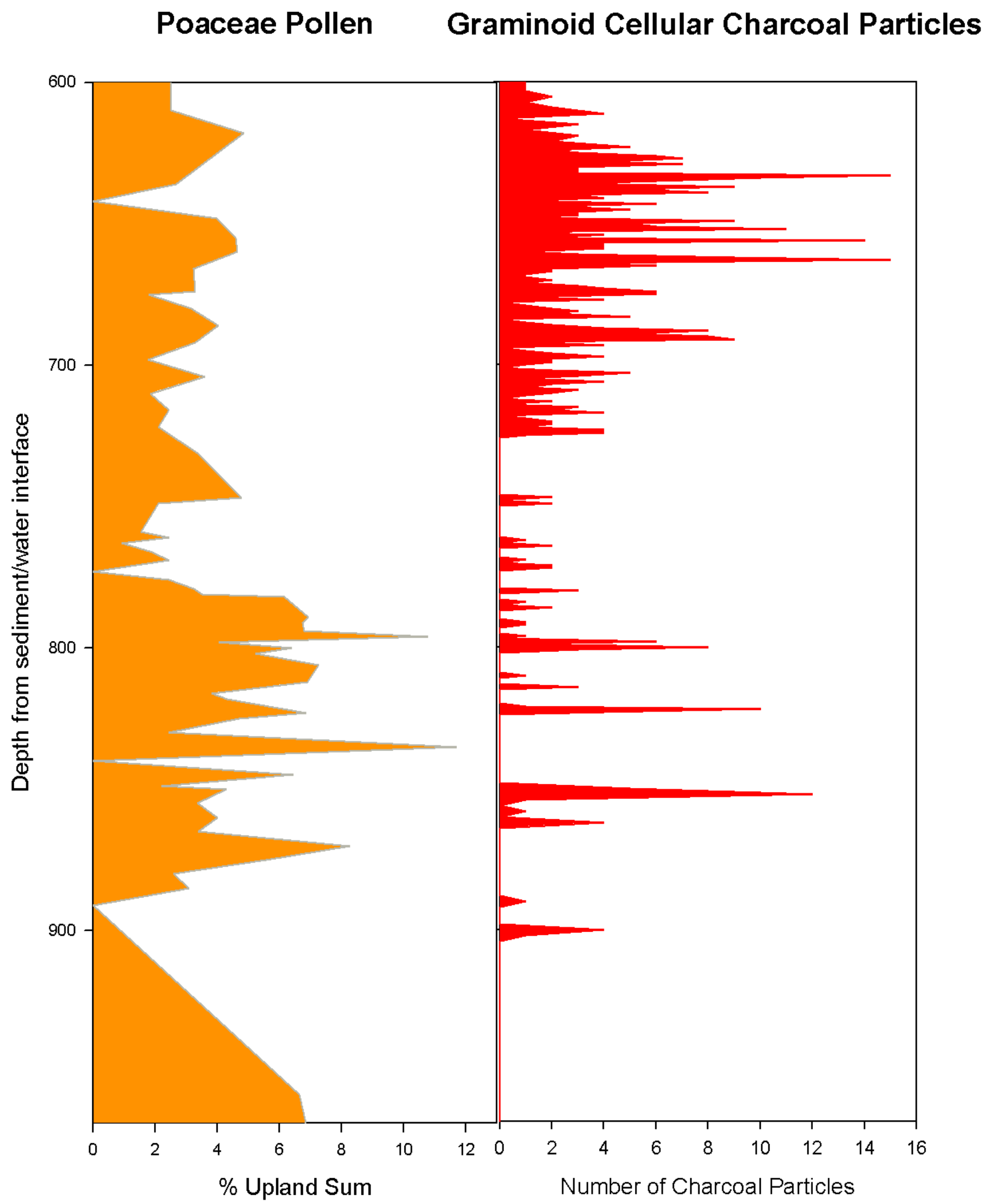


Figure 9: Figure 9 compares graminoid cellular charcoal particles with *Poaceae* (grass) pollen. Graminoid cellular charcoal indicates that grasses were burned. The charcoal peaks and the *Poaceae* pollen peaks do not usually occur simultaneously. It is possible that directly after fire occurred, grass regenerated and became more abundant.

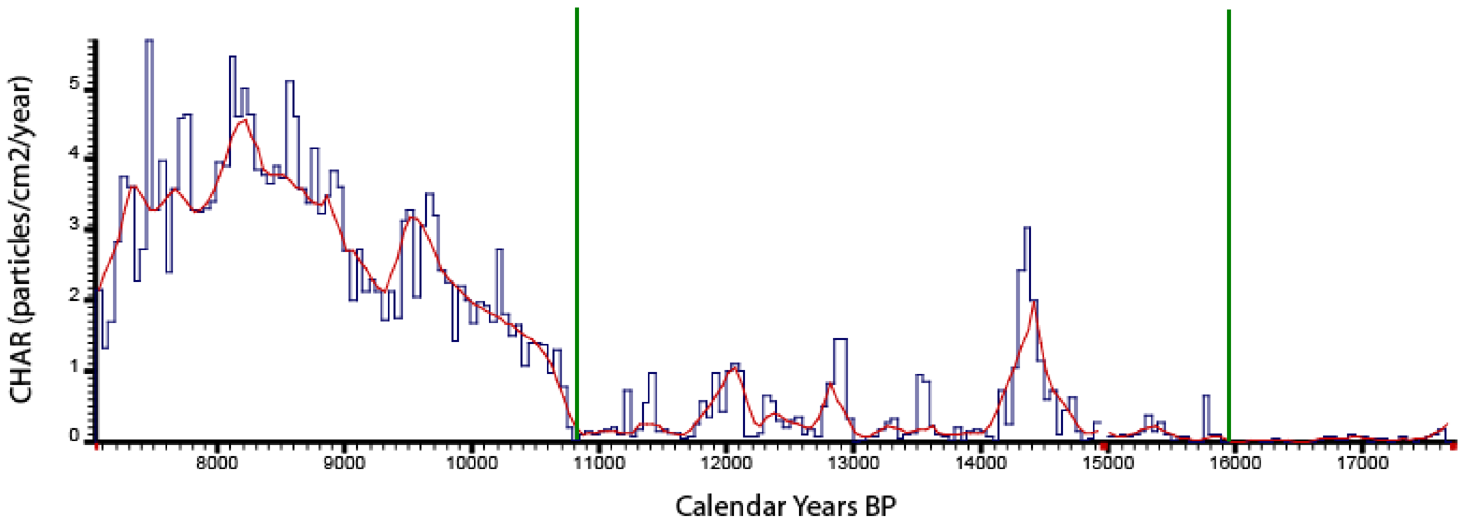
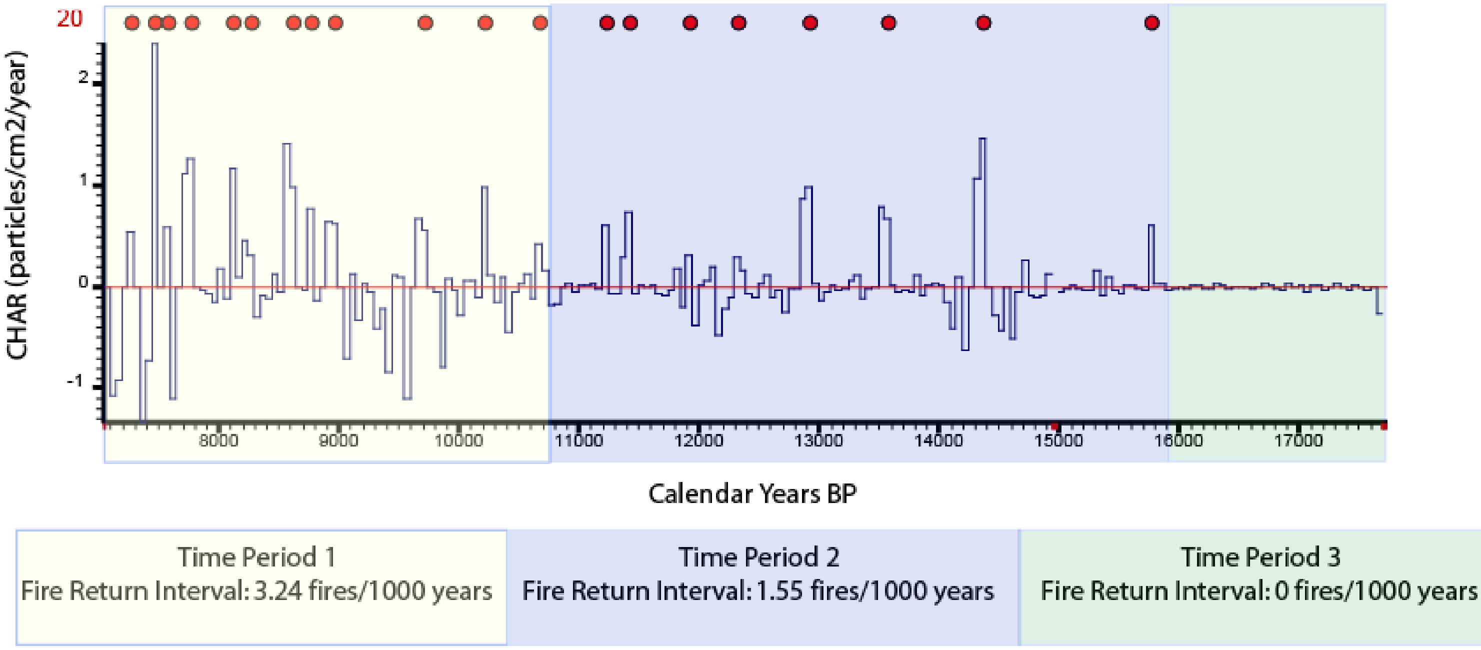


Figure 10: This figure shows the Appleman Lake charcoal record expressed as the charcoal accumulation rate (CHAR) versus time (calendar years Before Present). The blue line is the CHAR value for each sample, calculated by interpolating the raw counts in Figure 4 to a 50-year time step. The red line is the background level of CHAR, determined by applying a locally-weighted moving average to the record, with a window of 250 years. Three time periods are evident in the record (time periods are divided by the green lines in the figure above). In the third time period, from 17,600 to 15,900 cal yr BP, background CHAR does not exceed 0.3 particles/cm^2/yr. From 15,900 to 10,800 cal yr BP, background level drastically increases, reaching a maximum of 2 particles/cm^2/yr. In first time period, from 10,800 to 7,100 cal yr BP, the background CHAR drastically increases, reaching 4.5 particles/cm^2/yr. A high background level indicates high fuel load and biomass available for burning. Based upon the dates for each time period, the third time period is characterized as the late glacial, the second is the late glacial/early Holocene transition, and the first is the early Holocene. This plot was generated using CHARSTER.



<u>Figure 11:</u> Figure 11 shows the peaks component of the charcoal record with a difference threshold value set at 0.3 CHAR. The red line is the background level (a straightened version of the red line in Figure 10), and all peaks are shown as high-frequency deviations from the background line. Any peak that is 0.3 CHAR above the background level is counted as a fire event. In the third period (the late glacial period) there appears to be no fire events. The second time period (the transitional period) has 8 fire events. In the first time period (the early Holocene) there are 12 inferred fire events. The peak at 12,900 cal yr BP could correspond to the fires hypothesized to result from the Younger Dryas extraterrestrial event (Firestone et al. 2007). The boundary in almost all of the cores in Firestone et al. (2007) contains increased charcoal levels at ca. 12,900 cal yr BP, and the Appleman Lake core shows this signal as well. This plot was generated using CHARSTER.

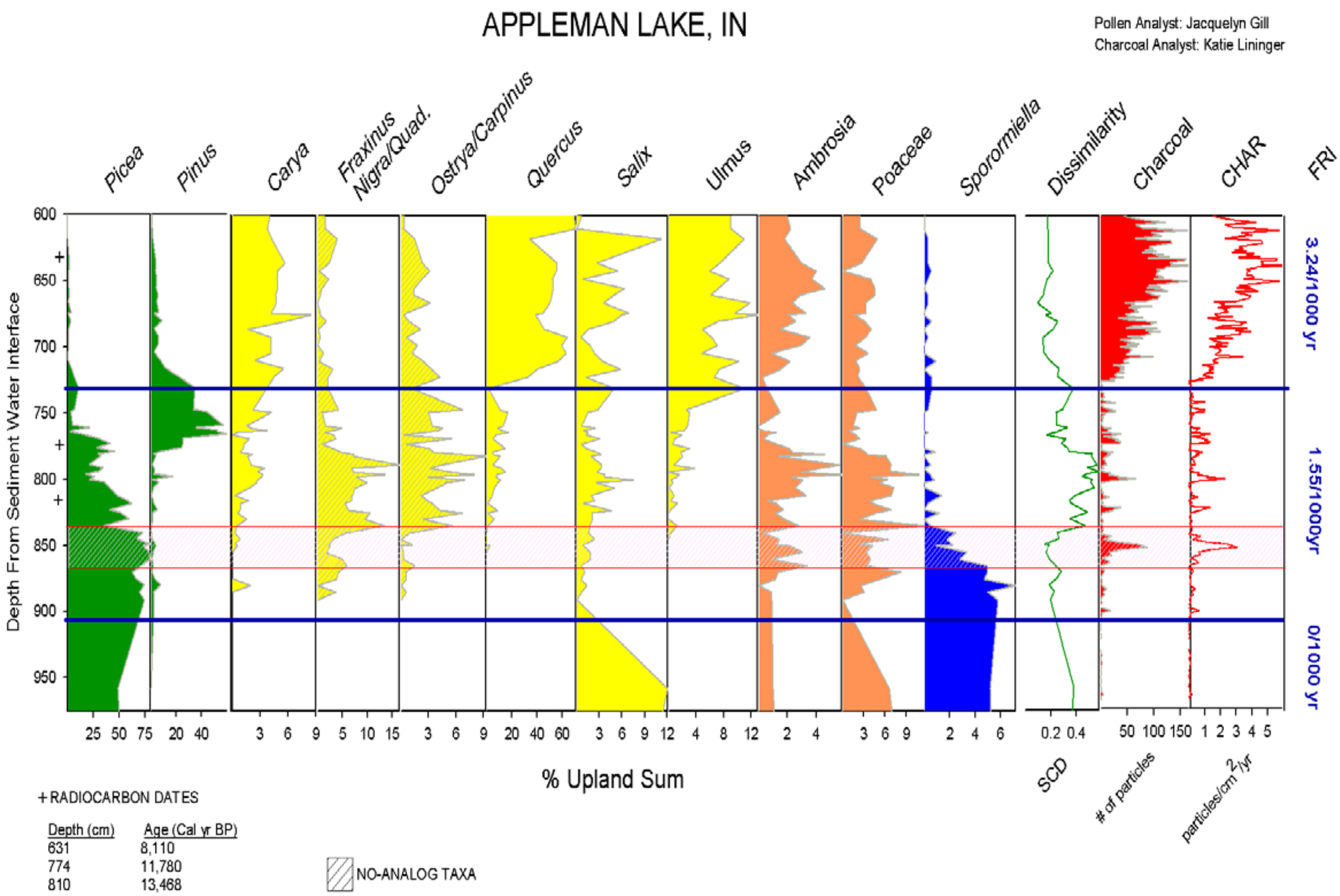


Figure 12: This figure synthesizes the charcoal data from this thesis with the *Sporormiella*, pollen and pollen-dissimilarity data (Gill 2007) for the Appleman Lake core. The three time periods of the record are divided by the blue lines, and the fire return intervals are listed on the right hand side of the figure. The late glacial period (968-905cm depth) is characterized by no inferred fire events, a *Picea* (spruce) dominated landscape, and the presence of megafauna indicated by the >2% level of *Sporormiella*. During the transitional period (905-725cm depth), fire activity increases, no-analogue vegetation assemblages appear (indicated by high dissimilarity), spruce declines and the megafauna become extinct (inferred by the decrease of *Sporormiella* below 2%). The fire event at 850cm depth bracketed by the two light red lines could have been caused by the arrival of humans, or a fire event associated with an increase in fuel load following the local decline of the megafauna. The early Holocene period (725-600cm depth) shows an increase in *Quercus* (oak) pollen and other deciduous taxa. Fire frequency and background level also increase during this period. Climatic warming most likely caused the shift to the early Holocene vegetation and fire regime.

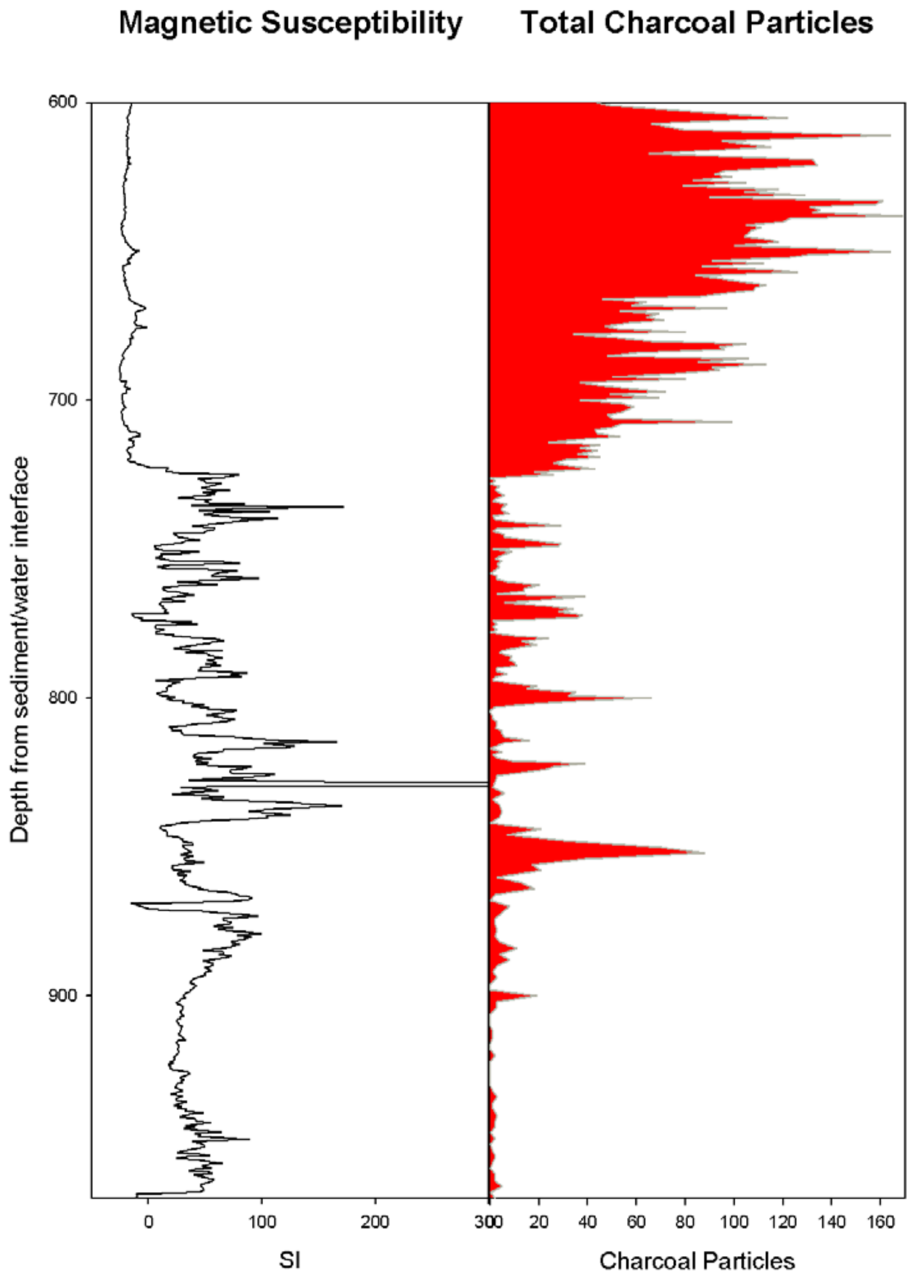


Figure 13: Figure 13 compares the raw charcoal record and the magnetic susceptibility record for Appleman Lake. The large charcoal peak at 850cm depth does not directly follow a peak in magnetic susceptibility, indicating that the charcoal peak was not a result of an erosional event. The charcoal peak at 850cm was most likely caused by an ecological signal, such as megafaunal extinction, climatic shifts, or human arrival.