AN 8,000-YEAR FIRE AND VEGETATION HISTORY OF AN OAK SAVANNA IN EAST CENTRAL MINNESOTA

by

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ABSTRACT

Oak savanna, a transitional ecosystem between open prairie and dense oak forest, was once widespread in central and southeastern Minnesota. As Europeans settled the area during the mid-1800s AD, much of the oak savanna ecosystem was destroyed through clearing for homesteads and agriculture, or converted into forest as a result of fire suppression practices. Since the middle of the 20th century, efforts to restore and preserve this now greatly reduced ecosystem have increased, and often include the reintroduction of fire. Though fire is known to serve an important role within oak savannas, there are currently few paleoecological studies which address issues of fire frequency, ecology, or natural range of variability on timescales longer than the last century. This research presents a fire and vegetation history spanning the last ~ 8000 years, using lake sediments collected on the Sherburne National Wildlife Refuge (SNWR) in east central Minnesota. The pollen record indicates a transition from woodland to prairie vegetation ca. 7500 cal yr BP as the climate became warmer and drier, followed by a gradual transition to oak savanna as conditions became wetter beginning ca. 6500 cal yr BP. The destruction of the oak savanna upon Euro-American arrival to the region is evident in the later part of the record, followed by restoration upon the establishment of the refuge. Fire activity appears to be driven by vegetation fuel loads, and ultimately climate, and is highest at periods in the record with greater tree and fewer herb taxa. These data provide insight into the natural fire regime, development,

destruction, and recovery of the oak savanna and information on the specific disturbance history of SNWR, and will be used to inform land management considerations when prescribing fire and developing restoration objectives for the refuge.

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INTRODUCTION

Paleoecological studies can provide invaluable information for the development of land management plans focusing on ecosystem restoration. Reconstructions of ecological conditions predating periods of intense human alteration can serve as targets for restoration efforts, and offer insight into ecosystem responses under a variety of climatic conditions (Lynch and Saltonstall, 2002; Foster and Motzkin, 2003; Faison et al., 2006; Oswald et al., 2010). For example, lake sediments have recently been used to determine whether widespread bark beetle outbreaks currently affecting conifer forests in the western United States are unprecedented over the Holocene (Morris et al., 2010). This long-term context for disturbance events provides land managers with a more accurate perception of the natural variability of bark beetle outbreaks in western forests.

Additionally, paleoecological reconstructions can help managers determine whether restoration of a certain set of conditions is a realistic goal for their area. For some sites, analog periods may not exist. Climate projections estimate an overall warming of up to 4˚C over the next hundred years (IPCC, 2007). Warming temperatures, along with the introduction of invasive species to many areas, have resulted in many novel ecosystems, for which restoration to a historic standard may not be possible. Paleoecological reconstructions can help managers to set realistic restoration goals, including restoration to a historic standard or, when such restoration is not feasible, focusing on restoration of ecological goods and services, such as wildlife habitat, timber or hiking trails (Jackson and Hobbs, 2010).

A great deal of paleoecological research has been conducted in midwestern North America. In particular, studies have focused on the sequence of glacial advances and retreats at the end of the last glacial period (Cushing, 1967), changes in climate and/or vegetation from deglaciation to present (Fries, 1962; Wright et al., 1963; McAndrews, 1968; Grimm, 1983; Keen and Shane, 1990; Laird et al., 1996; Anderson, 1998; Camill et al., 2003; Wright et al., 2004; Nelson and Hu, 2008; Williams et al., 2009; Williams et al., 2010), the movement and composition of the prairie-forest border throughout the Holocene (McAndrews, 1968; Grimm, 1983; Griffin, 1994; Camill et al., 2003; Nelson and Hu, 2008; Williams et al., 2009) and recently, studies have included analyses of fire activity, and driving factors among climate, fire and vegetation (Clark, 1990; Camill et al., 2003; Umbanhowar, 2004; Lynch et al., 2006; Nelson and Hu, 2008; Shuman et al., 2009; Long et al., 2011). These paleoecological reconstructions provide useful general information to land managers in the region; however, these managers can greatly benefit from paleoecological reconstructions which are focused on specific, management-driven research questions and conducted within the borders of their area of interest. This is especially important for managers interested in the possibility of restoration to a historic target.

This study seeks to reconstruct the development and disturbance history of an oak savanna ecosystem within the Sherburne National Wildlife Refuge (SNWR) in east-central Minnesota, with the intent of determining past ecological conditions to be used as a reference for developing and assessing restoration strategies.

Oak Savanna

Though the exact definition of oak savanna varies greatly, in general, oak savanna is a transitional vegetation type, made up of a prairie-like understory and dispersed, open grown oak trees (Scholes and Archer, 1997), which forms an ecotone between prairies and forests (Anderson, 1998). This vegetation type is typically described in terms of percent canopy cover or trees per unit area, and can range from as little as 10 % canopy cover to as much as 80 % (Anderson et al., 1999). This range of definition stems from the fact that savannas are transitional vegetation types. In areas near open prairie, a savanna will include very few trees, while tree density will increase nearer to forests.

Oak savanna was once widespread in midwestern North America, but was greatly reduced upon Euro-American settlement of the region, in the mid-1800s AD. Using official land survey records developed as Euro-Americans began to populate the Midwest, Marschner (1974) constructed a detailed map describing the vegetation of Minnesota prior to 1840 AD. From this map, Kratz and Jensen (1983) estimated that approximately 2,200,000 hectares (ha) of oak savanna existed in the state prior to Euro-American settlement. In contrast, surveys conducted in 1985 revealed that only 500 ha of healthy, intact oak savanna remained in Minnesota (Nuzzo, 1985). Surrounding states in the Midwest have experienced similar drastic reductions in oak savanna, with only about 0.02% of the presettlement communities remaining (Nuzzo, 1985). In total, oak savanna in the Midwest is estimated to have been reduced from 11,000,000 to 13,000,000 ha prior to settlement to a mere 2,607 ha in 1985 AD (Nuzzo, 1985).

Both clearing and overgrowth led to the loss of oak savanna in the Midwest (Wolf, 2004). Large-scale clearing of oak trees for agriculture and homesteads led to the loss of great swaths of oak savanna. Many of the remaining patches were then overgrown as a result of fire suppression practices. Oak trees, especially bur oak, are highly resistant to fire and can survive (and actually require) frequent, low intensity burns, which clear the understory and maintain prairie vegetation. In the absence of fire, oak savanna has been recorded to develop into dense woodland in as little as a few decades (Wolf, 2004).

Recently, many land management strategies have included the reintroduction of fire to remnant oak savannas in an attempt to restore and maintain this ecosystem (Will-Wolf and Stearns, 1999). Peterson and Reich (2001) analyzed the stand structure and composition of 14 study plots within the Cedar Creek Natural History Area on the Anoka Sand Plains in central Minnesota in order to determine optimal burning strategies for oak savanna maintenance. Each plot was burned from 0 – 26 times over a period of 32 years. The authors recommended mechanical thinning of densely overgrown patches, followed by prescribed burning every 1 to 3 years in order to maintain the openness of oak savannas.

Modern ecological studies provide useful information for prescribed burning strategies. However, they are not necessarily representative of conditions predating Euro-American influence. Additionally, composition, structure, and fire activity of oak savannas can vary greatly depending on local factors such as topography, soil quality, and climate (Leitner et al., 1991). Therefore, land managers can greatly benefit from site-specific reconstructions of vegetation and fire activity predating Euro-American influence when developing restoration strategies targeting conditions prior to intense human alteration.

STUDY AREA

Location

Sherburne National Wildlife Refuge (SNWR) is a 30,700 acre refuge located in east central Minnesota, approximately 50 miles northwest of Minneapolis/St. Paul (45˚ 28.115'N, 93˚ 45.405'W) (Figure 1 – site map). The refuge lies within the Anoka Sand Plains, a region of well-drained, sandy soil developed from glacial outwash deposited at the end of the last glaciation. A gentle topography exists due to underlying dunes which formed in the middle Holocene during a period of high aridity and low vegetation coverage beginning ca. 8000 cal yr BP (Keen, 1990).

Prior to the establishment of the refuge in 1965, four natural lakes existed within the current SNWR boundaries. A primary goal of the refuge managers has been to develop and maintain wetland habitat for waterfowl. To meet this goal, water has been diverted from the St. Francis River, which runs along the north and east edges of the refuge, in order to create additional wetlands or impoundments. Additionally, check dams have been installed to manipulate/maintain water levels throughout the year (www.fws.gov/midwest/sherburne).

The lake selected for this study, Johnson Slough, was chosen because it is one of the four natural lakes within the refuge, and it has not been modified by check dams. Additionally, Johnson Slough has no inlets and a relatively small surface area (approximately 287 x 1279 m) and is thus expected to contain sediments which record a fairly localized paleoecological signal (Jacobson and Bradshaw, 1981). This lake, like all lakes on the refuge, is shallow (approximately 1 m deep), flat bottomed and water levels are maintained by the water table. Johnson Slough contains a high level of aquatic vegetation and is ringed with *Typha spp.*(cattails), which give way to oak savanna as the topography gently rises away from the lake.

Vegetation

Vegetation within SNWR varies across wetland, big woods and oak savanna habitats. Surveys of vegetation have been ongoing within the refuge since 1970, and a detailed plant list can be found on the refuge's website (www.fws.gov/midwest/sherburne). Approximately one third of the refuge consists of manmade or natural wetlands, areas currently dominated by *Typha spp.* Big Woods vegetation, which consists predominantly of *Ulmus spp.* (elm), *Acer spp.* (maple), *Tilia americana* (American basswood), and *Ostra virginiana* (ironwood) (Grimm, 1983), is found near the northern border of the refuge and oak savanna currently exists in the upland areas.

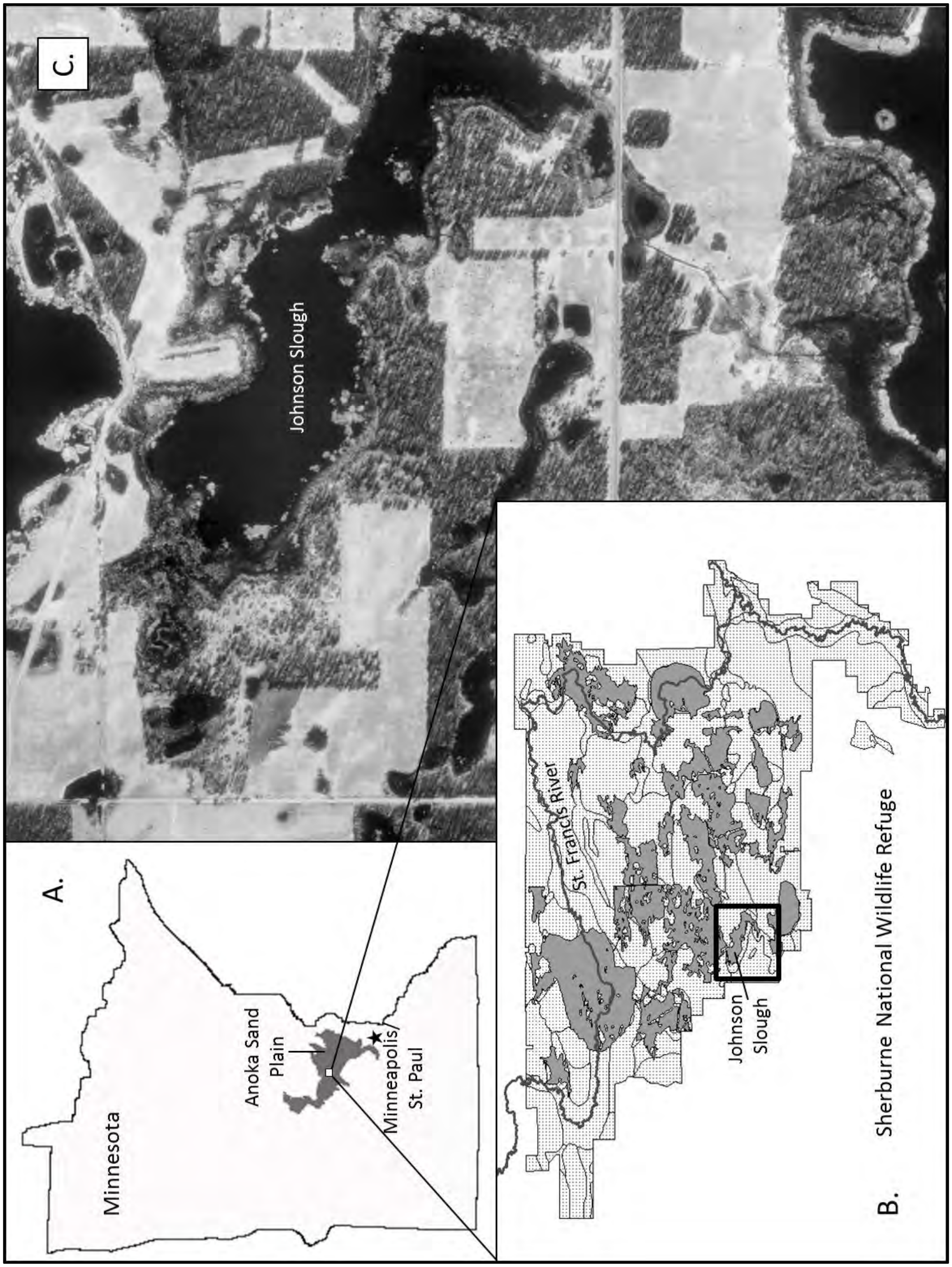
A tree ring study which established the age structure of remnant oak savanna within the Santiago Research and Natural Area in the west central region of the refuge revealed that overall, forest density appears to have increased within the refuge since about the 1940s (Kipfmueller, 2009). *Quercus ellipsiodalis* (northern pin oak) was found to be the most abundant tree, followed by *Q. macrocarpa* (bur oak), which represented some of the oldest trees on the refuge, and may have dominated prior to Euro-American settlement. *Populus tremuloides* (quaking aspen) was also abundant, and the dominant seedling was *Corylus americana* (American hazel). The increased abundance of *C.*

americana over the span of the age structure may be a result of the timing of prescribed burning in the spring (Kipfmueller, 2009).

Climate

Central Minnesota currently experiences a continental climate, with cold winters and warm, humid summers. Continental polar air masses dominate in the winter, causing cold, stable conditions for much of the season. Beginning in the spring and continuing during the summer and into the fall, the maritime tropical Gulf/Atlantic air mass brings warm, moist air into the region from the south, resulting in thunderstorms and increased precipitation. Mean monthly temperature and precipitation data spanning the years 1895 to 2010 AD were obtained from the US Climate Division Dataset (state 21, zone 5 – central, www.esrl.noaa.gov) and are plotted in Figure 2. Annual precipitation averages 27 inches, with maximum precipitation occurring in June. Mean annual temperature is 42˚F, mean January 10 ˚F, and mean July 71˚F.

Figure 1. Map of Johnson Slough, Sherburne National Wildlife Refuge (SNWR), Minnesota. A. Anoka Sand Plains (grey) within Minnesota. White box within the Anoka Sand Plains indicates SNWR (modified from www.dnr.state.mn.us/ecs/222Mc/index). B. Waterways within SNWR, including impoundments and the St. Francis River. Johnson Slough is indicated by a black box. C. Johnson Slough arial photograph.


A.
Minnesota
Anoka Sand Plain
Minneapolis/ St. Paul
B.
St. Francis River
Johnson Slough
Sherburne National Wildlife Refuge
C.
Johnson Slough

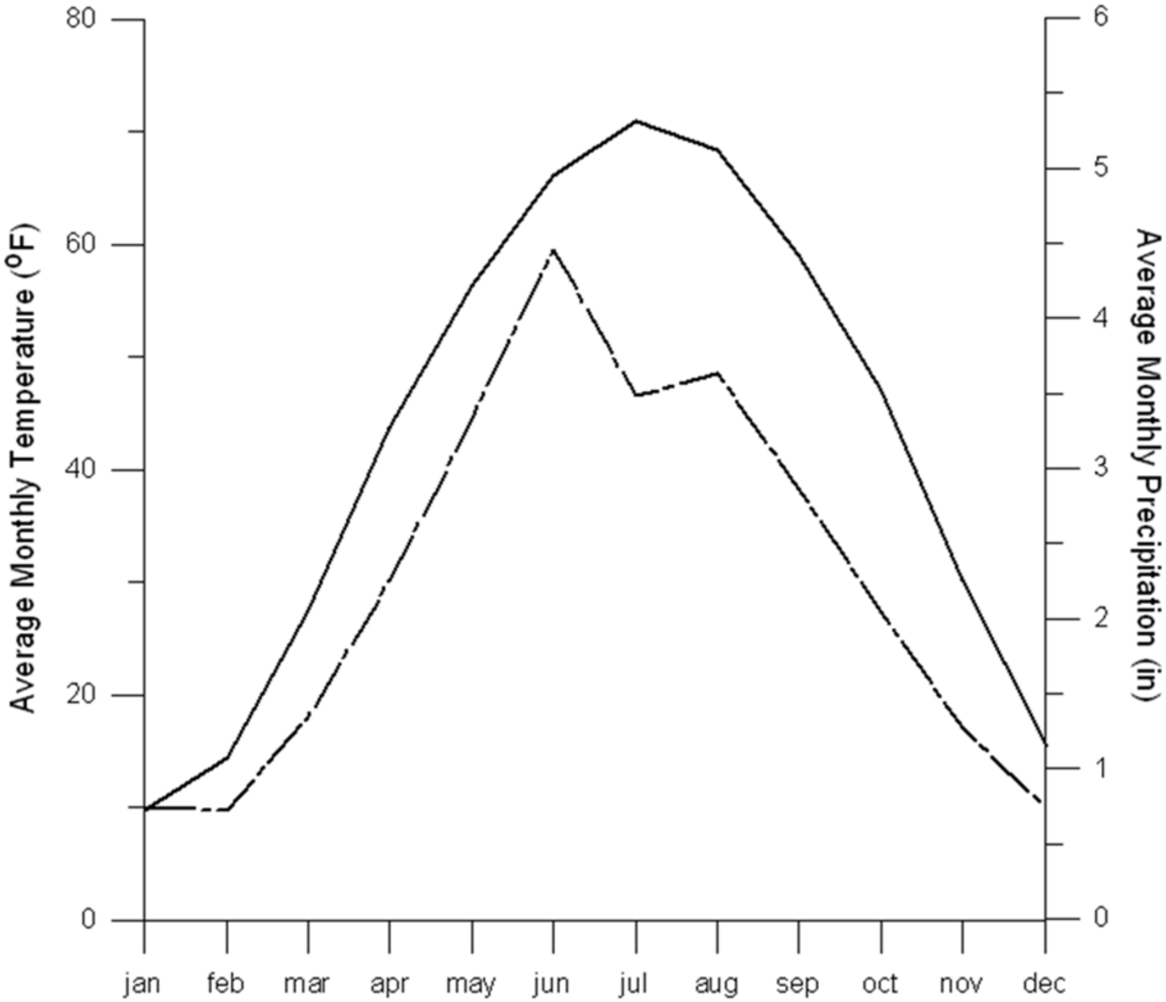


Figure 2. Climagraph for central Minnesota. Average monthly temperature (solid line) and precipitation (dashed line) from 1895 to 2010 (state 21, zone 5, www.esrl.noaa.gov).

METHODS

A multiproxy analysis of sediments collected from Johnson Slough was used to reconstruct the development and disturbance history of the oak savanna within SNWR. Sediment analysis techniques included the use of fossil pollen assemblages as proxies for vegetation and climate changes, and macroscopic charcoal as a proxy for fire activity. Additionally, the magnetic susceptibility of sediments aided in further analysis of disturbance events, and the organic and carbonate composition of sediments were used to determine changes in in-lake productivity. The following subsections describe each of these methods in detail.

Fieldwork

Sediment cores were collected from Johnson Slough from the platform of a modified AIRE Cataraft. Water depth was determined using a Zebco fish finder, and cores were taken from near the center of the lake, where vegetation was minimal (45˚ 28.115'N, 93˚ 45.405'W). A Klein short coring device fixed with a 4" diameter Lexan tube was used to collect the top 42 cm of sediment, which were extruded on site in 1 cm increments in order to capture the sediment-water interface. A modified Livingstone coring device was then used to collect the remaining sediment in approximately 1 m sections. Each section was wrapped in plastic and stored in AMS split tubes for transport to the Limnological Research Center's National Lacustrine Core Facility (LacCore) at the University of Minnesota, where an initial core description was conducted. The total sediment collected for analysis was 196 cm in depth, with 6 cm of overlap between the short and long cores. An additional long core was also retrieved and is currently archived at LacCore.

Magnetic Susceptibility

The initial core description conducted at LacCore included high resolution imaging, and measurements of magnetic susceptibility. These data can been used to identify changes in depositional and erosional activity, including eolian events and fires. Each section of the long cores was first run through a Geotek Multisensor Core Logger to determine magnetic susceptibility at 1 cm intervals. Cores were then split lengthwise with fishing line and imaged using a digital line scanner. High-resolution point-sensor magnetic susceptibility was then measured at 0.5 cm increments using a Geotek XYZ core scanner. The magnetic susceptibility of the surface sediments was measured separately, at 1 cm resolution, at the University of Utah using a Bartington Multisus 2 magnetic susceptibility meter.

Dating

In order to develop an age model to be used for the interpretation of sediment accumulation rates, four radiocarbon dates were obtained for the length of the cores, one from the bottom of the short core, and three spanning the length of the long cores. For each sample, four cubic centimeters (cm^3) of sediment was treated with a series of non-organic chemical rinses to isolate pollen, following the Schulze technique (Kapp et al., 2000). These samples were then suspended in distilled water and shipped to the Center for Applied Isotope Studies (CAIS) in Atlanta, Georgia for Accelerator Mass

Spectrometry (AMS) radiocarbon dating. Radiocarbon dates were calibrated using Calib version 6.0.

In addition, pollen analysis was expected to reveal a rise in *Ambrosia* pollen coincident with Euro-American settlement of the region at approximately 1860 AD which would be used as a stratigraphic marker. *Ambrosia*, or ragweed, is an herbaceous species which thrives in disturbed areas. Its increase with the arrival of Euro-Americans in the Midwest in the mid-1860s is well documented in pollen records, and widely used as an age marker in sediment cores (Van Zant et al., 1979; Umbanhowar, 2004). Alternatively, an increase in *Humulus/Cannabis* pollen has been used in some records as a similar stratigraphic marker for this period, as it indicates the introduction of *Cannabis sativa* for cultivation (Van Zant et al., 1979). However, neither a rise in *Ambrosia* nor a rise in *Humulus/Cannabis* pollen was clear within the pollen record of Johnson Slough and additional dating of the upper sediments was necessary; therefore, plutonium dating of the surface sediments was conducted.

Both the short and long cores were analyzed by $^{239+240}$Pu dating to identify the period of nuclear testing corresponding to 1963 AD (Ketterer et al., 2004; Ketterer and Szechenyi, 2008). The short core was analyzed at 1 cm resolution for the top 18 cm, then at 2 cm resolution for the remaining 24 cm. The long core was analyzed at 2-4 cm resolution to a depth of 60 cm, and approximately every 10 cm to a depth of 160 cm. Identification of $^{239+240}$Pu in sediment cores has recently been used as an alternative ^{137}Cs as an indicator of nuclear testing. It is possible to identify $^{239+240}$Pu through inductively coupled plasma mass spectroscopy, a method which is both less expensive and less time consuming than the gamma spectrometry method required for ^{137}Cs dating (Ketterer et al., 2004).

Charcoal Analysis

In order to identify periods of greater and lesser fire activity within the refuge, macroscopic charcoal analysis was conducted at 1 cm contiguous increments throughout the cores. Macroscopic charcoal best represents local fire activity, because it does not travel great distances from its source (Clark, 1988; Whitlock and Millspaugh, 1996; Gardner and Whitlock, 2001). For each sample, 1-2 cm^3 of sediment was placed in a whirl pak bag with a small amount of sodium hexametaphosphate as a disaggregating solution. Each sample was then rinsed through 250 and 125 micron nested sieves and transferred to gridded petri dishes. Charcoal particles were counted using a dissecting microscope at 20-32x magnification and concentration (particles cm^{-3}) was calculated. Statistical analysis of charcoal counts was conducted for the early to middle Holocene using CHAR Analysis software (Higuera, 2010). The record was first resampled to a median resolution of 43 years, and charcoal accumulation rate (CHAR; particles cm^{-2} yr^{-1}) was calculated. A lowess smoother which was robust to outliers was applied using a window of 750 years to determine background charcoal levels. Peaks were then identified using a locally defined threshold with a Gaussian mixture model to determine noise distribution, and the fire return interval was smoothed over 1250 years.

Pollen Analysis

Vegetation history was reconstructed by examining pollen assemblages at intervals ranging from 1 to 8 cm in varying resolutions, as seen in Table 1. Pollen was isolated from 1 cm^3 of sediment following techniques developed by Faegri et al. (1989). Pollen samples were then mounted in silicon oil on glass slides and examined with a light microscope at 400x magnification, and identified using dichotomous keys (e.g., McAndrews et al., 1973; Moore et al., 1991; Kapp et al., 2000) and modern reference slides. The addition of a 1 ml aliquot of a microsphere spike allowed for pollen influx (grains cm^{-2} yr^{-1}) to be calculated for each sample. A minimum of 300 pollen grains were counted for each sample, and Tilia software was used to develop percentage and influx diagrams. Terrestrial taxa percentages were determined using a pollen sum which included all terrestrial pollen types but excluded aquatic taxa, while aquatic percentages were determined using a pollen sum which included both terrestrial and aquatic pollen types.

Loss on Ignition

The organic and carbonate content of sediments was used to identify changes in in-lake productivity throughout the Holocene. Organic and carbonate sediment composition was determined by loss on ignition (LOI), which was conducted at contiguous 1 cm increments throughout the cores. For each sample, 1 cm^3 of sediment was first dried in an oven at 100˚C for 24 hours. Following drying, samples underwent a series of 2 hour burns in a muffle furnace at 550˚C and 900˚C to determine the percentage of the sample composed of organics and carbonates, respectively. Composition was determined by weight, following Dean (1974).

Table 1. Pollen sampling strategy.

Top depth (cm)	Bottom depth (cm)	Approximate top age	Approximate bottom age	Average sample interval (cm)	Average sample resolution (yr)
0	12	2010 AD	1978 AD	1	2.6
12	44	1978 AD	no age model	2	no age model
44	69	no age model	2600 cal yr BP	4	no age model
69	196	2600 cal yr BP	8100 cal yr BP	8	44

RESULTS

Chronology

Plutonium Dating

Plutonium measurements for the short core ranged from 1.52 to 2.46 Bq/kg from 0 – 15 cm, with an average of 1.88 Bq/kg (Figure 3). Values then increased to a peak of 2.93 Bq/kg at 18 cm. This peak, the greatest of the record, was assigned the date of 1963 AD. After 18 cm, values then dropped to 0.06 Bq/kg at 30 cm, and remained low until approximately 38 cm, when values increased sharply again, reaching a peak of 1.72 at 40 cm.

Plutonium measurements for the top of the long core were high, with a value of 2.51 Bq/kg at 36 cm. Values then dropped slightly before rising to a peak of 1.87 Bq/kg at 40 cm. Plutonium measurements then fell to undetectable levels by 52 cm, and remained undetectable throughout the remainder of the core. The highest value of 2.51 Bq/kg at the top of the long core is likely due to compression of the top few centimeters which occurred when the cores were split lengthwise. Because an unknown amount of compression occurred for this sample during sampling, the plutonium measurement is unreliable and unlikely to be as high as it appears. This sample was discarded, and alignment of the short and long cores was accomplished by matching the lower plutonium peak (Figure 3). This alignment resulted in an overlap between the cores of 6 cm, an amount 4 cm less than that estimated in the field, with a total sediment recovery length of 196 cm.

Radiocarbon Dating

Four AMS radiocarbon dates were obtained, with average calibrated dates ranging from 2076 cal yr BP at 44 cm to 7734 cal yr BP at 184 cm (Table 2).

Age Model

Two separate age models were developed, one for the historic period (ca*.* 1963 to 2010 AD), and another for the early to middle Holocene (ca*.* 8000 to 2600 cal yr BP). Due to agricultural disturbance (see discussion), an age model was not developed for the period from ca. 2600 cal yr BP to 1963 AD, and all analyses of this period are evaluated by depth, rather than by age (Figure 4).

The age model for the historic period was determined using linear interpolation between the top centimeter of sediment, which was assigned the date of 2010 AD (the year sediments were collected), and the plutonium peak at 18 cm, corresponding to 1963 AD. A constant deposition rate of 2.6 years cm^{-1} was calculated for this period.

The age model spanning the lower portion of the record was developed using a 2nd-order polynomial fitted to the oldest three radiocarbon dates. The youngest date of 2075 cal yr BP at 44 cm was not included in this age model, as it fell within the portion of the cores affect by agricultural disturbance. Deposition rate varies slightly throughout this period, ranging from approximately 62 yr cm^{-1} near the top, to approximately 27 yr cm^{-1} near the bottom, with an average of 45 yr cm^{-1}.

The lower section of the record was divided at 6500 cal yr BP into two zones, the early Holocene (ca. 8000 to 6500 cal yr BP) and the middle Holocene (ca. 6500 to 2600 cal yr BP). These zones were determined by constrained cluster analysis of terrestrial pollen assemblages using CONISS software (Figure 5; Grimm, 1987).

Magnetic Susceptibility

Historic Period (ca. 1963 AD to Present)

Magnetic susceptibility values in the historic period begin at a value of 9.3 SI at ca. 1963 AD, then decrease steadily to present, with the exception of two large peaks at ca. 1994 AD and ca. 2002 AD (Figure 6).

Disturbed Period (ca. 2600 cal yr BP to 1963 AD)

Magnetic susceptibility values within the period from ca. 2600 cal yr BP to ca. 1963 AD average 7.6 SI (Figure 7). The beginning of this period is marked by a large, stepwise increase in magnetic susceptibility at approximately 2600 cal yr BP (69 cm). Values then remain high, with several low deviations, until approximately 43 cm, when susceptibility gradually decreases to a minimum value of 2.7 SI, before rising again to 9.2 SI at 20 cm.

Middle Holocene (ca. 6500 to 2600 cal yr BP)

Throughout the middle Holocene, magnetic susceptibility of sediments varies greatly around a mean value of 1.75 SI (Figure 8). The highest peaks of this period occur prior to approximately 4700 cal yr BP, with the highest value (6.6 SI) for this period occurring at ca. 6000 cal yr BP. A minimum value of -0.3 SI occurs at ca. 4100 cal yr BP.

Early Holocene (ca. 8000 to 6500 cal yr BP)

The magnetic susceptibility of sediments is low in the early Holocene, with an average value of 2.7 SI (Figure 8). Susceptibility of sediments for this period is greatest prior to ca. 7300 cal yr BP, averaging 3.3 SI, and lowest after ca. 7700 cal yr BP, averaging 1.9 SI.

Charcoal

Statistical analysis of the charcoal record in the early and middle Holocene revealed that single fire peak detection for this record is inappropriate due to a low signal-to-noise index (Higuera, 2010). Therefore, results are reported based on charcoal accumulation rate (CHAR) and raw charcoal concentration values, and individual peaks within the record are not interpreted as single fires, but rather as fire episodes (Brunelle and Whitlock 2003).

Historic Period (ca. 1963 AD to Present)

Charcoal concentration within the historic period averages approximately 15.0 particles cm^{-3} (Figure 9), with an average CHAR of 4.24 particles cm^{-2} yr^{-1} (Figure 10). While large deviations are not apparent within this period, small peaks do occur approximately every 10 years (Figure 10).

Disturbed Period (ca. 2600 cal yr BP to 1963 AD)

Average charcoal concentration within the period of agricultural disturbance is 48 particles cm^{-3} (Figure 9). Low variability exists within this period, and no major deviations occur. CHAR was not calculated for this period due to the absence of an age model.

Middle Holocene (ca. 6500 to 2600 cal yr BP)

Average charcoal concentration within the middle Holocene is 88 particles cm^{-3} (Figure 9). CHAR averages 1.8 particles cm^{-2} yr^{-1} and seven peaks were detected within this period (Figure 11). All seven peaks occurred prior to ca. 3300 cal yr BP. CHAR for this period of high fire activity (ca. 6500 to 3300 cal yr BP) averages 1.9 particles cm^{-2} yr^{-1} (93 particles cm^{-3}). CHAR then decreases to an average of 1.1 particles cm^{-2} yr^{-1} (62 particles cm^{-3}) from ca. 3300 to 2600 cal yr BP, with no major fire episodes identified.

Early Holocene (ca. 8000 to 6500 cal yr BP)

Average charcoal concentration from ca. 8000 to 7700 cal yr BP is 45 particles cm^{-3} (Figure 9) and CHAR averages 1.6 particles cm^{-2} yr^{-1} (Figure 11). CHAR then drops to an average of 0.8 particles cm^{-2} yr^{-1} (26 particles cm^{-3}) for the remainder of the early Holocene. A total of four peaks were detected between ca. 8000 and 6500 cal yr BP, occurring at an interval of approximately 375 years (Figure 11).

Loss on Ignition

Historic Period (ca. 1963 AD to Present)

Both organic and carbonate percentages show little variability within the historic period (Figure 12). Organic content averages 54 %, while carbonate content averages 5 %.

Disturbed Period (ca. 2600 cal yr BP to 1963 AD)

Organic and carbonate content of sediments throughout the disturbed period also show little variability (Figure 13). Organic content averages 64 %, and carbonate content averages 1 %.

Middle Holocene (ca. 6500 to 2600 cal yr BP)

Throughout the middle Holocene organic content gradually rises, from a value of 23 % at ca. 6500 cal yr BP to a value of 66 % at ca. 2600 cal yr BP (Figure 14). Two distinct peaks occur at ca. 5400 and 5200 cal yr BP, and distinct dips occur at ca. 4400 cal yr BP and from approximately 3700 to 3300 cal yr BP.

Percent carbonate content decreases throughout the middle Holocene (Figure 14). Values begin at approximately 26 % at ca. 6500 cal yr BP and decrease to approximately 1 % by ca. 4200 cal yr BP. Carbonate content then remains near 1 % for the rest of the middle Holocene, with the exception of an increase to approximately 4 % from ca. 3750 to 3350 cal yr BP. Another peak is evident at ca. 4400 cal yr BP, and two prominent dips occur at ca. 5450 and 5200 cal yr BP.

Early Holocene (ca. 8000 to 6500 cal yr BP)

Percent organic content of sediments decreases very slightly from ca. 8000 to 6500 cal yr BP, averaging 25 % (Figure 14). Alternatively, carbonate content increases slightly over this period, but with a similar average of 24 % (Figure 14).

Pollen

While pollen influx (grains cm^{-2} yr^{-1}) was calculated for the historic and early-middle Holocene periods, comparison of these data was not appropriate due to the large difference in sediment accumulation rate between these periods. Additionally, pollen influx did not contribute additional insight regarding vegetation changes within these periods. Therefore, pollen analysis results are presented by percentage only.

Historic Period (ca. 1963 AD to Present)

Within the historic period, little variability exists in pollen percentages. Tree pollen averages 32.3 %, herbs 59.7 % and shrubs 3.5 % (Figure 15). A total of 19 tree taxa appear in the pollen record throughout this period. The majority of these taxa maintain pollen percentages lower than 10 %, with the exception of *Quercus*, which ranges from a low of 11.9 % in ca. 1968 AD to a high of 19.3 % in ca.1986 AD. *Pinus* is the second most abundant tree taxa, averaging 5.1 %. *Abies* occurs a single time in the historic period at ca. 1968 AD, with three instances of *Tilia*. Additionally, *Acer and Ulmus* increase slightly from ca.1968 AD toward present.

Herbaceous taxa are dominated by Poaceae, which averages 51.8 %. Each of the other 9 herbaceous taxa occurring in the historic period averages less than 5 %. *Ambrosia* makes up 3.7 % of the mean pollen percentage, other Asteraceae 2.2 % and Amaranthaceae 1.3 %. Additionally, *Zea mays* occurs twice in the historic period, at ca.1997 and 2005 AD.

The six shrub taxa found in this period are dominated by *Artemisia* 1.2 %, and Cupressaceae, which increases from 0.6 % at ca.1968 AD to 3.9 % at present. Finally, aquatic taxa within the historic period average 13.1 % and are dominated by Cyperaceae pollen (7.8 %).

Disturbed Period (ca. 2600 cal yr BP to 1963 AD)

Tree taxa within the disturbed period average 29.2 % of the pollen record, herbs 62.2 %, and shrubs 2.6 % (Figure 16). Twenty-two tree types are present, most of which average less than 5 % of the total pollen sum, with the exception of *Quercus*, with a mean of 12.3 % and *Pinus*, with a mean of 6.8 %. *Larix* c.f., *Castanea, Juglans, Platanus*, *Carya,* and Moraceae are each represented by five or fewer pollen grains within this period, and *Tilia* is absent altogether.

Fourteen herbaceous taxa occur within the disturbed period, eight of which are represented by five or fewer pollen grains. Poaceae averages 54.3 % of the total pollen sum, *Ambrosia* 2.5 %, other Asteraceae 3.2 %, and Amaranthaceae 1.2 %. Additionally, *Zea mays* occurs at depths of 20 and 32 cm.

Of the six shrub taxa found in this period, three are represented by five or fewer grains, *Artemisia* accounts for 1.9 % of the mean pollen sum, Cupressaceae 0.4 %, and Rosaceae 0.1 %. Aquatic taxa show little variability within this period, averaging 18.1 %, and are predominantly driven by Cyperaceae (14.0 %).

Middle Holocene (ca. 6500 to 2600 cal yr BP)

Throughout the middle Holocene, tree pollen averages 19.2 %, herbs 75.6 %, and shrubs 4.4 % (Figure 17). Of the 18 tree taxa present within this period, eight are represented by fewer than five pollen grains. *Quercus* pollen increases from 2.4 % at ca. 6500 cal yr BP, to 7.1% at ca. 3000 cal yr BP. *Pinus* taxa show little variability in the middle Holocene, averaging 4.7%, and *Ostrya*-type and *Tilia* pollen are absent from this period.

Of the 13 herbaceous taxa present, eight are represented by five or fewer pollen grains. In general, these taxa decrease over the middle Holocene, dominated by Poaceae, which makes up an average of 63.6 %. Amaranthaceae decreases from 5.4 % at ca. 6500 cal yr BP to 1.4 % at ca. 3000 cal yr BP, while *Ambrosia* and other Asteraceae remain fairly constant at approximately 1.7 % and 4.8 %, respectively.

Shrubs consist of only three taxa and show little variability within the middle Holocene. *Artemisia* increases slightly from 3.0 % at ca. 6500 cal yr BP to 3.6 % at ca. 3000 cal yr BP, Cupressaceae averages 0.8 %, and Rosaceae averages 0.5 %.

Aquatic taxa show significant variability within the middle Holocene, generally decreasing from 48.6 % at ca. 6500 cal yr BP to 15.7 % at ca. 3000 cal yr BP, and driven by Cyperaceae (39.7 % to 7.8 %). However, *Botryococcus* is seen to increase slightly throughout the middle Holocene.

Early Holocene (ca. 8000 to 6500 cal yr BP)

Throughout the early Holocene, tree pollen averages 12.2 %, herbs 80.1 %, and shrubs 7.3 % (Figure 17). In general, tree pollen decreases from ca. 8000 to 6500 cal yr BP. Sixteen tree taxa occur within this period, 12 of which are represented by five or fewer pollen grains. *Quercus* and *Pinus* are the dominant tree taxa in this period, averaging 3.2 % and 4.3 %, respectively. Additionally, *Ulmus* averages 1.3 % throughout the early Holocene.

Eight herbaceous taxa were detected within the early Holocene, four of which are represented by five or fewer pollen grains. In general, herbaceous taxa increase from ca. 8000 to 6500 cal yr BP, with Poaceae dominating at an average of 66.6 % of the total pollen sum. Amaranthaceae averages 7.6 %, *Ambrosia* decreases slightly from ca. 8000 to 6500 cal yr BP, and averages 2.8 %, and other Asteraceae average 2.7 %.

The predominant shrub taxon throughout the early Holocene is *Artemisia*, with a mean of 5.6 %. The other two taxa classified as shrubs during this period are Cupressaceae (0.9 %) and Rosaceae (0.8 %). Aquatic taxa average 22.9 % and generally increase from ca. 8000 to 6500 cal yr BP. This increase is driven by Cyperaceae, which averages 13.0 %, and *Typha*, which averages 2.7 %.

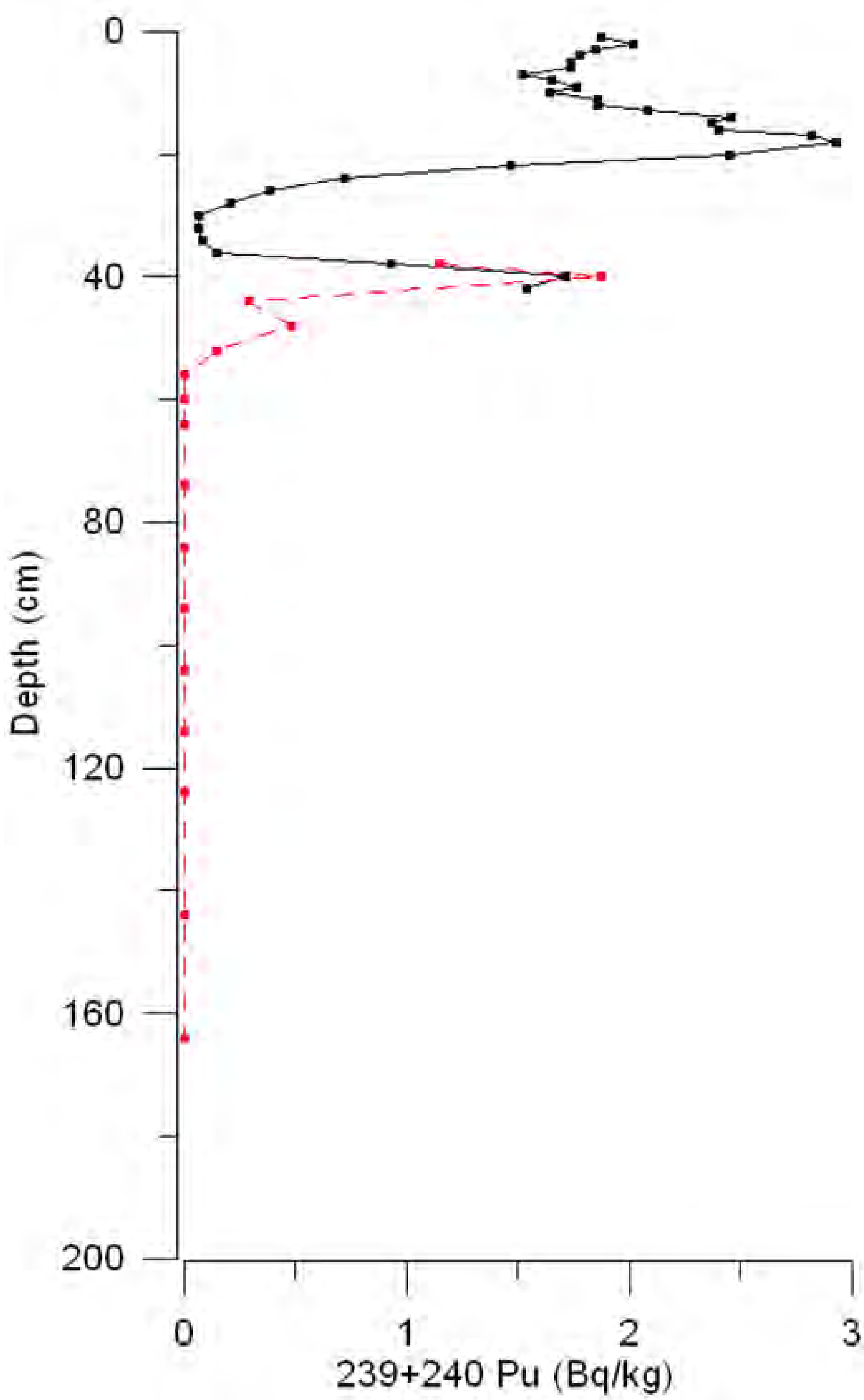


Figure 3. $^{239+240}$ Plutonium measurements for Johnson Slough. Solid black line indicates measurements from the short core, and dashed red line indicates measurements from the long core.

Table 2. AMS radiocarbon dates for Johnson Slough. Radiocarbon dates obtained from the Center for Applied Isotope Studies in Atlanta, Georgia, and calibrated using Calib version 6.0.

CAIS#/ UGAMS#	Depth (cm)	AMS ^{14}C dates (yr BP)	Calibrated dates (yr BP) midpoint (range)	Probability distribution	Dated material
06840	44	2110±25	2076 (2004 - 2147)	1.000	Pollen
06841	76	2890±25	3015 (2947 - 3082)	0.933	Pollen
8485	132	5060±25	3872 (3795 - 3949)	1.000	Pollen
06842	184	6900±30	7734 (7678 - 7789)	1.000	Pollen

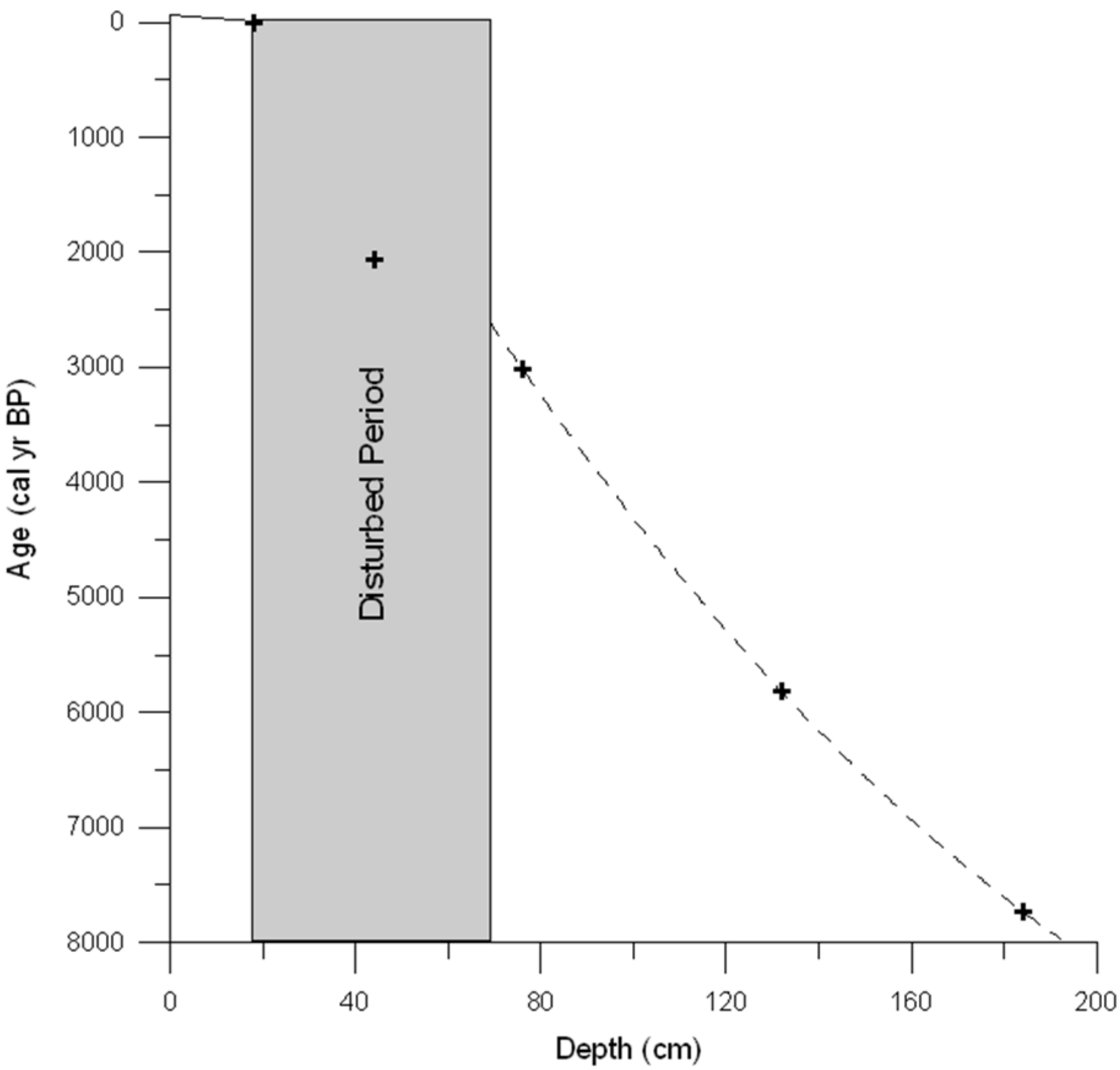
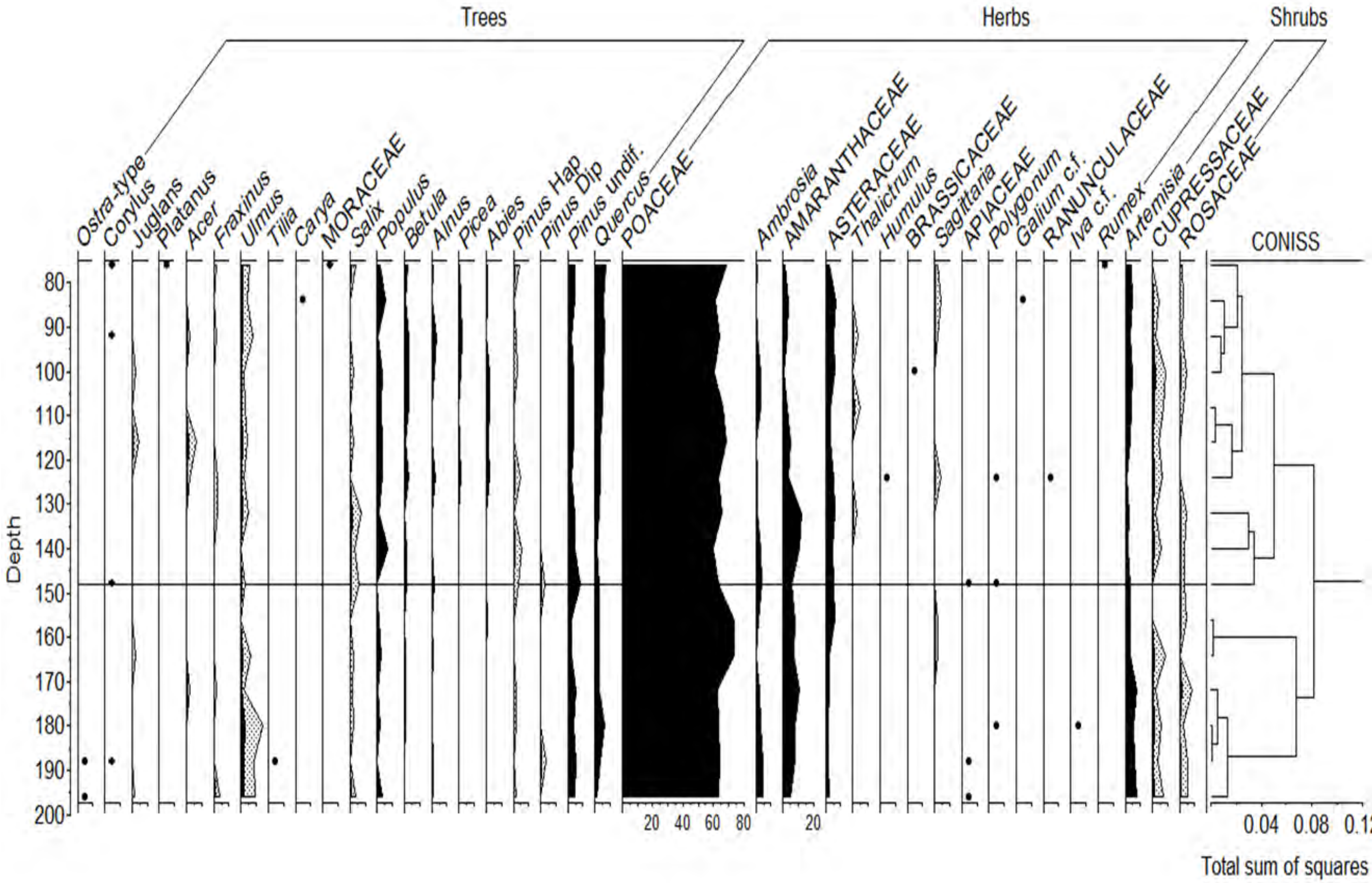


Figure 4. Age-Depth Model for Johnson Slough. Radiocarbon and Plutonium dates indicated by "+" symbol. A linear age model is used for depths 0 to 18 cm (solid line), and a second-order polynomial is used for the depths 69 to 196 cm (dashed line). Grey box represents the disturbed period, for which no age model was developed.

Figure 5. Pollen zonation for Johnson Slough. Division at 148 cm (ca. 6500 cal yr BP) was determined by constrained cluster analysis of terrestrial pollen percentages using CONISS software (Grimm, 1987). Grey shadowing represents a five times exaggeration of pollen percentages. *Pinus* Hap is likely *P. strobus,* while *Pinus* Dip may include *P. resinosa, P. banksiana* and *P. sylvestris*.



Trees
Herbs
Shrubs
Ostra-type
Corylus
Juglans
Platanus
Acer
Fraxinus
Ulmus
Tilia
Carya
MORACEAE
Salix
Populus
Betula
Alnus
Picea
Abies
Pinus Hap
Pinus Dip
Pinus undif.
Quercus
POACEAE
Ambrosia
AMARANTHACEAE
ASTERACEAE
Thalictrum
Humulus
BRASSICACEAE
Sagittaria
APIACEAE
Polygonum
Galium c.f.
RANUNCULACEAE
Iva c.f.
Rumex
Artemisia
CUPRESSACEAE
ROSACEAE
CONISS
Depth
80
90
100
110
120
130
140
150
160
170
180
190
200
20 40 60 80
20
0.04 0.08 0.12
Total sum of squares

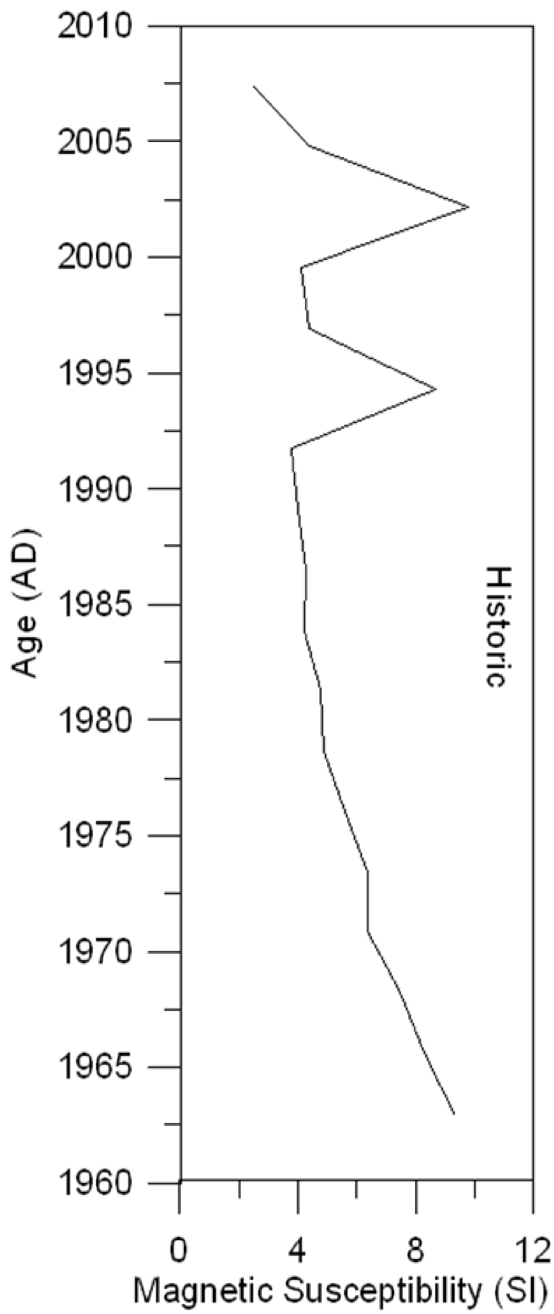


Figure 6. Magnetic susceptibility for the historic period.

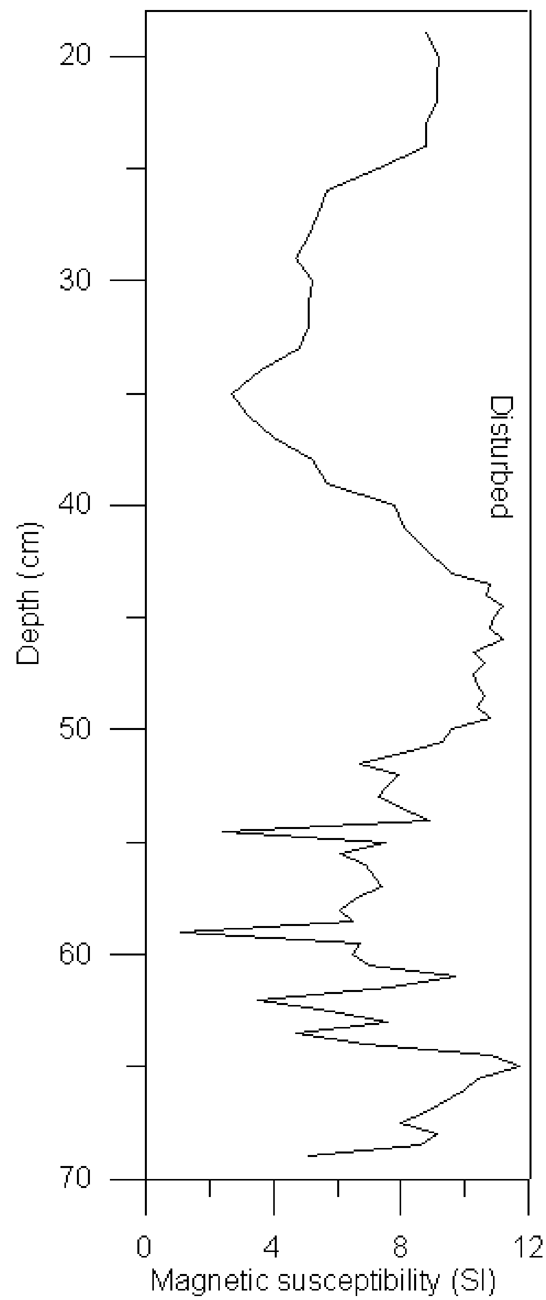


Figure 7. Magnetic susceptibility for the disturbed period.

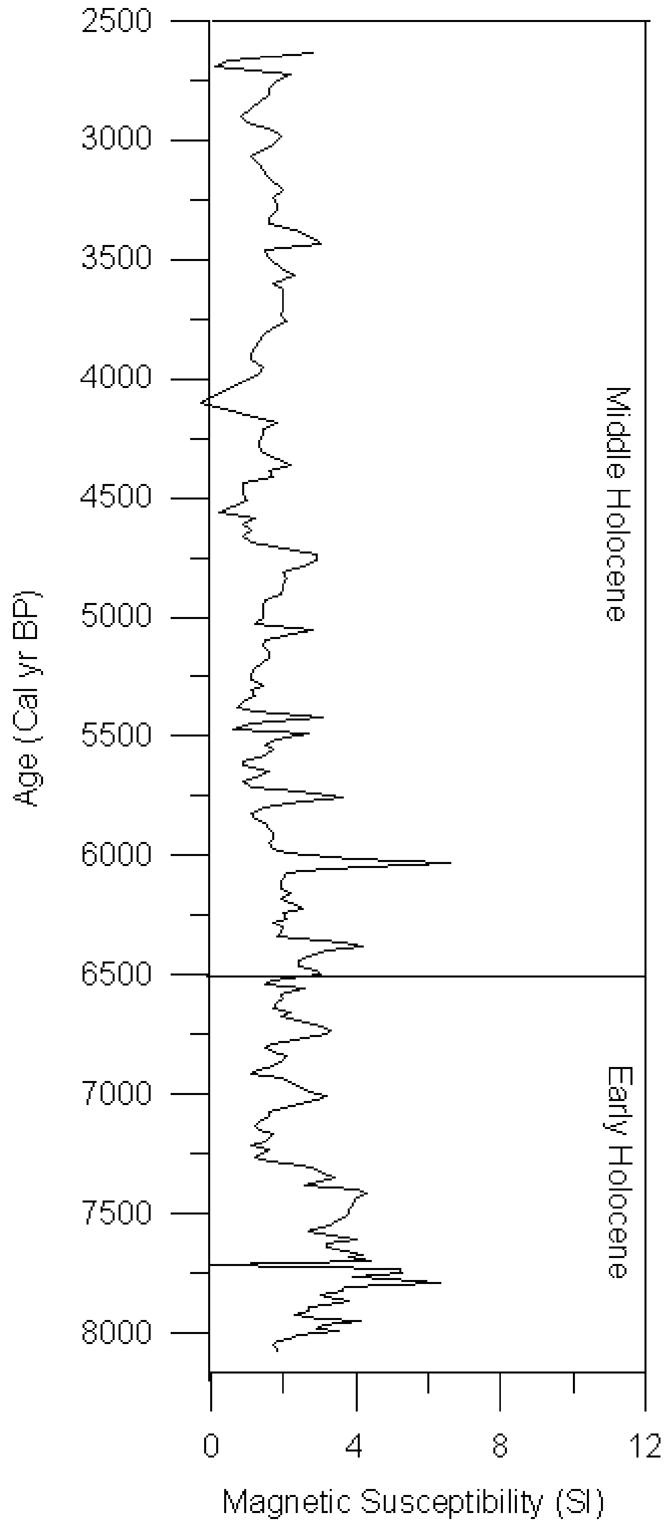


Figure 8. Magnetic susceptibility for the early-middle Holocene.

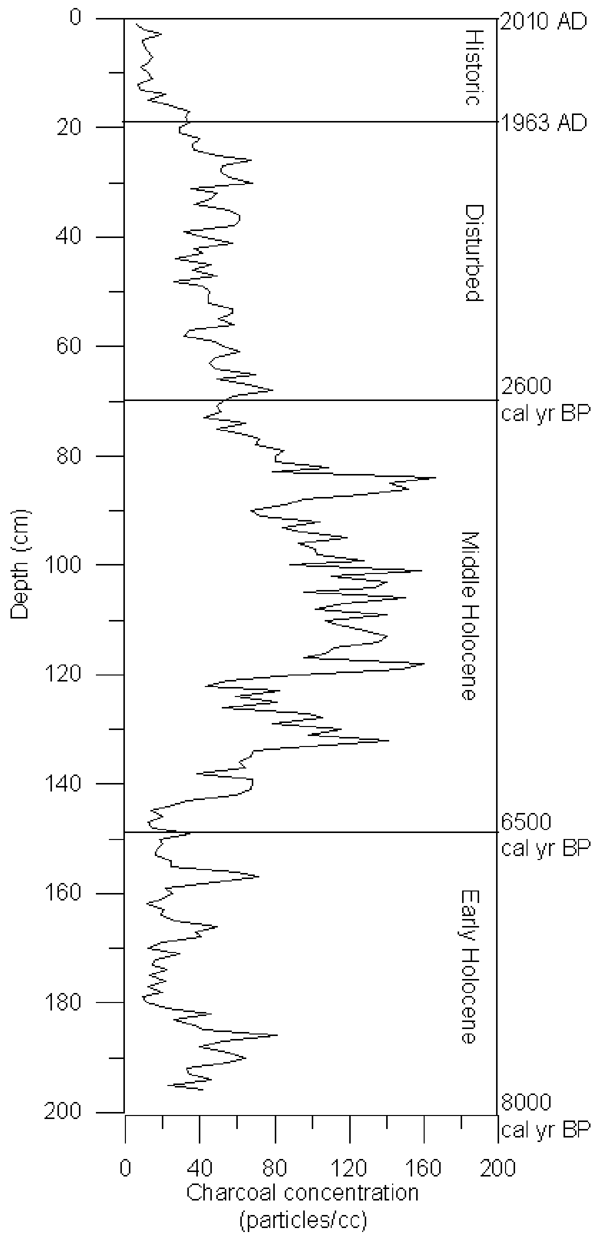


Figure 9. Charcoal concentration for Johnson Slough.

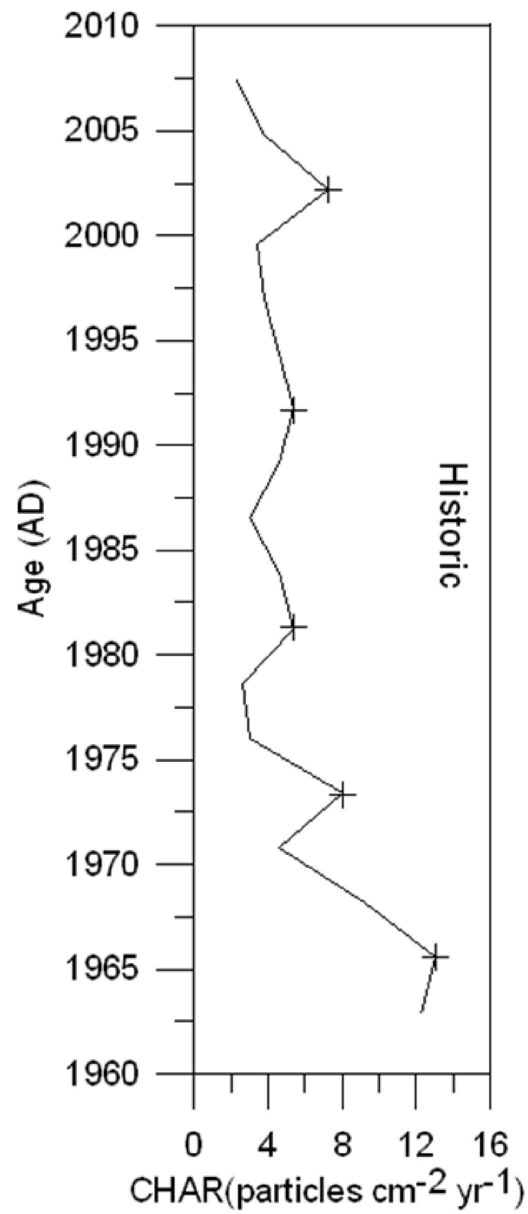


Figure 10. Charcoal accumulation rate (CHAR) for the historic period. "+" indicates episodes identified as "small peaks" in the text (note change in scale from Figure 9).

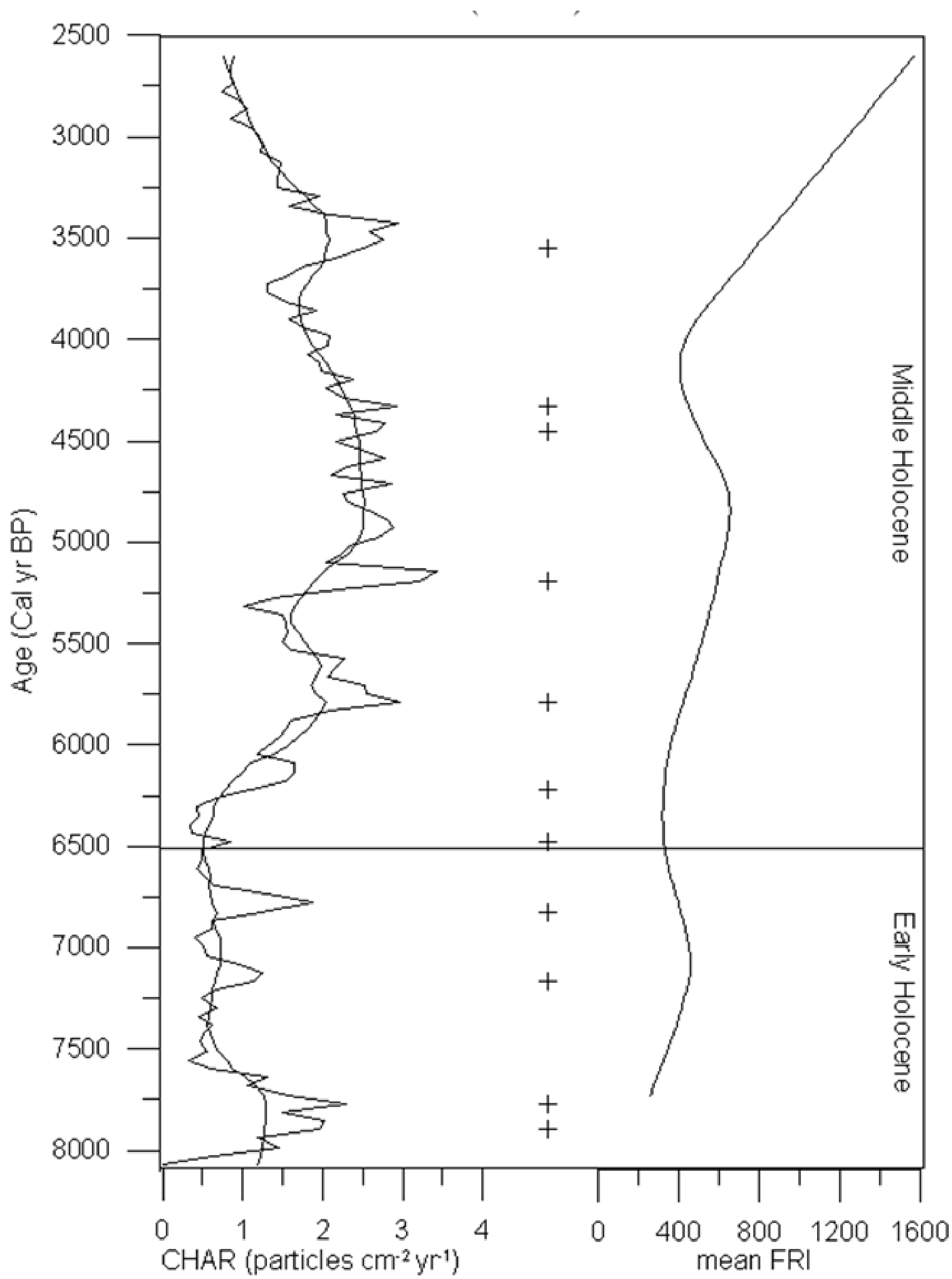


Figure 11. Fire activity for the early - middle Holocene period. Charcoal accumulation rate (CHAR) with background, which was developed using a lowess smoother applied over a 750 year window. Peaks, in which CHAR exceeds background, are indicated by "+", and mean Fire Return Interval (FRI) indicates the number of years between fire episodes.

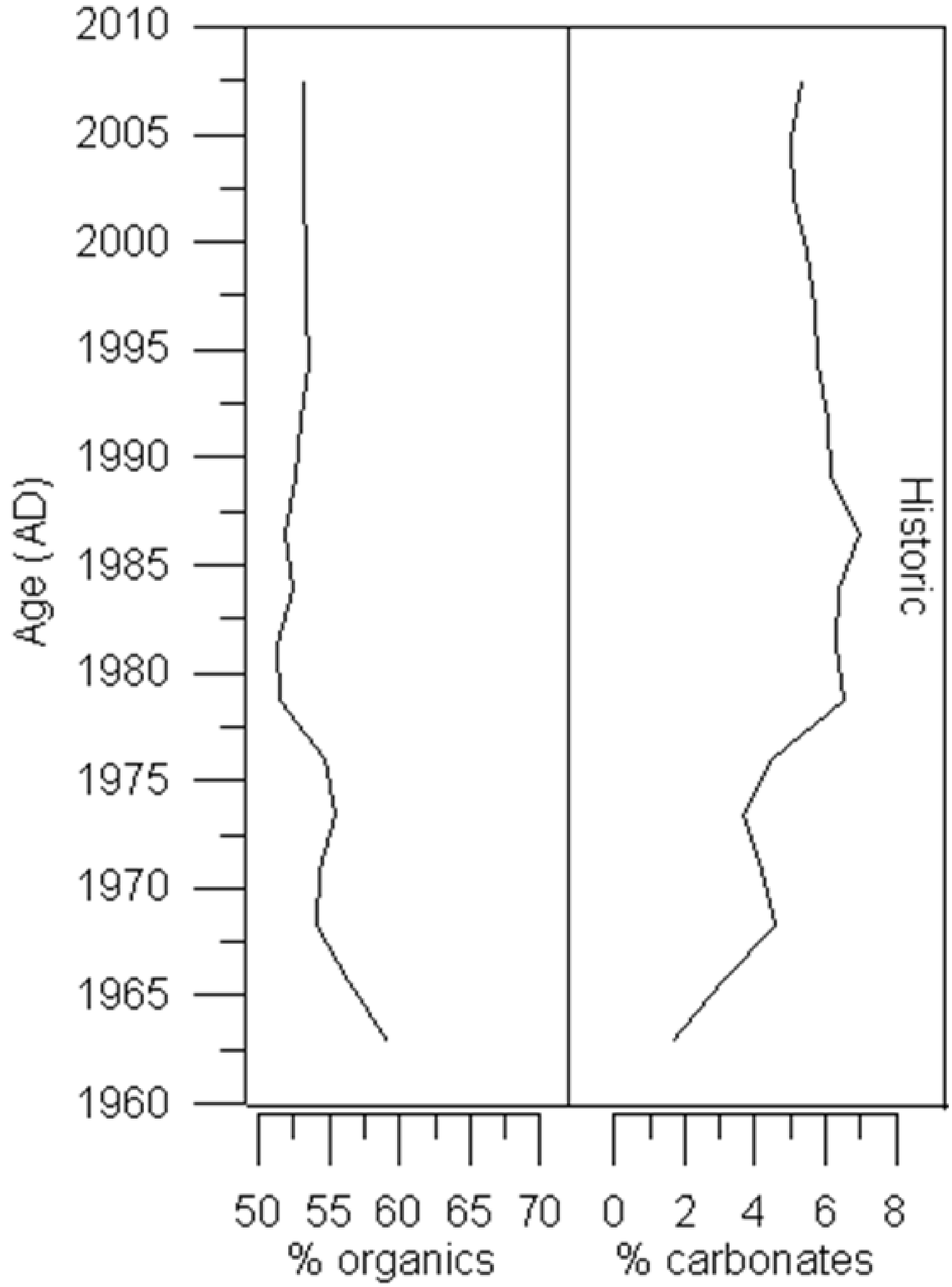


Figure 12. Loss on Ignition percentages for the historic period.

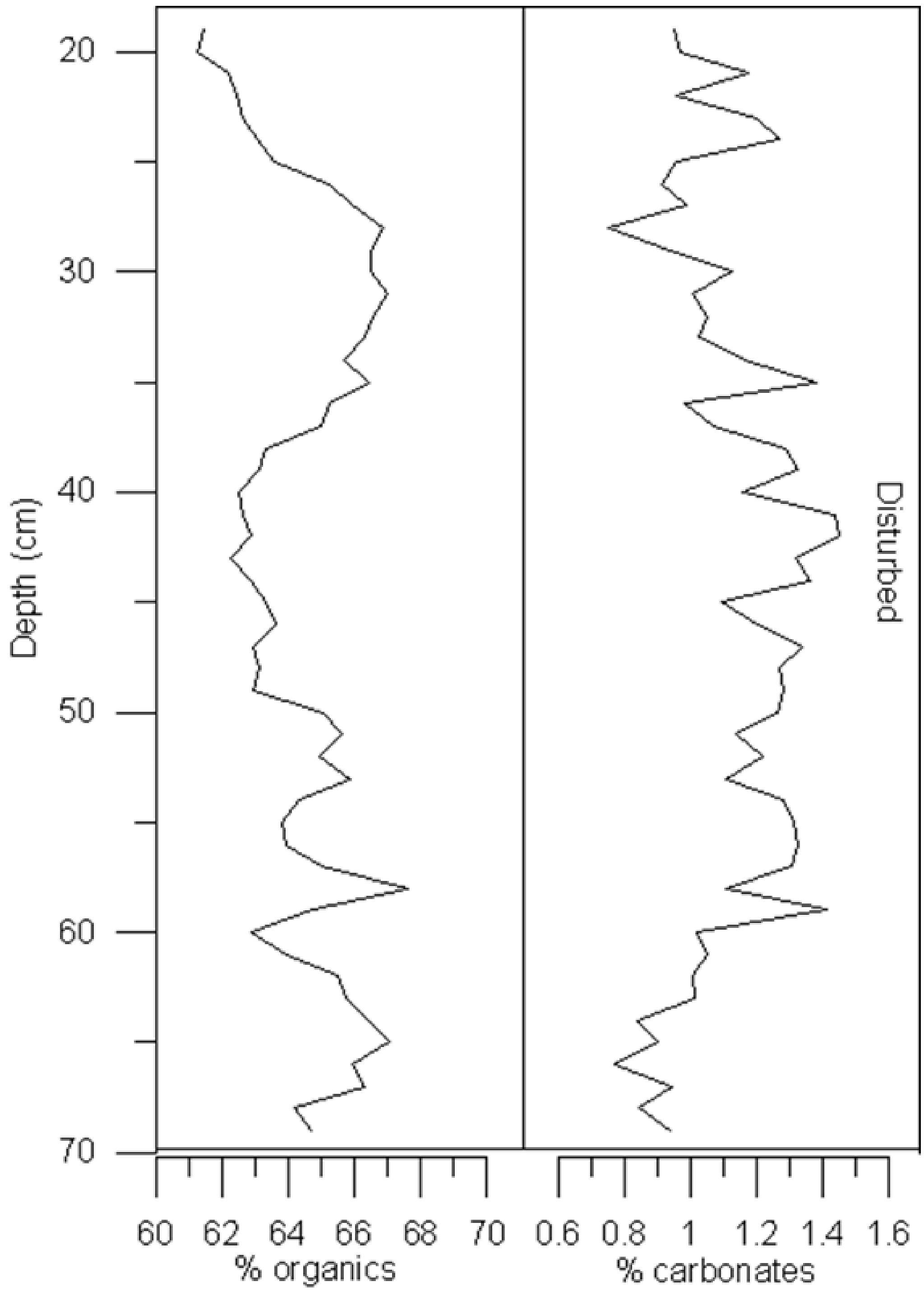


Figure 13. Loss on Ignition percentages for the disturbed period (note change in scale from Figure 12).

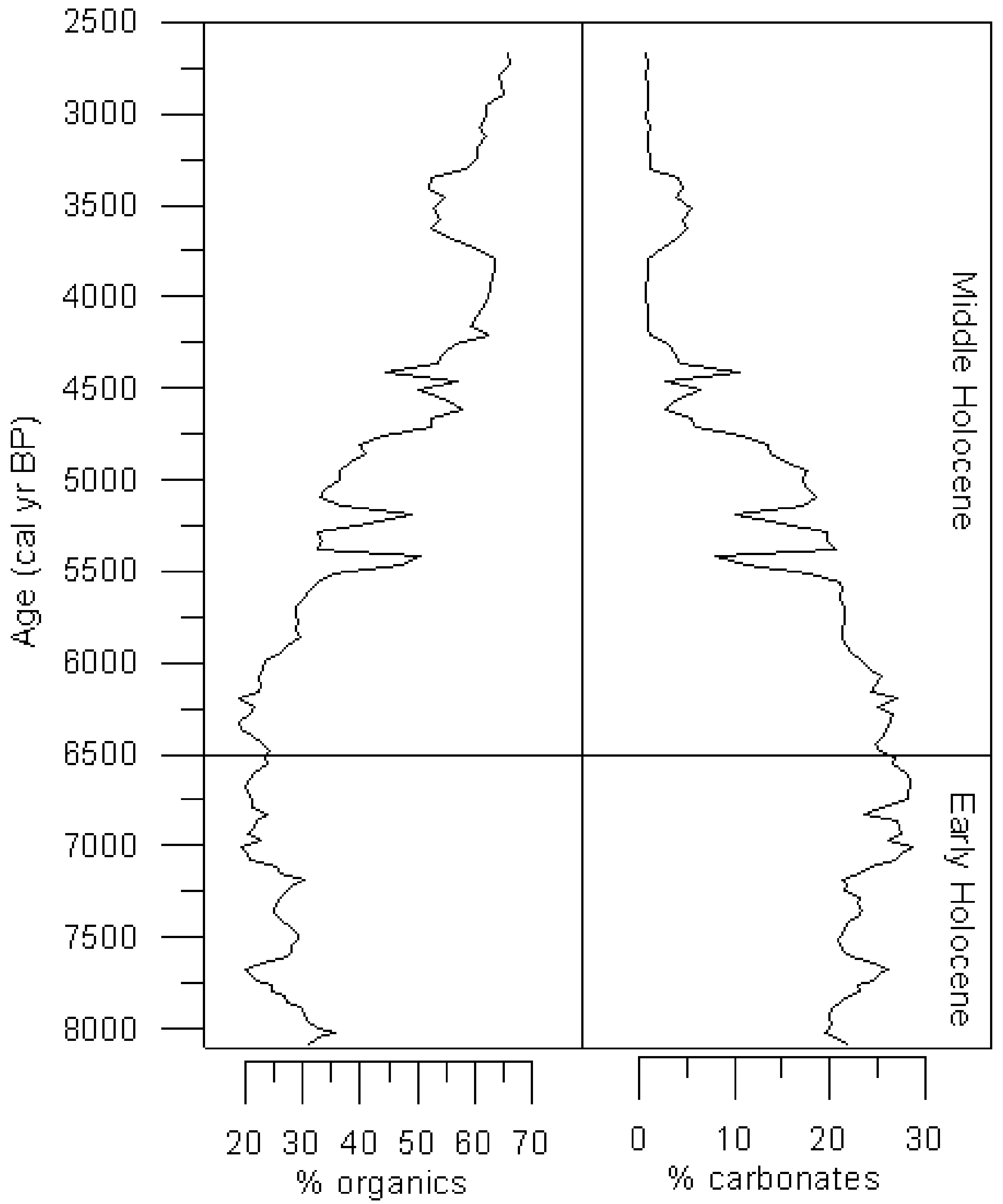


Figure 14. Loss on Ignition percentages for the early-middle Holocene period (note change in scale from Figures 12 and 13).

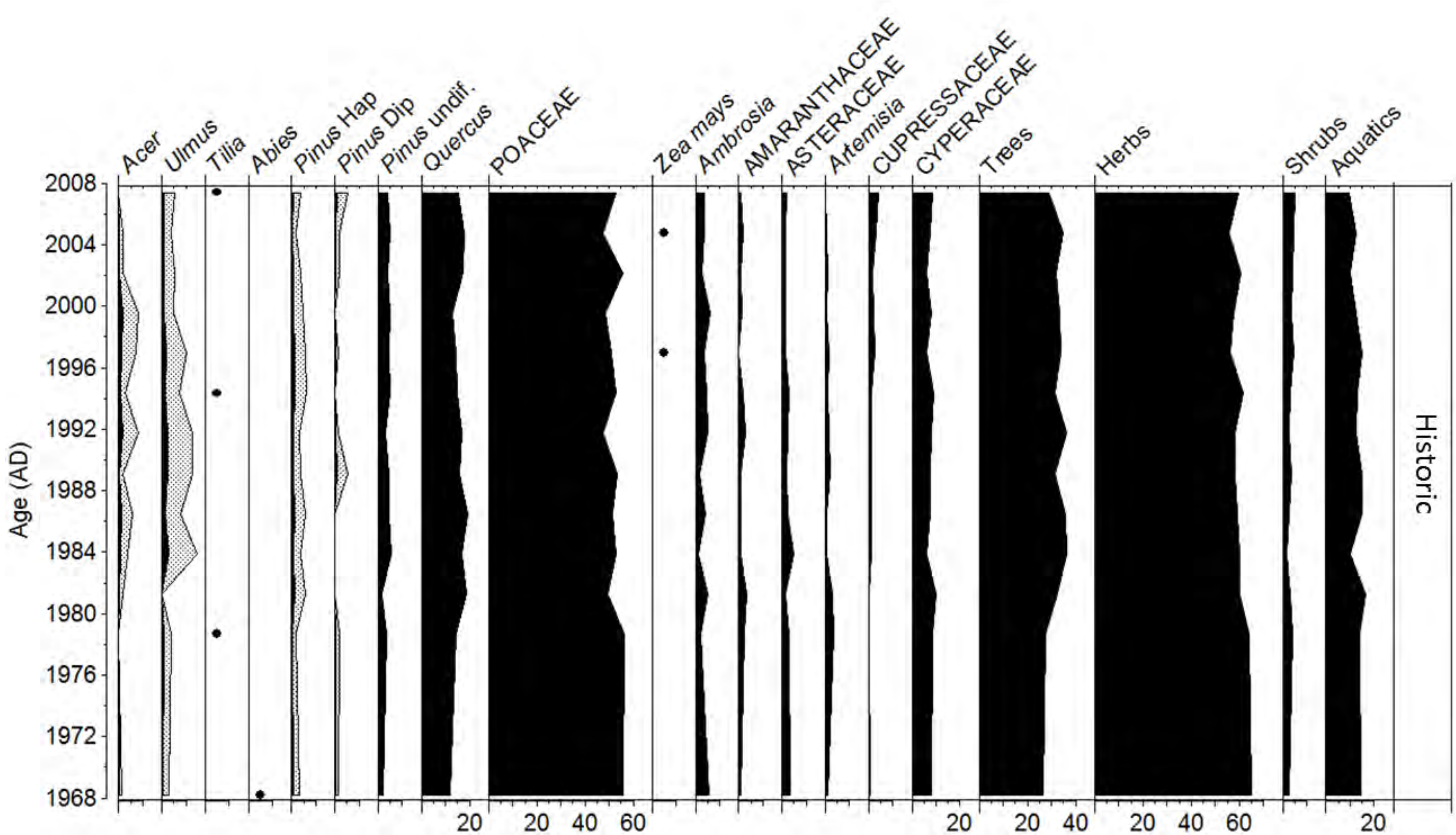


Figure 15. Pollen percentages for the historic period. Grey shadowing represents a five times exaggeration, and dots indicate presence. *Pinus* Hap is likely *P. strobus,* while *Pinus* Dip may include *P. resinosa, P. banksiana,* and *P. sylvestris*.

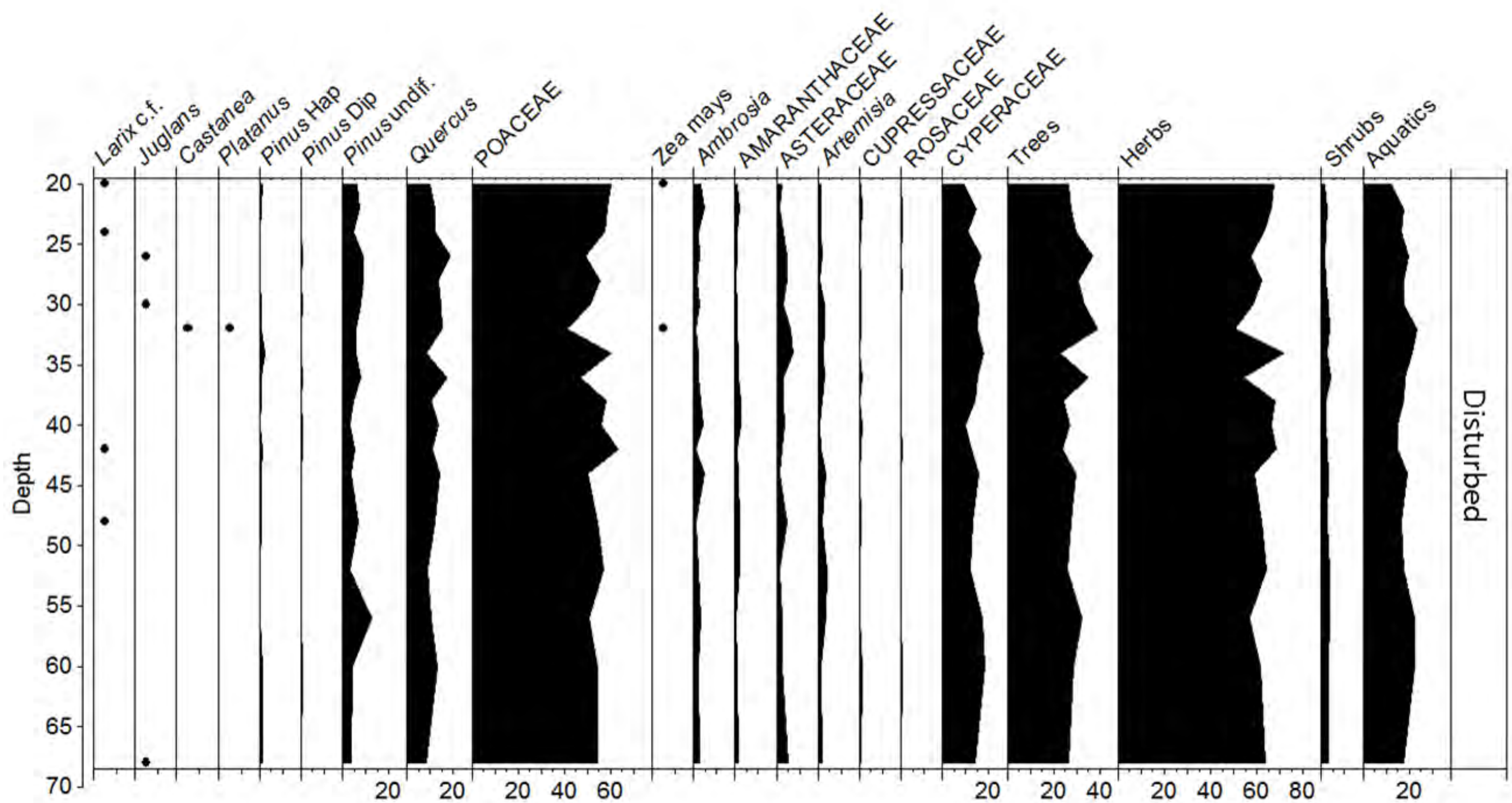


Figure 16. Pollen percentages for the disturbed period. Dots indicate presence. *Pinus* Hap is likely *P. strobus,* while *Pinus* Dip may include *P. resinosa, P. banksiana,* and *P. sylvestris*.

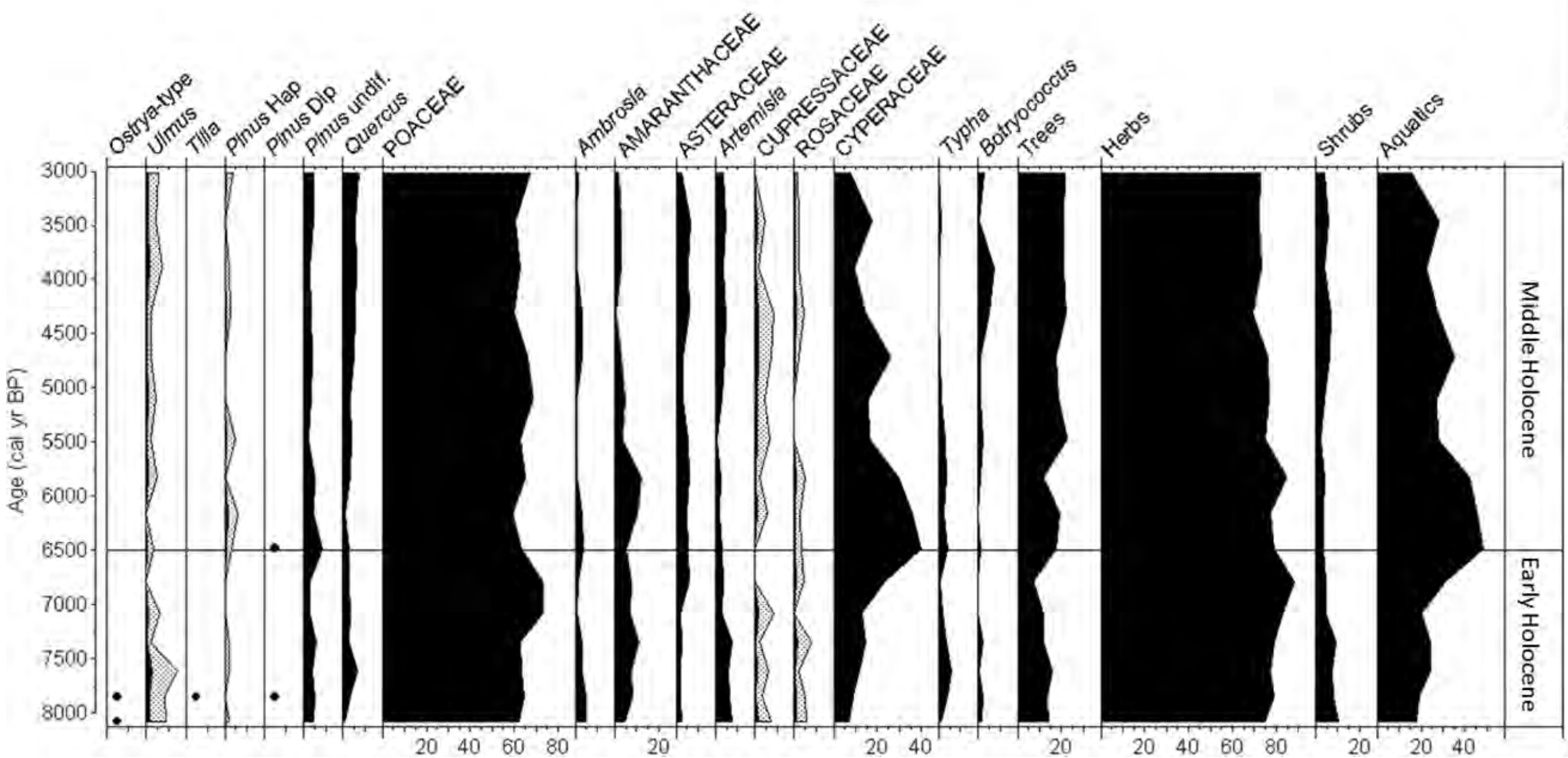


Figure 17. Pollen percentages for the early – middle Holocene period. Grey shadowing represents a five times exaggeration, and dots indicate presence. *Pinus* Hap is likely *P. strobus,* while *Pinus* Dip may include *P. resinosa, P. banksiana,* and *P. sylvestris*.

DISCUSSION

Historic Period (*ca.* 1963 AD to Present)

The historic period (ca. 1963 to 2010 AD) spans approximately the time since the establishment of the refuge in 1965 AD to present. While resolution of the age model throughout this period is high (2.6 yr cm^{-1}), sediments are expected to have experienced some mixing, due to the shallow depth of the lake. Despite this expected smoothing of the record, the charcoal and magnetic susceptibility measurements in particular reveal strong correlations to known refuge disturbances.

Since 1970 AD, refuge managers have been using prescribed burning to thin and maintain the remnant oak savanna within SNWR. Detailed records of acreage and location of burns within the refuge from 1980 to 2008 AD can be found on the refuge's website (www.fws.gov/midwest/sherburne). A review of these data reveals that peaks in CHAR are related to the fires which occur in close proximity to Johnson Slough. Since 1980, three fires have burned immediately surrounding Johnson Slough (2002, 1992, and 1983 AD) (Figure 18). These fires are recorded as three small increases in CHAR (Figure 10). This finding suggests that CHAR peaks within the historic period of the charcoal record are closely associated with localized fire events.

Magnetic susceptibility of sediments in the historic period also appear to correlate with known fires, most likely due to a destabilization of surrounding terrestrial sediments as a result of decreased ground cover. Two large peaks in magnetic susceptibility are recorded during this period (Figure 6), each of which closely coincides with one of the fire events occurring on the banks of Johnson Slough in 2002 and 1992 AD; however, there is no peak in magnetic susceptibility coinciding with the third fire surrounding Johnson Slough, which occurred in 1983 AD. Fire activity in 2002 and 1992 AD was widespread throughout the refuge, burning 6827 and 7978.5 acres, respectively, whereas in 1983, a total of only 2705 acres were burned. This suggests that peaks in magnetic susceptibility values are likely the result of a combination of high overall fire activity within the refuge and close proximity of burning to Johnson Slough.

Additionally, no peak in magnetic susceptibility occurred in 1998 AD, a year in which overall acreage burned was high (6,487 acres), but no fires occurred directly surrounding the lake. This again indicates that peaks in magnetic susceptibility values are correlated with large fires that are also in close proximity to Johnson Slough.

Percent organic and carbonate content of sediments within the historic period show little variation; however, long-term trends in these two proxies reveal significant changes over the last ~8,000 years (Figure 19). Organic content has steadily increased throughout the record, likely as a result of a general trend toward wetter climatic conditions in the region, which led to increasing biomass on the surrounding landscape, as well as greater in-lake productivity (Camill et al., 2003). Sediments within the historic period average 54 % organic content compared to an average of 45 % for the rest of the record, indicating a highly productive system at present. Because the organic and carbonate content are measured as a percentage, as one increases the other generally decreases. This inverse trend is apparent, as percent carbonate content gradually decreases throughout the record.

It is not possible to correlate changes in the pollen record to fire activity within the historic period due to lag times in vegetation responses and the smoothing of the record over this short time period. Pollen data across the entire record are fairly complacent, revealing only subtle changes in vegetation composition over the last ~8,000 years (Figure 20). Tree taxa reach maximum levels during the historic period, with herbs at the lowest levels of the record. In particular, *Quercus* pollen is high, while Poaceae pollen is slightly lower than earlier periods. A ratio of *Quercus* to Poaceae pollen throughout the record captures the development of oak savanna within the refuge (Figure 21), showing a transition from prairie (lower values) to savanna (higher values) beginning in the middle Holocene, decreasing at the end of the disturbed period, and recovering in the historic period.

A possible complication in using the *Quercus* to Poaceae ratio is that some of the Poaceae pollen may actually be due to wild rice growing on the surface of the lake, and thus be misrepresentative of prairie vegetation. Therefore, an additional ratio was developed which uses Asteraceae, *Ambrosia,* and Amaranthaceae pollen to represent prairie vegetation, rather than Poaceae (*Quercus:*(Amb+Ast+Ama); Figure 21). This ratio very closely matches the *Quercus* to Poaceae ratio, indicating that the comparison of *Quercus* to Poaceae pollen is a valid representation of shifts from prairie to savanna throughout the record. Both ratios capture the success of refuge management in recovering the oak savanna within the historic period, following its destruction upon the arrival of Europeans to the region.

Another objective of SNWR managers has been to develop waterfowl habitat through restoration of wetlands within the refuge. One of the strategies employed in reaching this goal has been to create additional wet areas through flooding controlled by check dams. This flooding has recently resulted in immense overgrowth of these areas by *Typha spp*. This known expansion of *Typha* is not reflected in the historic pollen record (Figure 15), a discrepancy which may be explained by the morphology of the *Typha* pollen grain. *Typha latifolia* pollen is released in a large tetrad which typically falls near the source plant, unless strong winds are present (Krattinger, 1975). For this reason, it is suspected that the *Typha* pollen within the Johnson Slough record is derived from the plants which ring the shallow border of the lake. Therefore, the *Typha* pollen signal will be more representative of the water level of Johnson Slough than of the entire refuge.

Typha and Cyperaceae are plants which require shallow standing water. The accurate interpretation of changes in the abundance of these taxa derived from sediment records can be difficult. An increase of these pollen types can signal an increase in standing water, due to the broadening of their range outward from the lake, or, inversely, a decrease in standing water, due to an extension of their range inward as the lake dries.

It appears that within the Johnson Slough sediment record, increases in *Typha* and Cyperaceae pollen reflect low water levels and the overgrowth of the lake surface by these taxa. The high water levels at present record some of the lowest *Typha* and Cyperaceae pollen of the record (Figure 20). Additionally, *Botryococcus*, a truly aquatic plant which requires standing water, is relatively high during the historic period and generally trends inversely with *Typha* and Cyperaceae pollen throughout the middle and early Holocene. By using all three of these aquatic taxa, it is possible to cautiously estimate periods of high and low water throughout the record. Higher (lower) water will be indicated by low (high) *Typha* and Cyperaceae and high (low) *Botryococcus*.

Disturbed Period (ca. 2600 cal yr BP to 1963 AD)

In 1933 AD, Sherburne County and the surrounding Anoka Sand Plains were experiencing the severe drought conditions which affected the Great Plains and Midwest regions during the period of the Dustbowl in the 1930s (www.esrl.noaa.gov; Northrup,1978). Farmers were unable to maintain their fields, and Orrock Lake (also referred to as Mud Lake or Big Mud Lake), within what is now SNWR, dried out. The Sherburne County Star News (1933) reported that "1933 was the year that „Mud Lake" in Orrock Township dried up and farmers cut hay on the lake bottom."

The slightly larger Orrock Lake is located only ~0.5 miles from Johnson Slough. Its greater size and close proximity to Johnson Slough indicate that if Orrock Lake was dry during this time, Johnson Slough would have been dry as well. Additionally, evidence from plutonium and radiocarbon dating, as well as from pollen and the magnetic susceptibility of Johnson Slough sediments, suggests that the lake"s surface was also farmed during this period.

Plutonium distributions for undisturbed sediments are expected to show no detectable levels of $^{239+240}$Pu prior to 1945 AD, followed by an increase to a single large peak in 1963 AD, then intermediate values to present. The plutonium series for Johnson Slough sediments reaches detectable levels by 52 cm, increases to an initial large peak at 40 cm, declines to very low levels, and then rises again to a second, greater peak at 18 cm (Figure 3). We interpret the largest peak at 18 cm to correspond to 1963 AD, and suspect that sediments of the 40 cm peak have been mixed and possibly compressed or otherwise modified by farming of the lake surface.

While farming in 1933 AD would not have affected the plutonium record, any farming on the surface of the lake after 1945 AD would have. The mean Palmer Drought Severity Index (PDSI) for the June to September growing season for the region shows that, while periods of drought as severe as in the 1930s did not occur between 1945 and 1963 AD, smaller droughts in the late 1940s and 1950s AD (Figure 22; state 21, zone 5 – central, www.esrl.noaa.gov) may have dried the surface of the smaller Johnson Slough enough to allow for some degree of farming, a practice which, started in 1933 AD, may have been repeated in less severe drought years.

Further evidence of sediment disturbance is provided by a radiocarbon date of ca. 2076 cal yr BP at 44 cm, which falls within the period of detectable plutonium, an age reversal indicative of disturbance. Additionally, *Zea mays* (corn) pollen was found at a depth of 32 cm. The large *Zea mays* pollen grain is poorly suited to long distance travel, and typically falls very near its source. While it is possible this pollen was transported from nearby fields, it is more likely the result of farming directly on the dried lakebed.

Finally, magnetic susceptibility of sediments abruptly increases at the end of the middle Holocene, and remains high during the disturbed period (Figure 23). These high levels of magnetically susceptible materials within the sediments may be due to the degradation of metal farming equipment used in preparing the lakebed for planting, or to the addition of fertilizers to enrich the soil. The addition of organic matter (i.e., fertilization) is further supported by loss on ignition data, which reveal that this period maintains the greatest percentage of organic content of the entire sediment record (Figure 19).

The abrupt rise in magnetically susceptible sediments at a depth of 69 cm was used to confine the lower limit of the agricultural disturbance. Due to the absence of historical documentation to aid in determining the latest occurrence of farming on the surface of Johnson Slough, the upper limit of the disturbed period was defined by the 1963 AD plutonium peak, which closely coincides with the establishment of the refuge in 1965 AD. While it is unlikely that farming of the surface sediments occurred this late in the record, caution was taken in defining the upper limit to ensure the validity of the historic period.

The evidence outlined above strongly suggests that the Johnson Slough sediments were disturbed through farming in the mid-1900s; however, the pollen, charcoal, magnetic susceptibility, and LOI records actually show less homogenization than would be expected to result from agricultural plowing of the sediments. Because of the uncertainty pertaining to the reliability of sediments within this period (ca. 2600 cal yr BP to 1963 AD), interpretation of the pollen and charcoal data for this section of the record is conducted with caution.

Charcoal concentration for the disturbed period averaged 48 particles cm^{-3}, values intermediate to those in the middle Holocene and the historic period (Figure 9). This burning was likely due to fires within the oak savanna prior to disturbance and to farming practices following disturbance. In the early 1900s AD, it was common practice for farmers to use fire to clear and prepare their fields for planting (Hepola, personal communication).

The pollen record, while somewhat homogenized, appears to have intermediate values compared to the middle Holocene and historic periods (Figure 20). However, the ratio of *Quercus* to Poaceae pollen may underestimate the extent of the oak savanna during this period (Figure 21). It is likely that the oak savanna continued to increase following the middle Holocene, to a degree greater than that reflected in the *Quercus* to Poaceae ratio. The clearing of the savanna upon European arrival in the region and later mixing of these sediments would have then smoothed the ratio and dampened the peak.

Middle Holocene (ca. 6500 to 2600 cal yr BP)

Sediment accumulation throughout the middle Holocene averaged 47.6 yr cm^{-1}, significantly slower than in the historic period (2.6 yr cm^{-1}), but still within the range of variability found by Webb and Webb (1988) in a survey of 291 small lakes and mires in eastern North America. In this study, the authors compared 1492 sediment accumulation rates to determine the range of variability of these rates throughout the Holocene and historic periods. The authors found that accumulation rates for the historic period ranged from 0.6 to 100.0 yr cm^{-1}, with a mean of 3.4 yr cm^{-1}, while accumulation rates for the Holocene ranged from 2.5 to 125.0 yr cm^{-1}, with a mean of 12.3 yr cm^{-1}. This difference in mean accumulation rates between the historic and Holocene periods is evident in the Johnson Slough sediments, and is attributed to both compression of older sediments and increased sedimentation in younger sediments resulting from human activity (Umbanhowar et al., 2011).

Webb and Webb (1988) estimate that rates ranging from 3.9 to 62.5 yr cm^{-1} throughout the Holocene indicate constant and continuous sedimentation, while rates slower than 100.0 yr cm^{-1} are indicative of non-constant accumulation (i.e., drying). With an average sediment accumulation rate of 47.6 yr cm^{-1} throughout the middle Holocene, the Johnson Slough sediments appear to have undergone constant and continuous sedimentation, perhaps with short periods of drying, which were not significant enough to have been reflected in the overall rate of sedimentation.

The younger limit of the middle Holocene period of the record was defined by the agricultural disturbance at ca. 2600 cal yr BP, while the older limit, at ca. 6500 cal yr BP, was determined by constrained cluster analysis of the pollen data using CONISS software (Figure 5; Grimm, 1987). This zone division appears to be driven by a minor increase in tree taxa, accompanied by slight decreases in both herb and shrub taxa. The ca. 6500 cal yr BP division is further supported by an increase in fire activity near this period in the record (Figure 11).

The ratio of *Quercus* to Poaceae pollen shows a very gradual transition from prairie to oak savanna within the middle Holocene (Figure 21). The overall shift in vegetation to more tree taxa and less herb and shrub taxa at this time is likely the result of a shift in climate from warm and dry to warm and wet. High *Typha* and Cyperaceae pollen, along with low *Botryococcus*, at the beginning of this period (ca. 6500 cal yr BP) indicate that the climate of the middle Holocene was initially dry (Figure 20). A shift to wetter conditions is then evident as *Typha* and Cyperaceae pollen decrease and *Botryococcus* increases.

Charcoal concentrations reach the highest levels of the record within the middle Holocene (Figure 9). This greater fire activity is likely due to the transition in fuel type from fine fuels (herbs and shrubs) to more robust fuels (trees) (Figure 17).

Peaks in the charcoal record within the historic period correlate with fires that occurred directly surrounding Johnson Slough. Additionally, peaks in magnetic susceptibility of sediments coincide with fires which not only occurred in close proximity to the lake, but that were widespread throughout the refuge. Five peaks occur simultaneously in both the charcoal and magnetic susceptibility records of the middle Holocene (Figure 11), suggesting that periods of widespread and localized fire activity occurred five times within this ~ 3900 year period. Additionally, two peaks are evident in the charcoal record which do not coincide with peaks in magnetic susceptibility values. These peaks likely represent smaller fire activity directly surrounding the lake.

Including only the five peaks reflected in both the charcoal and magnetic susceptibility records amounts to a mean fire return interval of 780 years, while including the additional two fires represented only in the charcoal record amounts to a mean fire return interval of 557 years. However, fire return interval based on charcoal peaks may not be a valid representation of fire activity for this record. This results from an uncertainty regarding the type of event which is represented by charcoal peaks within the Holocene. It is possible that these peaks represent changes in fuel source, for example, episodes in which the canopy burned, rather than just the understory. Peaks could also represent periods in which fires occurred across a greater area, or more frequently within the timeframe represented by the sediment sample. Due to this uncertainty, mean fire return interval is not a reliable indicator of changes in fire activity throughout the Johnson Slough record.

A transition from a warm and dry to a warm and wet climate is seen throughout the Midwest, occurring anywhere from about 6000 to 3500 cal yr BP (Keen and Shane, 1990; Anderson, 1998; Camill et al., 2003; Nelson and Hu, 2008; Williams et al., 2009). Increased moisture during this period likely led to increased tree cover, which in turn resulted in greater fire activity due to the change in fuel type (Camill et al., 2003; Nelson and Hu, 2008). Additionally, complex fire and vegetation feedbacks would have advanced the expansion of the oak savanna during this period. Similar climate-vegetation-fire interactions have been recorded in multiple records in the Midwest (Camill et al., 2003; Nelson and Hu, 2008), with the Johnson Slough record offering another example.

Early Holocene (ca. 8000 to 6500 cal yr BP)

Regional paleoclimatic records indicate that the Midwest experienced a cool and wet climate following deglaciation (ca. 12000 cal yr BP), transitioning to warm and dry conditions by ca. 8000 cal yr BP (Keen and Shane, 1990; Laird et al., 1996; Anderson, 1998; Camill et al., 2003; Nelson and Hu, 2008; Williams et al., 2010). Woodland taxa, such as *Ulmus* and *Ostrya*, were abundant at the end of the cool/wet period in this region, but were replaced by prairie taxa, such as Poaceae, as the climate warmed and dried (Wright et al., 1963; Camill et al., 2003).

The Johnson Slough pollen record extends to ca. 8000 cal yr BP, and appears to agree with regional records of the early Holocene. Aquatic taxa support a drying trend from ca. 8000 to 6500 cal yr BP (Figure 20). *Typha* and Cyperaceae pollen percentages are low at the beginning of the early Holocene (ca. 8000 cal yr BP), increasing toward the middle Holocene boundary (ca. 6500 cal yr BP). Additionally, *Botryococcus* is highest at the beginning of the early Holocene, though abundance of *Botryococcus* throughout this period is relatively low. The pollen record also appears to record the very end of the woodland conditions in this period and the transition to prairie conditions (Figure 17). In particular, *Tilia, Ulmus, Fraxinus, Acer, Juglans, Corylus, Ostrya*-type, and *Larix* c.f. taxa decrease, and in many cases disappear, from ca. 8000 to 6500 cal yr BP. Alternatively, herbs, particularly Poaceae, increase during this time period.

Fire activity in the early Holocene appears to respond to the shift in vegetation, and is seen to decrease as tree and shrub taxa are replaced by herbaceous taxa (Figure 11). Four peaks are present within the charcoal record, each of which corresponds with a peak in sediment magnetic susceptibility. The relationship between charcoal peaks and magnetic susceptibility peaks determined from the historic period indicates that large-scale fire activity occurred in close proximity to Johnson Slough approximately four times over this ~ 1500 year time period in the early Holocene, with a mean fire return interval of 375 years. This fire return interval is lower than that of the middle Holocene (557 – 780 years), but despite the higher mean fire return interval in the early Holocene, average charcoal concentration for this period is low (31.3 particles cm^{-3}; Figure 9), likely due to the low fuel prairie vegetation which dominates for the majority of this period.

Management Implications

Despite the disturbance to the critical time period from ca. 2600 cal yr BP to 1963 AD in the Johnson Slough record, the following questions regarding management for restoration of oak savanna within the refuge can be addressed:

1. *How does the oak savanna within the refuge today compare to that of the past?*

The *Quercus* to Poaceae pollen ratio provides an estimation of the overall extent of oak savanna surrounding Johnson Slough throughout the Holocene. A commonly targeted period for restoration selected by land managers is the time just prior to Euro-American arrival in the region. Despite the disturbance to this period within the Johnson Slough record, estimates of oak savanna extent are possible, and the ratio in Figure 21 shows that the current *Quercus* to Poaceae balance within the refuge is within the range of variability seen during the disturbed period. However, the maximum extent of oak savanna on the refuge likely exceeded that seen today and is dampened within the pollen record due to mixing of sediments following clearing of the trees by Euro-Americans.

While the period just prior to Euro-American arrival in the region (ca. 1840 AD) is a common target period for restoration, perhaps a better analog would be the middle Holocene. Climate in the middle Holocene was warmer and drier than today, and likely more similar to projected climate conditions than climate in the 1800s AD. The ratio of *Quercus* to Poaceae pollen shows a stronger tree component in the historic period than that seen in the middle Holocene, perhaps indicating that additional thinning of the current oak savanna stands is warranted.

It is important to note that this method of estimating oak savanna extent does not address issues of stand composition or density. For instance, a landscape made up of a homogenous mix of 50 % oak and 50 % prairie would result in the same *Quercus* to Poaceae ratio as one in which half of the landscape is dense oak forest and the other half open prairie. Therefore, while the *Quercus* to Poaceae ratio within the refuge is useful in estimating changes in the general extent of oak savanna over time, specific comparison of stand composition cannot be addressed with the Johnson Slough record.

2. *How does the level of prescribed burning within SNWR compare to fire activity throughout the development of the oak savanna?*

The Johnson Slough record provides two important means of interpreting past fire activity, the overall charcoal concentration, and peaks in CHAR and magnetic susceptibility of sediments. The peaks in CHAR and magnetic susceptibility were found to represent periods of widespread fire episodes which occur in close proximity to Johnson Slough. However, comparing the fire return intervals obtained from these episodes becomes difficult between the early-middle Holocene and the historic period because of the large difference in sediment accumulation rate between these periods. Peaks within the early-middle Holocene occur over decades, while peaks in the historic period can be tied to individual years. It is most likely that the peaks within the early-middle Holocene represent either prolonged periods of greater fire activity, or more severe fires, which could have included the burning of the canopy, rather than just the understory.

Because of the difficulty in comparing the fire return intervals interpreted through peaks in CHAR and magnetic susceptibility of sediments, overall charcoal concentration must also be considered (Figure 9). Currently, charcoal concentrations are at the lowest values of the sediment record, indicating that overall fire activity within the refuge is at the lowest levels of the last ~8,000 years. However, this is again complicated by the drastic shift in sediment accumulation rate from the early-middle Holocene to the present, and without a continuous age model spanning the disturbed period through to present it is difficult to be sure that this lower charcoal concentration in the historic period is in fact representative of lower overall fire activity within the refuge.

Ultimately, prescribed burning within the refuge is strongly influenced by safety factors. Considerations regarding proximity to developed areas, the seasonal timing of burning, and prevailing wind direction likely make it impossible to manage for the exact restoration of this particular ecosystem process. However, the Johnson Slough record shows that fire has been an important and persistent aspect of the oak savanna ecosystem throughout its development in the region, and continued prescribed burning is warranted.

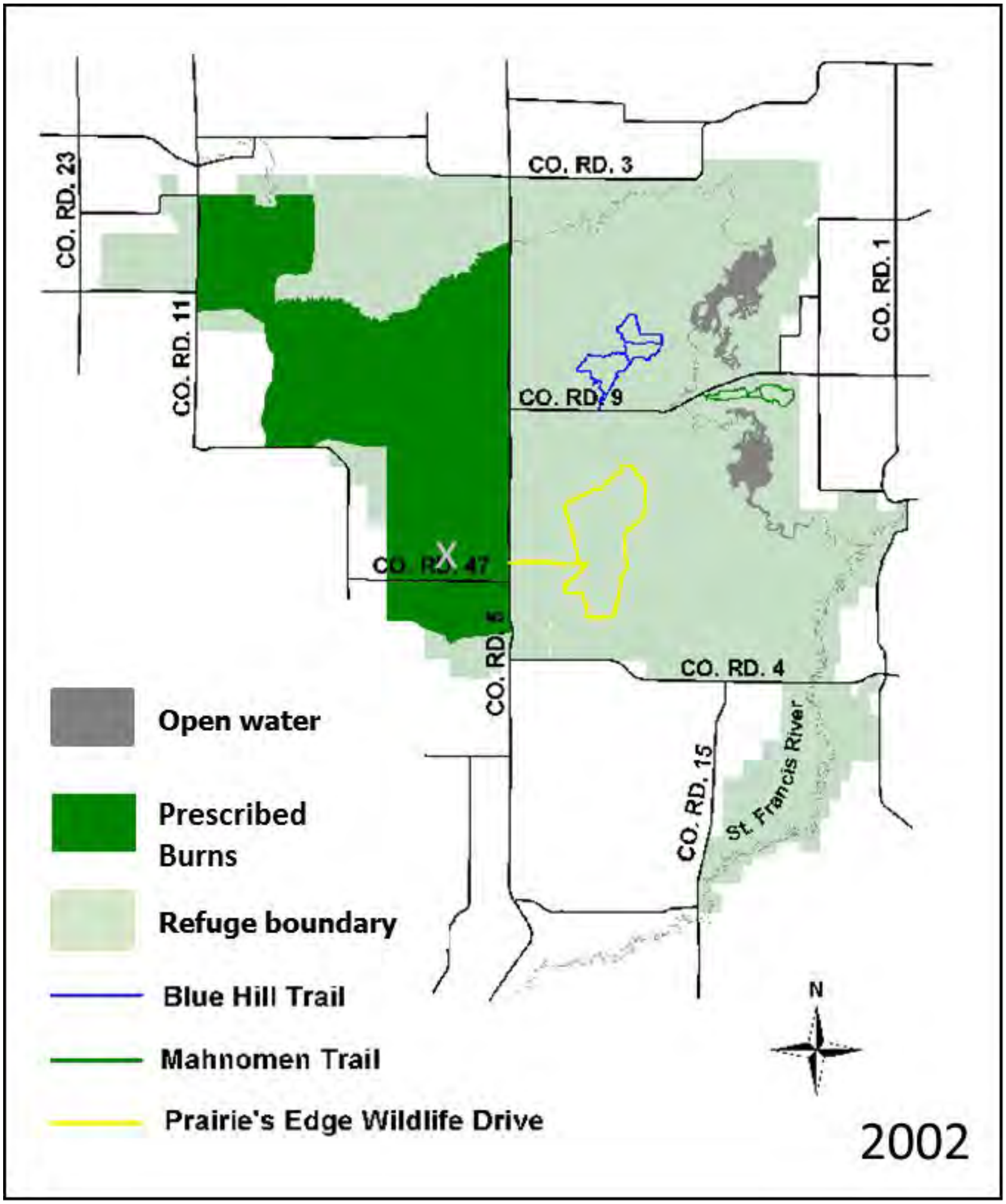


Figure 18. Maps of area burned within SNWR for the years 2002, 1992, and 1983 (Continued on following pages; modified from www.fws.gov/midwest/sherburne). Grey "x" indicates the location of Johnson Slough.

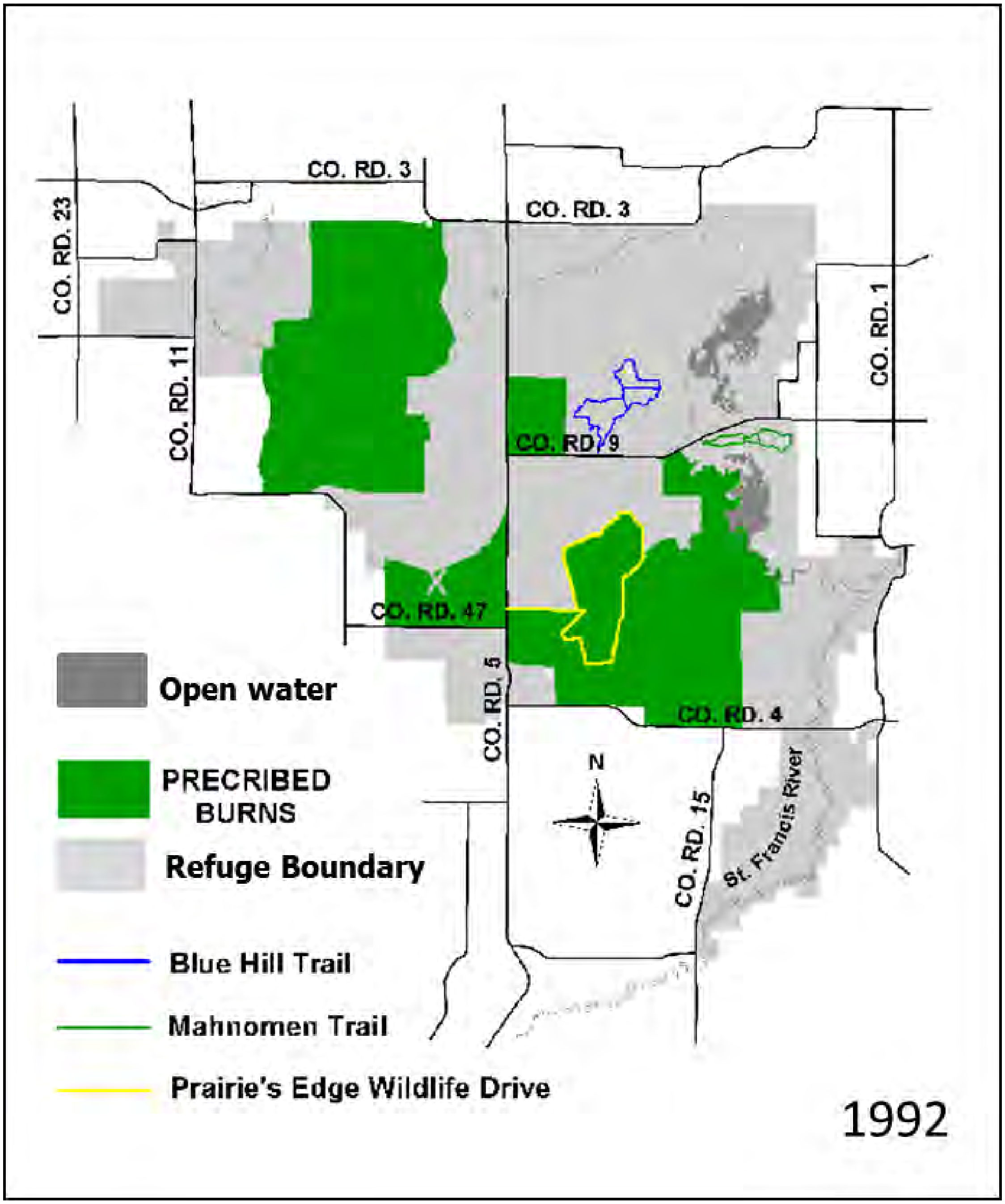


Figure 18, cont.

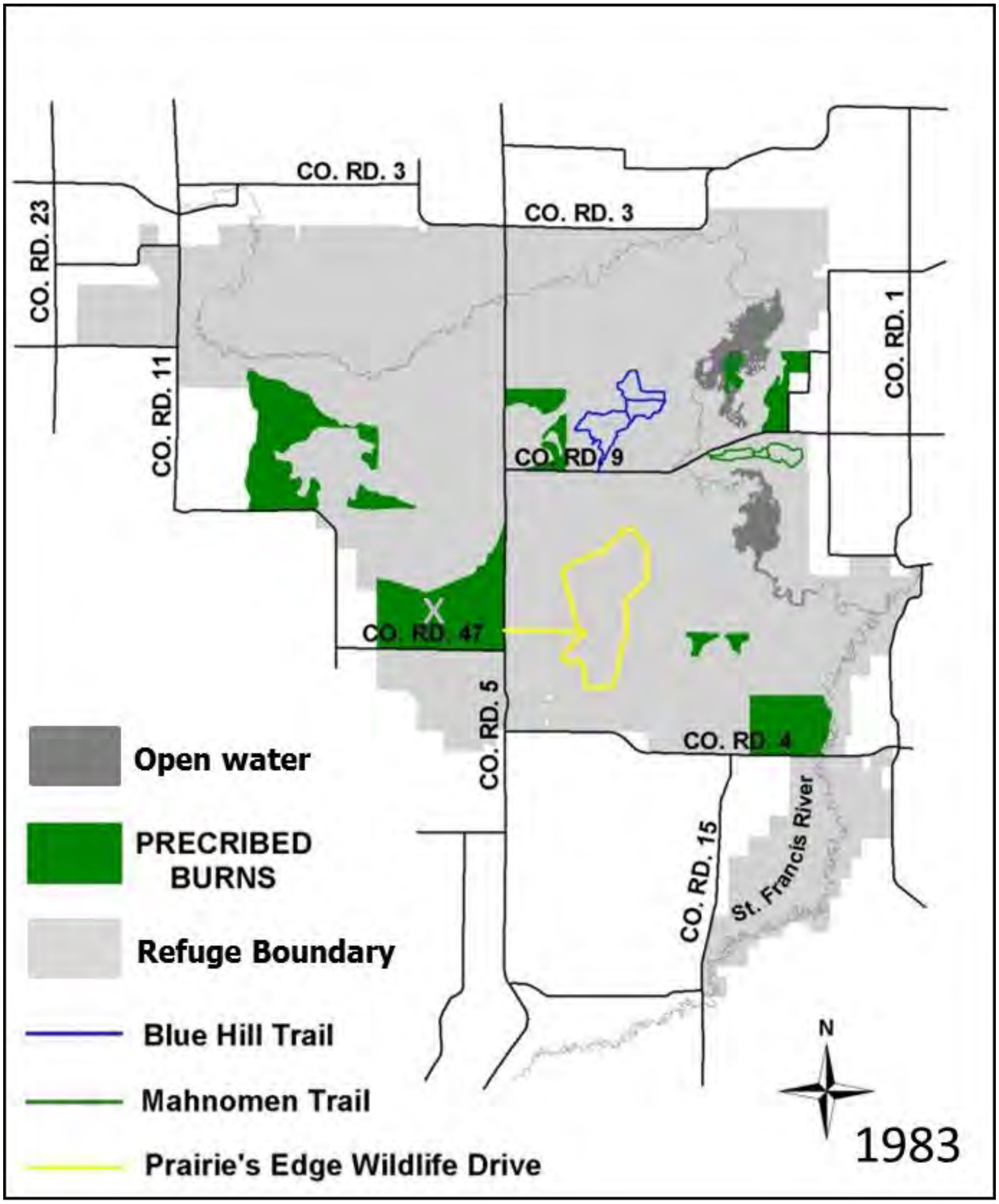


Figure 18, cont.

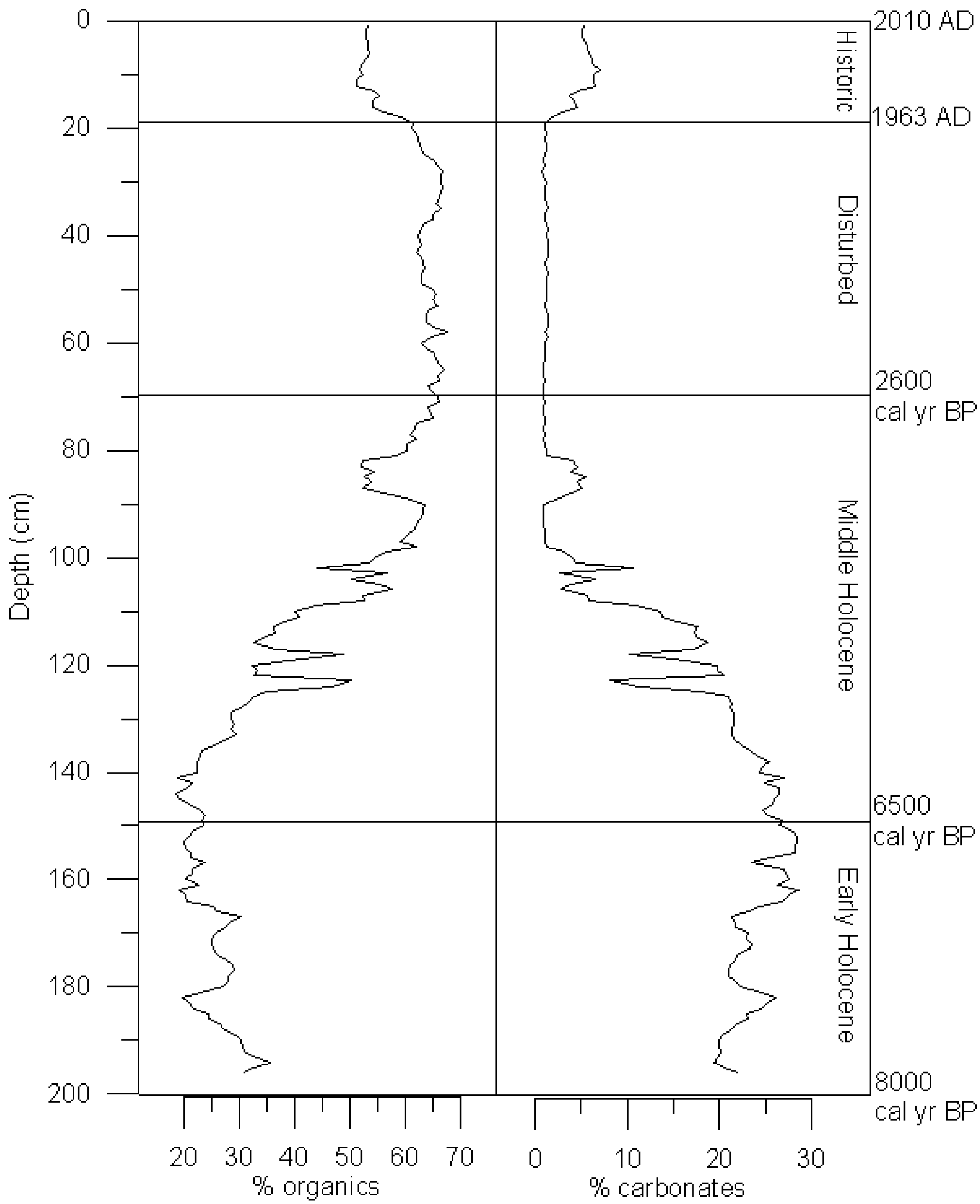


Figure 19. Loss on Ignition percentages for Johnson Slough.

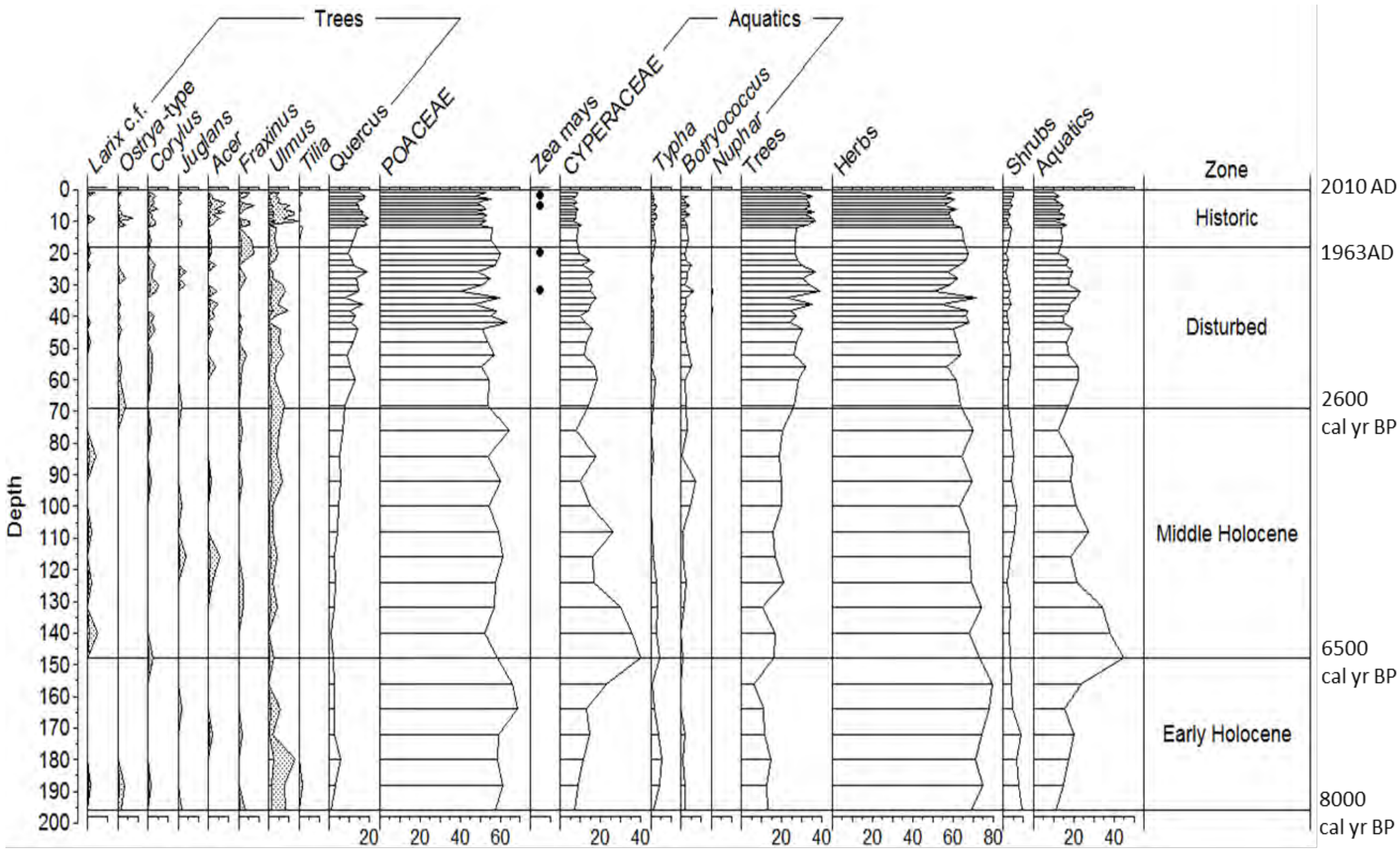
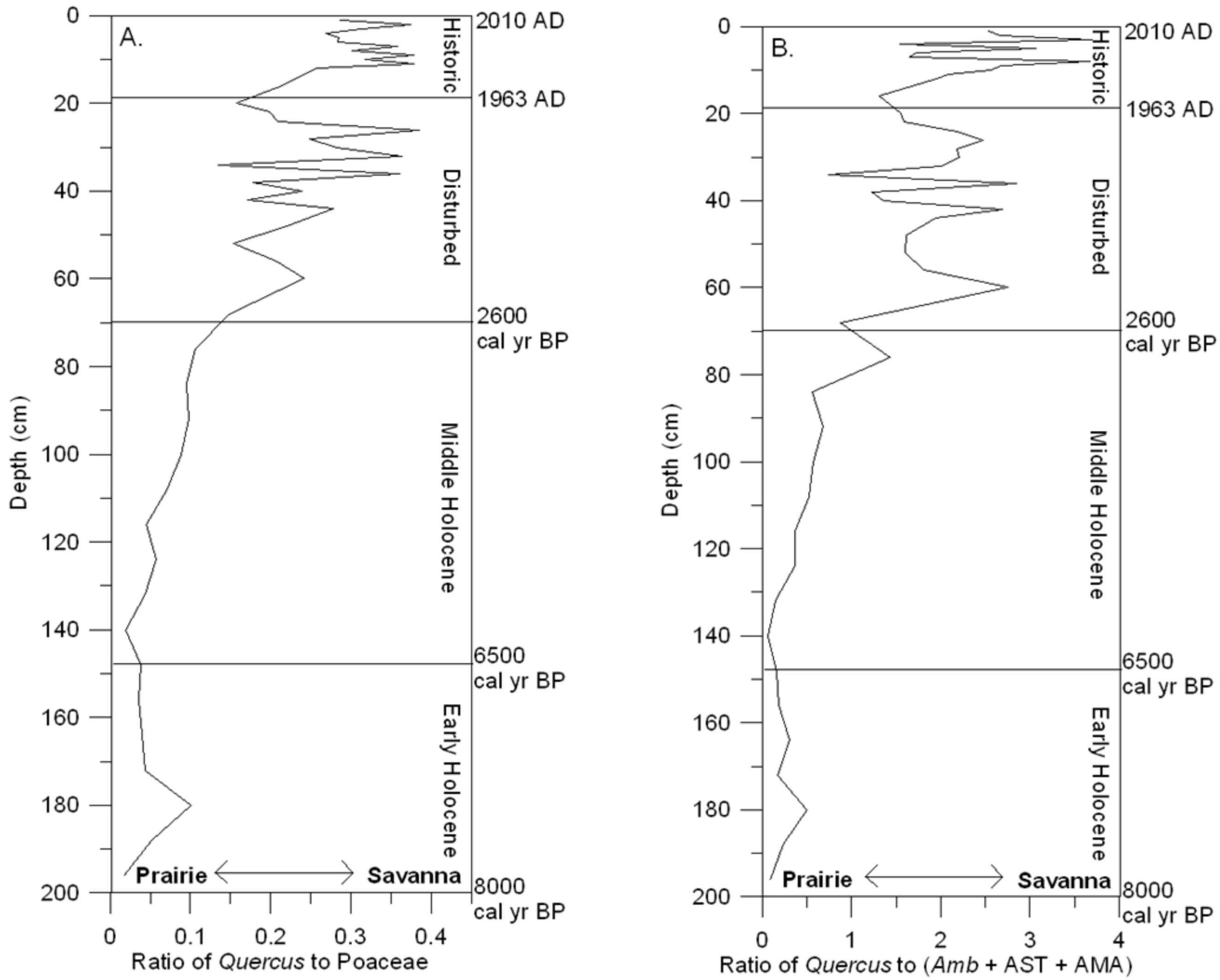


Figure 20: Pollen percentages for Johnson Slough by depth. Grey shadowing represents a five times exaggeration, and dots indicate presence.

Figure 21. Pollen ratios for Johnson Slough. A. Ratios of *Quercus* to Poaceae pollen. B. Ratios of *Quercus* to *Ambrosia,* ASTERACEAE (other), and AMARANTHACEAE pollen. Low values indicate more prairie-like vegetation, while higher values represent more savanna-like vegetation.


A.
Historic
Disturbed
Middle Holocene
Early Holocene
2010 AD
1963 AD
2600 cal yr BP
6500 cal yr BP
8000 cal yr BP
Depth (cm)
Prairie
Savanna
Ratio of Quercus to Poaceae
B.
Historic
Disturbed
Middle Holocene
Early Holocene
2010 AD
1963 AD
2600 cal yr BP
6500 cal yr BP
8000 cal yr BP
Depth (cm)
Prairie
Savanna
Ratio of Quercus to (Amb + AST + AMA)

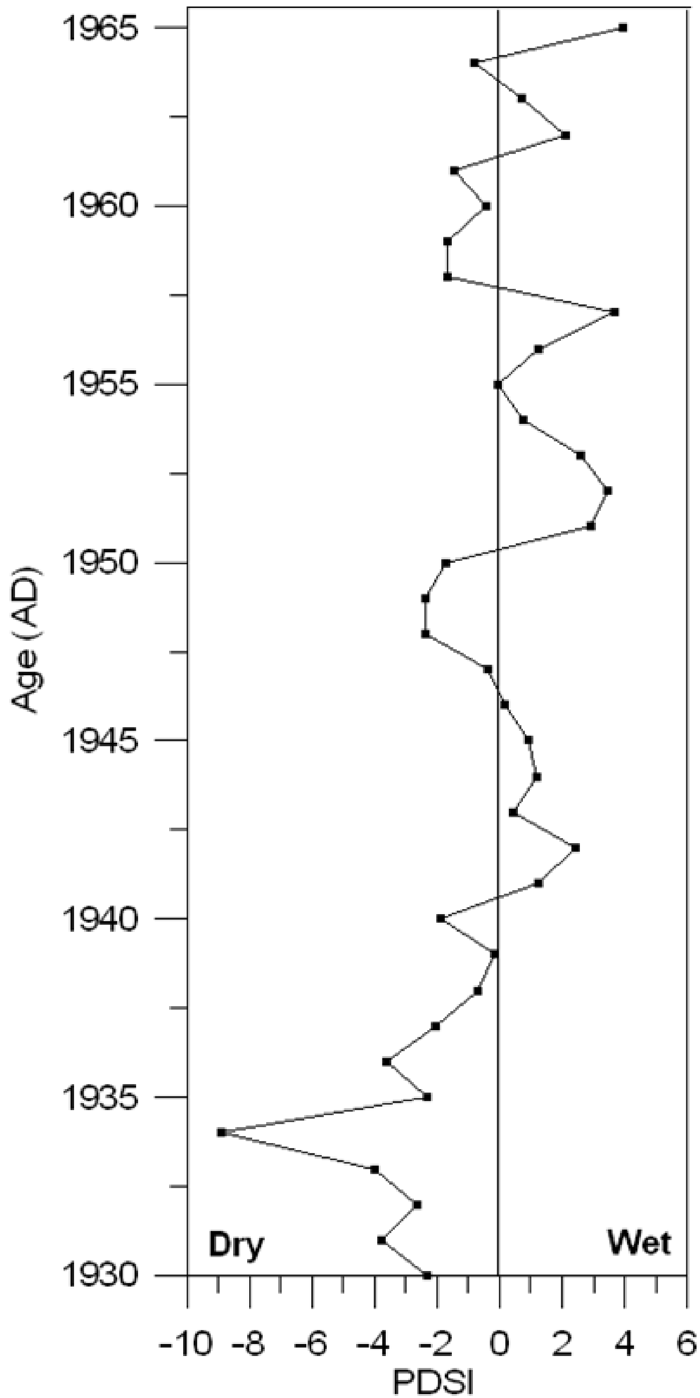


Figure 22. Palmer Drought Severity Index for central Minnesota from 1930 to 1965 AD (state 21, zone 5 – central, www.esrl.noaa.gov). Negative values indicate periods of drought.

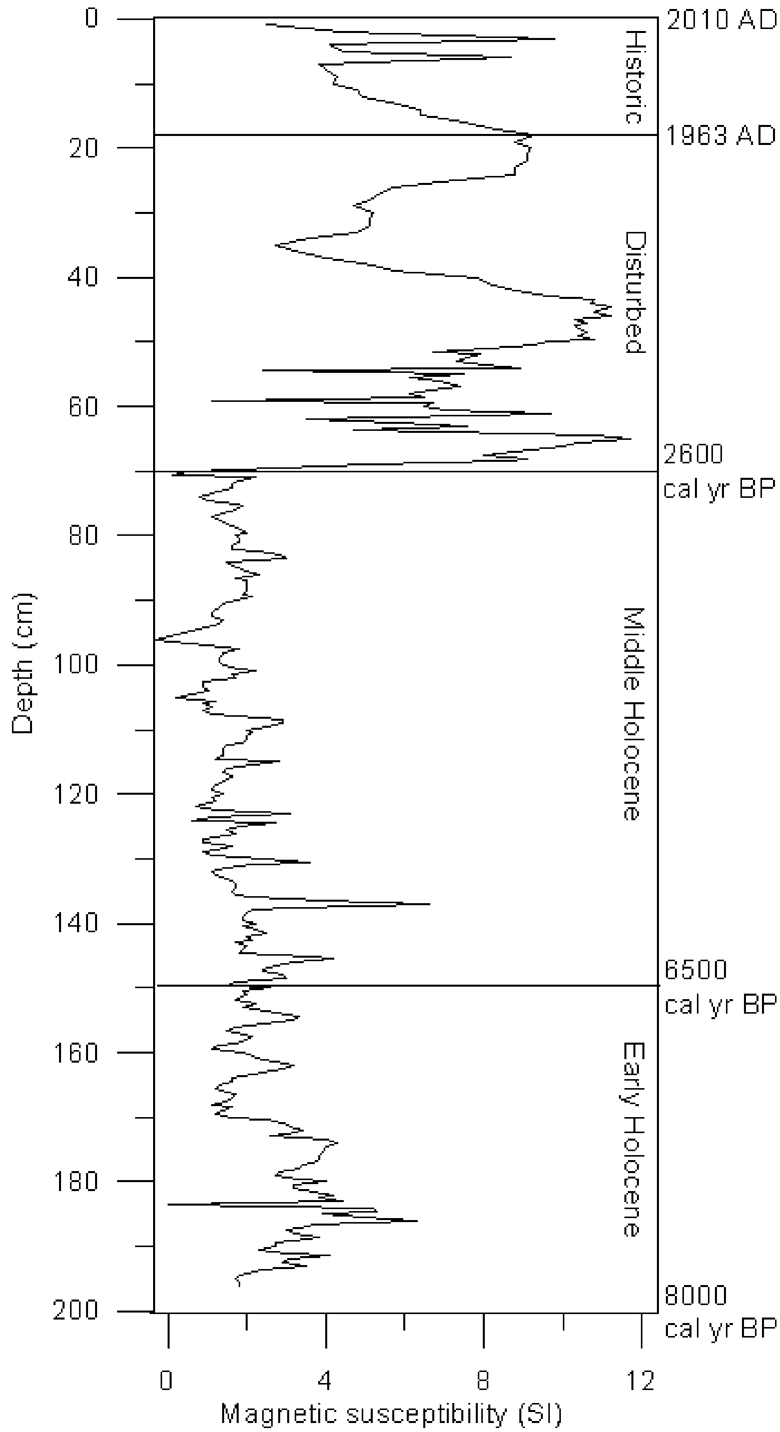


Figure 23. Magnetic susceptibility of Johnson Slough sediments.

CONCLUSIONS

This record reconstructs the development, destruction, and restoration of oak savanna vegetation within SNWR, and estimates the extent and proximity of past fire activity surrounding Johnson Slough over the last ~ 8,000 years. This paleoecological reconstruction agrees with regional records, which indicate an ecological system in which fire activity appears to be predominantly driven by vegetation, and ultimately by climate. Additionally, a unique agricultural disturbance within the refuge was discovered. This study provides a long-term ecological history for SNWR, which can be used in the development and evaluation of restoration strategies for this and similar refuges.

The pollen record for Johnson Slough captures the end of the early Holocene woodlands period on the refuge, as it transitions to prairie vegetation ca. 7500 cal yr BP. A shift to oak savanna vegetation begins ca. 6500 cal yr BP and steadily increases to ca. 2600 cal yr BP. Unfortunately, the continued development and subsequent destruction of the oak savanna within the refuge from ca. 2600 cal yr BP to ca. 1963 AD is distorted in the sediment record, due to possible farming upon the surface of Johnson Slough in the early-mid-1900s AD. Nonetheless, an abrupt reduction in oak savanna vegetation is evident near the end of this period, likely coinciding with the arrival of Euro-Americans to the region in the mid-1800s AD. Finally, since the establishment of the refuge in 1965 AD, the oak savanna is seen to recover within the pollen record, verifying the success of restoration efforts currently underway.

The large-scale transitions in vegetation described above, from woodland to prairie to oak savanna, are likely driven by shifts in climate over the last ca. 8000 years, from cool and wet (woodlands) to warm and dry (prairie) to warm and wet (oak savanna). These climatic and/or vegetational patterns have been recorded in a number of regional records (Wright et al., 1963; Keen and Shane, 1990; Camill et al., 2003; Nelson and Hu, 2008), and are further supported by shifts in aquatic vegetation within the Johnson Slough record.

Fire activity prior to the historic period appears to be driven by shifts in vegetation, and thus fuel production. Sedimentary charcoal concentrations are relatively low during the prairie period and high during the woodland and oak savanna periods, which have higher fuel loads (i.e., trees).

Detailed records of prescribed burning within the historic period reveal that peaks in sedimentary charcoal are the result of fires occurring directly surrounding Johnson Slough. Additionally, peaks in magnetic susceptibility correlate with fires which not only occur in close proximity to Johnson Slough, but which are also widespread throughout the refuge. This information allows for cautious interpretation of peaks within the early-middle Holocene periods of the record, and reveals that large-scale, close proximity fire events appear to have occurred in the early Holocene with a mean fire return interval of 375 years, and within the middle Holocene at a mean fire return interval of 780 years.

The Johnson Slough record adds to the regional collection of paleoecological studies focused on climate, vegetation, and fire activity throughout the Holocene, and provides unique information regarding the ecological history of SNWR. The next step in further understanding the role that fire has played in the oak savanna surrounding SNWR would be to obtain a higher resolution sedimentary record spanning the period which is largely disturbed within the Johnson Slough sediments, from ca. 2600 cal yr BP to present. Lake Ann, a glacial kettle lake located just outside the boundary of SNWR, is the ideal location for this analysis. Sedimentary pollen has been analyzed for this lake by Keen and Shane (1990) and McAndrews (www.neotomadb.org), verifying a higher sediment accumulation rate than Johnson Slough, and the absence of human disturbance to this record. The additional analysis of sedimentary charcoal for Lake Ann could be targeted to the time period of interest, further enhancing the understanding of the maximum extent of the oak savanna surrounding SNWR, and the role of fire therein.

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