A PALEOCLIMATIC INTERPRETATION OF SOUTHEASTERN LOWER MICHIGAN OVER THE LAST 2000 YEARS INFERRED FROM THE FOSSIL POLLEN RECORD OF OTTER LAKE

By

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ABSTRACT

A PALEOCLIMATIC INTERPRETATION OF SOUTHEASTERN LOWER MICHIGAN OVER THE LAST 2000 YEARS INFERRED FROM THE FOSSIL POLLEN RECORD OF OTTER LAKE

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The study of fossil pollen preserved in lakes reconstructs abundance shifts of plant species in response to climate changes, as each species has its particular tolerances for temperature and moisture. Although Michigan has an abundance of inland lakes (~11,000) and hence is a prime area for pollen research, there has been a scarcity of pollen studies, especially in the southeastern portion of the state south of the Tension Zone. Moreover, many of these previous studies were conducted at a poor temporal (centennial) resolution, and therefore do not capture subtle vegetation changes, such as those in response to the Medieval Warm Anomaly (MWA; ~1150-750 cal yr BP) and Little Ice Age (LIA; ~550-150 cal yr BP). The intent of this thesis research was to conduct pollen analysis of a sediment core from Otter Lake, Michigand at high-resolution (~33 years) for the last 2000 years to capture shifts in tree species dominance associated with the MWA and LIA. This research involved several laboratory procedures, which resulted in a pollen diagram that detailed vegetation change over time. The data suggest a weak signal for greater warmth and dryness during the MWA, as evidenced by an increase in the more xeric-adapted *Quercus* (oak) and *Pinus* (pine) at the expense of mesic-adapted species like *Fagus* (beech). A stronger signal was detected for decreased temperatures during the LIA, as indicated by greater abundance of *Pinus* and *Picea* (spruce), but the signals for moisture were conflicting. Dramatic decreases in all tree taxa abundance, along with a seven-fold spike in *Ambrosia* (ragweed), are indicative of land clearing by Euro-American settlers into the area.

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This thesis is dedicated, in loving memory, to my grandfather, Bernard Stachowicz.

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CHAPTER 1: INTRODUCTION

1.1 Forest Dynamics and Climate Change in the Great Lake Region

The Great Lakes region is covered by diverse forest ecosystems that span over 26 million hectares (Peters et al., 2013b). Three major biomes exist within this region (Figure 1.1). The prairie biome of the Great Plains reaches its eastern limit in the western portion of the Great Lakes region (Peters et al., 2013b). The eastern-broadleaf mixed deciduous forest of the southern Great Lakes is composed of tree species such as *Acer saccharum* (sugar maple), *Populus deltoides* (eastern cottonwood), and *Fagus grandifolia* (American beech), which reach their northern range limits at the 43ºN parallel (Roth, 1910; Webb, 1984; Dodge, 1995; Dickman and Leefers, 2003; Kost et al., 2007; Peters et al., 2013b). Northwards of this parallel lies the mixed coniferous-hardwood forest, which is characterized by conifers, such as *Tsuga canadensis* (eastern hemlock) and *Abies balsamea* (balsam fir), and a few cool-temperate hardwoods, like *Betula alleghaniensis* (yellow birch) (Roth, 1910; Webb, 1984; McCann, 1991; Maines and Mladenoff, 2000; Kost et al., 2007; Harman, 2009). The Forest Tension Zone is the term used for the ecotone between the mixed coniferous-hardwood forest and the deciduous forest in the region, which varies in width from ~24 to ~48 km and runs northeast-southwest across the middle of Lower Michigan (Andersen, 2005; Harman, 2009).

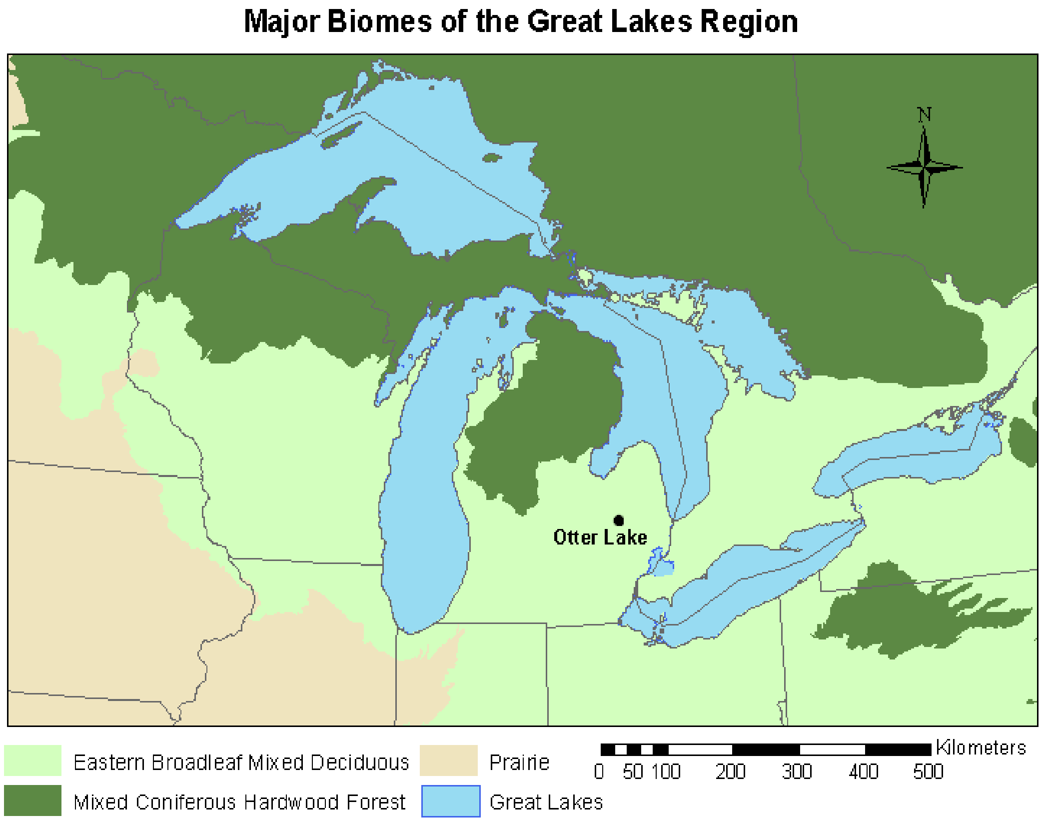

Figure 1.1: The major biomes of the Great Lakes Region. Level I Ecological region data provided by the Environmental Protection Agency, Commission for Environmental Cooperation, North American Atlas. Data accessed from http://www.epa.gov/wed/pages/ecoregions/na_eco.htm#Downloads.

The spatial distribution of the three biomes and the species diversity of the Great Lakes forests are primarily due to the variable climatology of the region, particularly a north-south temperature gradient and lake-effect moisture for those areas close to the Great Lakes (50-80 km downwind, on the leeward side of the lakes) (Braham and Dungey, 1984; Scott and Huff, 1996; Henne et al., 2007; Andresen et al., 2012). Although climate is the main constraint on the species composition on native plant communities and the natural range limits of individual taxon, soil fertility and texture (classified as soil types) can also explain the spatial distribution of tree species in certain circumstances (McKenney et al., 2007; Handler et al., 2012; Peters et al., 2013a). For example, *Populus balsamifera* (balsam poplar) generally thrives in areas where average temperatures generally do not exceed 24ºC and precipitation averages around 1000 mm, conditions inherent to the northernmost portion of the Great Lakes region, but can be found farther south where soil texture is coarser, and hence, well-drained (Prasad et al., 2007; Zasada and Phipps, n.d.).

With widespread Euro-American settlement in the mid- to late 19th century the main control on vegetation shifted from primarily natural causes to human-induced landscape disturbances. Deforestation, agriculture, and urbanization have had a greater impact on the age structure and species composition of the Great Lakes vegetation than natural forces since ~A.D. 1830-1870 (Dickmann, 2009). Pre-settlement plant migration rates have been reconstructed from the radiocarbon dating of pollen records, which suggest that in order to keep pace with currently changing climate trends plants will need to migrate 10-45 km northward per decade this century (Davis, 1989; Honnay et al., 2002; Yansa, 2006). If there were no barriers to tree migration this century, the northern range limit of the broadleaf deciduous forest would probably expand faster, at a rate of 100 km per degree of warming, than would the southern distributional limits for most northern species (Davis, 1989). Hence, in an unimpeded environment, tree species migration could potentially keep pace with gradually warming temperatures predicted to occur this century (Walther et al., 2002; Neilson et al., 2005; Root and Schneider, 2006). However, anthropogenic alteration of the landscape, especially forest fragmentation, will probably hinder this natural migration. Specifically, an expanding human population and the associated greater need of land for agriculture, residential, and industrial uses, create barriers to the spread of tree seeds via wind and animal vectors (Walther et al., 2002; Neilson et al., 2005; Root and Schneider, 2006). These recent and past changes in the species composition and range distribution of forests can be reconstructed from fossil pollen; information that is applicable to studies of future forest shifts this century.

1.2 The Use of Pollen Analysis for Documenting Past Forest Dynamics and Inferring Future Vegetation Changes

Pollen from trees, shrubs and herbs can be deposited by wind or runoff into lakes and other wet environments and subsequently be preserved in these depositional environments (Delcourt and Delcourt, 1980; Holloway and Bryant, 1985). Rapid burial of the pollen grains is crucial to prevent deterioration or corrosion of the individual grains (Delcourt and Delcourt, 1980). As this process of pollen transport and subsequent burial in lacustrine sediments continues over hundreds or even thousands of years, an accurate record of the surrounding vegetation can be studied for any particular area. Specifically, paleoecologists and geographers can extract these fossil pollen records via the collection of lacustrine sediment cores. Then sampling the core at equal intervals, chemically extracting the pollen from the sediments, examining the grains under a high-powered microscope, plotting the pollen data, and obtaining chronologies for these cores allows researchers to produce a fossil pollen record per site, which depicts vegetation shifts through time in that particular area.

Fossil pollen is an excellent proxy for paleoclimate studies because tree species respond to climate influences individually, i.e. on a taxon-by-taxon basis (Von Post 1946; Graumlich and Davis, 1993). Paleoclimate studies based on fossil pollen analysis rely on the correlation between each taxon and a specific climate variable, as each species has its own tolerance range for summer and winter temperatures and precipitation (Graumlich and Davis, 1993; Wahl et al., 2012). For instance, deciduous tree species are positively correlated with warmer temperatures, whereas coniferous taxa have a negative correlation with warm temperatures as they do better in places with a shorter growing season (Harman, 2009). Additionally, increased abundance percentages of certain taxa like *Betula* (birch), *Acer* (maple), and *Fagus* (beech) are indicative of mesic environments, while greater numbers of *Quercus* (oak) would suggest more xeric conditions and/or sandy soils (Hupy and Yansa, 2009a,b). Consequently, the possible influence of soil texture must be isolated when interpreting paleoclimate signals from fossil pollen, and anthropogenic factors must be considered as the main control on vegetation after the onset of Euro-American logging and settlement. The most difficult of these factors to interpret is the influence of soil texture, as xeric-adapted species can thrive in moist environments if the soils are coarse-grained. Coarse-grained soils allows precipitation to percolate through the soil column and reach the water table faster than fine-grained soils, which retain more moisture and have a higher recharge rate (Zhang and Schilling, 2006).

In the Great Lakes region there have been several prior fossil pollen studies that have inferred past climate conditions (Manny et al., 1978; Ahearn and Bailey, 1980; Bartlein et al., 1984; Graumlich and Davis, 1993; Delcourt et al., 2002; Booth and Jackson, 2003; Davis et al., 2005; Hupy and Yansa, 2009a; Booth et al., 2012, and others). These pollen data, in conjunction with geomorphic and other paleoenvironmental data, suggest that the Laurentide Ice Sheet began to recede from the southern Great Lakes region by 19,500 cal yr BP as temperatures started to increase, and by 10,000 cal yr BP the ice sheet was located in southern Canada while temperatures had risen 3 or 4ºC (Hu et al., 1997; Viau et al., 2006). The first vegetation to colonize this vacant landscape was tundra, followed by a boreal-type forest, forest (Kerfoot, 1974; Yu, 2000). Later, around 10,000 cal yr BP, soon after the onset of the Holocene interglaciation, this vegetation was succeeded by mixed coniferous-deciduous forest, consisting of the more temperate-adapted *Pinus* and deciduous tree taxa, including *Quercus*, *Ulmus* (elm), *Carya* (hickory), *Fagus*, and *Acer* (e.g., Kerfoot, 1974; Ahearn and Bailey, 1980). During the Hypsithermal Period, or Holocene Climate Optimum deciduous forest prevailed in southern Lower Michigan where *Quercus* was the dominant species, followed by *Fagus*, which suggest that warm and mesic conditions, respectively, were present in the Great Lakes region from ~9500 to 6000 cal yr BP (Manny et al., 1978; Ahearn and Bailey, 1980; Holloway and Bryant, 1985; Davis et al., 1986). Over time drier conditions prevailed, persisting for most of the mid-Holocene, as evidenced by an abundance shift from more mesic trees, such as *Fagus* and *Acer*, to greater numbers of xeric-tolerant species like *Quercus* (Ahearn and Bailey, 1980; Booth et al., 2002; Sawada et al., 2004; Booth et al., 2005; Finkelstein and Davis, 2006).

During the Late Holocene, cooler and xeric conditions became more prevalent (Manny et al., 1978; Booth et al., 2006). This is evidenced by an abundance decline of mesic species, most notably that of *Fagus*, and an increase in the drier adapted species like *Carya* and *Quercus* (Manny et al., 1978; Booth and Jackson, 2003; Booth et al., 2004; Nelson et al., 2010).The Medieval Warm Anomaly (MWA; ~1150 – 750 cal yr BP) was a time of a slight temperature increase in many parts of the world, which in the Great Lakes region was evident by the expansion of *Pinus* (pine) and other taxa adapted to warm-dry conditions (Booth and Jackson, 2003; Booth et al., 2012; Wahl et al., 2012). In contrast, the Little Ice Age (LIA; ~550-150 cal yr BP) was a period of global temperature decrease (Campbell and McAndrews, 1993; Soon and Baliunas, 2003; Jones and Mann, 2004). While some studies in the Great Lakes region suggest that this was also a time of greater effective moisture, that is the amount of water available in the soil that can be used by plants (Ahearn and Bailey, 1980; Booth and Jackson, 2003), other studies provide contradictory signals, that of more moist conditions (e.g., Manny et al., 1978).

Ambiguities and uncertainties in interpreting some of the paleoclimate signals from pollen studies previously conducted in the Great Lakes region reflect limitations in this regional dataset, including the coarse temporal resolution of several pollen studies, particularly those done in the 1960s-1980s, which may have missed or inadequately documented key paleoclimate intervals. While the pollen studies investigated in the last few decades have more accurate and finer temporal resolution, the spatial distribution of these study sites is uneven, with notable gaps in the coverage for the Great Lakes region. Numerous pollen studies are required for any region, because of pollen "rain" deposition, where the pollen deposited in a small lake comes from the vegetation within a ~20-30 km radius (Jacobson and Bradshaw, 1981), hence, a large network of pollen sites is required to capture the range of natural variability in forest habitats in the region. Thus, there is need for more high resolution studies within the Great Lakes region, including those for southern Lower Michigan that span the MWA and LIA to improve sub-regional paleoclimate interpretations.

1.3 Problem Statement

Even though there have been several prior pollen studies in the Great Lakes region, and Michigan has an abundance of inland lakes (~11,000), there has been a scarcity of pollen studies in Lower Michigan, especially in the southeastern portion of the state. Specifically, there have been only two prior pollen studies in the southeastern area of Lower Michigan, both of which were carried out on bogs. The first pollen study was conducted at Chippewa Bog in Lapeer County, by Ahearn and Bailey (1980), while the more recent study was completed at Minden Bog in Sanilac County (Booth and Jackson, 2002). This makes Otter Lake, located along the northern border of Genesee and Lapeer counties, the first lake to be studied in this corner of Lower Michigan, and hence situated in a prime location to provide a paleoclimate study.

Specifically, my high-resolution study will enhance the knowledge of past vegetation changes in response to both the Medieval Warm Anomaly (MWA; ~1150-750 cal yr BP) and the Little Ice Age (LIA; ~550-150 cal yr BP) in this area of the state. My study will not only provide paleoclimate information that fills a paleodata gap, but could potentially be useful to local farmers, government scientists, and other residents.

Several of the prior pollen studies conducted in Lower Michigan, and elsewhere in the Great Lakes region, were done at low temporal-resolution, 100-500 years between samples analyzed, which reconstructed extremely coarse changes in vegetation over past millennia. Pollen analysis at centennial to multi-centennial scales would miss most or all of the MWA or LIA, and hence provide data of very limited paleoclimate value. My high-resolution pollen analysis of Otter Lake will capture these two climatic events on a multi-decadal (~33 year) timescale, which will improve our understanding of the influence of climate on tree species in southeastern Lower Michigan, especially before, during and after the MWA and LIA. Also, Otter Lake is situated 64 km south of the southernmost limit of the mixed coniferous-deciduous forest (i.e., the Forest Tension Zone) and, therefore, an increase in conifer taxa in my pollen recorded would suggest past episode(s) of regional cooling. Hence, my pollen study of Otter Lake will be (1) comparable in its temporal reconstruction to the 30-year climate averages used in climate change research, and (2) provide a more accurate record of past vegetation responses to climate changes that can provide data relevant to studies of future forest dynamics in the region. My pollen study hence will provide a small, but important, contribution to the overall knowledge concerning climate change and associated impacts on vegetation in southeastern Lower Michigan over the last two millennia.

1.4 Research Objective and Questions

The objective of this research is to conduct a high-resolution (~33 year) pollen analysis study of Otter Lake, Michigan over the last 2000 years. Fossil pollen grains recovered from a sediment core previously collected from the deepest part of this lake were analyzed using standard laboratory methods and identified under a high-powered compound microscope. The chronology was based on a1 mm varve chronology prepared by Dr. Chad Wittkop (2004) during his dissertation research. My research will specifically address the following questions:

1. *What was the species composition of the vegetation surrounding Otter Lake prior to the onset of the Medieval Warm Anomaly (MWA; ~1150-750 cal yr BP)?*

The fossil pollen record from ~2000 to 1150 cal yr BP will provide the background context in which to evaluate the subsequent vegetation changes during the MWA. By looking at other pollen records in the region, I predict that during this time interval there would be greater abundance of mesic taxa, such as *Fagus*, than later during the MWA.

2. *What changes, if any, occurred in the vegetation surrounding Otter Lake during the MWA?*

The fossil pollen record generated from Otter Lake should clearly show an abundance increase in drought-tolerant species like *Pinus* and *Quercus* during the MWA, and a corresponding pronounced decline in the numbers of mesic-adapted taxa, such as *Fagus*. The changes in these species would provide definitive proof that xeric conditions prevailed in southeastern Michigan from ~1150-750 cal yr BP (as soil texture wouldn’t change at the site, so can be eliminated as a causal mechanism).

3. *Did the vegetation in the vicinity of Otter Lake change (shift in tree dominance) in response to the Little Ice Age (LIA; ~550-150 cal yr BP)?*

After the onset of the Little Ice Age, around 550 cal yr BP, the fossil pollen record should clearly show a pronounced pollen spike in *Betula* and *Acer*. Increases in these species would confirm that more mesic hydrologic conditions returned to Lower Michigan. Also there should be an abundance increase in conifer taxa, such as *Picea* (spruce) and *Abies* (fir), as they are found today in the mixed coniferous-deciduous forest north of my study site.

4. *Can a distinction be made between temperature and hydrological constraints on these vegetation changes?*

Certain species are better indicators for each of these variables than others, making the overall interpretation somewhat challenging. However, pollen abundance increases in *Fagus*, *Juglans* (walnut), and *Alnus* (alder) would suggest that both temperature and precipitation were increasing even in the presence of well-drained soils. Conversely, increased abundance of *Quercus* and *Pinus* have to be interpreted carefully as they could indicate dryness, but they can also be abundant in more mesic environments if the soils are sandy, hence well-drained, that creates dry soil conditions. Also, *Pinus* species in Michigan are northern taxa, restricted to the Tension Zone and the coniferous-deciduous forest, and so a greater abundance of pine can indicate lowering of temperatures. The appearance of *Picea* and *Abies* in the pollen record more strongly suggests that the climate was becoming cooler as they are native to the coniferous-deciduous and boreal forests.

5. *Does the pollen profile also reflect the onset and intensity of Euro-American settlement near Otter Lake?*

The pollen record should show a dramatic increase in the weedy taxon *Ambrosia*, which is indicative of land disturbance. There should also be a dramatic increase in other herbaceous taxa and corresponding decrease in tree pollen types which would have resulted from widespread land clearing carried out by Euro-American settlers in Lower Michigan.

1.5 Outline of Thesis

This thesis consists of five additional chapters. Chapter Two provides a literature review pertinent to pollen analysis as a proxy for paleoclimate studies and details the climate fluctuations known for the Holocene. Chapter Three includes a description of the study site. Chapter Four presents a synopsis of the materials and methods used in this thesis research. This work was conducted in several stages both in the field and in the laboratory. First, an overview of the sediment core extraction from 1999 is presented, followed by a description of my pollen analysis. Chapter Five presents the results of pollen analysis as well as an interpretation of the zones within the reconstructed pollen diagram. Chapter Six is a discussion of the results and includes a comparison of the pollen record of Otter Lake to the records of other sites in the region previously investigated by other researchers. Finally, a conclusion for the entire study is provided in Chapter Seven.

CHAPTER 2: LITERATURE REVIEW

2.1 Pollen as a Proxy for Paleoclimatic Studies

Several palynologists have previously analyzed fossil pollen extracted from lake and wetland sediments to infer past climate conditions in the Great Lakes region (Potzger, 1948; Manny et al., 1978; Ahearn and Bailey, 1980; Bartlein et al., 1984; Graumlich and Davis, 1993; Kapp, 1999; Delcourt et al., 2002; Booth and Jackson, 2003; Davis et al., 2005; Hupy and Yansa, 2009a,b; Minckley et al., 2011; Booth et al., 2012). Plant pollen is an excellent proxy for paleoclimate studies because tree species respond to climate influences individually, i.e., on a species-by-species basis (Von Post 1946; King and Graham, 1981; Graumlich and Davis, 1993; Davis et al., 2005; Minckley et al., 2011). Paleoclimate studies based on fossil pollen rely on the correlation between a specific taxon and a particular climate variable, usually temperature (Graumlich and Davis, 1993; Wahl et al., 2012). For instance, broadleaf deciduous (hardwood) tree species are positively correlated with warmer temperatures whereas coniferous (softwood) taxa have a negative correlation. Additionally, increased pollen percentages of certain taxa like *Betula* (birch), *Acer* (maple), and *Fagus* (beech) are indicative of mesic habitats, while greater abundance of *Quercus* (oak) and *Pinus* (pine) could indicate more xeric conditions and/or the local prevalence of well-drained sandy soils (Hupy and Yansa, 2009a).

Detailed knowledge of pollen production, dispersal and preservation is required to interpret paleoclimate signals from fossil pollen data. Most of the pollen grains deposited in lakes, swamps and acidic bogs are wind-blown, but some can result from slope runoff or the inflow of streams into basins (Delcourt and Delcourt, 1980; Holloway and Bryant, 1985). Rapid burial of the pollen grains in anoxic sediments below the water table is crucial to prevent deterioration or corrosion of the individual grains, as they undergo fungal and bacterial decay when exposed to air (Delcourt and Delcourt, 1980; Holloway and Bryant, 1985). As this process of pollen transport and subsequent burial in sediment under the water table continues over hundreds or even thousands of years, an accurate record of the surrounding vegetation can be reconstructed via pollen analysis for any particular area.

Paleoecologists extract fossil pollen records via the collection of lacustrine sediment cores. The two most common samplers are a Livingstone piston corer to extract lake-bottom sediments and a Russian peat sampler to collect cores of peat and muck from wetlands. Given that the length of the coring devices are only 1.0 (Livingstone corer) or 0.5 m (Russian peat corer) long, researchers have to collect multiple drives of sediment from the same coring hole and carefully label these cores to keep them in a stratigraphic context. Sediment cores are extruded in the field into longitudinally-split PVC tubes, wrapped in plastic wrap followed by tinfoil, and labeled.

In the laboratory, pollen samples (volume of 1 cm^3) are taken from the longitudinally split sediment core, and then the pollen grains are chemically extracted from the sediment. Microscopic counting and identification of fossil pollen along with construction of a chronology for the core based on radiocarbon dating and/or annual sediment varves allows researchers to reconstruct past vegetation shifts through time. There are several caveats in interpreting fossil pollen data, elucidated by studies of modern pollen production and dispersal including (1) some wind-pollinated species overproduce pollen as compared to their representation in a local flora, such as *Pinus*, which produces on average four times more pollen than its presence in the surrounding vegetation leading to overrepresentation in the pollen record (Davis et al., 1986; Molina et al., 1996). (2) The fossil pollen profile cannot distinguish between small nearby populations and larger populations that are farther away, especially if species farther away are high pollen producers like *Pinus* and *Quercus* (Delcourt and Delcourt, 1980; Bartlein et al., 1986; Davis et al., 1986). (3) The pollen of certain taxa, such as *Larix* (tamarack) and especially *Populus* (poplar/cottonwood), are very fragile and can deteriorate during transport and hence are under-represented in pollen records, whereas conifer pollen grains are very resilient (Holloway and Bryant, 1985). (4) Wind-pollinated species, such as *Ambrosia* (ragweed) and the conifers, produce significantly more pollen than insect-pollinated types, such as those in the Fabaceae (legume) family (Herrera et al., 1998). And (5) many pollen grains can only be identified to the genus level, a few as coarsely as at the family level, and as such it cannot be ascertained for many what particular species the pollen grains represent (Cain, 1940; Pant, 1954). Consequently, the taxonomic precision of a paleovegetation, and by inference, paleoclimate reconstruction is limited (Davis et al., 1991). Therefore, all of these limitations must be considered when palynologists interpret pollen diagrams, but despite these weaknesses meaningful paleoclimate information can still be obtained.

While many fossil pollen studies have been carried out in the Great Lakes region (Potzger, 1948; Manny et al., 1978; Ahearn and Bailey, 1980; Bartlein et al., 1984; Graumlich and Davis, 1993; Kapp, 1999; Delcourt et al., 2002; Booth and Jackson, 2003; Davis et al., 2005; Hupy and Yansa, 2009a,b; Minckley et al., 2011; Booth et al., 2012), only two have been conducted in the southeastern portion of the Thumb of Lower Michigan and these were done on bogs (Ahearn and Bailey, 1980; Booth and Jackson, 2003; Booth et al., 2012). This makes my pollen study of Otter Lake, located along the northern border of Genesee and Lapeer counties, somewhat unique as it fills a spatial gap in the pollen data coverage of southeastern Lower Michigan, and is the first in this part of Michigan that was conducted on a lake. Moreover, my research was conducted at a very fine temporal scale for pollen studies and thus provides the most robust paleoclimate record derived from pollen in southeastern Lower Michigan. Hence, my study will enhance the knowledge on past vegetation patterns that responded to the Medieval Warm Anomaly (MWA; ~1150-750 cal yr BP) and the Little Ice Age (LIA; ~550-150 cal yr BP) in this area of the state. These paleoclimate signals have been detected from the pollen study of Minden Bog (Booth and Jackson, 2003), located ~64 km northeast of Otter Lake, and Chippewa Bog (Ahearn and Bailey, 1980), situated ~23 km southeast of Otter Lake, and hence the trends in these pollen records are hypothesized to have also occurred at Otter Lake. Any difference in the pollen spectra between sites may reflect local variations in soil texture, as “xeric” taxa such as *Quercus* and *Pinus* can prevail in a locale with a mesic climate if the soils are sandy. This becomes especially important as both Minden and Chippewa bogs are surrounded by more fine-grained soils as opposed to Otter Lake which has an abundance of coarser-grained soils.

The fossil pollen record generated from Otter Lake should clearly show an abundance increase (i.e., higher pollen percents) of drought tolerant species, such as *Pinus* and *Quercus*, and conversely a pronounced decrease in mesic taxa like *Fagus* during the MWA. A signal for warmer temperatures during the MWA compared to before (Neoglacial, which started ~3200 cal yr BP) and after (just before and during the LIA), would be interpreted from higher pollen percents for taxa of southern affinities, the broadleaf deciduous taxa, and declines in the values for the northern taxa, such as *Larix* (tamarack), *Picea* (spruce), and *Tsuga* (hemlock). Peak pollen abundance of the cooler-adapted (northern) taxa should occur during the LIA (550 - 150 cal yr BP), and key taxa can identify if this climate episode was wetter (more swamp taxa) or drier (more pine and oak). Comparison of the pollen record of Otter Lake to those of other studies in the region will be key in discerning which patterns are indicative of climate, i.e., those trends in the pollen data that are similar between sites, vis-à-vis those that are not similar, therefore could be explained by the influence of local soil and hydrologic conditions. This study will produce only a small, but important, contribution to the overall knowledge concerning climate change in southeastern Lower Michigan over the last two millennia. Moreover, the sampling resolution of this study of Otter Lake is of much higher resolution, averaging 33 years, than most prior pollen studies conducted in Michigan, when averaged over a century (Potzger, 1948; Manney et al., 1978; Ahearn and Bailey, 1980; Graumlich and Davis, 1993; Woods and Davis, 1989; Kapp, 1999; Delcourt et al., 2002). Hence the paleovegetation data obtained in this study provide a precision on par with 30-year climate averages, facilitating pollen-inferred paleoclimate interpretations.

2.2 Holocene Climate

The recession of the Laurentide Ice Sheet margin out of the United States and into Canada, and the extinction of many Pleistocene megafauna, are some of the markers for the geologic boundary between the Pleistocene and the Holocene at ~11,400 cal yr BP. Climatic shifts that occurred during this transition are on the order of five times the magnitude of climatic changes we are currently experiencing (Parmesan, 2006). This difference is explained by orbital changes in insolation for this glacial-interglacial cycle which peaked at ~9000 cal yr BP (Kutzbach et al., 1989), shortly after the onset of the Holocene, which explains the current warm phase of climate on Earth (Hu et al., 1997; Viau et al., 2006). The Laurentide Ice Sheet retreated from southern Lower Michigan beginning at 17,000 cal yr BP, reached the Upper Peninsula of Michigan at 11,000 cal yr BP, and from there retreated north to finally disintegrate in the Hudson Bay area of Canada at about 7800 cal yr BP (Wanner et al., 2008; Hupy and Yansa, 2009b). The rate of temperature increase during the retreat of the Laurentide Ice Sheet was on the order of 3-4ºC from 14,000 cal yr BP to 10,000 cal yr BP (Yu, 2000; Viau et al., 2006).

Evidence of large scale climatic fluctuations is found in the oxygen isotope records of the Greenland Ice Cores and from oceanic sediment cores of the Atlantic Ocean (Riebeek, 2005; Viau et al., 2006). Based on these records alone, there appears to be a cyclical pattern of climatic changes, occurring roughly every 1500 years, throughout the Holocene (Viau et al., 2006).The vegetation record of southern Lower Michigan, though sparse, also allows inferences to be made as to the significant climatic changes that have occurred since deglaciation. The first vegetation that colonized the deglaciated landscape of Michigan and elsewhere in eastern North America was tundra, followed by a spruce parkland-sedge wetland in a swampy landscape created by the melting ice (Yansa, 2006; Hupy and Yansa, 2009b). As the climate warmed, deciduous species, like *Quercus* (oak), *Ulmus* (elm), *Carya* (hickory), and *Acer* (maple) first appear in the pollen record of Lower Michigan at 11,000 cal yr BP, accompanying a large abundance of *Pinus* (pine), most likely *P. banksiana* (jackpine), the coldest adapted of the pine species (Kerfoot, 1974; Ahearn and Bailey, 1980; Yu, 2000). The influx of *Pinus strobus* (white pine) into southern Lower Michigan beginning 10,200 cal yr BP is indicative of a warm and dry or well-drained environment (Manny et al., 1978; Ahearn and Bailey, 1980).

The warmest and driest interval of the Holocene, evidenced by peak abundance of *Quercus* and some prairie herbs, occurred during the Early Holocene and is known as the Hypsithermal Period, or Holocene Climate Optimum, which persisted from ~9500 to 6000 cal yr BP (Webb, 1974; King, 1981; Graumlich and Davis, 1993). Temperature increased by an estimated 1ºC from 9500 to 8000 cal yr BP, followed by a gradual mean temperature decrease until 6000 cal yr BP, as interpreted from tree-ring (Goldblum and Rigg, 2005) and pollen data (Viau et al., 2006). At ~8000 cal yr BP, *Fagus*, *Juglans*, *Tsuga* and several other mesic taxa increased in abundance, indicating greater precipitation in Lower Michigan than before (Manny et al., 1978; Ahearn and Bailey, 1980; Holloway and Bryant, 1985). The abundance of *Fagus* and other mesic taxa, which peak at ~7000 cal yr BP, suggest that the Hypsithermal in Lower Michigan was not xeric (Holloway and Bryant, 1985; Davis et al., 1986; Woods and Davis, 1989), whereas it clearly was in Indiana and Illinois and farther west (Barlein et al., 1984; Yansa, 2007).

The Middle Holocene, from ~6000 to 3200 cal yr BP, is characterized by oscillations between mesic and xeric conditions in the Great Lakes region, although abrupt fluctuations are not as evident during this time as compared to the Early Holocene (Booth et al., 2005; Viau et al., 2006). Maximum July temperatures at this time were analogous to those of today (Sawada et al., 2004). What distinguishes the Middle Holocene from the climate of today was a tendency towards drier conditions, including some drought intervals, as evidenced by proxies indicative of lower lake levels and taxonomic changes in the fossil pollen profiles throughout the region. Specifically, these profiles imply a transition towards greater abundance of more xeric tolerant species, such as *Quercus*, *Carya*, and herbs, especially in southern Michigan (Ahearn and Bailey, 1980; Booth et al., 2002; Sawada et al., 2004; Booth et al., 2005; Finkelstein and Davis, 2006). At this time, oak savanna and oak-dominated forest expanded in its areal coverage in southern Lower Michigan at the expense of beech-maple forest (Booth et al., 2002).

A megadrought has been identified in fossil pollen and isotopic data from lake sediments to have occurred throughout the region at ~4500 to 4000 cal yr BP (Graumlich and Davis, 1993; Booth et al., 2005; Finkelstein and Davis, 2006). At this time, spikes in *Quercus* and *Ambrosia* (ragweed) pollen reach their maximum for the Holocene, indicating extremely dry conditions (Booth et al., 2005).

By 3200 cal yr BP, the onset of the Late Holocene, mesic conditions largely returned to southern Lower Michigan as the patches of oak savanna diminished with greater abundance of mesic forest composed of *Fagus*, *Ulmus*, *Acer* and other trees (Booth et al., 2002; Finkelstein and Davis, 2006). Although mesic conditions characterize the Late Holocene, there are intervals of xeric conditions, but these were not as severe as those during the Middle Holocene (Manny et al., 1978; Booth et al., 2006b; Minckley et al., 2011). Pollen data from multiple sites in Lower Michigan, including the records from Wintergreen Lake (Kalamazoo County), Chippewa Bog (Lapeer County), and Minden Bog (Sanilac County) present evidence for increased precipitation at ~2300-2000 cal yr BP, as evidenced by peak pollen values for *Fagus* (Manny et al., 1978; Ahearn and Bailey, 1980; Jackson and Booth, 2002; Minckley et al, 2011).

Soon after *Fagus* reached its maximum abundance at ~2000 cal yr BP, this species was replaced, in part, by *Quercus* and *Carya* in the vicinity of Wintergreen Lake, Chippewa Bog, and Minden Bog, which suggests a shift to drier conditions again in southern Lower Michigan (Manny et al., 1978; Ahearn and Bailey, 1980; Holloway and Bryant, 1985; Booth and Jackson, 2003; Booth et al., 2004; Nelson et al., 2010; Minckley et al., 2011). Drier conditions prevailed in southern Lower Michigan for the next 1000 years.

Four major climatic oscillations occurred from 1200 cal yr BP until the present. The first, known as the Medieval Warm Anomaly (MWA), or Medieval Climate Anomaly, was a time of global temperature increases that began ~1150 cal yr BP and lasted until 750 cal yr (Lamb, 1965; Hughes and Diaz, 1994; Cronin et al., 2003; Mann and Jones, 2003) though data is lacking as to the exact extent of warming, especially in regards to Lower Michigan. There are some variations in the end and start dates for the MWA assigned by researchers, but I use here the dates from Mann and Jones (2003), as they are the most commonly used by other researchers. In southern Lower Michigan, pollen records imply that more xeric conditions were present during the MWA, as evidenced by an increased abundance of *Pinus* pollen at the expense of *Fagus*, with drier conditions peaking at around 1000 cal yr BP (Ahearn and Bailey, 1980; Booth and Jackson, 2003; Minckley et al., 2011; Booth et al., 2012; Wahl et al., 2012). This shift in the climate has been attributed to a greater frequency of La Niña events in the equatorial Pacific Ocean, which today are associated with increased temperatures and decreased precipitation during summers in the Midwest (Kumar et al, 2000; Wahl et al., 2012). In the vicinity of Wintergreen Lake, the vegetation stabilized by 1000 cal yr BP as the pollen record of this lake indicated that the *Quercus-Fagus* forest did not change in its taxonomic composition until the onset of Euro-American settlement (Manny et al., 1978).

The second major transition in climate, the Little Ice Age (LIA), occurred between ~550-150 cal yr BP and was a time of global temperature decrease (Hughes and Diaz, 1994; Russel and Davis, 2001; Mann and Jones, 2003). The drop in temperature between the MWA and LIA may have been as little as 1ºC, but the response of alpine glaciers, vegetation, and other components of the environment were quite dramatic (Booth and Jackson, 2003; Soon and Baliunas, 2003; Jones and Mann, 2004). A lack of high-resolution pollen studies in Lower Michigan hinders the exact reconstruction of the vegetation changes that occurred during the LIA. However, a low-resolution pollen study of Chippewa Bog reports a slight population increase of *Fagus* and a greater abundance of *Quercus* during this time (Ahearn and Bailey, 1980). This change is also evident in pollen studies from southern Ontario where *Fagus* abundance decreases considerably coinciding with increases in both *Pinus* and *Quercus* (Campbell and McAndrews, 1993). This could be inferred as a change from warm, xeric conditions to cooler, mesic conditions. High-resolution pollen and testate amoeba data from

Minden Bog, ~64 km northeast of Otter Lake, show that *Fagus* pollen values remained constant during this time, while those of the northern conifers *Tsuga* and *Picea* increased suggestive of a cooling trend (Booth and Jackson, 2003; Minckley et al., 2011).

Temperature and precipitation patterns during the LIA and the earlier MWA varied at local and regional scales, with some conflicting data regarding moistures levels during these intervals (Lamb, 1965; Bradley et al., 2003; Soon and Baliunas, 2003; Graham et al., 2011; Booth et al., 2012; Wahl et al., 2012). Hence, my study of Otter Lake provides another paleoclimate record that can improve our understanding of relative moisture levels during these prior climatic intervals. Also, noteworthy is that between the MWA and the LIA there was a 200 year interval where, in some places, an intense drought has been recorded, but not in other pollen records, especially those from Lower Michigan (Booth et al., 2006b). One explanation for this inconsistent climate signal during this interval from 750-500 cal yr BP is the resolution of pollen samples analyzed, as some of the earlier studies were done at centennial or multi-centennial scales, and therefore missed this interval. Euro-American logging and settlement of Michigan occurred during the latter part of the LIA, which is clearly evident in pollen records by a dramatic decrease in tree pollen and phenomenal spikes in the pollen of *Ambrosia* (ragweed), other herbs and grasses, including *Zea mays* (corn) (Manny et al., 1978; Ahearn and Bailey, 1980; Booth and Jackson, 2003). These changes in the pollen profiles are hence not attributed to climatic change, but rather to anthropogenic disturbances of the landscape.

CHAPTER 3: STUDY AREA

3.1 Location of Otter Lake

Otter Lake (43°13’07” N, 83°27’37” W, at its center, elevation of 260 meters above sea level, m asl) is a medium-sized (0.21 km^2 or 27.5 Ha) kettle lake located in southeastern Lower Michigan, located close to a small town that bears its name (Figure 3.1; www.lapeer.org; Wittkop, 2004). Otter Lake is 1.6 km across, at its widest point, and consists of two sub-basins which are separated by a sill (Wittkop, 2004). Otter Lake is situated across the border of Genesee and Lapeer counties. Currently, Otter Lake is surrounded by small homes on its southeastern, southern, and southwestern sides, with an operational public campground on its eastern side.

Figure 3.1: Location of Otter Lake (purple dot).

3.2 Geology, Topography, and Soils

Michigan is located in the physiographic region of the United States known as the Central Lowlands (Thornbury, 1965; Larson and Schaetzl, 2001; Blewett et al., 2009). The general topographic profile of the state has a gentle gradient from southeast Lower Michigan (~174 m asl) to the northwest (~500 m asl) (MI DEQ, 2012).The underlying bedrock of Lower Michigan consists of sedimentary layers, predominately sandstone and carbonate rock, which were deposited during the Paleozoic Era (Dorr and Eschman, 1970; Larson and Schaetzl, 2001; Blewett et al., 2009; Kehew et al., 2011).

The topographic features of this area are a direct result of the multiple advances and retreats of the Laurentide Ice Sheet. Specifically, this glacier carved out and eroded the softer bedrock like shale and gypsum to form the geomorphic features of the Michigan Basin which were then overlain by Quaternary sediments (Thornbury, 1965; McCann, 1991; Larson and Schaetzl, 2001; Blewett et al., 2009). During the multiple stages of growth and retreat of the Laurentide Ice Sheet, parent materials were transported into Lower Michigan from northern areas of the Canadian Shield (Schaetzl, 2009). This parent material, consisting of sandstone, limestone, and hard metamorphic and igneous rock types, was eroded to form various sediments that became the parent material for the different soils of Lower Michigan (Door and Eschman, 1970; Schaetzl, 2009). The current topography of this area reflects the final retreat of the Laurentide Ice Sheet during the Late Wisconsinan glaciation, which receded from Lower Michigan between 17,000 cal yr BP at the southwest corner of the state to 10,000 cal yr BP at the Mackinaw Straits (Larson and Schaetzl, 2001).

Glacial landforms that comprise the topography of Lower Michigan include, outwash plains, eskers, drumlins, and moraines. Upon melting of the Laurentide Ice Sheet, outwash plains developed when glacial meltwater sorted unconsolidated glacial drift, or till, leaving a gradient of gravel, sand, silt, and clay (Baker and Barnes, 1998; Leahy and Pregitzer, 2003; Blewett et al., 2009). Some of the sand and most of the silt and clay were picked up by wind and deposited downwind where it was incorporated into soils and, in certain cases, loess sheets formed of sorted silt (Schaetzl, 2008). In select areas, drumlins formed when the ice sheet readvanced over till, forming streamline hills (Leahy and Pregitzer, 2003; Monroe and Wicander, 2011). Eskers were streams that extended out of the stagnating ice margin that filled with sorted sediment and, once the glacier melted, revealed sinuous low hills (Monroe and Wicander, 2011).

Moraines in Lower Michigan and other glaciated areas are comprised of unsorted till, which contains a wide range of grain sizes, from boulders, cobbles, gravel, sand, and silt, to clay (Baker and Barnes, 1998). There are two main moraine types: (1) end moraines which resulted from till deposited at the glacier's margin when the ice sheet temporarily halted; and (2) ground moraines, composed of till deposited under the glacial ice (Leahy and Pregitzer, 2003). Of the two types, end moraines are much taller and linear, and demark prior margins of the ice sheet, whereas vast plains with low hills characterize ground moraines (Leahy and Pregitzer, 2003; Blewett, 2009). Till plains, which form behind moraines, are relatively flat areas modified by glaciofluvial processes (Thornbury, 1965).

One unique topographic feature in parts of Lower Michigan is interlobate zones, created by overlapping end moraines of converging ice lobes (Baker and Barnes, 1998; Brown et al., 1998; Leahy and Pregitzer, 2003). These ice-contact margin zones are characterized by very thick glacial drift. The most prominent of these is located in southeastern Michigan, which formed via convergence between the Saginaw and Huron-Erie lobes and runs from the tip of the "Thumb" southwestward to Hillsdale County near the Ohio border (Brown et al., 1998; Blewett et al., 2009).

After recession of the Laurentide Ice Sheet, blocks of ice buried by till in ground, end and interlobate moraine melted to create kettle basins that filled with water (Blewett et al., 2009). Otter Lake and most of the lakes in Michigan are such kettle lakes, and once formed, began to accumulate sediment and organic remains, which are preserved below the water table.

Regional soils developed from the glacial parent material transported into the area and are highly variable (Kaufman, 2000; Schaetzl, 2009). A majority of the soils in Lower Michigan are derived from sediments that came from limestone and sandstone, thus coarse-textured soils are widespread (Schaetzl, 2009). These soils are particularly found in outwash plains and surrounding eskers (Blewett et al., 2009: Schaetzl, 2009).

Vegetation also has an important role in soil formation and is the main determinant of three soil orders found in Michigan. The majority of the soils in Michigan are classified as (1) Alfisols, which form under broadleaf deciduous forest, (2) Spodosols under coniferous forest and (3) Histosols, which are highly organic soils (McCann, 1991; NRCS.USDA.gov). Histosols are found in low-lying bogs and fen marshes that dot the landscape of Michigan (NRCS.USDA.gov).

Otter Lake, specifically, is bordered by the Flint moraine to the north and west, and the Thetford Esker to the east, both of which formed on a till plain during ice stagnation during the final retreat of the Laurentide Ice Sheet from southeast Michigan (Leverett and Taylor, 1915; Bergquist, 1951; Dodge, 1995). Otter Lake lies in a low relief area of Lower Michigan that is approximately 260 m asl on the southern edge (Kehew et al., 2011). The topographic profile dips down toward Saginaw Bay where the elevation is approximately 100 m asl (Kehew et al., 2011; MI DEQ, 2012). Upslope from wetlands, clastic sediments are found in the immediate area surrounding Otter Lake and range from sandy to loamy Alfisols, whereas lowlying areas to the north and west have Histosols, which are primarily peat and black muck (McCann, 1991; Kaufman, 2000; Schnurrenberger et al., 2003; MI DEQ, 2012). Figure 3.2 details the different soil textures that surround Otter Lake. There are also numerous soil series surrounding Otter Lake which are depicted in Figure 3.3.

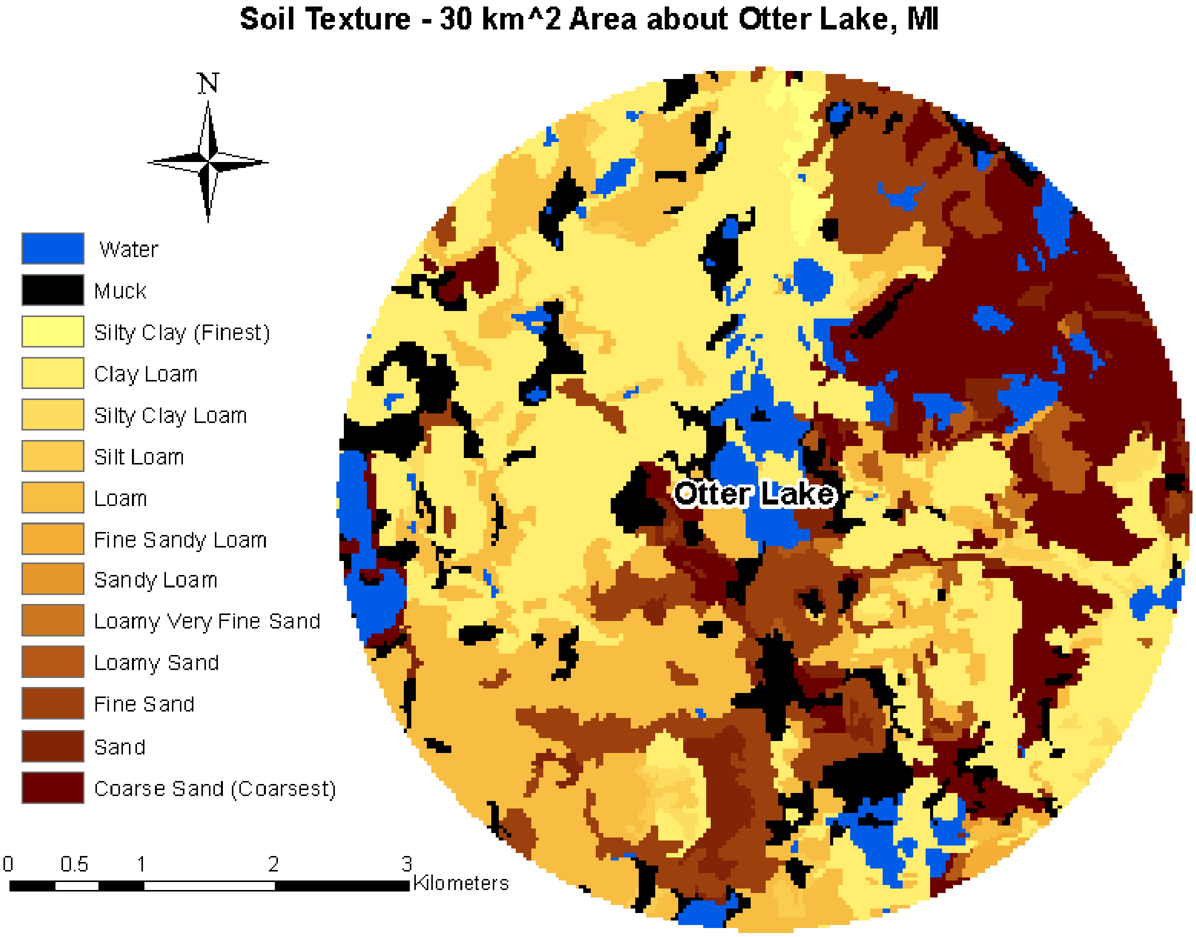

Figure 3.2: Map of the soil textures within a 30 km^2 area surrounding Otter Lake. Data provided by the United States Department of Agriculture Natural Resource Conservation Service. Data accessed from http://www.websoilsurvey.nrcs.usda.gov for the counties of Genesee, Lapeer, and Tuscola.

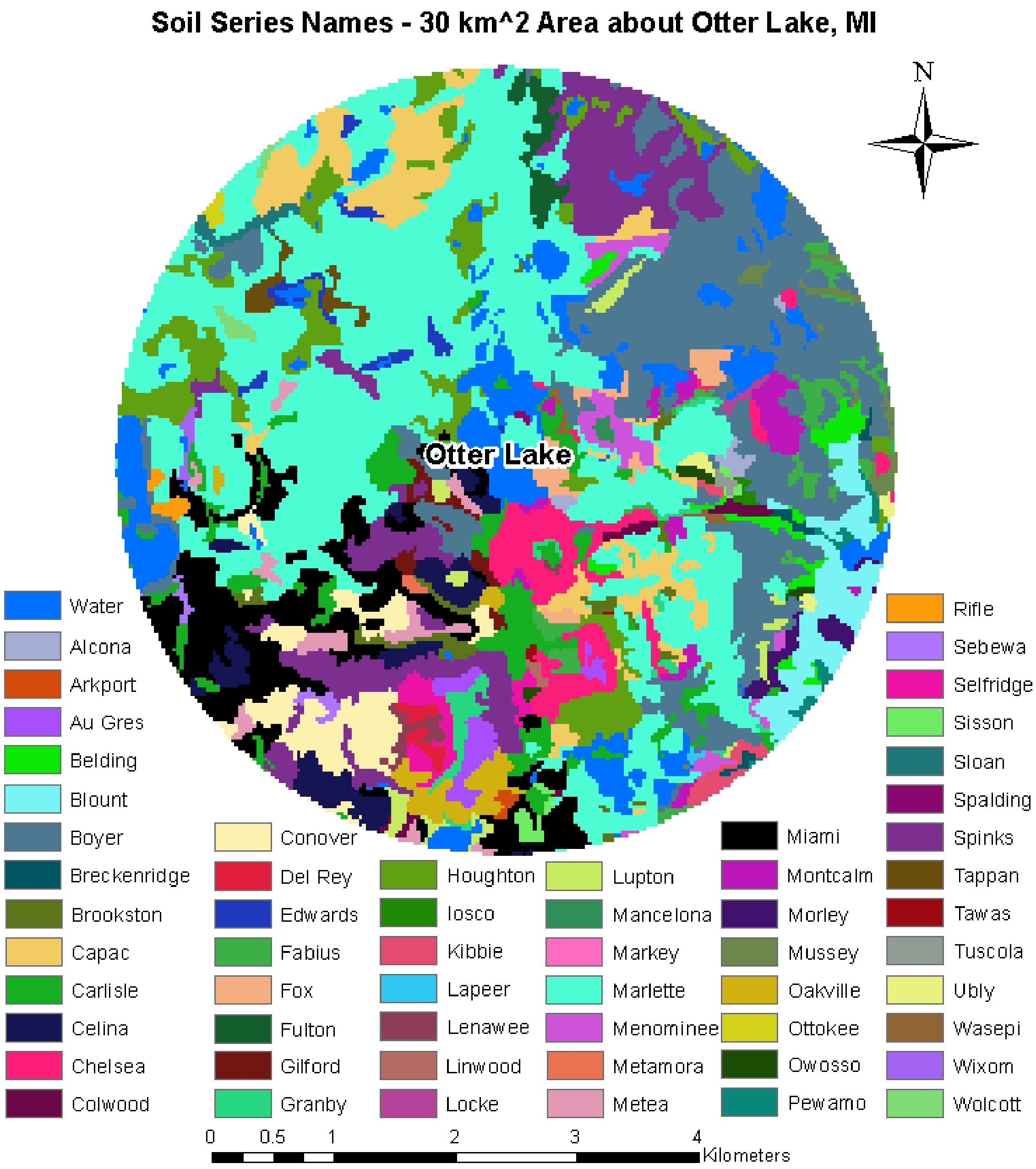

Figure 3.3: Map of the soil series within a 30 km^2 area surrounding Otter Lake. Data provided by the United States Department of Agriculture Natural Resource Conservation Service. Data accessed from http://www.websoilsurvey.nrcs.usda.gov for the counties of Genesee, Lapeer, and Tuscola.

3.3 Climate

The climate of southeastern Lower Michigan is characterized as humid, continental with hot summers (classification Dfb), according to the Köppen Climatic Classification system (Rohli and Vega, 2008). The first order classification (D) is indicative of a microthermal, or mid-latitude cold climate, in which the temperature thresholds are below 0ºC and above 10ºC for the coldest and warmest months, respectively (Rohli and Vega, 2008). The second and third order classifications (“f” and “b,” respectively) mean that precipitation is consistent throughout much of the year and the warmest month of the year reaches temperatures greater than 22ºC (Rohli and Vega, 2008). Figures 3.4 and 3.5 show minimum and maximum temperatures, averaged over a 30 year period from 1981-2010 for January and July, respectively. The general temperature trend for Michigan is from south-to-north with some moderation along the lakeshores in Lower Michigan. Figures 3.6 and 3.7 depict the average precipitation for the winter season (December – February) and the summer season (June – August), respectively, averaged over the same 30 year period. Winter season precipitation generally follows a southwest to northeast gradient in Lower Michigan, while the reverse trend is typically found in the Upper Peninsula of Michigan. Conversely, the summer season precipitation gradient is from the southwest to the northeast throughout both Upper and Lower Michigan.

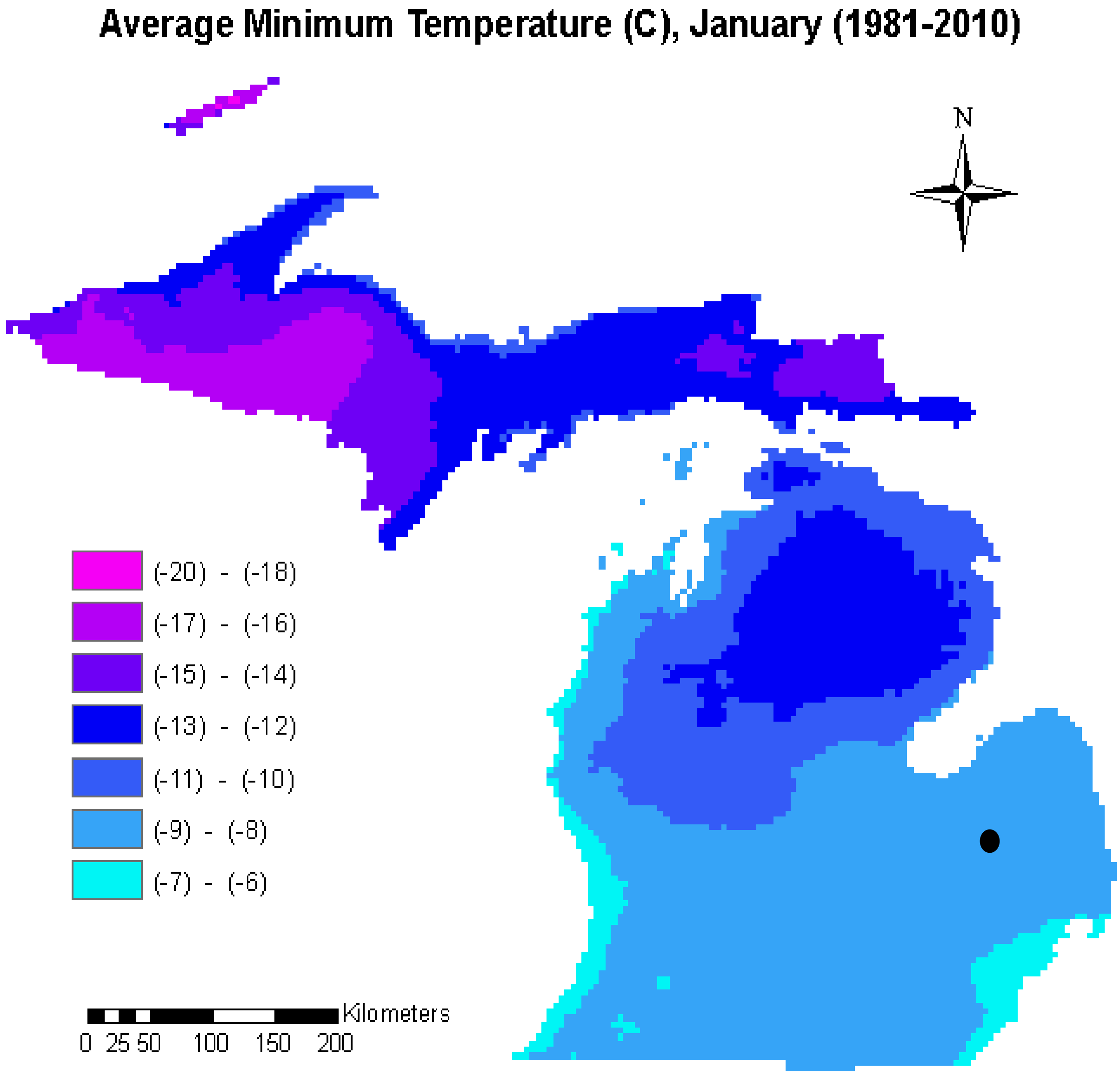

Figure 3.4: Average minimum January temperatures in Michigan with the location of Otter Lake (black dot). Data provided by the Northwest Alliance for Computational Science and Engineering based at Oregon State University and accessed from www.prism.oregonstate.edu/normals.

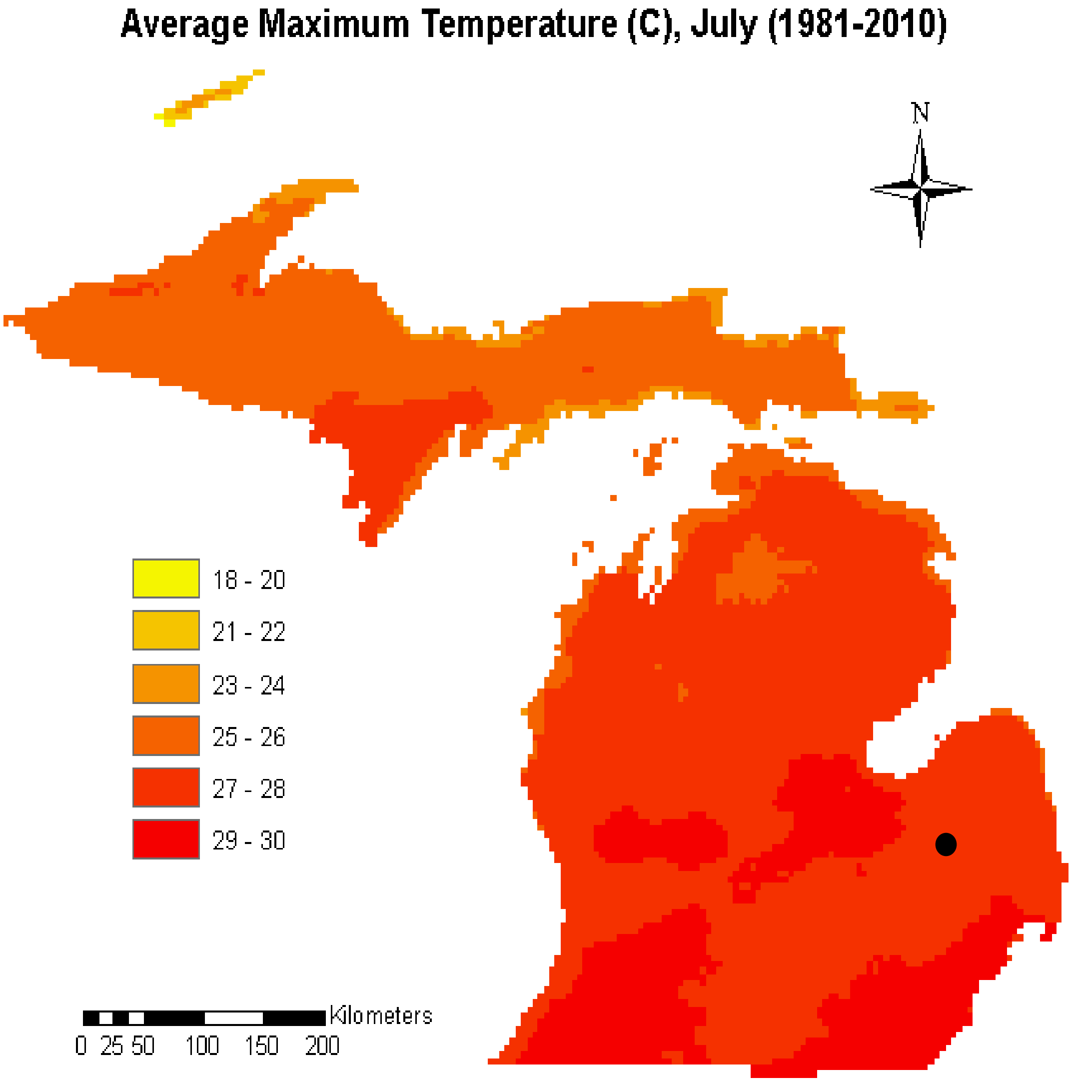

Figure 3.5: Average maximum July temperatures in Michigan with the location of Otter Lake (black dot). Data provided by the Northwest Alliance for Computational Science and Engineering based at Oregon State University and accessed from www.prism.oregonstate.edu/normals.

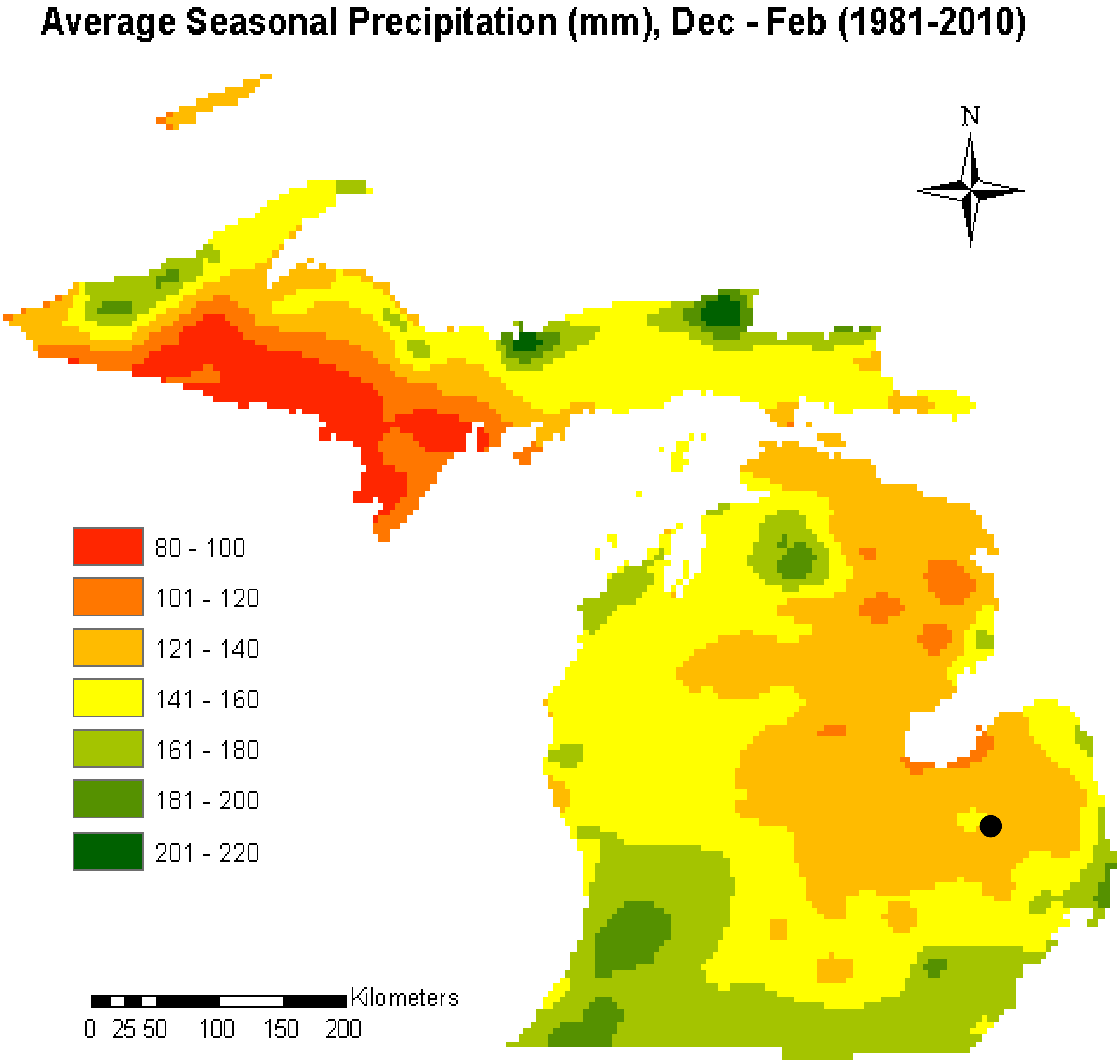

Figure 3.6: Average winter season precipitation in Michigan with the location of Otter Lake (black dot). Data provided by the Northwest Alliance for Computational Science and Engineering based at Oregon State University and accessed from www.prism.oregonstate.edu/normals.

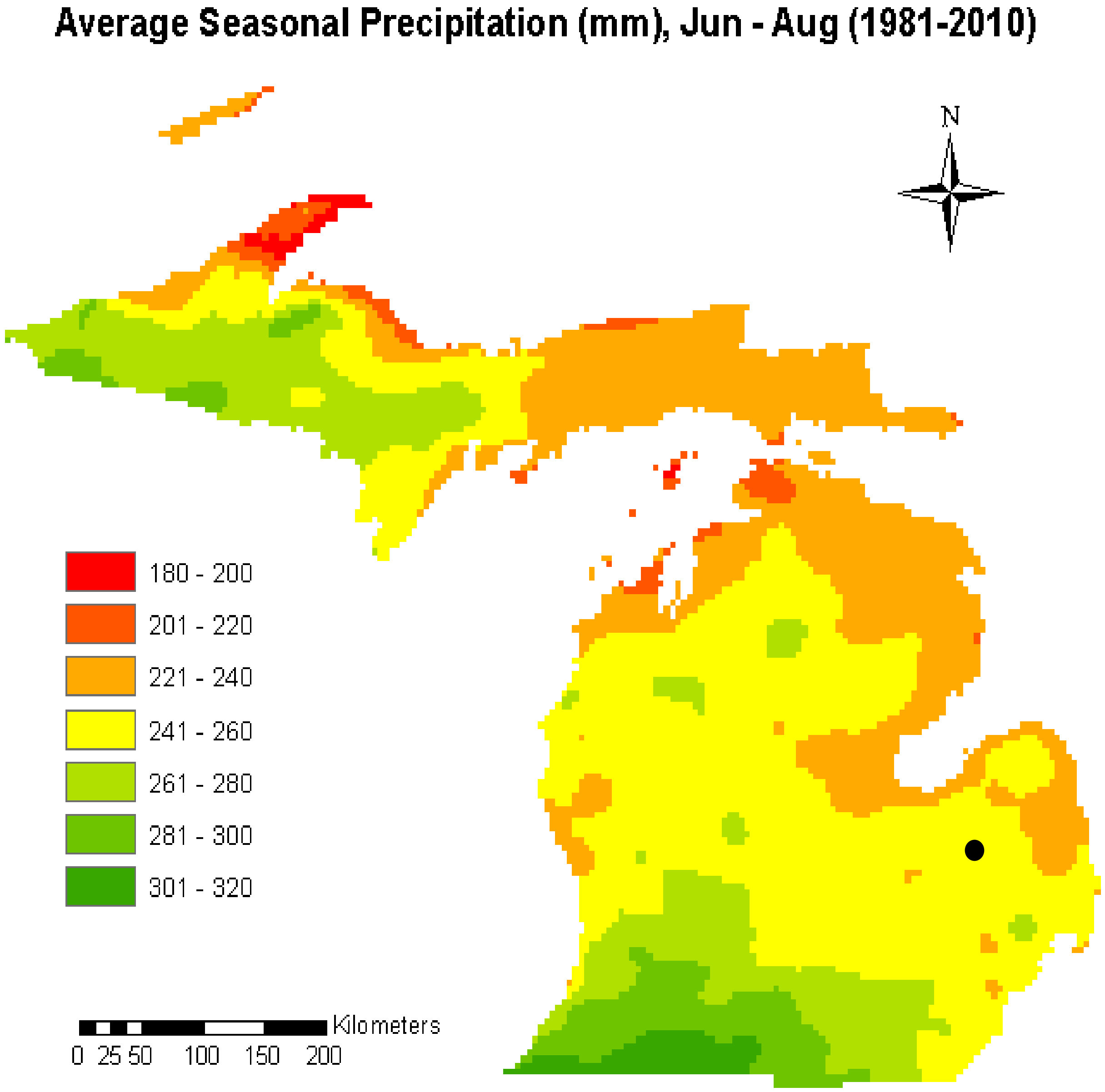

Figure 3.7: Average summer season precipitation in Michigan with the location of Otter Lake (black dot). Data provided by the Northwest Alliance for Computational Science and Engineering based at Oregon State University and accessed from www.prism.oregonstate.edu/normals.

Southeastern Michigan experiences predominately westerly wind flow patterns. This westerly flow results from two mesoscale processes. First, a thermal gradient develops which is caused by the advection of warm, tropical air northward and the subsidence of cold, polar air southward (Andresen and Winkler, 2009). As these air masses converge, their motion is deflected to the right (westward) as a result of the Coriolis Effect (Rohli and Vega, 2008).

Michigan experiences decipherable patterns associated with temperature and precipitation (Eichenlaub et al., 1990; Andresen et al., 2012). The spatial pattern is dependent mainly on two variables, latitude and proximity to the western Great Lakes (Lake Superior and Lake Michigan) (McCann, 1991; Andresen et al., 2012). One aspect of the climate of Lower Michigan is “lake effect,” where locations closer to the western side of the Great Lakes experience warmer temperatures and greater precipitation compared to locations further inland, especially in the winter months. Lake effect climate is produced whenever the cold polar air mass arrives from Canada into the area and flows over the warmer unfrozen lakes, picking up moisture that is deposited as snow on the leeward sides of the Great Lakes as far as 50-80 km from the lakeshore (Scott and Huff, 1996; Henne et al., 2007; Andresen et al., 2012). This phenomenon thus increases the cloud cover downwind of the lakeshores during winter. Conversely, cloud cover is decreased throughout the summer season as the marine tropical air mass flows over the cooler lakes. This results in a decrease in convective precipitation during the summer season as well as slightly cooler summer temperatures (Kumar et al., 2010). These patterns can be clearly demonstrated by comparing temperature and precipitation throughout Michigan. Table 3.1 shows eight locations in Lower Michigan and two locations in Upper Michigan with the associated high temperatures for January and July along with the summer and winter seasonal precipitation.

Temperature and precipitation also affects evaporation rates from soils and transpiration rates from plants, which add moisture to the atmosphere (Wetzel and Chang, 1986; Kumar et al., 2010). Evapotranspiration rates are highest during the summer growing season, with values dependent upon the interactions of air temperatures, vegetation cover, and soil moisture (Hamon, 1960; Wetzel and Chang, 1986; Delworth and Manabe, 1988; Andresen et al., 2001; Kumar et al., 2010). For instance, vegetation is the most important variable in reducing soil moisture content, thus increasing evapotranspiration rates, as vegetated landscapes are able to continue transpiration even after the uppermost soil layers dry out (Wetzel and Chang, 1986; Zhang and Schilling, 2006). Zhang and Schilling (2006) found that evapotranspiration rates on a grass covered surface can be as high as 2.84 mm/day greater than a surface covered by bare soil. Also evaporation rates are higher in sandy soils, in the short-term, because of higher permeability than in finer grained soils with higher silt and clay contents. However, finer grained soils are able to undergo moisture recharge more quickly due to capillary action thus can have higher evaporation rates in the long-term even when precipitation is scarce (Zhang and Shilling, 2006).

Table 3.1: Table with values of average January and July high temperatures in ºC and average yearly precipitation as rain and snow in mm. Data converted from English to Metric units. Data source: US Climate Data http://www.usclimatedata.com.

Location (West to East, South to North)	Average high January (C)	Average high July (C)	Average summer precipitation (mm)	Average winter precipitation (mm)
Holland	0.5	28.3	933.5	1778
Grand Rapids	- 0.5	28.3	972.1	1930.4
Flint	- 1.1	27.7	797.1	1219.2
Pontiac	- 1.1	27.7	809.0	914.4
Baldwin	- 1.1	28.3	877.1	1955.8
Traverse City	- 2.2	26.6	841.3	2590.8
Cheboygan	- 2.7	25.5	782.8	2362.2
Harrisville	- 2.7	24.4	779.0	1346.2
Marquette	- 3.8	23.3	740.2	3022.6
Sault Ste. Marie	- 5	24.4	840.2	3149.6

3.4 Extant Vegetation

The south-to-north temperature gradient is reflected in the natural vegetation of Lower Michigan, which is diverse because it consists of species of two different forest types: the northern mixed coniferous-deciduous forest and the southern broadleaf deciduous forest. A boundary between these two forests, in other words an ecotone dubbed the "Floristic Tension Zone," lies along the 43rd North parallel that runs east from Muskegon (along Lake Michigan) to Saginaw (near the Thumb) (Webb, 1984; McCann, 1991; Dodge, 1995; Delcourt and Delcourt, 1996; Maines and Mladenoff, 2000; Anderson, 2005; Henne et al., 2007; Kost et al., 2007). Here species of the mixed coniferous-hardwood forest reach their southern limit, which overlaps with the northernmost range distribution of deciduous hardwood species.

North of this Tension Zone, the mixed coniferous-hardwood forest, also called the Laurentian mixed forest, consists of six forest types dominated by: aspen-birch; maple-beech-birch; elm-ash-cottonwood; oak-hickory; spruce-fir; and pine (Peters et al., 2013b). While abundance levels of species in the northern mixed coniferous forest vary depending on the soil type at any given location, the major species that comprise this forest are *Tsuga canadensis* (eastern hemlock), *Betula alleghaniensis* (yellow birch), *Betula papyrifera* (paper birch), *Abies balsamea* (balsam fir), *Populus tremuloides* (quaking aspen), *Picea glauca* (white spruce), *Quercus rubra* (red oak), *Ulmus americana* (American elm) and *Thuja occidentalis* (white cedar) (Roth, 1910; Webb, 1984; McCann, 1991; Maines and Mladenoff, 2000; Kost et al., 2007; Harman, 2009). While many of these species reach their southern limits well north of the Tension Zone (e.g. *Betula alleghaniensis*), other species, like *Thuja occidentalis* and *Ulmus americana*, can be found south of the 43rd parallel if soil conditions are conducive to their establishment, e.g., cool and wet. These latter two species along with *Larix larcinia* (tamarack) and *Picea mariana* (black spruce) inhabit wetlands where soil temperatures are considerably cooler and moister than upland soils.

South of the Tension Zone, many species of the eastern broadleaf deciduous (hardwood) forest reach their northern geographic limits. There is some debate, however, as to the how much the location of this Tension Zone can be solely attributed to climate (McCann, 1979; Medley and Harman, 1987) and what influence soil texture (sandy vs fine-grained) has on defining this zone (Elliot, 1953). In either case, south of this ecotone lies the broadleaf forest, which is mainly composed of two main upland communities, the (1) dominant *Fagus grandifolia* (American beech)-*Acer saccharum* (sugar maple) forest with other mesic, shade-tolerant, fire-intolerant species including *Acer rubrum* (red maple), *Tilia americana* (basswood), *Carpinus caroliniana* (American hornbeam); and (2) the xeric, shade-intolerant, fire-tolerant *Qurecus rubra* (red oak) which hybridizes with *Quercus velutina* (black oak), and found with *Carya cordiformis* (bitternut hickory) (Dickman and Leefers, 2003; Kost et al., 2007). In the Tension Zone and northwards oaks co-inhabit the same areas with *Pinus strobus* (white pine) and *P. resinosa* (red pine), which are all dependent upon fire and tolerate infertile soils (Dickman and Leefers, 2003; Kost et al., 2007). The vegetation that occupies mesic to hydric soils along the edges of streams and lakes include *Populus deltoides* (eastern cottonwood), *Fraxinus pennsylvanica* (red ash), *Fraxinus nigra* (black ash), and *Salix nigra* (black willow) (Roth, 1910; Webb, 1984; Dodge, 1995; Dickman and Leefers, 2003; Kost et al., 2007). Here too, northern species such as *Larix larcinia* and *Picea mariana* can tolerate the warmer temperatures south of the Tension Zones so long as they receive sufficient moisture, hence these trees live in waterlogged soils as far south as northern Indiana and Ohio, and can tolerate periodic flooding (Dodge, 1995). Table 3.2 depicts the individual tolerances to temperature and precipitation for some of the species mentioned above.

Table 3.2: Table of average minimum and maximum temperature and precipitation for select tree species. This table reflects the optimum ranges of average temperature and precipitation. Data obtained from http://www.na.fs.fed.us.

Species	**Average Minimum Temperature (ºC)**	**Average Maximum Temperature (ºC)**	**Average Minimum Precipitation (mm)**	**Average Maximum Precipitation (mm)**
Abies balsamea	(-18) – (-12)	16 - 18	760	1100
Betula papyrifera	(-30)	13	300	1520
Fagus grandifolia	4	21	760	1270
Juglans cinera	4	16	630	2030
Juglans nigra	7	19	890	1780
Larix laricina	(-30) – (-1)	13 - 24	180	1400
Picea mariana	(-30) – (-6)	16 - 24	380	760

Otter Lake, at 42.3ºN, is located south of the Tension Zone. There are abundant wetlands that surround the northern and western side of the lake and elsewhere resides forested areas where there aren't agricultural fields. Hence, a variety of habitats exist around this lake. The most common species in the wetlands surrounding Otter Lake are *Larix laricina*, *Thuja occidentalis* (white cedar), *Salix discolor* (pussy willow), and a variety of *Carex* subspecies (sedges) (Reznicek et al., 2011, Voss and Reznicek, 2012). The forested areas are just as diverse as the wetlands, and include species of both the beech-maple dominated forest and oak-hickory forest. Dominant trees in the area are *Fagus grandifolia* (American beech), *Acer rubrum* (red maple), *Cornus foemina* (gray dogwood), *Ulmus americana* (American elm), *Quercus bicolor* (swamp oak), and *Juglans nigra* (black walnut) in mesic soils and *Quercus alba* (white oak) and *Carya cordiformis* (bitternut hickory) in the drier soils (Aheran and Bailey, 1980; Reznicek et al., 2011, Voss and Reznicek, 2012). The nearest native locale for *Pinus strobus* (white pine), the dominant species of the Tension Zone and important species in the vegetation of the northern mixed coniferous-deciduous forest, is north of Otter Lake (Sisk, 1998). It is important to note, however, that there were areas where white pine was able to colonize the landscape, albeit in small numbers, immediately south of the Tension Zone. The vegetation surrounding Otter Lake is reflective of recent conservation efforts, and although it approximates the species composition prior to Euro-American logging and settlement, there are some differences.

Knowledge of pre-settlement forest composition is based on witness tree data captured in the notes and maps of the massive surveying efforts by the Deputy Surveyors of the General Land Office between 1816 and 1856 (Comer et al., 1995b; Dickmann, 2009). These surveys laid out the township and ranges throughout the state by marking witness trees at corners and line trees along section lines and recording the identity of the trees used to provide these land marks, while reporting on the quality of the land for agriculture (Comer et al., 1995b). These surveyors were not botanists and their respective abilities to identify trees varied, but the data provided are the most accurate available for this time immediately prior to widespread Euro-American settlement and land clearance (Dickmann, 2009). These data indicate that the forests of southeastern Lower Michigan were largely comprised of broadleaf deciduous species, such as *Quercus alba* (white oak), *Quercus rubra* (red oak), *Juglans nigra* (black walnut), *Fagus grandifolia* (American beech), *Acer rubrum* (red maple) along with many wild fruit species like *Rubusidaeus* (raspberry) and *Rubusfruticosus* (blackberry) (Roth, 1910; Whitney, 1987; Comer et al., 1995a; Dickman and Leefers, 2003).

Some Euro-Americans in New York State and elsewhere in the east began abandoning their lands in search of better agricultural lands out west, with many of them settling in Lower Michigan, especially after 1837 when Michigan officially became a state (Comer et al., 1995b; Dickmann, 2009; Kumar et al., 2010). The Saginaw Valley, not far from Otter Lake, was beginning to be cultivated by the few settlers as early as the 1830s, where they planted wheat, barley, and rye, crops that were beginning to emerge as major agricultural commodities (Kapp, 1999). A growing demand for land prompted the United States Congress to pass the Swamp Lands Acts of 1849 and 1850 in an attempt to facilitate large-scale drainage efforts in the Midwest, including Michigan, in an attempt to increase viable agricultural land (Kumar et al., 2010). Also with the arrival of these settlers came large-scale logging industries that began decimating the pine forests of Lower Michigan, beginning in 1870 (Whitney, 1987; Kapp, 1999; Dickmann, 2009). By 1890, the two main species of pine, *Pinus strobus* and *Pinus resinosa*, were completely harvested in Lower Michigan and loggers began massive cutting of hardwood species like *Acer saccharum* (sugar maple) and *Acer rubrum* (red maple) (Whitney, 1987). The

Saginaw area of Michigan, just north of where Otter Lake is located, produced over 10 million board feet of lumber in 1882 (Dickmann, 2009). By the early 1900s, timber production was nearly exhausted and Lower Michigan’s landscape was reduced to a treeless, abandoned landscape. Reforestation began during the Great Depression via the Civilian Conservation Corps, whose aim was, in part, to transplant millions of seedlings back into the previously forested areas of Michigan (Dickmann, 2009). This effort is partially responsible for the forested landscapes seen in Michigan today.

CHAPTER 4: METHODS

4.1 Lacustrine Sample Collection

In July 1999, a sediment core was extracted from Otter lake using a 7-m Kullenberg piston corer as part of the dissertation research of Dr. Chad Wittkop, then a Ph.D. student at the University of Minnesota and now faculty at the Minnesota State University. Upon return from the field, the sediment core was immediately archived in cold storage at LacCore, the National Lacustrine Core Repository, which is part of the Limnological Research Center at the University of Minnesota. The analyses of sediment samples from the Otter Lake core form the basis of this thesis research.

Dr. Wittkop shared all field notes, his dissertation (Wittkop, 2004), and a recent publication (Wittkop et al., 2014) which reported on his field and laboratory (geochemical) work, and are summarized here. This core was obtained from the deepest part of Otter Lake, at about 35.6 m water depth. All lacustrine cores are extracted from the deepest part of lakes, when possible, as that is where most pollen grains are concentrated. The core was taken as a continuous drive of aluminum casing to a maximum depth of penetration, 730 cm below the sediment-water interface, which did not capture the complete postglacial sediment record. The aluminum casing was cut into about 1.5 m lengths for transport. At LacCore, core segments, called “drives,” were split longitudinally, described for sedimentology and stratigraphy, photographed, and underwent geotech processing, which is a non-invasive data-capturing procedure where gray scale and other data were collected about sediment stratigraphy and composition. Drives were stored in refrigeration when not in use. To note, only the “working” longitudinal halves of the drives were sampled, whereas the other “archive” halves are kept in perpetuity at LacCore.

Sediment samples for pollen analysis were originally collected from the Otter Lake core at LacCore by Dr. Jerry Urquart of Michigan State University in 2005. He collected these samples, kept them in cold storage at Lyman Briggs College – Michigan State University, but never analyzed them and made them available to Dr. Yansa in March 2014. Dr. Urquart informed us that he used a stainless steel sampler to extract 1 cm^3 of sediment for each samples and placed the sediment into 1-dram glass vials, which were labeled with core identification number and depth. The sampling resolution he used was 5-cm intervals, which is too coarse of a resolution for my study.

To supplement these samples, Dr. Catherine Yansa, Albert Fulton, and I travelled to the LacCore facility in June 2014. We collected samples for pollen analysis for the levels in between Dr. Urquarts' sampled levels (which were clearly evidence by the holes in the sediment core), so beginning in drive 1 at 2.5 cm (Dr. Urquart had started at 0 cm) and concluding at 727.5 cm in drive 6. Hence the final resolution is 2.5 cm between samples, but to note that not all of these samples were analyzed for this thesis, which focuses just on the pollen record of the last 2,000 years.

We exercised caution during the collection process for pollen analysis to collect each sample from the middle of the drive in order to avoid collecting sediment along the outer part that had been disturbed during the coring process. We can see from the holes in the core that Dr. Urquart had done the same. Samples (1 cm^3 of sediment) were extracted using a stainless steel spatula which was rinsed after each use. Samples collected for pollen analysis were placed in small Ziploc^{TM} bags labeled with the core location and depth. Afterwards, the rest of the working core was sliced into continuous 2.5-cm long segments and placed in larger Ziploc^{TM} bags labeled with depth range (eg. 2.5– 5 cm) and specified as plant macrofossil samples, to provide material for radiocarbon dating and for later seed analysis by Dr. Yansa. These samples were then transported back to Michigan State University and placed in cold storage.

The thesis research described here utilized samples from drives 1, 2, and approximately two-thirds of drive 3, accounting for the upper 347.5 cm of lacustrine sediment. Air gaps were present in drive 3 at 307.5-320 cm, 327.5-330 cm, and 340-342.5 cm, therefore no sediment samples could be collected from these intervals. One radiocarbon date of 650 +/- 150 cal yr BP., acquired from drive 2 at a depth of 152 cm by Dr. Chad Wittkop, served a check on the varve chronology, which is used for both his study and the current study described in this thesis. This radiocarbon date is considered to be the most reliable as it was carried out on a charcoal fragment whereas the other three were conducted on pollen grains (2) and a leaf fragment, respectively. Varves, annually deposited sediment layers, are rarely found in lakes, especially in Michigan, and are highly valued because counting the rings provides a chronology, just like tree rings. Otter Lake has a unique geochemistry that produces varves, most of which were comprised of layers of siderite (iron oxide), which Wittkop (2004) counted to produce an age-depth model (Figure 4.1). Siderite is absent in more recent sediments of Otter Lake, those younger than 1200 cal yr BP (Wittkop et al., 2014). Sediments older than 1200 cal yr BP, however, contain abundant siderite precipitates which range from 5 to 18.7% (Wittkop et al., 2014). Radiocarbon dating is thus not absolutely necessary, given that such ages are standard deviations, but as an additional check an attempt was made to obtain two more ^{14}C ages to compare to the varve chronology. Unfortunately, after sieving a total of 8 samples, there was not sufficient material to send for radiocarbon dating. Nonetheless, the varve chronology for Otter Lake is considered to be accurate (Wittkop et al., 2014), and hence provided a reliable chronology for the pollen record. A total of 60 samples, counted to a minimum of 400 pollen grains were analyzed for fossil pollen from a depth of 30 to 347.5 cm for this research, and based on the chronology, equates to ~32.45 years between samples analyzed. This sampling resolution was selected, because it appropriates the 30-year running average used in climatological studies (WMO 1989). Another advantage to carrying out a study of this resolution, coupled with a high pollen grain count, is that more of the rare species can be detected while subtle shifts in the major vegetation types are more accurately accounted for.

The topmost sample analyzed (30 cm depth) dates to about 100 cal yr BP which coincides with the approximate time of arrival of Euro-American settlement in this area. For this reason, sediment samples above 30 cm were not analyzed in this study. The bottommost sample (347.5 cm) dates to 2047 cal yr BP, so a time span of 1947 years was covered in this study.

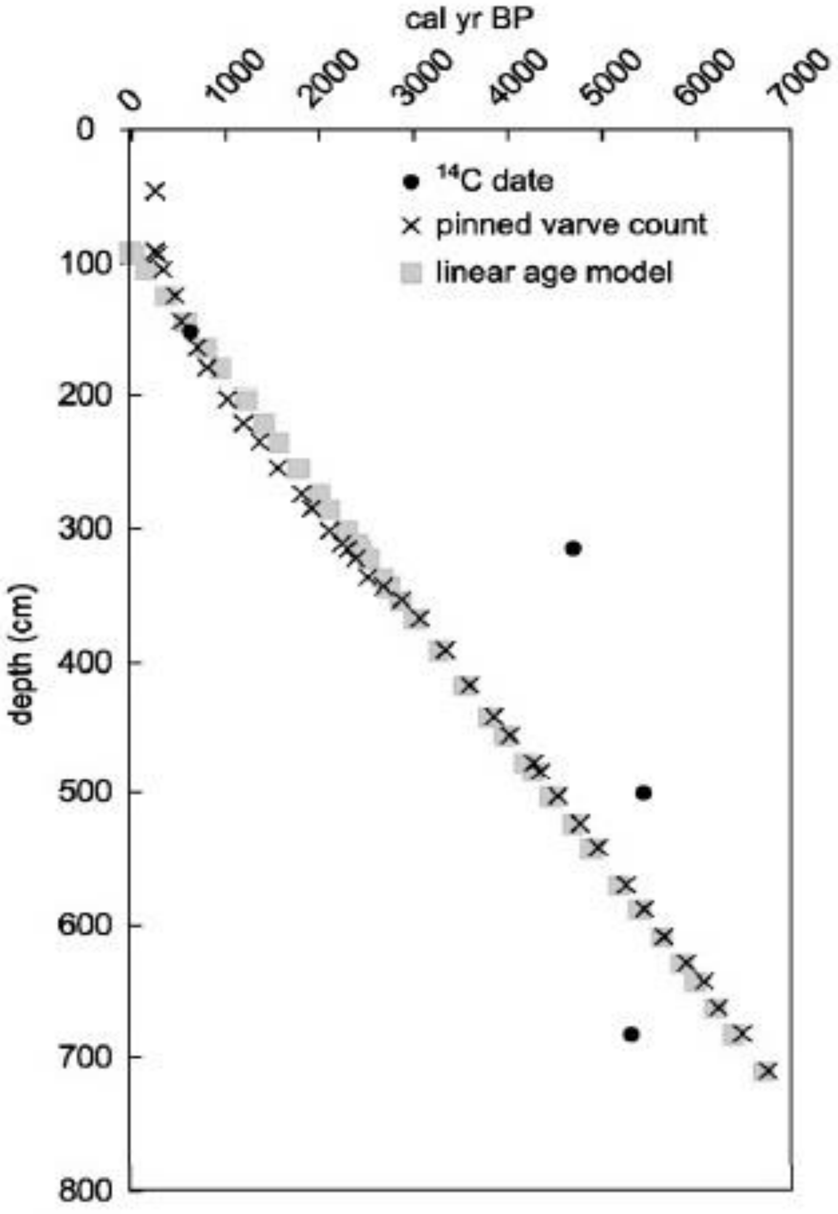

Figure 4.1: Sediment age versus depth showing AMS ^{14}C dates, pinned varve counts, and linear age model (from Wittkop, 2004).

4.2 Sample Preparation

The preparation of sediment samples was conducted in the Pollen Laboratory located in the Geography building at Michigan State University. The samples were divided into five batches for chemical processing. The first two batches consisted of 4 and 8 samples, respectively, and were processed under the supervision of Dr. Catherine Yansa. The remaining three batches consisted of 16 samples each. The samples varied in color from dark to light yellowish brown, the exceptions being at a depth of 130 cm where an olive tint was present in the sample and those samples that were analyzed below 225 cm, which is the approximate depth of increased siderite abundance, which appeared reddish-brown. The gradient of color in the samples was punctuated by the 1 mm annually laminated varves that were present throughout this upper portion of the core. All samples contained sediment that contained a significant amount of organic muck from decayed plant remains.

All five batches were prepared using a series of chemicals to remove extraneous materials, following the standard pollen preparation procedure as laid out by Faegri and Iverson (1975). For each step a chemical is added to test tubes, one per sample (1 cm^3 of sediment), stirred, and for some heated in a hot-water bath to accelerate the chemical reaction. Then the test tubes are centrifuged at 3000 rpm for 4 minute to settle down the pollen and other materials from the supernate (liquid), which is decanted (poured off into a hazardous waste container). No reaction to HCl (10%) was apparent in the first two batches, which indicated a lack of calcium carbonate material in the samples; hence this step was skipped for the remaining batches. The samples also lacked clay materials, because during the sodium pyrophosphate ($Na_4P_2O_7$) treatment, a step described in Bates et al. (1978), there were not any suspended clay particles in the supernate decanted. Pollen grains are silt-sized; hence this step is designed to remove some of the clay from samples, but was not necessary for these samples, and thus was not done for the three remaining batches.

A step not described in Faegri and Iverson (1975), but which has since become common practice, is to sieve each sample to remove coarser material (wood fragments, sand, etc.) from the pollen sample. Hence, each sample was sieved, by dumping the contents of each test tube into a 125 µm metal screen sieve, using a steady spray of water from a dispensing bottle to transfer the contents and to “cleanse” the coarse material from the finer material, including pollen grains, which went into an underlying glass beaker. The coarse material was discarded, and the finer material in the glass beaker was poured back into the test tube, a process which involved several centrifuges to extract excess water and to leave only the fine grained material in the test tubes.

Samples were next treated with KOH (10%) and placed in a hot water bath for 10 minutes. This was an effective amount of time to remove humic material from the samples when decanted, followed by at least four water rinses. Then, approximately 6 ml of HCl (10%) was added to each test tube in order to make the sample acidic, centrifuged, and then decanted. A 48% concentration of hydrofluoric acid (HF) was added to each sample then transferred to a hot water bath for 30 minutes in order to dissolve any silicate matter present in the sample. This chemical is the most dangerous to handle in this procedure, so additional safety precautions were taken. Immediately following the extraction of samples from the hot water bath, HCl (10%) was added to each sample to remove the dissolved silicates via decanting. Glacial acetic acid ($C_2H_4O_2$) was then added to each test tube in order to dehydrate the samples. An acetolysis mixture (6 ml) containing sulfuric acid (H_2SO_4) and acetic anhydrite ($(CH_3CO)_2O$) was added to each test tube and placed in a hot water bath at 100°C (rolling boil) for 1.5 minutes to dissolve cellulose and etch the surface of pollen grains which eases identification. The acetolysis reaction was immediately neutralized by the addition of glacial acetic acid, and then centrifuged and decanted. The final step involved dehydration of the samples using ethyl alcohol and tertiary-butanol alcohol (TBA) $(CH_3)_3COH$). The material remaining in the test tubes was then transferred into 0.5 dram glass vials, via glass pipettes, and silicon oil (3000 cs) was added to each vial. These vials were then transferred to a hot plate where they remained for approximately 8-12 hours to evaporate any remaining TBA, and topped up with a bit more silicon oil which disperses and preserves the pollen grains, and finally capped for long-term storage.

4.3 Pollen Counting

Small amounts of processed material ("pollen concentrate") from each sample were transferred to glass slides and examined under a microscope; typically 2 slides were scanned per sample. Initially a LEICA DMLB light microscope, using a magnification of 400x, was utilized to count pollen grains until an AMSCOPE compound microscope was acquired, using the same 400x magnification. Each sample was counted to a minimum of 400 pollen grains of upland vegetation (excluding aquatic herbs) with an average count of 453 grains over 60 samples. This count is very robust, as the minimum in pollen analysis is 300 grains per sample (Bennett and Willis, 2001).

Pollen grains were identified first to the genus level and, where decipherable, to the species level. For example, *Quercus* grains are not segregated into species whereas *Juglans* pollen grains can be differentiated into *Juglans cinera* and *Juglans nigra*. Pollen grains were identified using pollen keys (McAndrews et al., 1973; Kapp et al., 2000), viewing of a slide collection of modern pollen types in the Department of Geography at MSU, and, when unsuccessful, analyzed under the microscope by Dr. Catherine Yansa. Any grains that not identifiable after all these steps, a very small number, were counted as “indeterminable,” as per standard practice.

Data from each sample was initially documented on a pollen count sheet (hard copy) where total counts for each sample were tabulated. These count data were then entered into an Excel file where relative abundance, based on percentage levels, were calculated. Too many taxa are in this file to be plotted in a diagram so a second Excel file was created to include only 28 taxa, where related species were grouped according to genus and taxa with low counts were excluded, unless they were ecologically important. One grouping consisted only of *Lycopodium*, a spore producing plant. Data contained in this second Excel file (Appendix A) was uploaded into the Tilia 1.7.16 program, to produce a pollen percentage (abundance) diagram. The CONISS cluster analysis tool in this program was used to mathematically distinguish pollen zones, breaks where there are significant abundance shifts evident in the pollen record.

CHAPTER 5: RESULTS AND INTERPRETATION

5.1 Overview of Pollen Data and Cluster Analysis

Pollen data from Otter Lake, expressed as percentages per taxon over time, are shown in Figure 5.1. The highly saw-toothed pollen record results from the high resolution of samples analyzed, which represent a sampling interval of approximately 32 years. Deciphering important changes in the abundance of key taxa, particularly those that are mesic- versus xeric-adapted, was accomplished with the aid of a dendrogram, used to identify zone boundaries within a pollen diagram. A zone in a pollen diagram is considered to represent a plant community type of the past, and changes between zones are thought to reflect shifts in the dominance of key taxa over time.

The dendrogram was determined by cluster analysis using the CONISS application in the Tilia software (discussed in Chapter 4). Cluster analysis is based on the sum of squares to delineate zones within a pollen diagram. Specifically, CONISS performs this hierarchical, quantitative assessment by recognizing changes in main taxa, those having abundance over 3%, while negating less abundant pollen types (Grimm, 1987). The dendrogram created illustrates the hierarchical clustering using a divisive, or “top down” approach, and each cluster is considered to be a zone or subzone. This mathematical method works well for stratigraphic sequencing data because it is based on sample-to-sample variability and, in most instances, coincides with natural breaks, or zones, that would be evident upon visual inspection of the pollen diagram (Grimm, 1987). Figure 5.1 also shows the associated dendrogram of Otter Lake used to identify the five zones discussed below. Some pollen studies may further divide major zones into smaller sub-zones, however nothing in the pollen profile of Otter Lake warranted such subdivisions. The lack of clear taxonomic changes in zone 2 is the reason why this zone

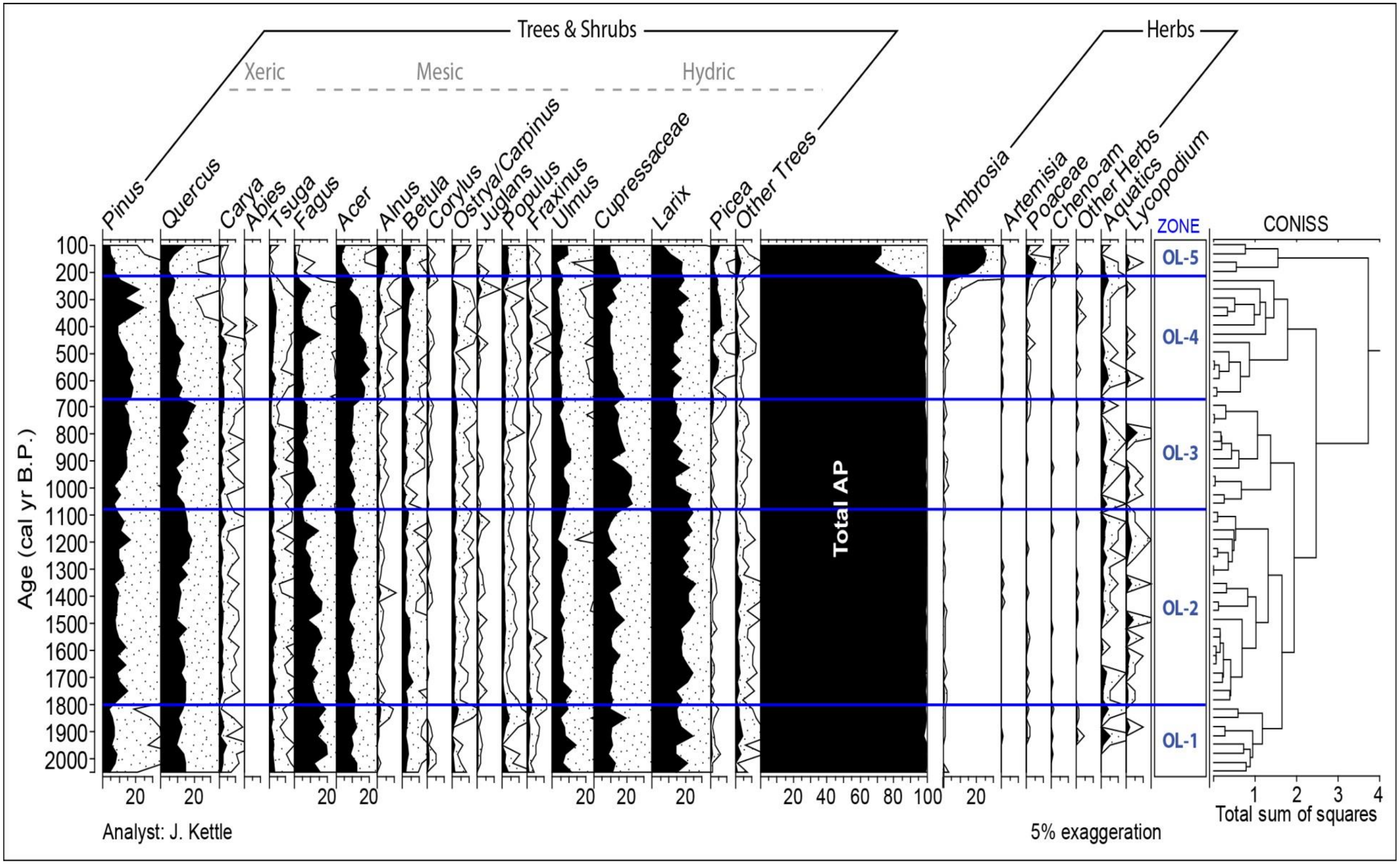

Figure 5.1: Pollen diagram and associated dendrogram for Otter Lake, Michigan

encompasses a large time span compared to other zones interpreted for Otter Lake. Furthermore, five pollen zones over the last 2000 years would be considered quite reasonable by other paleoecologists, as comparable to the zonation of other pollen records from Michigan of the same timespan (e.g. Hupy and Yansa 2009a).

5.2 Pollen Record of Otter Lake

The Otter Lake pollen record (Figure 5.1) is characterized by three habitat types: xeric upland mixed coniferous-deciduous forest; mesic upland deciduous forest; and lowland mixed coniferous-deciduous swamp forest. Of these, the latter two, currently exist in the study area, whereas the closest natural occurrence of xeric upland mixed coniferous-deciduous forest today is approximately 60 km to the north. Of these habitats, the mesic upland deciduous forest is most dominant, which reflects that the area is situated within the deciduous forest biome of eastern North America (Figure 1.1), and the common occurrence of fine- to medium-textured soils in the area (Figure 3.2). The co-existence of these three habitats within a small area reflects the 1) topographic variability of the area, with swamps in kettle basins surrounded by upland vegetation on knolls, and 2) that the study area is situated south of the Tension Zone, which explains the presence of upland coniferous-deciduous forest in patches of xeric (sandy) soils (e.g white pine), a vegetation type that dominates the northern Lower Peninsula and the Upper Peninsula of Michigan. The most dramatic aspect of this record is clear evidence for Euro-American deforestation and agriculture (Zone OL-5), followed by limited reforestation, near the top of the record. The vegetation prior to historic land clearance of the Otter Lake area, from ~2000 to 100 cal yr BP, reflects subtle, although important, changes in the dominance and inferred spatial extent of certain species within these three habitat types, which are interpreted as vegetation responses to the Medieval Warm Anomaly (MWA; ~1150-750 cal yr BP) and Little

Ice Age (LIA; ~550-150 cal yr BP) climates, discussed below. Modern habitat and geographic range information used in interpreting the vegetation of the past are obtained from Reznicek et al. (2011).

5.3 Pollen Zones of Otter Lake

5.3.1 Zone OL-1: 347.5-290 cm; *Fagus-Larix-Ulmus-Quercus* (2047-1800 cal yr BP)

This zone of the Otter Lake pollen record is primarily characterized by the dominance of certain tree species within the three different habitat types that are distinct from the taxa most abundant in latter zones. The mesic deciduous forest habitat was dominated by *Fagus,* which has to be *F. grandifolia* (American beech) as it's the only beech species in the region. The pollen data reveal that beech pollen increased from 15% at the bottommost section of this zone to 20% by the middle, staying at that abundance for the rest of the zone, and that these values are higher than those for this taxon in the subsequent zones. A study of modern pollen production reported that *Fagus* produces pollen in proportion to its abundance as trees in the local vegetation (Davis et al., 1986), so this mesic, fire-intolerant species would have comprised a comparable proportion of the vegetation during this time.

Fagus grandifolia coexists with *Acer saccharum* (sugar maple) today as well as reported in the 19th century land survey records for the study area (Comer et al. 1995b). However, *Acer* pollen cannot be easily distinguished to species, and so some of the maple pollen identified in the Otter Lake record may be of *Acer saccharum,* but others may be of *A. rubrum* (red maple), *A. saccharinum* (silver maple), and *A. negundo* (box elder). Compounding the problem is that sugar and red maple trees occupy mesic habitats, whereas silver maple and box elder inhabit swamps. Consequently, the pollen identified as *Acer* is interpreted as representative of a mesic/swamp taxon. An additional problem is that *Acer* is typically underrepresented in pollen profiles as it's a low pollen producer, so its presence in smaller percentages should be considered as significant. In this zone, *Acer* pollen percentages remains relatively stable at around 14%, which indicate that it was probably as common as *Fagus grandifolia* on the landscape. Other mesic taxa that occupied this habitat in smaller numbers include: *Betula* (birch, most likely *Betula alleghaniensis* (yellow birch) (5%), based on geographic range as the other candidate, paper birch, is a boreal species); *Populus* (most probably *P. deltoides*, eastern cottonwood) (5%); *Alnus rugosa* (speckled alder) (1%); *Corylus* (hazelnut) (5%); *Ostryra*/*Carpinus* (hophornbeam/hornbeam) (4%); and *Fraxinus* (both *F. pennsylvanica* and *F. americana*, green and white ash respectively) (3%); *Juglans* (both *J. nigra* and *J. cinera*, black walnut and butternut, 1%). There is also a low percentage (2% to 3%) of *Tsuga* pollen, that of the only species of this genus in the region, *Tsuga canadensis* (eastern hemlock), is a mesic-adapted conifer that is a dominant taxa north of the Tension Zone. Other trees identified in this zone, though not recorded on the pollen diagram because of very low percentages (>1%), include *Tilia americana* (basswood), *Morus rubra* (red mulberry), *Cornus* (dogwood), *Nyssa sylvatica* (black gum), *Salix* (willow), and Rosaceae (rose family).

The lowlands were inhabited by a mixture of coniferous and deciduous trees as they are today. *Larix* (would have to be *Larix laricina*, the only tamarack species in eastern North America) is the most abundant taxon in this zone, with pollen values that fluctuate between 15% and 25%. The southernmost occurrence of tamarack today is extreme northern Indiana and Ohio (USDA, 2006). Cupressaceae (cypress family) also increases in this zone from a minimum of 10% to 20% near the top of the zone. There are two possible candidates for the identified Cupressaceae, *Juniperus* spp., but these are limited to the rocky shores around the Great Lakes and xeric soils in western North America, and *Thuja occidentalis* (northern white cedar) which is a common swamp tree in Michigan. Hence, the Cupressaceae pollen is interpreted as that of *Thuja occidentalis*. The main deciduous swamp tree was *Ulmus*, having to be *U. americana* (American elm), the only elm species currently existing in this area of Michigan. The abundance of this taxon shifts from an initial 13% to a high of 16% in the middle of this zone. Some of the *Fraxinus* and *Alnus* identified may have been from trees/shrubs that inhabited the swamp, as these grow in both hydric as well as mesic soils.

The xeric habitat was characterized by primarily *Quercus* (oak), which could have been any of the ten native species that currently exist in Michigan. All but two of them are upland xeric taxa, so the oak pollen identified in the Otter Lake record are considered to be primarily of oaks that inhabit well-drained sandy soils. Pollen values for *Quercus* range between 9% and 15% in this zone. These values when interpreted should be cut by half, as modern pollen production studies report that oak typically produces twice as much pollen as represented by trees in the local vegetation (Molina et al., 1996). *Quercus*' companion, *Carya* (hickory, with four possible species), occurs in very low abundance levels (1% to 2%). *Pinus* abundance is negligible as it is a high pollen producer (usually four times that represented by trees in the local flora; Molina et al., 1996) and its abundance never reaches more than 10% in this zone.

In summary, Zone OL-1 clearly identifies the three habitat types that currently reside in the study area. What distinguishes this zone from later ones is that it has the highest values for *Fagus*, and fairly high values for *Acer* and *Populus*, suggesting that the upland habitat was quite mesic. This interpretation of ample precipitation is also supported by the abundance of wetland trees, mainly *Larix*, Cupressaceae (*Thuja occidentalis*), and *Ulmus*, that inhabited low-lying areas. The upland xeric patches were limited in spatial extent, as suggested by low pollen values of *Pinus*, *Quercus* and *Carya*. Together these data present evidence for a mesic climate, as typifying the Neoglacial that began in Michigan ~3200 cal yr BP (Hupy and Yansa 2009b), with xeric taxa present where soils are sandy, and hence very well-drained.

5.3.2 Zone OL-2: 290-212.5 cm; *Acer-Betula-Quercus-Pinus-Larix* (1800-1040 cal yr BP)

This zone is characterized by an abundance decline in some upland mesic taxa, particularly that of *Fagus*, as evidenced by a pollen decrease from 15% to 6%, and a decline of *Populus* pollen from 4 to 1%, while those of *Juglans*, *Fraxinus*, *Corylus*, *Alnus*, and *Ostrya*/*Carpinus* are still very low never exceeding 2%. The exceptions are *Acer*, pollen values of which remain relatively stable at 10%, and those of *Betula* increase slightly from 2% to 6%, which is the greatest abundance of this taxon in the entire 2000-year record. The wetland habitat is well represented by *Larix*, which reaches its highest percentages in this zone, consistently between 20% and 25%, indicating that local water tables are still high. Pollen values for Cupressaceae (8% to 20%) and *Ulmus* (6% to 11%) are slightly lower and more variable than in the previous zone. The xeric habit expanded slightly, as suggested by the minor increases in *Quercus* (~18%, up slightly from 15% in Zone OL-1) and a notable rise in *Pinus* values (4% to 16%), even after taking into account the overproduction of these two pollen types. Other trees identified in this zone include *Tilia americana* (basswood), *Morus rubra* (red mulberry), *Cornus* (dogwood), *Nyssa sylvatica* (black gum), *Salix* (willow), *Castanea dentata* (chestnut), and Rosaceae.

In summary, the pollen data from Zone OL-2 provides a weak signal for a drying trend, with a possible associated slight warming, as suggested by the slight increase of *Pinus*, fairly consistent *Quercus*, and a notable decline in *Fagus* in the local flora. This may indicate the beginnings of vegetation response to the MWA, as some researchers propose this warmer-drier interval began ~1200 cal yr BP (Lamb, 1965; Hughes and Diaz, 1994; Cronin et al., 2003; Mann and Jones, 2003). However, any climate shift would have been very subtle as the wetland vegetation was still prevalent, as evidenced by fairly large areas of swamps dominated by *Larix* and, in lesser amounts, by Cupressaceae (again, probably *Thuja*), and *Ulmus*.

5.3.3 Zone OL-3: 212.5-170 cm; *Quercus-Pinus*-Cupressaceae (1040-680 cal yr BP)

This zone is distinguished by the continued decline of *Fagus* (11% to 5%), whereas the values for *Acer* are quite consistent (~11%) and those for the other mesic deciduous trees are very low as in the previous zone. Both *Populus* and *Ostrya/Carpinus* are steady at ~2%. *Tsuga* rises from 2% at the bottom of this zone to 6% in the middle before decreasing at the top. *Fraxinu*s and *Juglans* are in low numbers, with abundance levels never going over 1% for either species. The swamp taxa are still quite abundant, but all undergo a decline during this interval. Cupressaceae reaches its greatest abundance in the 2000-year record at the bottom of this zone, ~20%, but declines to ~10% at the top of this zone. Similarly, *Larix* undergoes its first decline from ~20% to13%, and *Ulmus* decreases from 10% to 3% throughout this zone. In contrast, there is a notable increase in the abundance of xeric taxa, in that *Quercus* increases from 15% to 21% and *Pinus* values rise from 15% to 19%. The other taxa identified in this zone are the same as those found in zone OL-2.

Together these patterns in the pollen data for this zone provide a very weak signal for the MWA, as first illustrated by a *Fagus* decline, a delayed decrease in the prevalence of wetland taxa that began ~880 cal yr BP, and slight abundance increases in the xeric-adapted *Quercus* and *Pinus*. The slight response of the Otter Lake vegetation to the MWA, compared to other pollen sites in the region (Ahearn and Bailey, 1980; Booth and Jackson, 2003; Hupy and Yansa, 2009a), may reflect the predominance of an overall moist late Holocene climate in the Thumb of Lower Michigan. Also, unlike other pollen studies in the Great Lakes region, there is no noticeable increase in herbaceous taxa like *Ambrosia* (ragweed), *Artemesia* (wormwood) and Poaceae (grasses), indicating the absence of any prairie or oak savanna patches in the area. Therefore, evidence is lacking at Otter Lake for an increased frequency of La Niña events based on the vegetation changes which reflected very slight shifts in climate as compared to the preceding zones and is comparable, with regards to species and habitat types, to those of today.

5.3.4 Zone OL-4: 170-70 cm; *Pinus-Picea-Betula* (680-215 cal yr BP)

This zone captures the most significant shifts in species abundance of all of the zones dating to before Euro-American settlement. In the mesic deciduous forest habitat, *Acer* reaches a peak pollen abundance of 18% in the middle of this zone, before declining to 6% near the top of the zone. Similarly, the pollen data for *Fagus* are relatively stable with abundance levels hovering around 2%, except for a spike of 18% in the middle of the zone before a sharp decline. *Betula* has a slight pollen increase from 2% to 5% in this zone as well. The first decipherable increases in *Juglans* (to 4%) and *Alnus* (2%) pollen grains in the entire record occur near the top of this zone. The mesic conifer *Tsuga* is also present in this zone with abundance levels reaching 4% in this zone and other taxa identified in low numbers, and so not plotted on the pollen diagram, are the same as reported above for the previous two zones.

There are declines in the pollen abundance of the swamp taxa Cupressaceae (20% to 10%) and *Ulmus* (5% to 3%), whereas the values of *Larix* consistently fluctuated between 10% and 21%. *Picea mariana* (black spruce) makes a notable appearance in this zone with abundance ranging from 2% to 5% in the bottommost portion of the zone before declining again to 3% at the top of the zone. Black spruce, along with tamarack would have co-inhabited the swamp with elm and ash, occupying the shoreline, as observed today. The southernmost occurrence of black spruce in large numbers today is north of the Tension Zone in northern Lower Michigan, although it can occur in wetlands as far south as northern Indiana and northern Ohio because of the perennially moist conditions (USDA, 2006). Nonetheless, the notable appearance of *Picea mariana* and lesser numbers of *Larix* and *Abies* (balsam fir) implies that the climate was cooler during the LIA than it is today, as these northern conifers are currently absent in the Otter Lake area. Also, an increase in *Pinus* from 16% to 25% throughout the zone also lends support for the interpretation of a slight cooling trend in the Otter Lake area during the LIA.

While the cooling trend is clearly identified for the LIA, the signals for moisture are conflicting. The *Pinus* increase, mentioned above, could suggest a drying trend, but the other xeric taxa, *Quercus* and *Carya* both decrease in abundance, oak from 12% to 4% and hickory from 5% to 1%. However, the *Pinus* provides a better signal (i.e., more xeric conditions) than does the *Quercus* decline, as the latter includes a few (two of the ten) species that inhabit swampy locales, whereas all pine species inhabit well-drained sandy soils. Similarly, the shifiting abundances of the mesic-adapted taxa provide conflicting signals. The greatest abundance of *Acer* is seen in this zone, compared to the other four zones, suggests mesic conditions, but *Fagus*, a key mesic taxon, is less abundant than in earlier zones. Although the swamps were occupied by *Picea mariana* and *Larix*, suggesting hydric conditions, there are lesser numbers of Cupressaceae and *Ulmus*, indicating similar or slightly declining water levels during this zone. So again, the moisture trend during the LIA is not clear-cut and hence is considered to be ambiguous

In summary, the abundance of coniferous taxa, particularly the appearance of *Picea mariana*, is striking in this zone, however they never reach abundance levels as high as those typical of the mixed coniferous-deciduous forest that exists north of the Tension Zone. Deciduous species are still more prevalent at this time, though the composition of the forest had undoubtedly changed slightly. Therefore, the characterization of this forest composition remains the same as the other zone, though elements of the mixed coniferous-deciduous forest begin migrating southward into the area surrounding Otter Lake, as exemplified by the *Pinus* increase and appearance of the northern conifers *Picea mariana* and *Abies*.

5.3.5 Zone OL-5: 70-30 cm; *Ambrosia-Alnus-Ulmus* (215-100 cal yr BP)

This zone represents the influx of Euro-Americans into the area surrounding Otter Lake where they logged the forest, planted crops and created settlements. Historic records indicate that the land in the vicinity of Otter Lake was clear-cut between 1837 and 1897 (Dickmann, 2009; Lewis, 2009), which is clearly discerned in the pollen record. Some areas of Lower Michigan, including the Saginaw Valley, were beginning to be cultivated by the few settlers in the area as early as the 1830's and most of the land surrounding Otter Lake was agriculturally productive by 1845, coinciding with widespread forest clearance in the area (Kapp, 1999; Lewis, 2009). The strongest signal in this zone is the dramatic increase of *Ambrosia* (ragweed), which has a eight-fold increase in abundance levels, rising from 3% to 25%. *Ambrosia* is indicative of land disturbances as ragweed quickly colonizes areas that are void of other vegetation, and is detected in all pollen records in eastern and central North America during this time period (Webb, 1974; Webb et al., 1983; Russell and Davis, 2001). There is also a clear pollen increase of Poaceae (1%

to 6%), which can be inferred to represent mainly the onset of widespread cereal crop (corn, wheat, and rye) cultivation. There are also low, but significant, values for Cheno-Am (Chenopodiaceae-Amaranthaceae 2%), which is representative of weedy taxa, as expected for widespread agriculture.

Corresponding there is a decline in all tree species that strongly indicates 19th century deforestation, with the topmost sample having higher values for trees suggestive of some reforestation in the early 20th century, which typifies the pattern of Euro-American impacts in the region (Dickman, 2009; Lewis, 2009). Specifically, *Fagus* virtually disappears from the pollen record with abundance levels around 0.5%, and *Acer* declines from 10% to 3%, which is expected as these trees were cut for timber and to clear prime land (those with fine- and medium-grained soils) for agriculture. *Pinus* declines from an abundance of 25% to 3%, which is explained by white pine being highly prized by loggers for extraction (Whitney, 1987; Dickmann, 2009). *Larix* declines from 17% to 6%, which suggests that even the wetlands were logged to some extent, or alternatively they were burned. The historic 1881 “Thumb” fire that burned the entire study area and more than 400,000 hectares probably partly accounts for these vegetation changes (Dickmann, 2009). This fire would have disseminated the remaining vegetation, particularly the mesic fire-intolerant beech, maple, and cedar, and possibly burned some of the wetlands (Carey, 1993; Dickmann, 2009).

The populations of *Pinus*, *Larix* and *Fagus* do not recover after this logging and fire, but there was regrowth of *Picea* (to 8%) and *Ulmus* (rise from 3% to 10%) in the wetlands and *Acer* (7%), *Betula* (5%), *Populus* (4%), and *Quercus* (15%) in the upland habitats. Of these, *Betula* and *Populus* are well recognized early successional taxa that grown quickly after disturbance

(Whitney, 1987). *Alnus* reaches its highest abundance in this zone, increasing from 2% to 8%, which is explained by this native shrub being a weedy, invasive taxon (USDA, 2006).

In summary, the pollen record of Otter Lake demonstrates weak signals for both the MWA and LIA making climate interpretations extremely difficult. While zone OL-2 can be interpreted as a decrease in available moisture during the MWA, this conflicts with the interpretation of zone OL-3 which still has abundant levels of mesic taxa during the latter part of the MWA. This is likely due to the abundant wetlands that surround Otter Lake and may not accurately reflect slight decreases in available moisture that is presumed for the MWA. Conversely, the response of vegetation to the LIA was somewhat more pronounced. Although there are uncertainties in interpreting the precipitation regime during zone OL-4 (LIA) at Otter Lake, the decline in mesic and hydric (swampland) taxa, coinciding with an increase of the xeric-adapted *Pinus* weakly suggests a drying trend. This zone better illustrates a cooling trend, as evidenced by the appearance of the northern conifers *Picea* and *Abies* in the middle portion of this zone. The strongest signal in the entire record of Otter Lake is zone OL-5, which records Euro-American land clearance and agricultural cultivation of the surrounding area. This is evidenced by a large spike in the abundance of *Ambrosia* and other herbs and associated decline in all tree taxa, which is attributed to logging, before a reoccurrence in the 20th century of early successional species like *Quercus* and *Acer* as well as the reemergence of swampland taxa like *Ulmus*.

CHAPTER 6: DISCUSSION

6.1 Vegetation Shifts in the Otter Lake Area

High-resolution paleoecological studies, like the one conducted for this thesis, are valuable because they are able to more accurately reconstruct subtle shifts in species abundance in a particular area over time. This makes the study of Otter Lake especially valuable as any increase in coniferous taxa, as seen during the LIA (~550-150 cal yr BP), could suggest that the location of the Tension Zone has shifted through time. These data, in turn, can then be used to decipher small-scale climatic changes that have occurred and can also be helpful for predicting future forest composition shifts that may result from impending future climate change. Although the forests today are fragmented, and hence have more barriers to migration in response to climate change as compared to the past (discussed in chapter one), fossil pollen analysis still provides important insights regarding the rates of individual species migration and the shifting taxonomic composition of forests resulting from changes in temperature and precipitation regimes.

In order to accurately assess the effects of climate change on individual plant species, a “baseline” must first be established. Thus, the first objective of this thesis research was to document the forest composition prior to the onset of the Medieval Warm Anomaly (MWA), which was shown in zone OL-1, and spanned from 2047-1800 cal yr BP. The pollen spectra of this and subsequent zones reflect shifting abundance levels of key species, characteristic of three plant communities – mesic upland (fine-grained soils), xeric upland (coarser textured soils), and swamp lowlands – which are used to interpret hydrologic and climatic changes over time.

Zone OL-1 was characterized mainly by mesic upland deciduous tree species such as *Fagus* (beech), *Acer* (maple) and *Populus* (poplar) and swampland taxa that today are commonly found in the mixed coniferous-deciduous swampland forest, including *Larix* (tamarack), Cupressaceae (Thuja occidentalis), and *Ulmus* (elm). Species belonging to the xeric upland mixed coniferous-deciduous forest, like *Quercus* (oak) and *Carya* (hickory), had low abundance levels in this zone which also supports the hypothesis that a predominately moist climate was prevalent at this time. Temperate species, including *Juglans* (walnut), were also abundant, though to a lesser extent than the mesic taxa, throughout this zone. Thus, this can be inferred as a time of warm, moist conditions in southeastern Lower Michigan.

Zones OL-2, from 1800-1040 cal yr BP, and OL-3, 1040-680 cal yr BP, reflect changes that occurred in species abundance during the MWA, which is why I have combined them here. There was an abundance decline of the mesic trees *Populus* and especially *Fagus*, suggesting a drying trend supported by an identified increase in the more xeric-tolerant *Quercus* and *Pinus* (pine) in the upland environment surrounding Otter Lake. Swampland taxa were still prevalent and abundant in the lowland environment throughout zone OL-2 with notable changes in abundance levels occurring in zone OL-3. By 880 cal yr BP, well into the MWA, *Quercus* and *Pinus* increased in numbers as the climate became drier. This interpretation of drier hydrological conditions is also supported by the decline in the abundance of swampland taxa *Larix* and especially that of *Ulmus*, which reached its lowest abundance in the 2000-year record prior to Euro-American settlement. Interestingly, warm-adapted species did not increase in abundance, which does not disprove the idea that the MWA was a warm interval, but could instead be interpreted as a period in which the hydrologic constraints coupled with large areas of coarse-grained soil surrounding Otter Lake outweighed any increase in temperature for species such as *Juglans* and *Populus*.

Zone OL-4, 680-215 cal yr BP, captures the entire change in species composition throughout the Little Ice Age (LIA), prior to landscape disturbances resulting from widespread Euro-American settlement of Lower Michigan. This zone is characterized by a prominent influx of more northern species, which strongly suggests an overall temperature decrease during the LIA. *Pinus* reached its highest abundance in this zone for the entire record. More compelling evidence for decreasing temperatures throughout this zone is the appearance of both *Picea mariana* (black spruce) and *Abies balsamea* (balsam fir) in the record, which are common north of the 43rd North parallel, or Tension Zone today, in the mixed-coniferous deciduous and boreal forests. While it is not surprising that the fossil pollen record would provide evidence for lower temperatures during the LIA, it is a bit unexpected to find that spruce and fir inhabited the area surrounding Otter Lake as they are absent in the area today.

While taxonomic shifts from the pollen data clearly reveal that the climate was in a cool phase, signals for the hydrologic conditions of the LIA were more ambiguous, but more likely suggest a drying trend. The mesic conifer *Tsuga canadensis* (eastern hemlock) reached peak abundance during this time. *Larix* and *Acer* also remain abundant, which solidify the interpretation that mesic conditions were persisting during the LIA. However, there are some indications for a drying trend. The abundance of Cupressaceae and *Ulmus* both declined as did that of *Populus*. *Fagus* abundance was low for this zone, except for a brief spike around 425 cal yr BP, which could indicate that mesic conditions were intermittent during the LIA. The greater abundance of *Pinus* could also imply that xeric conditions were more prevalent during the LIA. Again, interpretations of the hydrological conditions during the LIA in the Otter Lake area are inconsistent and difficult to decipher.

Zone OL-5, 215-100 cal yr BP, clearly depicts the arrival of Euro-Americans into Otter Lake and the surrounding area. This zone exemplifies the deforestation that occurred as people began altering the landscape. This zone is characterized by a dramatic decrease in all tree taxa, which would be expected given settlers cleared the land for widespread agriculture production and built homes. This extensive logging and agriculture can be clearly seen in the pollen record by the dramatic decline in the abundance of tree taxa and coeval rise of weedy taxa such as *Ambrosia* (ragweed), which became extremely abundant, Cheno-Am (Chenopodiaceae-Amaranthaceae) and Poaceae (grasses). No maize was detected during microscopic examination of pollen grains in this time interval, but some of the grass pollen could possibly be those of wheat and rye, which are not distinguishable. By 100 cal yr BP, early successional trees and shrubs began growing in the area, as shown by the slight increase of *Alnus* (alder), *Populus*, and *Betula* (birch), which are known to propagate after widespread disturbances (Whitney, 1987).

6.2 Comparison of Otter Lake's Record to Those of Other Studies

Here the Otter Lake pollen record is compared and contrasted to those of the other two studies previously conducted in southeastern Lower Michigan, followed by a brief overview of other site throughout the Great Lakes Region (Figure 6.1).

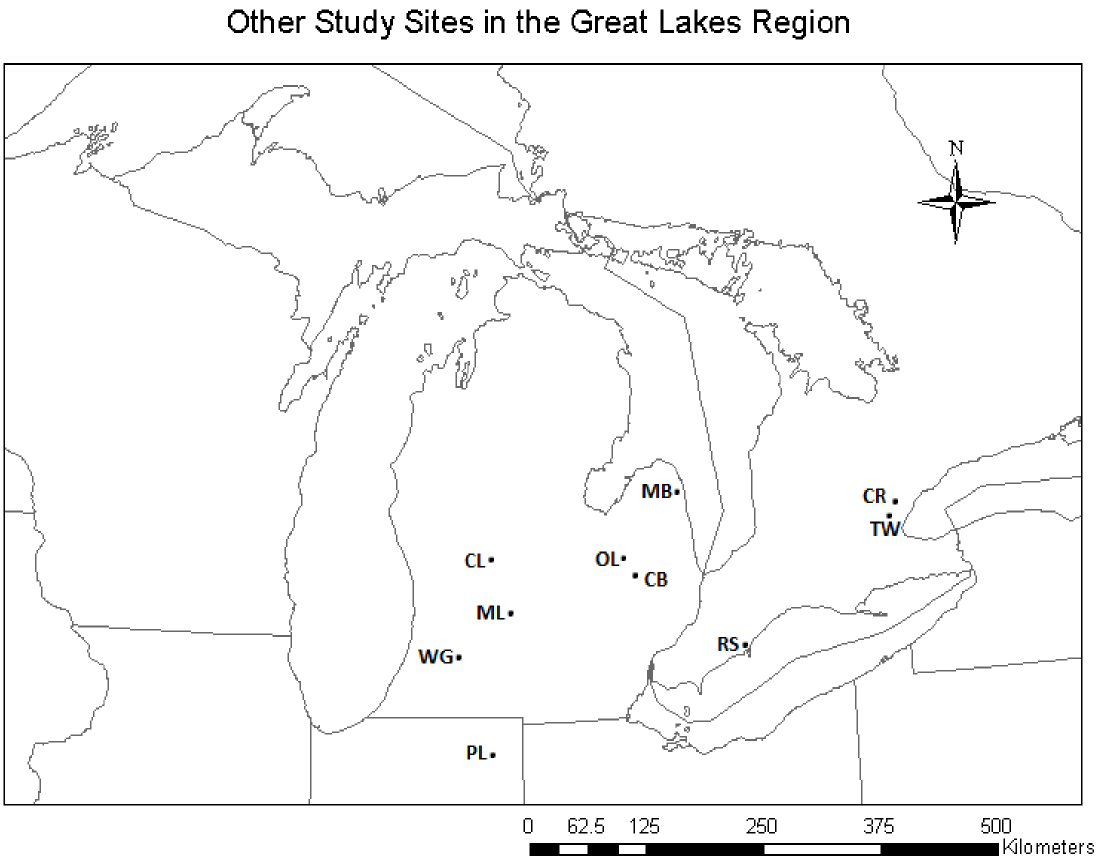

Figure 6.1: Locations of other study sites mentioned in this chapter. OL = Otter Lake, CB = Chippewa Bog (Ahearn and Bailey, 1980); CL = Cowden Lake, ML = Morrison Lake (Hupy, 2006; Hupy and Yansa, 2009a); CR = Crawford Lake, TW = Twiss Marl Pond (Yu, 2003); MB = Minden Bog (Booth and Jackson, 2002); PL = Pretty Lake (Williams, 1974); RS = Rondeau Spit (Finkelstein and Davis, 2006); WG = Wintergreen Lake (Manny et al., 1978).

6.2.1 Otter Lake and Minden Bog

Minden Bog, located in Sanilac County, was investigated by Booth and Jackson (2002) and all the information presented here comes from this study. Although pollen was investigated in the Minden Bog study, this work was primarily focused on testate amoebae analysis. Testate amoebae are protozoa (each producing a shell known as a “test”) that live in raised *Sphagnum* bogs, and rely solely on substrate moisture rather than ground water (Booth and Jackson, 2002). Therefore, testate amoebae species can detect short-term droughts and high moisture intervals, unlike trees with roots that can uptake subsurface water.

The pollen analysis conducted for Minden Bog was done at a coarser temporal scale, averaging ~103 years between samples, than my analysis (~33 year sampling interval). Moreover, the Minden Bog pollen study was done at a somewhat poorer taxonomic resolution, being that only 250 pollen grains were counted per sample, as opposed to the average of 452 grains counted for Otter Lake, which can detect rarer pollen types. However, the Minden Bog record is longer, spanning the last 3500 cal yr BP. Also noteworthy is the location of Minden Bog, which lies just within the Tension Zone at 43º36’N, as compared to Otter Lake which is south of this ecotone. Nonetheless, some insight can be gained by comparing the two pollen records. By including the data from testate amoebae, which provides greater precision and a purer signal about past precipitation changes than do pollen, the hydrological conditions can more accurately be reconstructed for Minden Bog.

2047 – 1800 cal yr BP (Comparable to Otter Lake’s Zone OL-1)

Testate amoebae analysis shows that at around 2000 cal yr BP the water table was approximately 8cm lower than the 3500 year mean before there was an increase to 3 cm above the mean by 1800 cal yr BP, which indicates that this is a time of gradually increasing precipitation. This interpretation is consistent with the abundance of mesic species, particularly *Fagus*, detected in the Otter Lake record. Minden Bog had about the same abundance of *Fagus* during this interval, but, unlike at Otter Lake, a relatively low abundance of *Acer*. The Minden Bog record reveals a profusion of *Tsuga*, *Pinus*, and *Picea*, as expected as the site is located farther north, within the Tension Zone, where conifers are more common due to the slightly shorter growing season. *Larix* and *Ulmus* are nearly absent at Minden Bog during this interval which could indicate that wetlands were more limited during this interval.

1800 – 1040 cal yr BP (Comparable to Otter Lake's Zone OL-2)

Testate amoebae analysis shows a dramatic increase in moisture availability, and therefore precipitation, at Minden Bog, where the water table averaged 5 cm above the mean over this time interval. In fact, this is the wettest period inferred for the entire record, which again spans the last 3500 years. Similar to the Otter Lake record, *Fagus* and *Betula* remained highly abundant at Minden Bog, although again *Acer* is uncommon. *Larix* is not detected in the pollen record from Minden Bog and *Ulmus* remains low which is in direct contrast to that of Otter Lake elm population during this time. As expected, the abundance of *Picea* at Minden Bog begins to decrease dramatically, which is most likely a direct result of increasing temperatures during the onset of the MWA. The pollen record of Minden Bog shows relatively stable abundance of *Pinus* and *Tsuga*, unlike that of Otter Lake, which may be attributed to well-drained (sandy) soils surrounding Minden Bog, which would have allowed these species to continue inhabiting the area during more moist conditions.

1040 – 680 cal yr BP (Comparable to Otter Lake's Zone OL-3)

Testate amoebae analysis shows a dramatic decline in moisture availability as compared to the previous zone for the duration of this time interval with an average decrease in water table depth of ~7 cm. In contrast to Otter Lake, the population of *Fagus* remains stable at Minden Bog, instead of decreasing, and abundance of *Quercus* decreases dramatically, whereas it increases at Otter Lake. At both sites, there are abundance increases in *Pinus*, *Tsuga* peaks near the center of this zone and *Acer* remains stable. While the pollen record at Minden Bog is similar for this time interval, it does not directly correlate to that of Otter Lake, although the testate amoebae analysis depicting drier conditions is consistent with my findings.

680 – 215 cal yr BP (Comparable to Otter Lake's Zone OL-4)

Testate amoebae analysis indicates that this is still a very dry period with moisture availability being the lowest for the entire record at Minden Bog. In fact, there is some evidence that from 750 to 550 cal yr BP the area surrounding this bog was experiencing drought-like conditions and the water table depth was estimated to be 10 cm below the 3500-year calculated mean, before rising. Over the next ~150 years, from 500-400 calyr BP, testate amoeba from Minden Bog indicates more mesic conditions returned to the area, based on increases in mesophytic taxa, such as *Amphitremaflavum* and *Heleoperasphagni* (Booth and Jackson, 2003; Booth et al., 2006b). Again at 400 cal yr BP, the Minden Bog record depicts another dry period that lasted ~100 years. This testate amoebae paleohydrology correlates well with the fossil pollen record of Otter Lake, as zone OL-4 is characterized by conflicting moisture signals.

The pollen records of the two sites report similarities and differences. Both locations report very low abundances of *Fagus* in conjunction with increases of *Pinus* and *Picea*. In fact, this is the first notable appearance of *Picea* in the record from Otter Lake, which was interpreted as a result of decreasing temperatures during the LIA that fostered the southward migration of black spruce. *Quercus* is relatively stable at Minden Bog, which is consistent with the overall drying trend inferred from testate amoebae. In contrast, at Otter Lake, *Quercus* abundance declines dramatically which is different from the interpretation of a drying trend, but given that paleoprecipitation is more precisely inferred from testate amoebae, the climate during the LIA was most likely drier than during the preceding MWA.

215 – 100 cal yr BP (Comparable to Otter Lake's Zone OL-5)

The testate amoebae analysis indicates that this is the driest time interval of the entire record which culminated with a 20 cm drop in the water table by 100 cal yr BP. Interpretations of this dry interval at Minden Bog is supported by abundant charcoal fragments on the pollen slides, which are thought by the researchers to have resulted from frequent wildfires, associated with drier, in conjunction with burning by Native Americans. I propose that the abundance of charcoal at Minden Bog could be a product of the "Thumb" fire of 1881 (mentioned in Chapter 5), which burned the entire area, although I cannot rule out intermittent natural wildfires and/or prior burning by Native Americans as causes. Supporting my interpretation is a sharp decline in all tree taxa and abrupt rise in *Ambrosia* in both the Minden Bog and Otter Lake pollen records, which is expected for the logging and clearing of land for crop planting that occurred throughout this part of Michigan during the late 19th century.

6.2.2 Otter Lake and Chippewa Bog

There are some ambiguities in comparing the pollen records of Otter Lake and Chippewa Bog, located 5 km north of Lapeer, Michigan (Lapeer County), because this study by Ahearn and Bailey (1980) used an undisclosed number of pollen samples for their analysis. Also, this investigation was of coarser resolution, with only 200 pollen grains counted per slide, which is less than half of the average counted and analyzed for Otter Lake. The Chippewa Bog record spans the last ~10,500 years, thus providing a longer record, but of coarser temporal scale. Compounding the problem is that calibration of radiocarbon (^{14}C) dates against the tree-ring master chronology was not available at the time of Ahearn and Bailey (1980) study, hence all of their dates are recorded as ^{14}C yr BP instead of cal yr BP. Some of their zones, particularly zone 3, span as much as 7000 years (from 8100-1070 yr BP) which captures more than half of the time interval in which Otter Lake was studied. Another difficulty in assessing the differences and similarities between the two sites is a lack of abundance percentages reported for Chippewa Bog in the paper; therefore, I estimated abundances for this record via visual interpretation of the published pollen diagram. Also this study did not analyze the uppermost portion of the core, which means that land clearing by Euro-Americans was not captured in the Chippewa Bog record. However, an attempt will be made to compare this study to that of Otter Lake, given the paucity of pollen records in southeastern Lower Michigan.

2047 – 1800 cal yr BP (Comparable to Otter Lake's Zone OL-1)

There is a distinct lack of swampland taxa present at Chippewa Bog, hence another limitation in comparing / contrasting data between the two sites. The dominant taxa at Chippewa Bog during this time interval are *Quercus* followed by *Fagus*. Conversely, Otter Lake has higher percentages of *Fagus* than *Quercus* and also abundant swampland taxa. The variation between these two sites is most likely due to variation in topography and soils, with more coarse-textured soils near Chippewa Bog, rather than climatic factors as these sites are spatially close to one another, with Chippewa Bog being located 23 km southeast of Otter Lake.

1800 – 1040 cal yr BP (Comparable to Otter Lake's Zone OL-2)

At Chippewa Bog, there is an increase in *Fagus,* which is in direct contrast to the decrease of this mesic taxon in the vicinity of Otter Lake. There is greater abundance of *Pinus* and *Betula* (birch) in both pollen records, which could indicate a slight warming trend that I interpret as dating to the beginning of the MWA. In contrast, the pollen record of Chippewa Bog shows a decline in *Quercus* whereas the population of this taxon is stable in the Otter Lake area.

1040 – 680 cal yr BP (Comparable to Otter Lake's Zone OL-3)

The decline of *Fagus* coupled with the increase in *Pinus* at both sites could indicate that drier conditions were becoming more prevalent during the MWA. *Pinus* rises sharply in numbers at Chippewa Bog and becomes the dominant taxa for this area during this time interval. This is consistent with an increase in *Pinus* at Otter Lake, though swampland taxa continue to dominate the pollen record at this site. However, there is an opposite trend for *Quercus* between the sites, with a sharp decrease in oak abundance at Chippewa Bog with an increase of this taxon in the Otter Lake record for this interval.

680 – 215 cal yr BP (Comparable to Otter Lake's Zone OL-4)

In this zone, the first decipherable increase in *Larix* is present at Chippewa Bog which could indicate increased moisture availability. However, this moisture trend is not evident at Otter Lake, nor at Minden Bog where the testate amoebae analysis clearly shows a lowering of the water table. *Quercus* increases considerably in this zone at Chippewa Bog, which again is inconsistent with the three-fold decrease of this taxon at Otter Lake. However, the *Fagus* decreases around Chippewa Bog are similar to that in the Otter Lake area. Hence the conflicting moisture signals for Chippewa Bog at this time is strikingly similar to that reported for Otter Lake, which has two possible explanations. First, the noted drought-like conditions reported at Minden Bog were punctuated by a brief increase(s) in available moisture that supported more mesic and hydric trees evident in the pollen records of Chippewa Bog and Otter Lake. Or, secondly, the relatively low pollen counts at Chippewa Bog, less than half of the grains tabulated for Otter Lake, coupled with the meso-scale resolution of the study carried out in 1980 did not captured the nuanced changes in tree dominance that were identified in the Otter Lake record. And, as noted above, the pollen record of Chippewa Bog does not capture the land clearing carried out by Euro-American settlers so no comparison can be made for zone OL-5.

6.3 Regional Pollen and Paleoclimate Reconstruction

Throughout the Great Lakes region, the anomalies associated with both the MWA and LIA are verified through multiple proxy data. As noted above, testate amoebae is an excellent proxy for capturing the paleohydrology of an area and confirms the assumption that both the MWA and LIA were, overall, periods of decrease precipitation in the Great Lakes region. Other proxy records confirm the assumption that these were relatively warmer and cooler periods, respectively. These temperature changes are minor relative to the last 11,000 years, as recorded in both the Greenland and the Antarctic ice core records, however these polar records do reveal that the MWA and LIA were global events (Johnsen et al., 2001;Soon and Baliunas, 2003; MacFarling et al., 2006). Estimates range from a 1 to 2ºC temperature change between the MWA and LIA (Soon and Baliunas, 2003; Jones and Mann, 2004), which seems minor, but was enough to affect the population dynamics and ranges of both floral and faunal species in the middle and high latitudes (Domack and Mayewski, 1999; Domack et al., 2001).

Forest composition responded to these climate changes in the Great Lakes region in most locales, but not at all. For example, northern Indiana and Ohio did not experience the typical climate patterns associated with the MWA and the LIA (Williams, 1974; Holloway and Bryant, 1985). At the height of the MWA, *Quercus* and *Carya* pollen decrease as *Fagus* and *Acer* increase (Williams, 1974). This *Fagus-Acer* forest suggests a cooler, moister climate at a time when global temperatures were thought to have increased by as much as 1°C (Williams, 1974; Wahl et al., 2012). Conversely, *Quercus* and *Carya* begin to rebound in numbers during the LIA in northern Indiana, by converting ^{14}C dates I estimate this to have occurred ~670 cal yr BP (Williams, 1974). These species are well adapted to warmer and drier climates not typical of the LIA (Williams, 1974; Wahl et al., 2012).

The landscape of southern Ontario experienced minimal change until the onset of the LIA (Yu, 2003). During the MWA and until 500 cal yr BP, *Quercus* abundance remained high along with that of *Betula*, but slowly *Pinus* began increasing until reaching maximum abundance during the late Holocene (Finkelstein and Davis, 2006). This *Pinus* spike marks the beginning of the LIA in southern Ontario (Yu, 2003; Finkelstein and Davis, 2006). This pollen spectra is interpreted as a mixed hardwood forest, which was the dominant vegetation in the area until the beginning of European settlement (Yu, 2003; Finkelstein and Davis, 2006).

Near Wintergreen Lake in Kalamazoo County, Michigan, the landscape was generally stable, dominated heavily by *Quercus* and *Carya* ~1000 cal yr BP, and the pollen record does not reveal any significant changes in taxa until the mid-1800's, concurrent with Euro-American settlement (Manny et al., 1978). Taxonomic shifts interpreted as a response to both the MWA and LIA are recorded in two pollen records from southern Lower Michigan, those of Cowden Lake in Montcalm County, and Morrison Lake in Ionia County. (Hupy, 2006; Hupy and Yansa, 2009a). In the Cowden Lake area, situated within the forest Tension Zone, *Quercus*-dominated forest was gradually replaced by a forest that included more mesic taxa, such as *Ulmus*, suggesting increased moisture at the onset of the MWA (Hupy, 2006). This mesic deciduous forest remained abundant throughout the LIA, though increases in *Tsuga* and *Pinus* suggest that the northern conifers were expanding southward during this cooling interval, as was the case at

Otter Lake. The pollen record of Morrison Lake, situated south of the ecotone at a latitiude comparable to that of Otter Lake, suggests that the moisture regime was different than at Cowden Lake to the north. Xeric-adapted *Quercus* and *Carya* were the dominant species in the Morrison Lake area until the end of the MWA when mesic species, such as *Fagus,* began increasing (Hupy, 2006; Hupy and Yansa, 2009a). Fluctuations in the relative abundance of *Quercus* vs. *Fagus* abundance throughout the LIA was detected not just in the Morrison Lake record (Hupy, 2006), but, as noted above, also in the Otter Lake pollen record and the testate amoebae record of Minden Bog that showed a variable moisture pattern (Booth and Jackson, 2002). In summary, although there are general similarities in the pollen spectra dating to the MWA and LIA between these various sites within the Great Lakes region, there are some disparities in forest species composition, which are likely attributed to individual micro-climates at each location and/or the influence of local soil characteristics (texture and fertility).

CHAPTER 7: CONCLUSION

7.1 Project Summary

The primary objective of this research was to document and interpret the vegetation response to the two most notable climatic episodes of the last 2000 years prior to the widespread Euro-American settlement of Lower Michigan: the Medieval Warm Anomaly (MWA; ~1150-750 cal yr BP) and Little Ice Age (LIA; ~550-150 cal yr BP). These shifts in the dominance of different tree species, as interpreted from the study of fossil pollen from Otter Lake, reflect shifts in the relative areal coverage of three habitat types, mesic upland, xeric upland, and hydric swampland, within a broadleaf deciduous forest that is close to its northern range limit. This study constitutes a small piece of the larger puzzle as to the exact conditions in southeastern Lower Michigan during the MWA and the LIA, but does provide meaningful data as previous interpretations of temperature and precipitation trends during these episodes can sometimes be contradictory or ambiguous. Although there are uncertainties in interpreting some of the signals in the Otter Lake pollen record, some trends are clearly evident from the data produced.

Conditions were undoubtedly warming during the MWA, as compared to the centuries before, evidenced by the population increase of *Quercus*, and a drying trend detected by the decreasing abundance of all mesic as well as hydric swampland taxa. This shift in species dominance at Otter Lake is similar to the vegetation pattern reconstructed in other pollen studies conducted within the Great Lakes region during the MWA.

Vegetation changes at Otter Lake were more pronounced in response to the LIA, marked by the first notable appearance of the cooler adapted *Picea mariana*, native to regions within and north of the Tension Zone, in the pollen record. While the cooling trend is clear, the hydrological conditions during the duration of the LIA are not. There are conflicting signals for moisture in the pollen records of Otter Lake and in those of two bogs (Minden and Chippewa) in southeastern Lower Michigan as well as in the data from other pollen sites in the region. Moreover, the moisture trends in these pollen data differ, to some degree, from the higher resolution testate amoebae data of Minden Bog (Booth and Jackson, 2002). This microscopic animal proxy reconstructed that drought-like conditions prevailed at 550 and again at 400 cal yr BP, in between times of greater moisture availability. The inconsistencies could be attributed to micro-climatic variability that can occur within homogenous climate zones. Only with future research may we be able to better comprehend the exact climatic conditions during these two events and more accurately predict vegetation changes that may occur in the Great Lakes region as a result of future climate change in the 21st century.

7.2 Future Research Potential

What is clear from my analysis of pollen data from Otter Lake and comparison of these results to those of Minden and Chippewa bogs, is that there is a great need for conducting further high-resolution research in this part of Lower Michigan. Only with additional high-resolution studies of pollen and other proxies at a variety of sites spaced across the area, can a clearer picture of the changing climatic conditions in southeastern Lower Michigan over the past millennia be made. Abundant opportunities exist throughout the area as this study was the first in the area to be conducted on a lake, and lakes are numerous in this formerly glaciated region.

There is also great potential for an in-depth assessment of plant migration rates as only one such study has been conducted thus far in Michigan. This was not done here as multiple sites, three at a minimum, would need to be analyzed to produce pollen diagrams. By analyzing the pollen profiles from multiples sites calculating rates of migration for individual species can be carried out to infer future forest composition changes.

APPENDIX

Table A.1: Final pollen data, expressed in percents, of key taxa used to produce the Otter Lake pollen diagram via the Tilia 1.7.16 program (298 – 100 cal yr BP).

Scientific Name	**Common Name**	**cal yr BP**	**100**	**133**	**166**	**199**	**232**	**265**	**298**
Pinus	Pine		4.2	5.0	7.6	6.9	10.7	21.9	13.1
Picea	Spruce		0.0	0.0	0.0	0.2	0.0	0.4	0.0
Abies	Fir		0.0	0.0	0.0	0.2	0.0	0.4	0.0
Cupressaceae (Juniperus/Thuja)	Juniper / Cedar		9.8	9.6	12.7	14.6	15.8	10.6	13.1
Larix	Tamarack		6.4	11.2	17.8	17.2	18.7	15.3	21.5
Tsuga	Hemlock		1.1	0.0	0.5	0.2	1.2	1.9	3.2
Acer	Maple		5.5	3.4	3.4	6.9	10.5	7.7	13.3
Alnus	Alder		2.9	6.4	4.1	4.1	1.9	1.2	1.6
Betula	Birch		4.9	4.6	2.0	2.7	3.9	6.8	4.1
Corylus	Hazelnut		0.0	0.9	0.2	0.7	1.2	0.0	0.0
Ostrya/Carpinus	Hophornbeam/ Hornbeam		2.2	1.6	0.2	0.2	0.0	2.1	2.5
Carya	Hickory		1.1	0.7	0.2	0.5	0.7	0.2	0.5
Fagus	Beech		0.7	0.5	2.4	1.1	3.4	9.5	6.6
Fraxinus	Ash		0.4	1.6	1.0	1.6	1.7	0.4	0.9
Juglans	Walnut		0.7	0.2	0.0	1.4	0.5	2.7	0.2
Populus	Poplar		3.1	3.7	3.2	4.1	2.9	0.4	2.5
Quercus	Oak		14.0	7.6	4.4	4.6	8.5	7.4	4.1
Ulmus	Elm		9.1	9.6	2.4	4.8	6.1	3.3	4.1
Other Trees			0.9	1.6	3.2	2.1	0.7	1.0	0.2
Ambrosia	Ragweed		23.3	25.9	24.6	18.5	4.1	2.1	1.6
Artemisia	Wormwood		0.2	0.2	0.5	0.2	0.2	0.0	0.2
Poaceae	Grasses		1.8	0.5	5.6	3.7	1.5	0.8	0.5
Cheno-am			2.0	0.9	1.0	0.2	0.5	0.0	0.0
Other Herbs			0.0	0.0	0.0	0.7	0.0	0.0	0.7
Aquatics			0.2	0.0	0.5	0.5	1.0	0.4	0.2
Lycopodium			0.0	0.0	0.5	0.0	0.0	0.2	0.0

Table A.2: Final pollen data, expressed in percents, of key taxa used to produce the Otter Lake pollen diagram via the Tilia 1.7.16 program (529 – 331 cal yr BP).

Scientific Name	**Common Name**	**cal yr BP**	**331**	**364**	**397**	**430**	**463**	**496**	**529**
Pinus	Pine		24.6	17.3	9.1	8.9	11.2	14.4	14.7
Picea	Spruce		0.0	0.0	1.5	0.0	0.2	0.0	0.0
Abies	Fir		0.0	0.0	1.5	0.0	0.2	0.0	0.0
Cupressaceae (Juniperus/Thuja)	Juniper / Cedar		7.3	11.5	9.5	9.7	9.5	11.4	11.3
Larix	Tamarack		14.9	18.5	16.9	18.4	12.4	12.5	16.7
Tsuga	Hemlock		4.2	3.8	3.8	2.6	2.7	2.2	2.0
Acer	Maple		15.3	16.0	14.8	14.1	17.6	18.5	16.5
Alnus	Alder		3.0	0.9	1.1	0.4	0.8	2.4	1.4
Betula	Birch		3.8	2.9	4.6	3.7	3.3	3.2	2.0
Corylus	Hazelnut		0.0	0.5	0.0	0.6	0.8	0.2	0.2
Ostrya/Carpinus	Hophornbeam/ Hornbeam		2.8	1.8	1.5	3.0	2.5	0.4	1.4
Carya	Hickory		0.4	0.5	2.1	0.6	4.6	3.2	1.6
Fagus	Beech		4.4	4.5	5.9	15.8	7.1	4.5	5.0
Fraxinus	Ash		2.4	0.7	2.3	2.8	0.8	2.8	1.6
Juglans	Walnut		0.0	0.2	0.4	0.0	1.2	0.2	0.5
Populus	Popular		1.0	1.6	1.9	1.1	1.2	1.9	2.3
Quercus	Oak		4.8	5.2	8.3	8.9	13.9	10.3	11.3
Ulmus	Elm		4.0	4.5	6.1	5.2	3.9	6.5	4.1
Other Trees			0.8	1.6	0.6	1.3	2.5	2.4	0.9
Ambrosia	Ragweed		0.4	0.5	1.5	0.6	0.8	0.0	0.7
Artemisia	Wormwood		0.0	0.2	0.4	0.0	0.2	0.0	0.2
Poaceae	Grasses		0.0	0.0	0.4	0.0	1.0	0.0	0.5
Cheno-am			0.0	0.0	0.0	0.0	0.0	0.0	0.0
Other Herbs			0.2	1.1	0.2	0.0	0.0	0.2	0.0
Aquatics			0.2	0.2	0.2	0.0	0.2	0.4	0.2
Lycopodium			0.0	0.0	0.0	0.2	0.0	0.2	0.0

Table A.3: Final pollen data, expressed in percents, of key taxa used to produce the Otter Lake pollen diagram via the Tilia 1.7.16 program (760 – 562 cal yr BP).

Scientific Name	Common Name	cal yr BP	562	595	628	661	694	727	760
Pinus	Pine		18.1	15.8	18.0	17.1	12.8	15.7	15.4
Picea	Spruce		0.0	0.0	0.0	0.0	0.0	0.0	0.0
Abies	Fir		0.0	0.0	0.0	0.0	0.0	0.0	0.0
Cupressaceae (Juniperus/Thuja)	Juniper / Cedar		11.2	13.9	14.4	18.3	11.7	14.8	13.9
Larix	Tamarack		11.0	17.2	12.9	12.0	14.6	14.0	17.5
Tsuga	Hemlock		1.4	4.0	2.2	1.6	0.9	1.2	1.0
Acer	Maple		19.8	14.5	17.6	16.9	10.3	10.5	9.9
Alnus	Alder		1.2	1.9	0.7	0.9	0.0	1.2	0.5
Betula	Birch		3.1	3.4	2.0	2.1	2.5	1.4	2.9
Corylus	Hazelnut		0.2	0.4	0.0	0.2	0.7	0.4	0.5
Ostrya/Carpinus	Hophornbeam/ Hornbeam		2.1	1.3	1.1	2.1	2.7	3.3	2.6
Carya	Hickory		2.6	1.7	2.7	2.8	3.0	1.9	1.7
Fagus	Beech		4.8	4.8	6.2	4.5	7.3	7.6	7.2
Fraxinus	Ash		1.0	1.3	0.4	0.7	0.7	1.6	1.4
Juglans	Walnut		0.2	0.2	0.2	0.0	0.0	0.0	0.0
Populus	Popular		1.7	1.9	1.3	1.9	1.6	1.2	1.2
Quercus	Oak		10.0	9.0	12.7	10.3	20.4	17.3	15.9
Ulmus	Elm		4.3	4.4	5.6	4.9	6.9	4.1	6.0
Other Trees			1.0	0.6	0.7	0.9	0.5	1.4	1.7
Ambrosia	Ragweed		0.2	0.2	0.2	0.0	0.2	0.4	0.0
Artemisia	Wormwood		0.0	0.2	0.2	0.0	0.2	0.0	0.0
Poaceae	Grasses		0.5	0.4	0.2	0.5	0.5	0.4	0.0
Cheno-am			0.0	0.0	0.0	0.2	0.0	0.0	0.0
Other Herbs			0.5	0.0	0.0	0.0	0.2	0.0	0.2
Aquatics			0.7	0.8	0.2	0.0	0.5	0.0	0.2
Lycopodium			0.0	0.4	0.0	0.0	0.0	0.0	0.0

Table A.4: Final pollen data, expressed in percents, of key taxa used to produce the Otter Lake pollen diagram via the Tilia 1.7.16 program (991 – 793 cal yr BP).

Scientific Name	Common Name	cal yr BP	793	826	859	892	925	958	991
Pinus	Pine		16.8	15.2	13.8	14.5	14.1	11.1	6.8
Picea	Spruce		0.0	0.0	0.0	0.0	0.0	0.0	0.0
Abies	Fir		0.0	0.0	0.0	0.0	0.0	0.0	0.0
Cupressaceae (Juniperus/Thuja)	Juniper / Cedar		14.8	16.5	18.5	10.3	17.7	22.2	22.3
Larix	Tamarack		15.7	12.1	18.1	15.0	21.8	13.6	14.0
Tsuga	Hemlock		4.0	2.2	2.9	2.0	4.6	1.4	2.5
Acer	Maple		9.3	11.2	8.6	10.0	7.4	10.2	11.7
Alnus	Alder		0.4	1.1	0.5	1.0	0.7	1.4	0.9
Betula	Birch		2.2	2.4	1.6	2.7	2.6	0.9	0.5
Corylus	Hazelnut		0.2	0.2	0.5	0.7	0.2	0.2	0.0
Ostrya/Carpinus	Hophornbeam/ Hornbeam		1.3	2.0	2.0	2.7	1.2	1.8	1.1
Carya	Hickory		1.1	3.1	1.1	2.3	1.0	1.8	3.2
Fagus	Beech		7.9	5.1	7.7	8.1	7.7	11.1	12.8
Fraxinus	Ash		0.9	0.4	0.7	1.0	0.2	0.9	0.5
Juglans	Walnut		0.0	0.2	0.0	0.7	0.7	0.2	0.2
Populus	Popular		2.6	0.7	0.9	0.5	1.2	0.9	1.4
Quercus	Oak		12.4	16.3	11.3	14.0	8.9	12.2	10.1
Ulmus	Elm		7.1	8.6	10.8	11.0	6.7	6.9	9.9
Other Trees			0.9	1.1	0.7	2.0	1.4	1.4	0.7
Ambrosia	Ragweed		0.2	0.0	0.0	0.5	0.5	0.2	0.7
Artemisia	Wormwood		0.0	0.0	0.0	0.0	0.0	0.2	0.0
Poaceae	Grasses		0.0	0.0	0.0	0.2	0.0	0.0	0.0
Cheno-am			0.0	0.0	0.0	0.0	0.2	0.0	0.0
Other Herbs			0.0	0.0	0.0	0.3	0.0	0.0	0.0
Aquatics			0.4	0.7	0.5	0.2	0.7	0.5	0.2
Lycopodium			1.3	0.2	0.0	0.0	0.2	0.5	0.2

Table A.5: Final pollen data, expressed in percents, of key taxa used to produce the Otter Lake pollen diagram via the Tilia 1.7.16 program (1156 – 1024 cal yr BP).

Scientific Name	Common Name	cal yr BP	1024	1057	1090	1123	1156
Pinus	Pine		10.8	7.1	8.8	12.5	10.8
Picea	Spruce		0.0	0.0	0.0	0.0	0.0
Abies	Fir		0.0	0.0	0.0	0.0	0.0
Cupressaceae (Juniperus/Thuja)	Juniper / Cedar		20.2	22.9	13.7	10.1	8.0
Larix	Tamarack		23.2	21.0	24.4	20.6	23.7
Tsuga	Hemlock		2.8	1.9	2.8	2.6	0.9
Acer	Maple		8.7	11.3	9.8	10.3	11.9
Alnus	Alder		0.5	0.6	0.9	0.7	0.5
Betula	Birch		1.8	0.8	3.7	3.1	1.4
Corylus	Hazelnut		0.0	0.2	0.0	0.2	0.5
Ostrya/Carpinus	Hophornbeam/ Hornbeam		2.1	1.3	2.3	1.9	1.2
Carya	Hickory		0.9	1.3	1.9	3.8	1.2
Fagus	Beech		7.3	4.8	4.9	5.8	14.3
Fraxinus	Ash		0.2	0.8	0.7	0.5	0.5
Juglans	Walnut		0.0	0.4	0.2	1.4	0.5
Populus	Popular		0.7	1.3	1.4	1.0	0.7
Quercus	Oak		9.2	13.6	14.7	15.8	15.5
Ulmus	Elm		10.1	8.2	7.7	6.2	5.4
Other Trees			1.1	1.0	0.5	1.2	1.4
Ambrosia	Ragweed		0.0	0.2	0.2	0.0	0.0
Artemisia	Wormwood		0.0	0.2	0.0	0.0	0.0
Poaceae	Grasses		0.0	0.0	0.0	0.0	0.0
Cheno-am			0.0	0.0	0.0	0.0	0.2
Other Herbs			0.0	0.0	0.0	0.2	0.0
Aquatics			0.0	0.6	0.0	0.7	0.5
Lycopodium			0.5	0.0	0.2	0.2	0.5

Table A.6: Final pollen data, expressed in percents, of key taxa used to produce the Otter Lake pollen diagram via the Tilia 1.7.16 program (1321 – 1189 cal yr BP).

Scientific Name	Common Name	cal yr BP	1189	1222	1255	1288	1321
Pinus	Pine		16.3	9.3	9.5	12.5	13.1
Picea	Spruce		0.0	0.0	0.0	0.0	0.0
Abies	Fir		0.0	0.0	0.0	0.0	0.0
Cupressaceae (Juniperus/Thuja)	Juniper / Cedar		9.4	13.3	7.4	12.9	14.7
Larix	Tamarack		18.2	22.0	17.8	21.9	18.0
Tsuga	Hemlock		3.0	1.9	3.6	2.8	3.7
Acer	Maple		10.9	10.5	13.1	10.4	8.6
Alnus	Alder		0.2	0.7	0.8	0.5	0.4
Betula	Birch		3.0	1.6	2.3	2.8	2.0
Corylus	Hazelnut		0.0	0.2	0.4	0.2	0.0
Ostrya/Carpinus	Hophornbeam/ Hornbeam		2.6	1.9	2.5	1.2	1.8
Carya	Hickory		0.9	1.9	2.3	1.4	1.0
Fagus	Beech		7.7	6.3	9.7	9.2	11.4
Fraxinus	Ash		1.3	0.7	1.5	0.7	0.6
Juglans	Walnut		0.2	0.0	0.2	0.2	0.6
Populus	Popular		1.1	1.4	1.1	1.6	1.0
Quercus	Oak		18.2	16.8	16.7	12.2	15.9
Ulmus	Elm		2.8	8.9	8.9	6.8	5.1
Other Trees			2.4	0.9	0.8	1.6	1.0
Ambrosia	Ragweed		0.0	0.2	0.0	0.2	0.2
Artemisia	Wormwood		0.0	0.0	0.0	0.2	0.0
Poaceae	Grasses		0.0	0.2	0.0	0.0	0.0
Cheno-am			0.0	0.0	0.0	0.0	0.0
Other Herbs			0.0	0.0	0.0	0.0	0.2
Aquatics			0.4	0.2	0.6	0.2	0.2
Lycopodium			0.6	0.5	0.2	0.0	0.0

Table A.7: Final pollen data, expressed in percents, of key taxa used to produce the Otter Lake pollen diagram via the Tilia 1.7.16 program (1486 – 1354 cal yr BP).

Scientific Name	**Common Name**	**cal yr BP**	**1354**	**1387**	**1420**	**1453**	**1486**
Pinus	Pine		6.9	9.6	8.4	8.5	7.6
Picea	Spruce		0.0	0.0	0.0	0.0	0.0
Abies	Fir		0.0	0.0	0.0	0.0	0.0
Cupressaceae (Juniperus/Thuja)	Juniper / Cedar		15.9	9.1	11.3	12.6	17.9
Larix	Tamarack		25.9	21.6	21.5	25.4	21.8
Tsuga	Hemlock		1.2	1.5	3.9	3.4	3.5
Acer	Maple		8.8	9.8	11.5	8.7	7.9
Alnus	Alder		0.2	2.2	0.2	0.7	0.7
Betula	Birch		2.6	2.7	1.6	1.6	4.4
Corylus	Hazelnut		0.2	0.5	0.6	0.0	0.0
Ostrya/Carpinus	Hophornbeam/ Hornbeam		1.4	1.7	0.8	1.4	2.0
Carya	Hickory		2.4	1.5	1.0	2.3	2.4
Fagus	Beech		9.0	12.0	16.8	16.0	7.9
Fraxinus	Ash		1.4	0.7	1.2	0.5	0.7
Juglans	Walnut		0.7	1.0	0.0	0.0	1.1
Populus	Popular		0.7	1.5	1.6	1.4	1.3
Quercus	Oak		10.2	12.3	10.9	10.3	9.2
Ulmus	Elm		6.2	7.4	4.9	4.6	7.2
Other Trees			4.0	3.4	2.9	1.4	2.8
Ambrosia	Ragweed		0.0	0.0	0.0	0.5	0.2
Artemisia	Wormwood		0.2	0.0	0.4	0.0	0.0
Poaceae	Grasses		0.0	0.2	0.0	0.0	0.0
Cheno-am			0.0	0.0	0.0	0.0	0.0
Other Herbs			0.0	0.2	0.0	0.2	0.2
Aquatics			0.5	0.2	0.2	0.5	0.2
Lycopodium			0.7	0.0	0.0	0.0	0.9

Table A.8: Final pollen data, expressed in percents, of key taxa used to produce the Otter Lake pollen diagram via the Tilia 1.7.16 program (1651 – 1519 cal yr BP).

Scientific Name	Common Name	cal yr BP	1519	1552	1585	1618	1651
Pinus	Pine		8.1	9.6	14.0	8.6	13.7
Picea	Spruce		0.0	0.0	0.0	0.0	0.0
Abies	Fir		0.0	0.0	0.0	0.0	0.0
Cupressaceae (Juniperus/Thuja)	Juniper / Cedar		12.2	10.0	10.5	15.4	11.6
Larix	Tamarack		17.1	18.6	17.2	17.9	21.2
Tsuga	Hemlock		2.6	4.6	2.0	2.9	1.9
Acer	Maple		10.8	8.8	9.3	10.7	9.8
Alnus	Alder		0.4	0.8	0.4	0.6	0.2
Betula	Birch		4.9	4.2	4.9	2.9	3.3
Corylus	Hazelnut		0.0	0.0	0.2	0.0	0.0
Ostrya/Carpinus	Hophornbeam/ Hornbeam		1.6	1.9	1.4	1.3	0.9
Carya	Hickory		1.8	1.0	2.4	1.7	2.1
Fagus	Beech		14.3	16.7	13.0	12.0	10.5
Fraxinus	Ash		0.6	2.3	0.8	1.7	0.9
Juglans	Walnut		0.2	0.6	0.2	0.6	0.2
Populus	Popular		1.8	1.3	1.2	0.8	0.9
Quercus	Oak		15.5	10.6	12.8	14.1	14.2
Ulmus	Elm		5.3	6.5	6.7	5.9	5.6
Other Trees			1.6	1.5	2.2	2.1	2.1
Ambrosia	Ragweed		0.2	0.2	0.2	0.0	0.2
Artemisia	Wormwood		0.0	0.0	0.0	0.0	0.0
Poaceae	Grasses		0.2	0.4	0.2	0.0	0.0
Cheno-am			0.2	0.0	0.0	0.0	0.0
Other Herbs			0.0	0.0	0.0	0.2	0.0
Aquatics			0.0	0.0	0.2	0.0	0.0
Lycopodium			0.0	0.4	0.0	0.4	0.2

Table A.9: Final pollen data, expressed in percents, of key taxa used to produce the Otter Lake pollen diagram via the Tilia 1.7.16 program (1816 – 1684 cal yr BP).

Scientific Name	Common Name	cal yr BP	1684	1717	1750	1783	1816
Pinus	Pine		8.7	10.2	14.9	9.2	3.7
Picea	Spruce		0.0	0.0	0.0	0.0	0.0
Abies	Fir		0.0	0.0	0.0	0.0	0.0
Cupressaceae (Juniperus/Thuja)	Juniper / Cedar		10.8	10.8	9.8	11.1	9.3
Larix	Tamarack		24.3	21.3	14.2	17.8	14.9
Tsuga	Hemlock		2.1	3.9	2.2	3.0	1.6
Acer	Maple		6.6	8.5	7.6	11.3	10.7
Alnus	Alder		0.0	0.4	0.9	0.2	1.9
Betula	Birch		3.8	6.1	2.0	3.2	3.3
Corylus	Hazelnut		0.2	0.0	0.0	0.0	0.0
Ostrya/Carpinus	Hophornbeam/ Hornbeam		1.9	1.7	0.9	0.9	3.5
Carya	Hickory		1.4	1.5	2.4	0.7	0.2
Fagus	Beech		13.9	10.8	11.8	13.9	18.8
Fraxinus	Ash		1.4	1.3	1.1	2.3	2.3
Juglans	Walnut		0.7	0.2	1.1	0.2	0.2
Populus	Popular		0.5	0.7	0.9	1.8	2.3
Quercus	Oak		12.0	14.5	14.9	14.8	13.0
Ulmus	Elm		6.8	6.1	11.3	7.6	9.3
Other Trees			2.6	1.3	2.2	0.9	2.1
Ambrosia	Ragweed		0.5	0.0	0.4	0.5	0.2
Artemisia	Wormwood		0.0	0.0	0.0	0.0	0.0
Poaceae	Grasses		0.2	0.0	0.4	0.0	0.2
Cheno-am			0.0	0.2	0.0	0.0	0.2
Other Herbs			0.0	0.0	0.0	0.0	0.2
Aquatics			0.7	0.4	0.2	0.2	0.9
Lycopdium			0.2	0.0	0.2	0.2	0.0

Table A.10: Final pollen data, expressed in percents, of key taxa used to produce the Otter Lake pollen diagram via the Tilia 1.7.16 program (1981 – 1849 cal yr BP).

Scientific Name	**Common Name**	**cal yr BP**	**1849**	**1882**	**1915**	**1948**	**1981**
Pinus	Pine		5.9	6.8	7.0	5.5	8.7
Picea	Spruce		0.0	0.0	0.0	0.0	0.0
Abies	Fir		0.0	0.0	0.0	0.0	0.0
Cupressaceae (Juniperus/Thuja)	Juniper / Cedar		19.0	10.7	10.3	11.2	8.5
Larix	Tamarack		15.1	17.3	24.3	14.2	14.3
Tsuga	Hemlock		2.2	1.3	2.0	3.0	2.1
Acer	Maple		10.7	12.4	9.2	10.2	8.9
Alnus	Alder		1.5	0.2	0.2	0.0	0.0
Betula	Birch		2.9	2.3	2.2	3.3	3.7
Corylus	Hazelnut		0.0	0.4	0.7	0.2	1.0
Ostrya/Carpinus	Hophornbeam/ Hornbeam		2.4	0.2	0.0	1.2	0.6
Carya	Hickory		1.7	2.8	0.9	4.5	2.1
Fagus	Beech		14.4	17.9	14.0	19.3	19.8
Fraxinus	Ash		1.0	1.5	1.3	1.0	1.0
Juglans	Walnut		0.5	0.2	0.4	0.6	0.4
Populus	Popular		4.1	1.9	0.9	0.0	2.1
Quercus	Oak		10.2	12.4	11.0	9.3	13.7
Ulmus	Elm		4.6	7.2	7.9	14.4	8.1
Other Trees			2.4	3.2	4.2	1.2	3.3
Ambrosia	Ragweed		0.2	0.2	0.2	0.0	0.0
Artemisia	Wormwood		0.0	0.0	0.2	0.0	0.0
Poaceae	Grasses		0.0	0.4	0.4	0.0	0.0
Cheno-am			0.0	0.0	0.2	0.0	0.2
Other Herbs			0.2	0.0	0.9	0.0	0.0
Aquatics			0.2	0.0	1.1	0.2	0.0
Lycopodium			0.0	0.4	0.0	0.0	0.0

Table A.11: Final pollen data, expressed in percents, of key taxa used to produce the Otter Lake pollen diagram via the Tilia 1.7.16 program (2047 – 2014 cal yr BP).

Scientific Name	Common Name	cal yr BP	2014	2047
Pinus	Pine		7.6	4.2
Picea	Spruce		0.0	0.0
Abies	Fir		0.0	0.0
Cupressaceae (Juniperus/Thuja)	Juniper / Cedar		13.0	11.0
Larix	Tamarack		21.0	14.6
Tsuga	Hemlock		2.6	3.3
Acer	Maple		12.6	12.5
Alnus	Alder		0.4	0.0
Betula	Birch		2.4	1.9
Corylus	Hazelnut		1.1	0.0
Ostrya/Carpinus	Hophornbeam/ Hornbeam		1.1	1.7
Carya	Hickory		2.4	1.5
Fagus	Beech		12.1	15.6
Fraxinus	Ash		0.4	0.8
Juglans	Walnut		0.4	0.0
Populus	Popular		1.3	3.8
Quercus	Oak		14.7	15.0
Ulmus	Elm		6.5	11.9
Other Trees			0.2	1.5
Ambrosia	Ragweed		0.0	0.6
Artemisia	Wormwood		0.0	0.0
Poaceae	Grasses		0.0	0.0
Cheno-am			0.0	0.0
Other Herbs			0.0	0.0
Aquatics			0.0	0.0
Lycopodium			0.0	0.0

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