

**Non-pollen palynomorphs and thecamoebians as proxies of environmental
and anthropogenic change: a case study from Lake Simcoe, Ontario,
Canada**

Olena Volik, M.Ed., Ph.D.

Department of Earth Sciences

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Abstract

The distribution of aquatic microfossils and pollen in the long core from Lake Simcoe (LS07PC5) shows synchronous response since deglaciation, highlighting the potential of little-known non-pollen palynomorphs (NPP) as paleolimnological indicators. Upcore variations in NPP, thecamoebians and pollen reflect hydrological and climatic variations: onset of the Main Lake Algonquin, the draining of Lake Algonquin, the early Holocene drought, the mid- to late Holocene climate shifts including mid-Holocene drought and the Little Ice Age, and human settlement. The distribution of microfossils in the short cores (CB1 and SB1) shows the level of eutrophication decreasing gradually from Cook's Bay to the Atherley Narrows outflow due to differences in the extent of anthropogenic impact and cumulative retention of phosphorous within sediments. Changes in assemblages and concentration of NPP within the cores reflect the history of settlement within Lake Simcoe basin, recording temporal differences in eutrophication.

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List of Abbreviations

asl	above sea level
aci	acidic
alk	alkaline
atm	atmospheric
ben	bentic
BP	before present
C	carbon
°C	degrees Celcius
C:N	carbon-to-nitrogen ratio
cal BP	calibrated radiocarbon date
cal yr BP	calibrated radiocarbon date
cc	cubic centimeter
¹⁴ C yr BP	uncalibrated radiocarbon date
C _P	concentration of palynomorphs in the sample
C _T	concentration of theca in sample
AD	anno domini
BOD	biochemical oxygen demand
Ca	calcium
cm	centimeter
D	deglaciation
DO	dissolved oxygen
DOC	dissolved organic carbon
E	east
ED	early Holocene drought
ES	European settlement
eu	eutrophic
H	Shannon-Weaver diversity index
ha	hectare
HCL	hydrochloric acid
HW	Holocene warming
GC	glacial conditions
ka	thousand years

kg	kilogram
km	kilometer
KOH	potassium hydroxide
L	liter
LH	late Holocene
\ln	natural logarithm
LOI	Loss On Ignition
LSEMS	Lake Simcoe Environmental Management Strategy
LSRCA	Lake Simcoe Region Conservation Authority
LSPP	Lake Simcoe Protection Plan
m	meter
MD	mid-Holocene drought
mes	mesotrophic
Mg	magnesium
mg	milligram
MM	mid- Holocene moist period
mm	millimeter
ml	milliliter
MOE	Ministry of Environment of the Province of Ontario, Canada
N	north
N	Nitrogen
N_n	total number of individuals
N_i	number of individuals (N) belonging to i th species
N_L	number of markers (<i>Lycopodium</i>) that were added to the sample
NAP	non-arboreal pollen
neu	neutral
NO_2^-	nitrite
NO_3^{2-}	nitrate
NPP	non-pollen palynomorphs
O	oxygen
oli	oligotrophic
P	phosphorus
Pb	lead

pH	measure of the $-\log(H^+)$
P_i	proportion of individuals of the total sample belonging to i th species
PL	proglacial lake
pla	planktonic
ppm	parts per million
S	south
S_s	total number of species
SDI	species diversity index (Shannon-Weaver diversity index)
SI	magnetic susceptibility
sp.	a single species within a genus
spp.	many species within a genus
t	metric ton (1,000 kg)
TC	total carbon
TN	total nitrogen
TOM	total organic matter
TP	total phosphorus
YD	Younger Dryas
yr BP	before present
V	volume of the sample
W	west
WPCPs	water pollution control plants
WWII	World War II
$\sum C_L$	– the number of markers that were counted in the sample
$\sum P$	the sum of counted palynomorphs in the sample
$\sum T$	the sum of counted theca in the sample
μg	microgram
μm	micrometer
$\delta^{13}C_{OM},$ $\delta^{13}C_{calcite}$	stable isotopes

Chapter 1: Introduction

1.1. Algal palynomorphs as proxies of paleoenvironmental change

Inorganic and organic sediments deposited over millennia in aquatic environments serve as an excellent source of data for paleoenvironmental reconstruction using variety of proxies (geochemical, isotopic, biological, etc.). Of particular interest are microfossils, fossilized microorganisms (i.e. unicellular pro- and eukaryotic organisms and their colonies), and fossilizable microscopic parts of larger organisms (scales, teeth, stomata, pollen, spores,) and the juvenile forms of many larger animals, that are present in sufficient quantities for statistical analysis and can provide detailed records of past changes. Moreover, microfossils are a reliable and extremely useful tool in many applications, including sediment dating, hydrocarbon exploration, and environmental evaluation (Lipps, 1981). Algae and their fossilizable parts are abundant microfossils in freshwater sediments, but little attention has been paid to most groups other than diatoms.

Initial studies of diatoms as paleoindicators date back to the late 19th and early 20th centuries when the first papers devoted to response of diatoms to water pollution (Kolkwitz and Marsson, 1908) and environmental change (Nipkow, 1920) were published. Since then diatom analysis has become a powerful tool in paleoenvironmental reconstruction due to the abundance and broad distribution of diatoms in aquatic ecosystems, their excellent preservation in sediments, their tolerance to variety of habitats, the wide range of ecological factors that they can adapt to, and their quick response to environmental changes (Battarbee et al. 2001). Numerous studies demonstrated the response of diatoms to changes in temperature (Hustedt, 1956; Vyvermann and Sabbe, 1995; Pienitz et al., 1995; Lotter et al., 1997; Richardson et al., 2000; Korhola et al., 2000), turbulence (Bradbury and Dieterich-Rurup, 1993), pH (Charles and Whitehead, 1986; Jones et al., 1989; Whitehead et al., 1989; Battarbee et al., 1990; Birks et al., 1990; Cumming et al., 1992), ice cover (Psenner, 1988; Catalan and Camarero, 1993), pollution (Dixit et al. 1992; Reavie and Smol

1998) and other environmental variables such as light, salinity, and rainfall (Battarbee et al., 2001). Diatom species possess great sensitivity to nutrient availability and so are valuable markers of eutrophication (Bennion et al., 1996; Little et al., 2000; Ekdahl et al., 2007; Hall and Smol, 2010; Smol, 2010; Tropea et al., 2011; Hawryshyn, 2010).

Diatom analysis has been used for tracing natural and anthropogenic changes in freshwater ecosystems in Southern Ontario since the second half of 20th century (e.g., Sreenivasa and Duthie, 1973; Duthie et al., 1996). The response of diatom assemblages to the mid-Holocene drought was shown by Boucherle et al. (1986), Hall and Smol (1993), and St. Jacques et al. (2000). Numerous studies have demonstrated the utility of diatoms as indicators of changes in water quality associated with anthropogenic impact in Southern Ontario (e.g., Christie and Smol, 1993; Hall and Smol, 1996; Little et al., 2000; Reavie and Smol, 2001; Ekdahl et al., 2007; Quinlan et al., 2008;).

An analysis of diatom assemblages in cores from Lake Simcoe recovered a 200-year history of water quality changes that were attributed to multiple factors, ranging from increased phosphorus load and regional rise in temperatures to invasion of dreissenid mussels (Hawryshyn, 2010; Hawryshyn et al., 2012). Three shifts in diatom assemblages took place: 1) minor changes in assemblages when human impact on the lake was relatively small in the late 19th - early 20th century; 2) a substantial increase in eutrophic diatoms with intensification of agriculture, deforestation and urbanization after 1930s, and 3) even more pronounced changes towards eutrophic assemblages in the mid-20th century.

Other common groups of algae in the summer phytoplankton are very common in pollen slides, and they are potential bioindicators in paleoenvironmental studies because of a number of factors (Komarek and Jankovska, 2001), namely:

- 1) their resistance to chemical treatment during pollen slide preparation,
- 2) their abundance in freshwater lakes and wetlands,
- 3) their global distribution.

Numerous studies have shown the importance of green algae (Division Chlorophyta) for reconstructing the depth, salinity, temperature, pH, and nutrient status variables of aquatic paleoenvironments (Jankovska and Komarek, 2000; van Geel, 2001). One of the most frequently reported green algae is the distinctive genus *Pediastrum* (Order Chlorococcales), but most studies (e.g., Burden et al., 1986; Hu et al., 1995; Kuhry, 1997; Yu, 2000; Mileckal and Szeroczynska, 2005; Cook et al., 2011, Danesh et al., 2013) do not identify *Pediastrum* to species level. Variations in total *Pediastrum* concentrations are typically interpreted as a response to nutrient enrichment (natural or anthropogenic) and rate of erosion in the watershed (Komarek and Jankovska, 2001; Zippi et al., 1990; Van Geel, 2001), but according to Jankovska and Komarek (2000), identification to species or even to subspecies can be crucial for paleoecological reconstructions. Indeed, recent studies have shown varying response of different *Pediastrum* species to changes in pH (Weckstrom et al., 2010; Turner, 2012), nutrient availability (Bradshaw et al., 2005; Komárek and Jankovská, 2001; Pasztaleniec and Poniewozik, 2004), lake level (Kaufman et al. 2010; Whitney and Mayle, 2012), water quality (Jankovska and Pokorny, 2002; Cabecinha et al., 2009), and littoral vegetation (Danielsen et al., 2010). Whitney and Mayle (2012) concluded, however, that the evolution of landscapes after deglaciation may outweigh the effects of climatic change on *Pediastrum* assemblages, so that paleoclimatic conditions can be inferred from *Pediastrum* predominantly in areas where the catchment has been relatively stable.

Botryococcus spp. are other acid-resistant green coccal algae (Family Botryococcaceae) that can be used as paleoenvironmental indicators (Jankovska and Komarek, 2000; van Geel, 2001). The response of *Botryococcus* to climatic conditions and the trophic state of water bodies was reported by Guy-Ohlson (1992), Kuhry (1997), Jankovska and Komarek (2000), Smittenberg et al. (2005); Haas et al. (2007), Medeanic (2010), Levine et al. (2012), Stutz (2012), Garel et al. (2013). A response to turbidity and depth changes was reported by Blackburn and Temperley (1936), Dulhunty (1944), Singh et al. (1981), Davis (1999). More detailed studies of these species are required because of their taxonomy and

paleoecology remain unclear (Komarek and Marvan, 1992).

Jankovska and Komarek (2000) showed the indicative value of other coccal green algae such as *Coelastrum*, *Sorastrum*, *Tetraedron*, and *Scenedesmus*. However, data on the implication of these algae as paleoindicators is insufficient except for a few publications such as van Geel (1978), Baker et al. (1981), Medeanic (2010), Pinto da Luz (2002), and Gelorini et al. (2011).

Fossil zygospores and aplanospores (asexual resting spores) of the Class Zygnemataceae have been reported as common microfossils in pollen preparations (Davis 1975; van Geel 1976; 1979). An overview of information about the Zygnemataceae and their relevance for palynologists and paleolimnologists was given by van Geel and Grenfell (1994) and extraction of zygospores from lake sediments was described by Zippi et al. (1991). Fossil spores of Zygnemataceae were used as proxies of paleoenvironmental change by van Geel (1976), van Geel and van der Hammen (1978), Ellis-Adam and van Geel (1978), Rich et al. (1982), van Geel et al. (1989), Zippi et al. (1990), Head (1993), Kuhry (1997); Rull et al. (2008), Cook et al. (2011), and Montoya et al. (2011).

In addition to zygospores, parts of filamentous and coccoid Zygnemataceae are recognized as paleoindicators (Komarek and Jankovska, 2000; van Geel, 2001). For instance, half-cells of desmids (Order Desmidiales) are often found in pollen slides, but information on their paleolimnological significance is scarce, so relatively few papers have demonstrated their use as indicators of paleoecological change (van Geel et al., 1981; 1989; Carrion et al., 2002; Rull et al., 2008; Montoya et al., 2012; Menozzi et al., 2010; Cook et al., 2011; Levine et al., 2012; Danesh et al., 2013). In recent years, these algae have been used predominantly for environmental monitoring, as many species are connected to certain types of aquatic habitats and reflect changes in contamination, pH, and trophic status of water bodies (Coesel, 1984; Boricsetal, 1998; Fehér, 2003; Krasznai et al., 2008; Štastný, 2010). Moreover, Coesel (1998; 2003) proposed a method for assessing the nature conservation value of

aquatic habitats based on the occurrence, rarity and maturity of desmids.

Although a variety of paleoecological studies (e.g., Miller et al., 1982; Findlay et al., 1998; Matthiessen et al., 2000) use the occurrence of freshwater dinocysts as an indicator of freshwater depositional environment or freshwater flux to marine environments, they generally provide very limited taxonomic detail. Only a few detailed studies dedicated to freshwater dinoflagellates have been published in the last several decades (Evitt et al., 1985; Burden et al., 1986; Norris and McAndrews, 1970; Zippi et al., 1990; 1991; Li et al., 1992; Wu and Chou, 1998; Kouli et al., 2001; Wang et al., 2004; Tardio et al., 2006; Chu et al., 2008; McCarthy et al., 2011; Danesh et al., 2013; Krueger et al., 2011; Krueger, 2012, and McCarthy and Krueger, 2013). According to Krueger (2012), the main obstacles in studies of freshwater dinoflagellates are poorly understood theca-cyst relationships, the lack of studies on their ecology, as well as taphonomic issues. More detailed research on dinocysts in lacustrine deposits, coupled with experimental encystment/excystment studies and DNA analysis, as demonstrated by McCarthy et al. (2011) would be beneficial for their successful use in environmental interpretations.

1.2. Indicative value of lacustrine thecamoebians and other protozoans

Since the mid-19th century, thousands of distributional and descriptive studies on thecamoebians have been performed (Medioli et al., 1999). Thecamoebians is an informal name of a very diverse group of polyphyletic group of amoeboid protozoans (also known as testate amoebae) that have a simple sac-like agglutinated chitinous theca. Thecamoebians include amoeba belonging to two different classes and several orders within the Phylum Sarcodaria, Subphylum Sarcodina, Class Rhizopoda (Scott et al., 2001).

Several reviews of testate amoebae studies have been published (Medioli et al., 1990; Beyens and Meisterfeld, 2001; Patterson and Kumar, 2002; Scott et al., 2001). Biogeographic studies on distribution of thecamoebians in North American lakes were performed by Patterson et al. (1985), Collins et al. (1990),

Charman and Warner (1997), Neville et al. (2010), and the identification key of Kumar and Dalby (1998) unified the approach to taxonomy and morphology of lacustrine thecamoebians. Although they are occasionally found in palynological preparations, and thus constitute a type of NPP, their occurrence in palynological preparations does not accurately reflect fossil populations, as demonstrated by Danesh et al. (2013), but it does indicate their presence.

Thecamoebians are ideal tools for paleoenvironmental and anthropogenic impact studies because of their:

1) occurrence in wide variety of environments such as lakes, peatlands and rivers from temperate to Arctic regions (Patterson and Kumar, 2002; Medioli and Scott, 1988);

2) abundance and excellent preservation in late Quaternary and Holocene sediments (Patterson et al., 1985; Medioli et al., 1999);

3) quick response to environmental changes due to their short generation time and sensitivity to various environmental variables (Patterson and Kumar, 2002).

Scott and Medioli (1983) and Medioli and Scott (1988) showed that post-European settlement had a profound effect on thecamoebian assemblages in Lake Erie and several later studies have shown their sensitivity to settlement history and land-use changes (e.g., Reinhardt et al., 2005; Danesh et al., 2013). McCarthy et al. (1995) showed that postglacial climate change strongly controlled the succession of thecamoebian assemblages in small lakes in Atlantic Canada by comparing their upcore distribution with pollen. Several later studies also showed thecamoebians to be useful proxies of climate change (Dallimore et al., 2000; Boudreau et al., 2005; Wall et al., 2010). They also record paleohydrological changes in lakes (Patterson and Kumar, 2002; McCarthy et al., 2012) and pH changes (Costan and Planas, 1986; Beyens et al., 1995; Tolonen et al., 1992; Ellison, 1995; Kumar and Patterson, 2000). Several studies have used thecamoebians as biomonitors of mining-derived pollution and for evaluating the effectiveness of reclamation efforts (Reinhardt et al., 1998; Patterson and Kumar, 2002; Patterson and Kumar, 2002; Neville et al., 2011;

Kihlman and Kauppila, 2012). Patterson et al. (2012) developed a thecamoebian-based transfer functions for sedimentary phosphorus in lakes.

Remnants of other freshwater Protozoa groups are less commonly present in lake sediments (Beyens and Meisterfeld, 2001). The loricae of tintinnid ciliates (Phylum Ciliophora, Class Spirotrichea, Order Tintinnida) are sometimes seen in palynological preparations (Frey, 1964). Their chitinous loricae preserve well, and they have been reported from Proterozoic to modern sediments – a longer geological history than any other heterotrophic plankton (Dolan et al., 2012). The Tintinnida are mostly marine organisms, with only a few present in freshwater environments (Moore, 1980; 1981; Hunt and Chein, 1983; Dolan et al., 2012). Ecological data on these organisms was put together by Foissner et al. (1991); a review of paleontological significance of these organisms was done by Pokorny (1975). Some Tintinnids species, for example *Codonella cratera*, can be mistaken for *Diffflugia protaeiformis* (Beyens and Meisterfeld, 2001). Both of these species are increasingly abundant in eutrophic waters where oxygen depletion at the bottom greatly reduces the numbers of benthic protozoa (Barbieri and Orlandi, 1989); *Codonella cratera* was also reported from Cook's Bay (Lake Simcoe) and was related by bottom hypoxia (Danesh et al., 2013).

There are other protozoans that possess time- and chemical-resistant structures or stages, for example *Suctorina* that form permanent cysts, can be potentially useful paleolimnological tools, but at this point in time more in-depth studies are required (Beyens and Meisterfeld, 2001).

Rotifers are other fossilizable microorganisms that can be found in freshwater lakes and streams and can be preserved in lake sediments. They are planktonic herbivores feeding on unicellular algae and bacteria. Their population density can become quite significant if enough food is available, up to and above 5000 per liter of water (Wallace and Snell, 1991). Eutrophication can be traced by rotifer abundance in water samples, for instance, increased influx of phosphorus is followed by increase in numbers of *Keratella cochlearis* and *Kellicottia longispina* (Edmondson and Litt, 1982). Fossilized rotifers are generally rare, with the exception of resting eggs (van Geel, 2001; Cook, 2009),

but Swadling et al. (2001) reported *Notholca* loricas from Holocene mud of an Antarctic lake. In contrast, sediments from Crawford Lake contain numerous well-preserved rotifer loricas (Turton and McAndrews, 2006).

1.3. NPP and thecamoebian studies in southern Ontario

Non-pollen palynomorphs (NPP) include representatives from all eukaryotic kingdoms of life in addition to algae, and they include microscopic remains of Fungi, Rotifera, Tardigrada, Rhizopoda, Vermes, Cladocera, Chironomideae (van Geel, 2001). Since the publication of a pioneering paper by van Geel (1972), a number of palynologists have used NPP for reconstructing Quaternary paleoenvironments (van Geel, 2006). According to Miola (2012), more than 1300 NPP have been described.

In southern Ontario non-pollen palynomorphs have been used mainly as proxies of cultural eutrophication in lakes (e.g., Burden et al., 1986; Zippi et al., 1990; Turton and McAndrews, 2006; McCarthy et al., 2011; Danesh et al., 2013).

The available studies can be divided into three main groups:

- 1) studies focused on one or more groups of NPP;
- 2) studies based on thecamoebian analysis;
- 3) complex studies that include algae and testate amoebae.

The first group of studies includes Georgian Bay, lakes in the Haliburton-Muskoka region, and Crawford Lake.

Based on palynological analysis of cores from Second and Gignac lakes (Awenda Provincial Park, Georgian Bay basin), Burden et al. (1986) showed that the distribution of algae reflects the two cycles of forest clearance identified in the pollen record (Figure 1.1): by Huron (Wendat) between AD 1450 and 1650, recorded by a decrease in tree pollen (*Acer*, *Fagus*, and *Quercus*) and an increase in *Pteridium*, *Artemisia*, and other herbs coupled with appearance of *Zea*, and beginning in the mid-19th century, by European settlers, identified by a reduction in tree pollen, rise of *Ambrosia*, Gramineae, *Rumex* and *Plantago*.

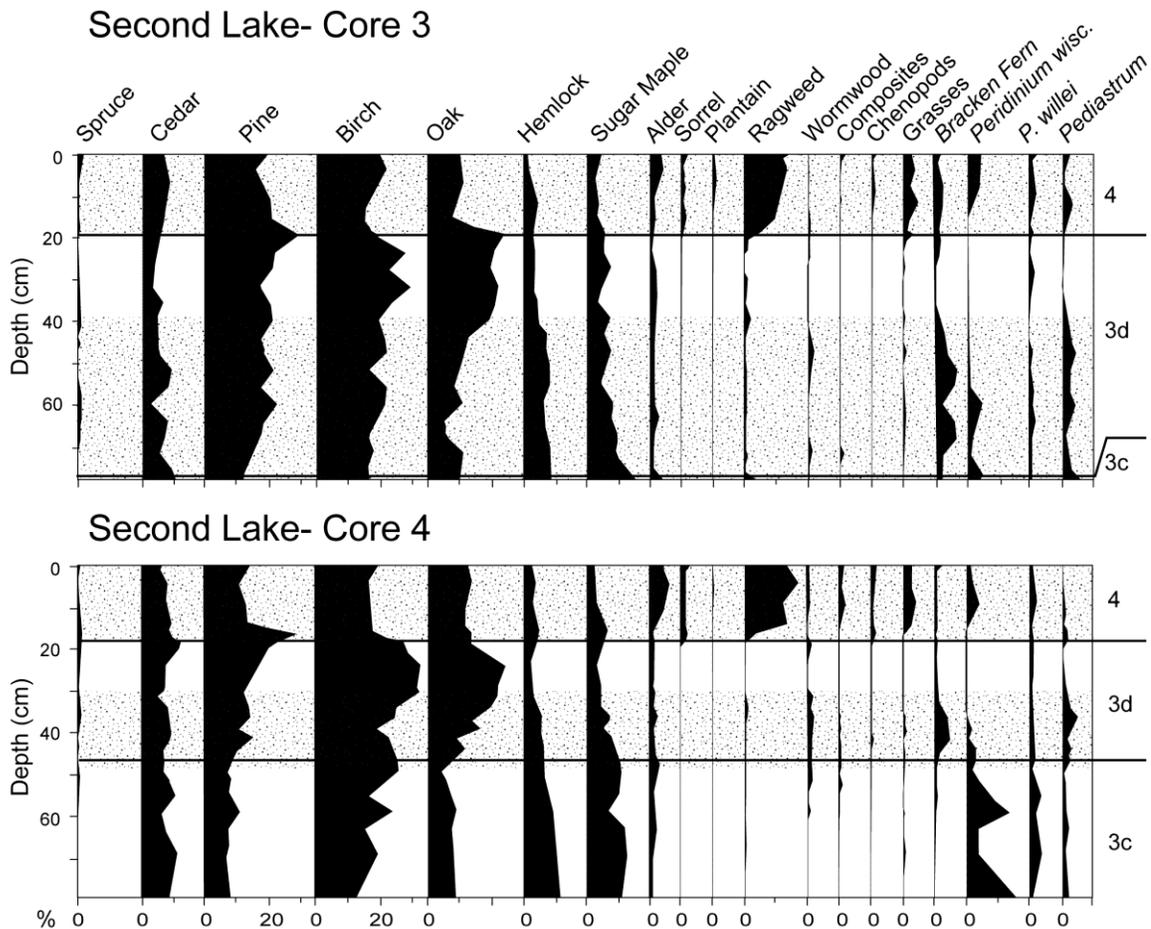


Figure 1.1. Distribution of palynomorphs in the core from Second Lake (Awenda Provincial Park) (modified Burden et al., 1986) Stippling identifies anthropogenic impact by Wendat and Euro-Canadian settlers accompanied by an increase in dinocyst (*Peridinium wisconsinense* and *Peridinium willei*) and *Pediastrum* abundance, reflecting cultural eutrophication.

Freshwater dinoflagellates, particularly *Peridinium willei*, and the coccal green alga *Pediastrum* increased in both lakes due to increased nutrient influx accompanying both phases of human settlement. In contrast, *Peridinium wisconsinense* was the most abundant before Indian settlement, during reforestation, and in the upper 10 cm, probably suggesting rapid improvement of water quality since the establishment of the provincial park in the mid-20th century (McCarthy et al., 2011).

Zippi et al. (1990; 1991) studied 11 lakes in the Haliburton-Muskoka region of Ontario. Their original focus of research was on zygospores of the Zygnematophyceae, a class of green algae including orders Zygnematales and

Desmidiaceae (desmids), as paleoindicators of acidification. However, they found that *Pediastrum* spp. and *Peridinium* spp. may be more informative. *Pediastrum* spp. and *Peridinium* spp. showed distinctive dependence on pH, having more abundant *Peridinium* cysts with increased acidity, while *Pediastrum* coenobia numbers were decreasing. Four dinocyst morphotypes were identified, and assigned to *Peridinium willei*, *Peridinium bipes*, *Peridinium limbatum* and *Peridinium wisconsinense* following Norris and McAndrews (1970). The cysts identified as *Peridinium willei* and *P. bipes* were present in most of the lakes studied these taxa tolerate a relatively wider range of pH values (5.5 – 8.7). *P. limbatum* and *P. wisconsinense* were found exclusively in lakes with narrower pH ranged from 5.5 to 6.7. The authors also touched on the inverse relationship of TP (total phosphorus) load and pH in the lakes, indicating anthropogenically-induced nutrient enrichment.

Based on analysis of dinocysts from Honey Harbour (Georgian Bay, Lake Huron), McCarthy et al. (2011) reported the sensitivity of freshwater dinoflagellates to cultural eutrophication. Combining palynological and phyecological approaches, they identified the two common distinct morphotypes as *Peridinium wisconsinense* and *Peridinium willei*. Down-core variances in the numbers of these species were interpreted as a result of increased influx of nutrients due to land-use changes in Severn Sound region over the last six centuries (Figure 1.2).

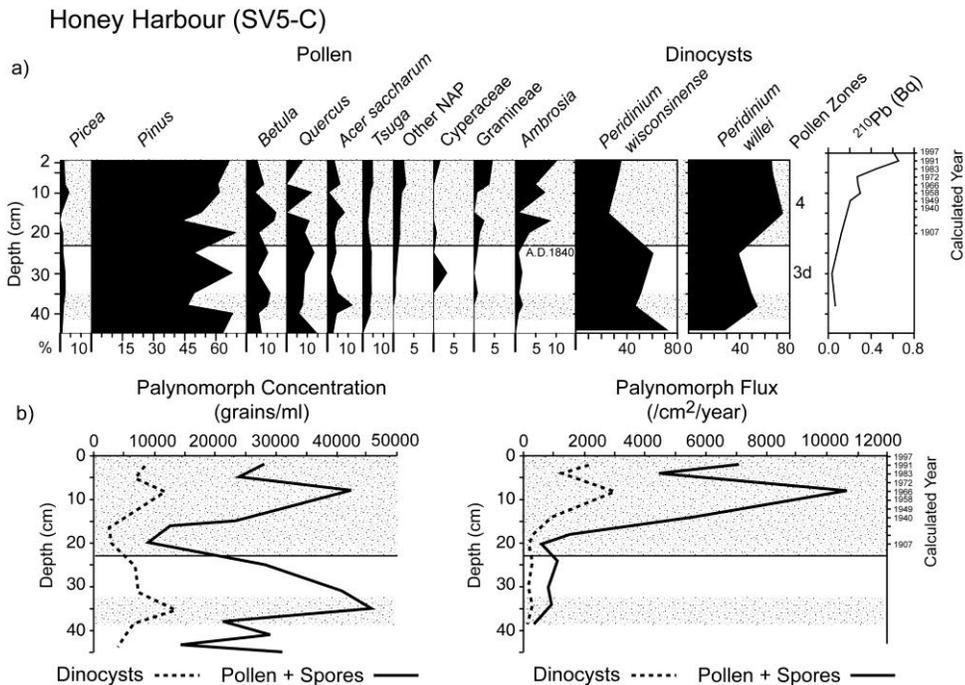


Figure 1.2. Increases in dinocyst abundance and flux and a relative increase in *Peridinium willei* correspond to human impact from Wendat and subsequent Euro-Canadian settlement (stippled) in a core from Honey Harbor, Ontario (from McCarthy et al., 2011)

Peridinium wisconsinense was a more common dinoflagellate cyst species in Honey Harbor prior to Euro-Canadian settlement. Land-clearing by the Wendat (“Huron”) caused an increase in *P. willei* with concurrent decrease of *P. wisconsinense* within pollen zone 3d of McAndrews (1994). Euro-Canadian settlement and land-clearing that began in the Midland-Penetanguishene region around 1840 AD are recorded by rise in *Ambrosia* (ragweed), Gramineae (grasses) and other herbs (non-arboreal pollen), and by increased cyst concentration that reached its maximum in 1966 AD (approximately 3000 cysts/ cm^2/year).

Similarly, Krueger et al. (2011) and McCarthy and Krueger (2013) illustrated the potential of dinocysts as indicators of anthropogenic eutrophication based on their study of sediments from meromictic Crawford Lake. High total cyst concentrations were associated with both Iroquoian (1268 - 1486 AD) and Euro-Canadian settlement of the region (since 1840 AD) (Figure 1.3).

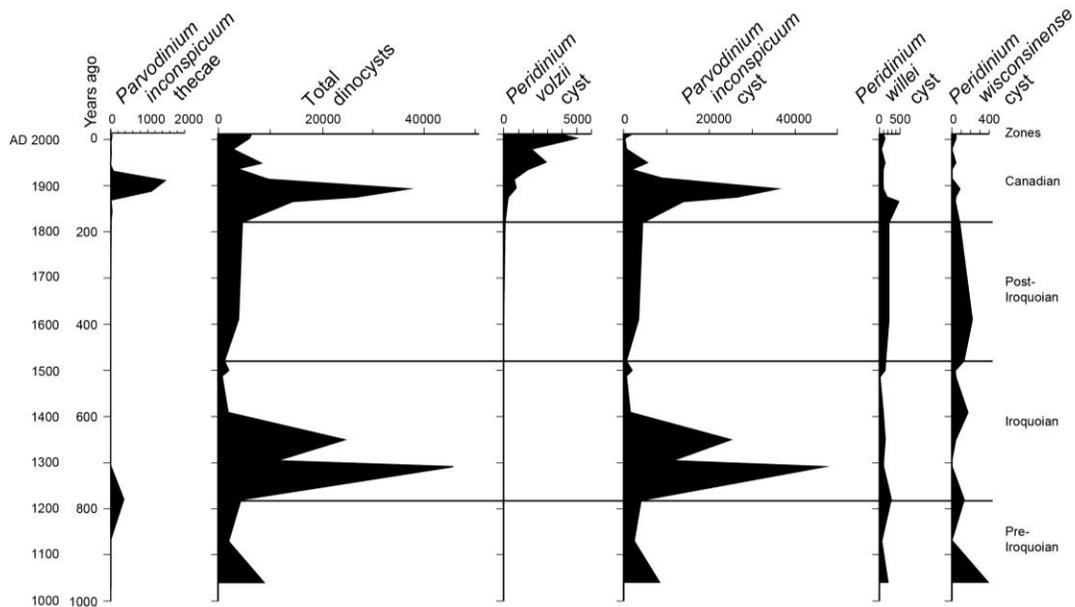


Figure 1.3. Downcore distribution of (A) thecae and (B) cysts in a freeze core collected from the deepest part of Crawford Lake, Ontario, Canada on January 25, 2011. The highest abundance of cysts, from 64 through 59 cm and from 30 through 21 cm is mainly comprised of tiny cysts assigned to *Parvodinium inconspicuum*, whose distinct thecae were also preserved in palynological preparations from 67 cm and in the upper 30 cm of the core, particularly around 21 cm. (Krueger, 2012)

Four morphologically distinct cyst types were identified as *Peridinium wisconsinense*, *Peridinium willei*, *Parvodinium* [*Peridinium*] *inconspicuum*, and *Peridinium volzii*. Prior to Iroquois impact and between the two phases of human settlement, the dinoflagellates in Crawford Lake were represented mostly by *Peridinium wisconsinense*. *Peridinium* [*Parvodinium*] *inconspicuum* was abundant in sediments associated with both phases of human settlement around Crawford Lake, with *Peridinium volzii* being abundant only in the sediments deposited after 1880 AD, apparently due to introduction during fish stocking (Krueger, 2012).

Two distinct periods of human activities around Crawford Lake were also identified by Turton and McAndrews (2006). They reported the abundance of rotifer loricas (*Keratella* sp. and *Kellicottia* sp.) reflecting increased phytoplankton production due to an influx of limiting nutrients (Figure 1.4).

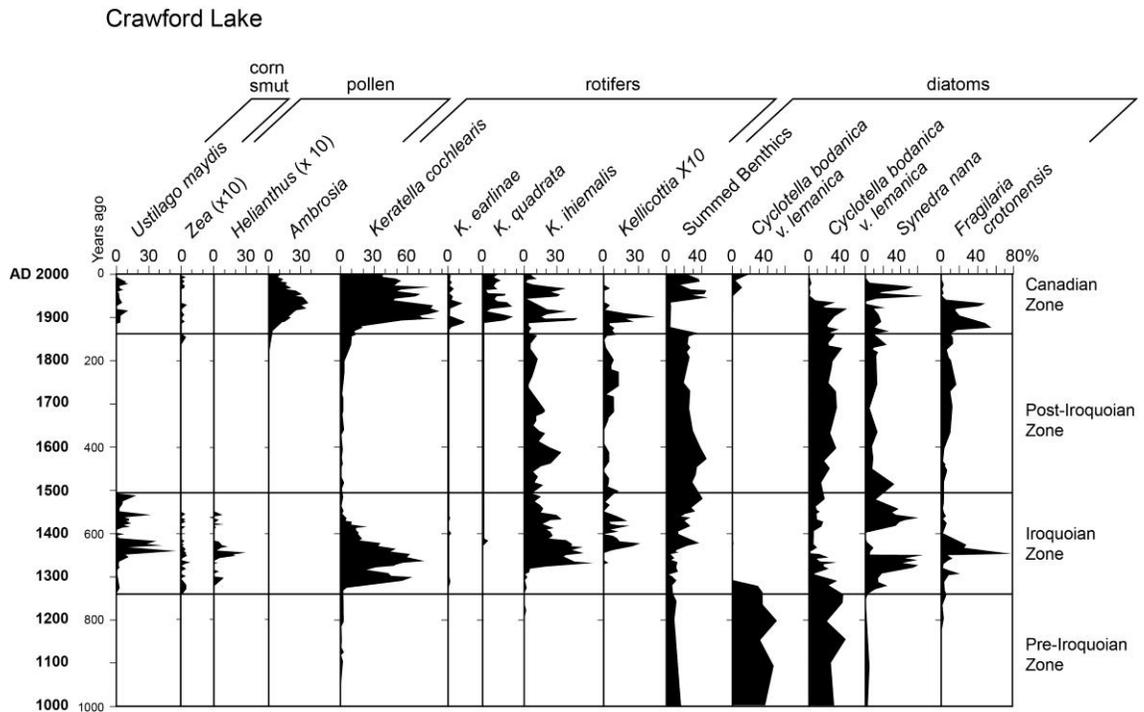


Figure 1.4. Diagram showing percentages of selected tree and herb pollen grains, *Ustilago maydis* spores, diatoms and rotifer loricas. Percentages are calculated on a sum of 200 tree pollen grains. To increase diagram visibility, the rare pollen of *Zea*, *Helianthus* and *Portulaca* are multiplied by 10 whereas *Kellicottia loricas* were multiplied by 10 to account for loricas lost in sieving (Turton and McAndrews, 2006)

Based on studies of 21 lakes and ponds in the Greater Toronto Area (GTA), Roe et al. (2010) assessed relationships between thecamoebians and a variety of environmental conditions, including water properties attributes (e.g. pH, conductivity, dissolved oxygen), substrate properties, sediment-based phosphorus (Olsen P, or OP) and 11 environmentally available metals (Figure 1.5). They also recognized the influence of elevated conductivity measurements on testate amoebae, which they connected to salt wash-off from roads during winter.

phosphorus loading and to derive a transfer function for reconstruction of phosphorus levels during the post-European settlement era (AD 1870s onward) using a chronologically well-constrained core from Haynes Lake on the environmentally sensitive Oak Ridges Moraine, within the GTA (Figure 1.6).

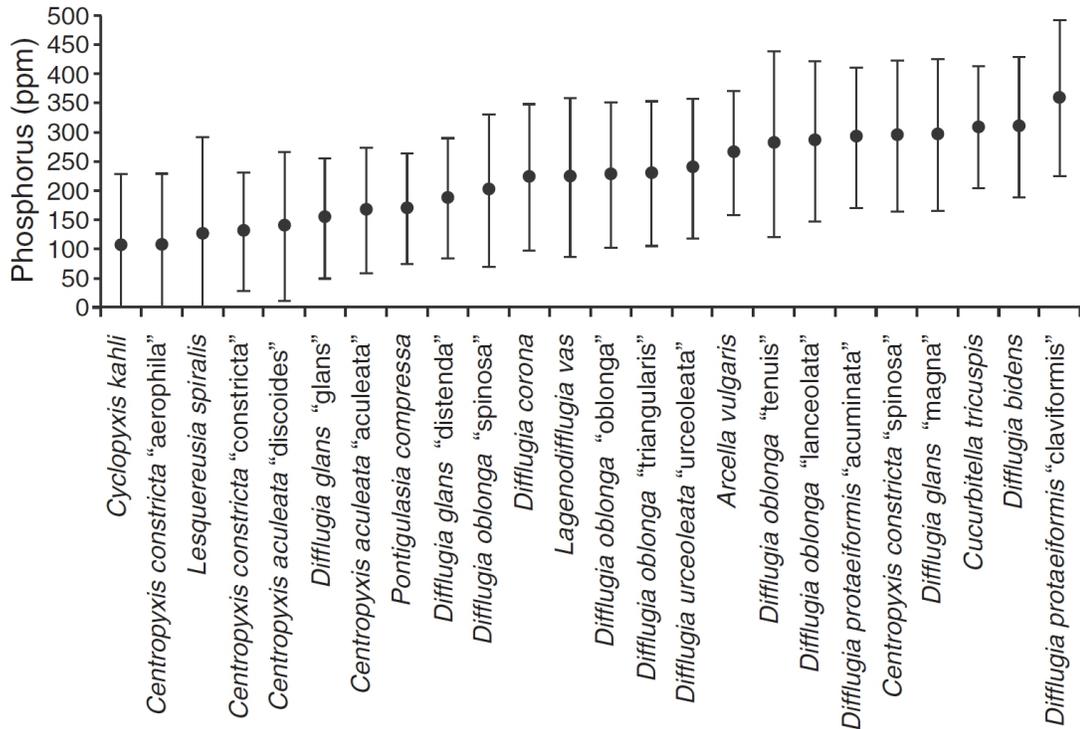


Figure 1.6. Phosphorus tolerance and optima statistics for the 24 testate amoebae species and strains present in statistically significant numbers in 21 lakes and ponds in the Greater Toronto Area. Taxa showing a particularly wide and high tolerance to phosphorus include *Diffflugia oblonga* "linearis", *Pontigulasia compressa* and *Diffflugia oblonga* "oblonga", whilst *Centropyxis constricta* "constricta", *Centropyxis constricta* "aerophila" and *Diffflugia oblonga* "tenuis" appear to be intolerant to phosphorus levels in excess of 200–250 ppm (Patterson et al., 2012).

Reinhardt et al. (2005) based on thecamoebian analysis, traced land-use changes and eutrophication in Frenchman's Bay (Pickering, Ontario). A strong correlation was found between the abundance of *Cucurbitella tricuspis*, the concentration of thecamoebians and the magnetic susceptibility of the sediments (Figure 1.7). According to Reinhardt et al. (2005), the eutrophication of the bay rose incrementally from approximately the mid-19th century (AD 1850±56) and then increased sharply in the mid-1940s to late 1950s.

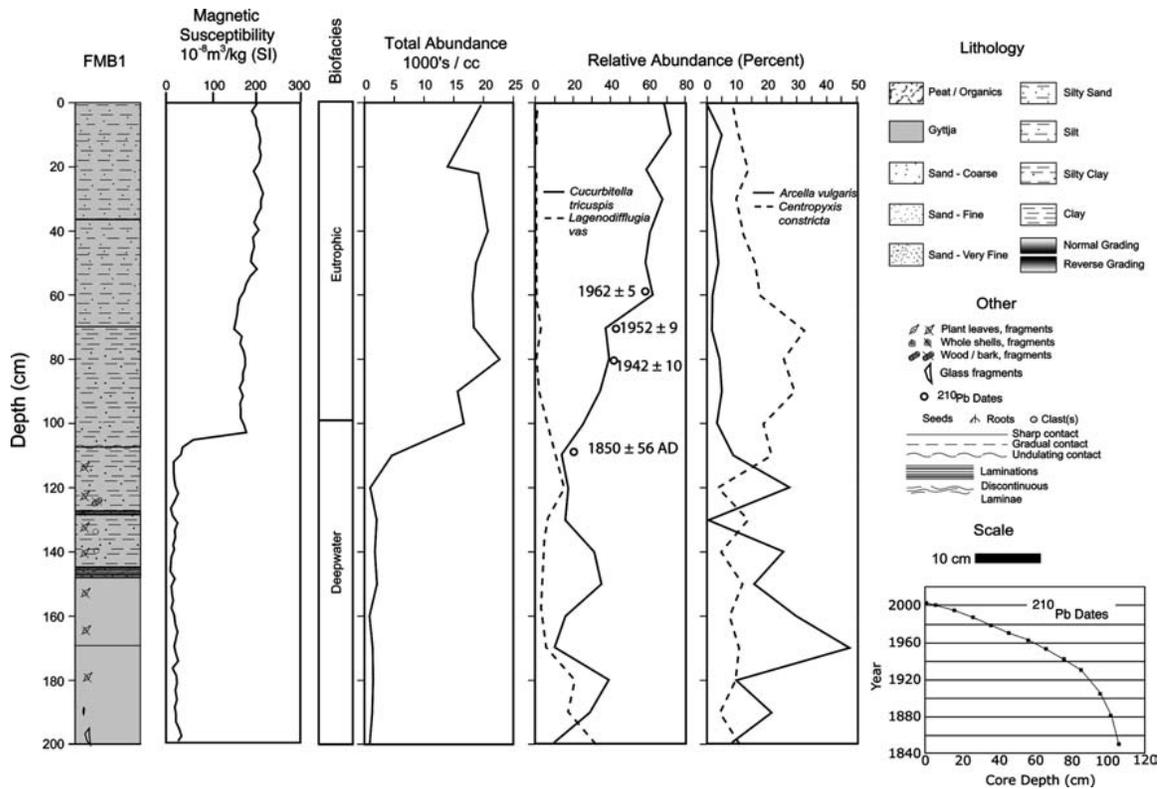


Figure 1.7. Sedimentology, magnetic susceptibility, ^{210}Pb dates, biofacies, and dominant species in the core from Frenchman's Bay (FMB 1). A distinct correlative transition at 60 cm and 110 cm is marked by a rapid increase in thecaamoebian concentrations and a large increase in *Cucurbitella tricuspis* (from approx. 10–20% to 40–70%). This transition correlated with a marked increase in magnetic susceptibility at the same depth, which was attributed to elevated levels of detrital magnetic minerals derived from land clearance and soil erosion in the watershed. It was indicated by ^{210}Pb dates indicate that there was a gradual onset of eutrophication in the mid-19th century (AD 1850±56) and a more rapid rise in the mid-1940s to late 1950s. (Reinhardt et al., 2005)

Patterson et al. (2002) used thecaamoebians as indicators of paleolimnological changes in Swan Lake, southwestern Ontario, comparing the results to conventional palynological analysis. Rapid land clearing in the 1850s was evident upon palynological analysis, showing a shift from Woodland to High Diversity assemblages. Thecaamoebians responded by changing from the Pre-European Settlement Assemblage to European Deforestation Assemblage, indicating low diversity, stressed environments (Figure 1.8). After World War II substantial increase of the algae *Pediastrum* (High Nutrient Assemblage), as well as an algalphilic eutrophication assemblage was noted in palynological and

testate amoebae analyses respectively, that are attributed to the introduction of chemical fertilizers in that time period.

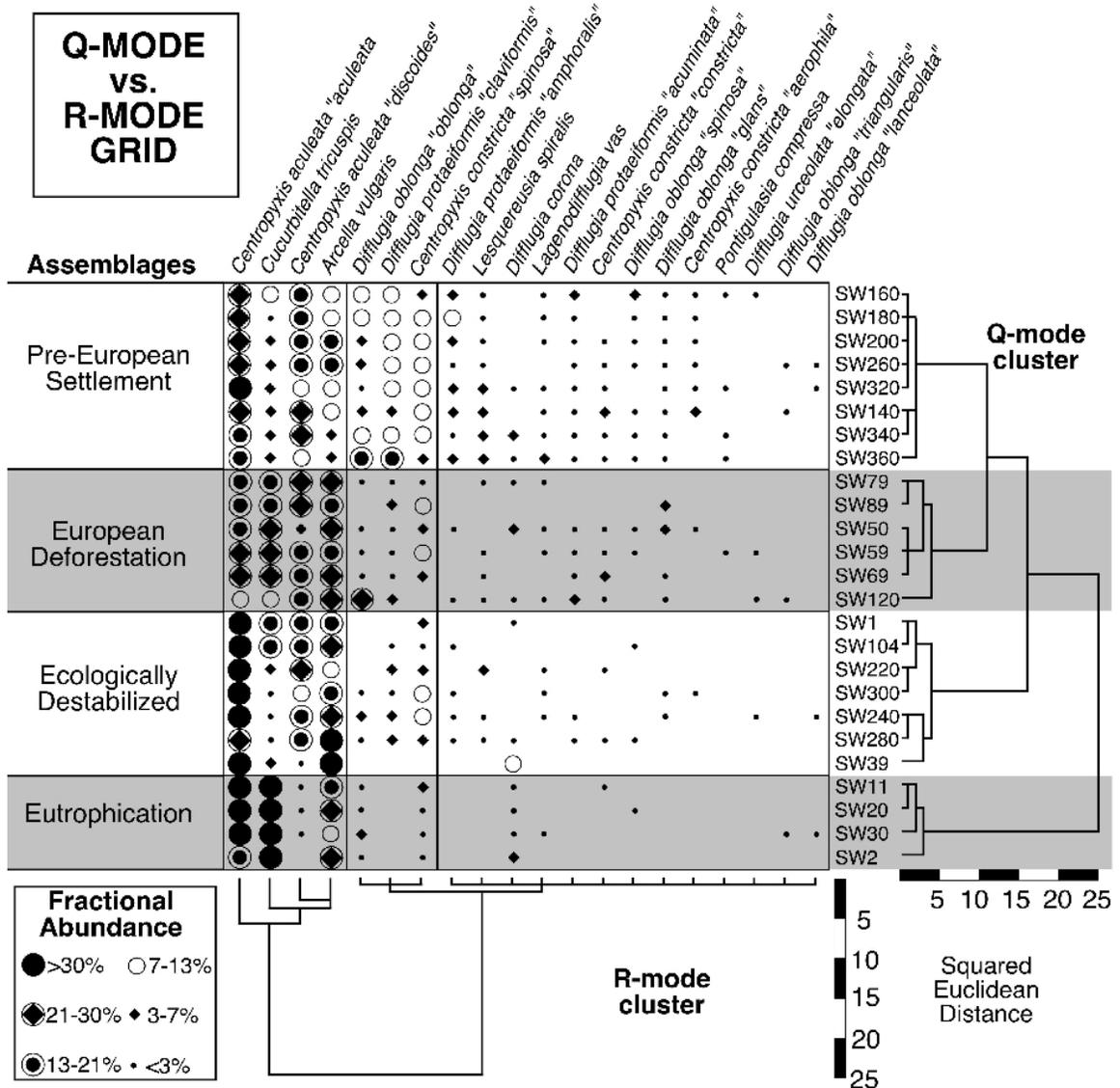


Figure 1.8. Distribution of thecamoebian and assemblage relationships in the core from Swan Lake. Thecamoebian distribution has been shown to be influenced by various environmental variables (Patterson et al., 2002)

One of the first comprehensive studies in southern Ontario that included a variety of algal palynomorphs and thecamoebians was based on a core from Cook's Bay (Lake Simcoe) by Danesh et al. (2013). This research used a multiproxy approach to analysis of the sediments, including chemical analysis (Figure 1.9) of the main water quality indicators, different NPP such as desmids,

dinoflagellates, and *Pediastrum*, as well as thecamoebian and ciliates. A correlation between distribution of microfossil assemblages and known milestones of human impact in the region (European settlement, Holland Marsh draining and post-WWII urbanization and industrialization) was found (Figure 1.10). It's worth mentioning that this study was preliminary, based on only one part of the lake, and identification of NPP was not detailed, so further and more meticulous research is warranted.

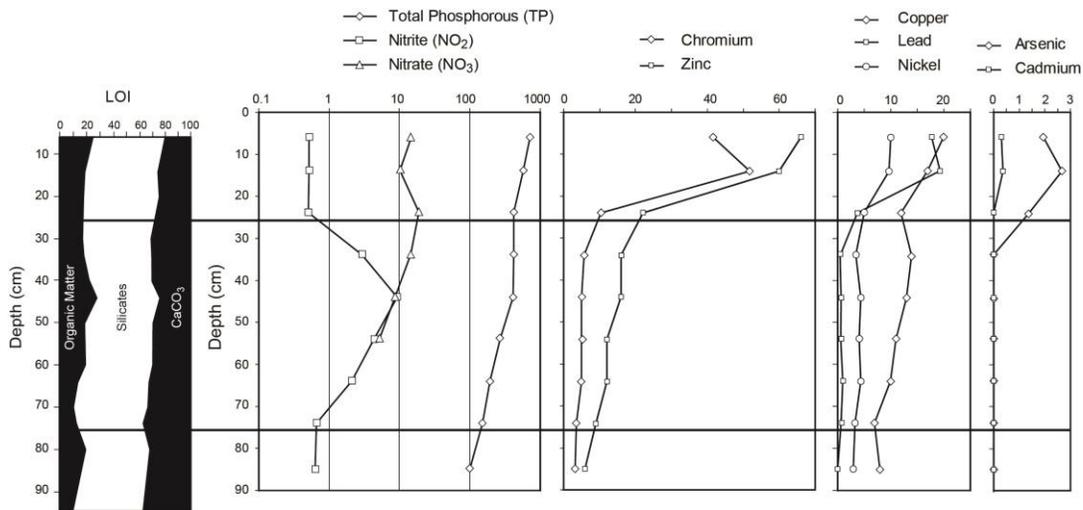


Figure 1.9. Loss On Ignition (LOI) and metal concentrations scaled by depth from a sediment core taken within Cook's Bay, Lake Simcoe (Ontario, Canada). Values for nitrate and nitrite are almost the same in the bottom 3 samples and nitrate values begin to increase at approximately 65cm. This figure shows organic, marly mud with a slight increase in silicates and negligible concentrations of metals until the mid-1990s. The solid horizontal lines delineate the two significant *Ambrosia* rises (Danesh, 2011; Danesh et al., 2013)

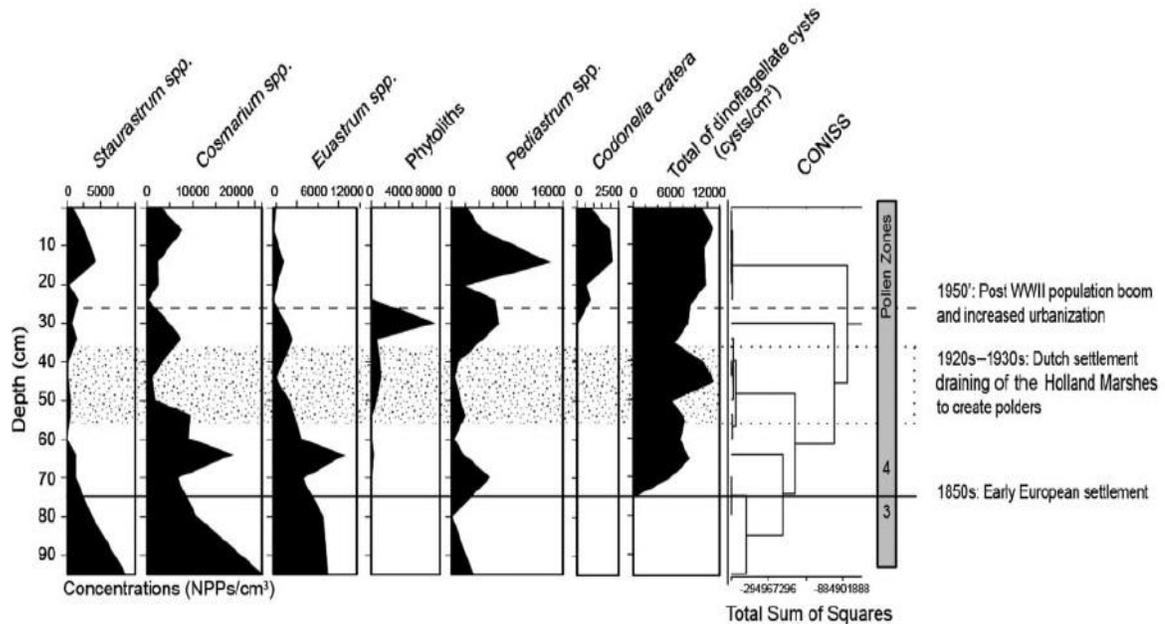


Figure 1.10. Distribution of NPP in the core from Cook's Bay (Danesh et al., 2013). NPP assemblages in the core from Cook's Bay show response to changes in anthropogenic impact. Desmids are most abundant below 75 cm, recording oligotrophic environments prior to European settlement in the late 18th C. Increase in *Pediastrum* and *Peridinium* above 75 cm, indicates anthropogenic disturbance and higher nutrient levels. The presence of phytoliths, peak in *Peridinium* and an unknown non-pollen palynomorph between 50cm and 40cm (stippled) is probably due to the drainage of the Holland Marsh and resulting organic flux into Cook's Bay during the 1920s and 30s. The presence of *Codonella cratera* in the upper part of the core records low DO, probably resulting from high BOD since the end of the Second World War, when the Cook's Bay watershed became intensely urbanized (Danesh, 2011; Danesh et al., 2013).

Despite relatively high interest in NPP as the proxies of anthropogenic impact, only little attention was paid to them as the proxies of natural environmental changes. For example, Yu (2000) used multiproxy data (including analysis of *Pediastrum* concentration) from sediment core from Twiss Marl Pond to indicate ecosystem response to late glacial and early Holocene climate oscillations in the Great Lakes region. Although pollen data show no forest transformation in response to cooling during the Younger Dryas, a slight increase in non-arboreal pollen, high concentrations of erosion elements, and a peak in *Pediastrum* concentration, record more openings in the forests and increased erosion in the watershed. According to Yu (2000), maximum concentration of

Pediastrum during the Younger Dryas and its persistence during the *Picea-Pinus* transition suggested sensitivity of aquatic flora to limnological and climatic changes.

Based on thecamoebian analysis of cores taken throughout Georgian Bay, McCarthy et al. (2012) reported the existence of closed-basin conditions during early Holocene (8,800–7,200 (9,900–8,050 cal) yr BP) (Figure 1.11).

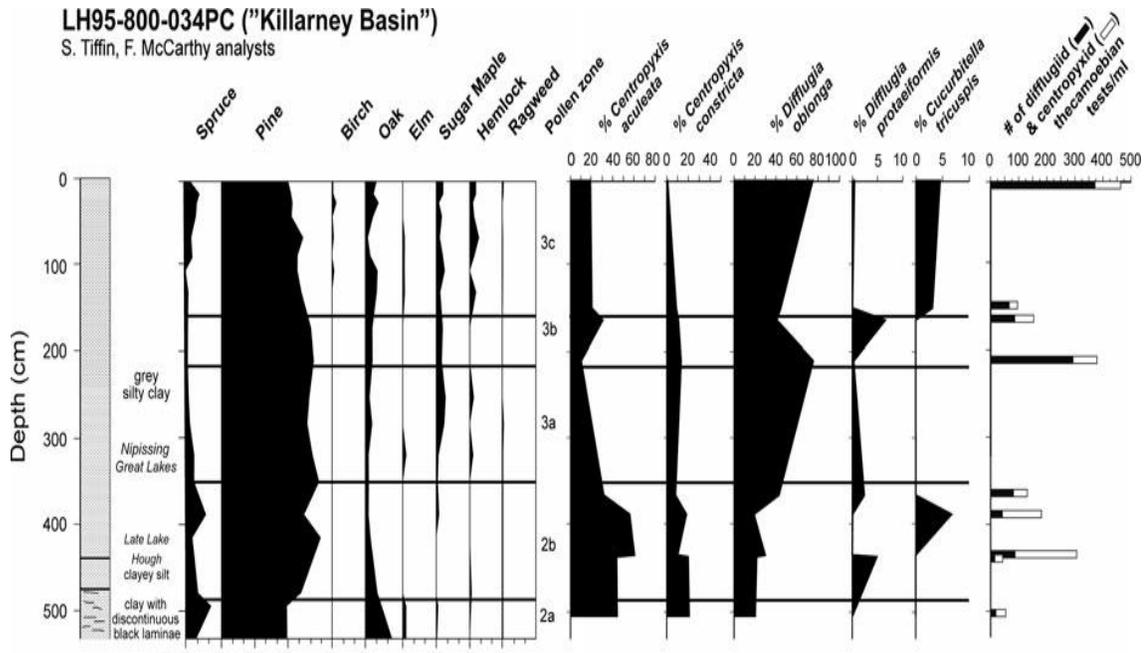


Figure 1.11. Summary of sediment, pollen and thecamoebian data from the “Killarney Basin” piston core (LH95-800-034PC; “34”). The core recovered sediments assigned to pollen zones 2a to 3c, recording more continuous postglacial deposition than at most other sites in northern Georgian Bay. Siltier, more organic muds below 440 cm in the core record low water levels during the late Lake Hough phase. The transition from a centropyxid to diffugiid dominated fauna occurs toward the top of pollen zone 2b. Centropyxid thecamoebians (*Centropyxis aculeata* and *Centropyxis constricta*) dominate the assemblage below 365 cm, while *Diffflugia oblonga* strongly dominates the assemblage in the rest of the piston core except in the sample at 165 cm, where a slight resurgence of centropyxids is noted at the top of pollen zone 3b (the “hemlock minimum”) (McCarthy et al., 2012).

A low-diversity centropyxid-dominated thecamoebian fauna around the boundary between pollen subzones 2a and 2b, ~8200 ca yr BP (McAndrews, 1994) recorded the development of slightly brackish conditions due to a hydrologic deficit associated with low precipitation in the Great Lakes basin. Subsequent climate amelioration (warmer, wetter conditions associated with the

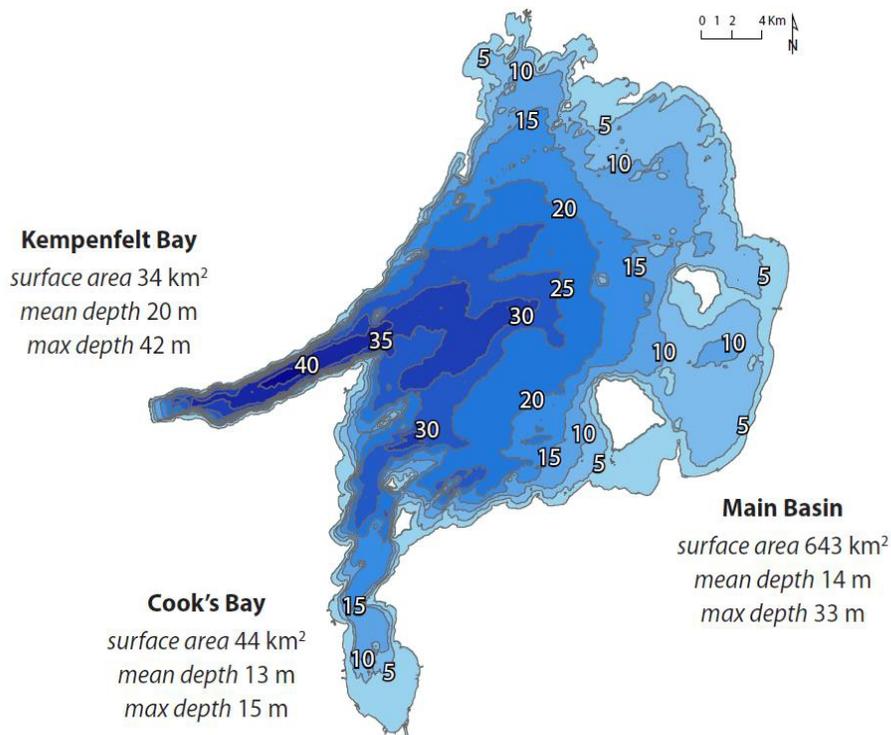
transition to pollen zone 3) is indicated by more diverse difflugiid-dominated fauna, and *Diffflugia oblonga* was the most abundant species prior to human settlement. The increase in *Cucurbitella tricuspis* up-core is interpreted as a result of cultural eutrophication because of the strong presence of Wendat First Nations people around Severn Sound and development of agriculture in the region.

1.4. Study area

1.4.1 General characteristics of Lake Simcoe

Lake Simcoe, the largest (722 km²) lake within southern Ontario (LSEMS, 2003), extends ~ 45 km south to north (44°11'40.75"N to 44°35'24.87"N) and ~ 40 km west to east (79°41'21.17"W to 79° 9'11.73"W). Situated ~ 70 km north of Toronto and ~ 40 km southeast of Georgian Bay, it drains northward to Georgian Bay via Lake Couchiching and the Severn River (LSEMS, 2003).

The main parts of Lake Simcoe are the main basin (mean depth 14 m), the deep and narrow Kempenfelt Bay (average depth 20 m, maximum depth 42 m), and the shallow Cook's Bay (mean depth- 13 m, maximum depth - 15 m) (Canadian Hydrographic Service, 1987) (Figure 1.12).



Bathymetry information derived by the OMNR from Canadian Hydrographic Service original depth sounding field sheet, 1957, scale 1:36,000. This map should not be relied on as a precise indicator of routes or locations, nor as a guide to navigation. The OMNR shall not be liable in any way for the use of, or reliance upon, this map or any information on this map.

Figure 1.12. Lake Simcoe and its sub-basins (Young et al., 2010). Tributaries and watershed are shown on Figure 1.13

This hard-water (mean calcium concentration of 41 mg/L, mean alkalinity of 116 mg/L, mean sulphate concentration of 20 mg/L) dimictic lake mixes twice a year (in spring and fall) and has two periods of thermal stratification (summer and winter) (Young et al., 2010). The lake has volume of $10.6 \times 10^9 \text{ m}^3$ and residence time of about 11 (Young et al., 2010) to 13 years (Winter et al., 2007).

1.4.2. Water body characteristics

Surface temperatures of Lake Simcoe usually reach their hypolimnetic maximum (21-22°C) in early August, and sometimes as early as during the first week of July (Young et al., 2010). Shallow or relatively isolated areas of the lake

reach hypolimnetic maximum temperatures that are 2 to 3°C warmer than in open lake areas. In deep water, in contrast, the hypolimnetic maximum (10 to 11°C) can be reached later in the season just before the fall breakdown of thermal stratification (Ministry of the Environment, 1975; Baird and Associates, 2006.). Summer stratification is common for the deeper parts of Lake Simcoe; however, Stainsby et al. (2011) reported that the lake stratified earlier in the spring, mixed later in the fall and remained stratified for more than a month longer in 2008 compared to 1980. Changes in stratification are most dramatic in Cook's Bay where the onset of stratification has advanced by approximately 25 days and the turnover of the bay in the fall takes place approximately 24 days later.

Over the past thirty years, in response to stringent limits on phosphorus loading, water clarity in the lake has improved by 30 to 50%, and recent Secchi disc readings range from 1.9 to 5.1 meters, with average depth about 3.9 meters (LSEMS, 2003). Comparable to the Secchi disc readings, the mean chlorophyll *a* concentrations vary considerably. Chlorophyll *a* ranged from a low of 1.7 µg/L in the main basin to a high of 4.5 µg/L in Kempenfelt Bay; the overall mean concentration for the lake was 2.6 µg/L (Young et al., 2010).

The estimated total phosphorous loads to Lake Simcoe in 2004 -2007 ranged from 71.5 to 77.3 t/year, compared to the 1980s when it averaged 102 t/year. The largest sources were tributaries (37.2-47.3 t/year) and the atmosphere (15.1-22.5 t/year) (LSRCA, MOE, 2009). In general, total phosphorous (TP) levels are the highest in Cook's Bay (~22.7 µg/L), followed by Kempenfelt Bay and the main basin (each ~13.3 µg/L), and are lowest in the outflow at the Atherley Narrows (~10.2 µg/L) (Eimers et al., 2005). The highest concentrations of nitrogen were detected in Cook's Bay (0.56 mg/L), and the influence of the river was evident in the higher concentrations of nitrogen in the southern half of Cook Bay; the mean euphotic zone concentration is 0.40 µg/L. Due to eutrophication, bottom water DO concentrations dropped to 2 mg/L or lower in most years in the 1980s. Conditions improved in the mid-1990s, although measured DO concentrations still fell below 2 mg/L in some years

(Young et al., 2010).

Since 1971, the concentration of chloride ions measured at the lake outflow has increased from 11 mg/L to 40 mg/L in 2008, and it is still increasing. Seasonal values of chloride concentrations vary, and in most measurements they are the highest during winter months, between December and March (Young et al., 2010). Heavy metal concentration was highest in Kempenfelt Bay due to proximity to urban and industrial sources of pollution. With distance, the concentration of pollutants decreases along a west to east gradient (LSEMS, 2003). Historically significant metal concentrations (e.g., chromium) have already decreased from their peak levels, but they are still much higher compared to background concentrations prior to 1800s. Some metals, such as zinc, still maintain increased level in the lake due to uncontrolled urban stormwater run-offs (Young et al., 2010).

1.4.3. Biological features of the lake

Diatoms (Class Bacillariophyceae) are the most prevalent group of algae in Lake Simcoe, representing two-thirds of the total algal biovolume of the lake. Cryptomonads (Class Cryptophyceae) and dinoflagellates (class Dinophyceae) are next as the most abundant of the remaining groups. Other less common algae are the blue-green algae (Phylum Cyanophyta) and green algae (Class Chlorophyceae), but they are environmentally significant due to their ability to form water blooms with higher nutrient availability, i.e., with organic pollution (LSRCA, 2003). Macrophyte presence is notably greater near tributary outlets, which are sources of nutrients (LSRCA, 2003).

Forty-nine warm-water and cold-water fish species live in Lake Simcoe. Bottom hypoxia resulted from nutrient enrichment coupled with subsequent algal blooms led to dramatic decrease in cold-water fish population in the lake. The populations of lake trout (*Salvelinus namaycush*) and lake whitefish (*Coregonus clupeaformis*) that are important to the economy of the area are now sustained artificially by annual stocking programs, and the numbers of other cold-water species such as lake herring, rainbow smelt and burbot has also declined

substantially due to the same reason (LSRCA, 2003).

Similar to the Great Lakes, the introduction of invasive species has been occurring in Lake Simcoe since European settlement. Some examples of aquatic invasive species in the Lake Simcoe basin are the zebra mussel (*Dreissena polymorpha*), quagga mussel (*Dreissena bugensis*) spiny water flea (*Bythotrephes cederstroemi*), common carp (*Cyprinus carpio*), black crappie (*Pomoxis nigromaculatus*) and Eurasian Watermilfoil (*Myriophyllum spicatum*). The round goby (*Neogobius melanostomus*) is the most recent documented invader, first identified in 2004 in the Pefferlaw River (Young et al., 2010).

1.4.2. Lake Simcoe watershed

The total area of Lake Simcoe watershed is 3,576 km², and it is drained by 35 tributary rivers, five of them (Talbot, Beaver, Black, Holland Rivers and the Pefferlaw Brook) draining more than 60% of the area (LSRCA, 2003) (Figure 1.13). The Lake Simcoe basin is part of the Western St. Lawrence Platform; the stratigraphic succession in the Lake Simcoe basin consists of Ordovician rocks (limestone, shale, dolostone, siltstone, sandstone) that are part of the Simcoe Group; the Blue Mountain Formation is represented only in the southeast part of the watershed (Armstrong, 2000). The limestone bedrock underlying the catchment makes Lake Simcoe a hardwater lake.



Lake Simcoe Region Conservation Authority Sub - Watersheds

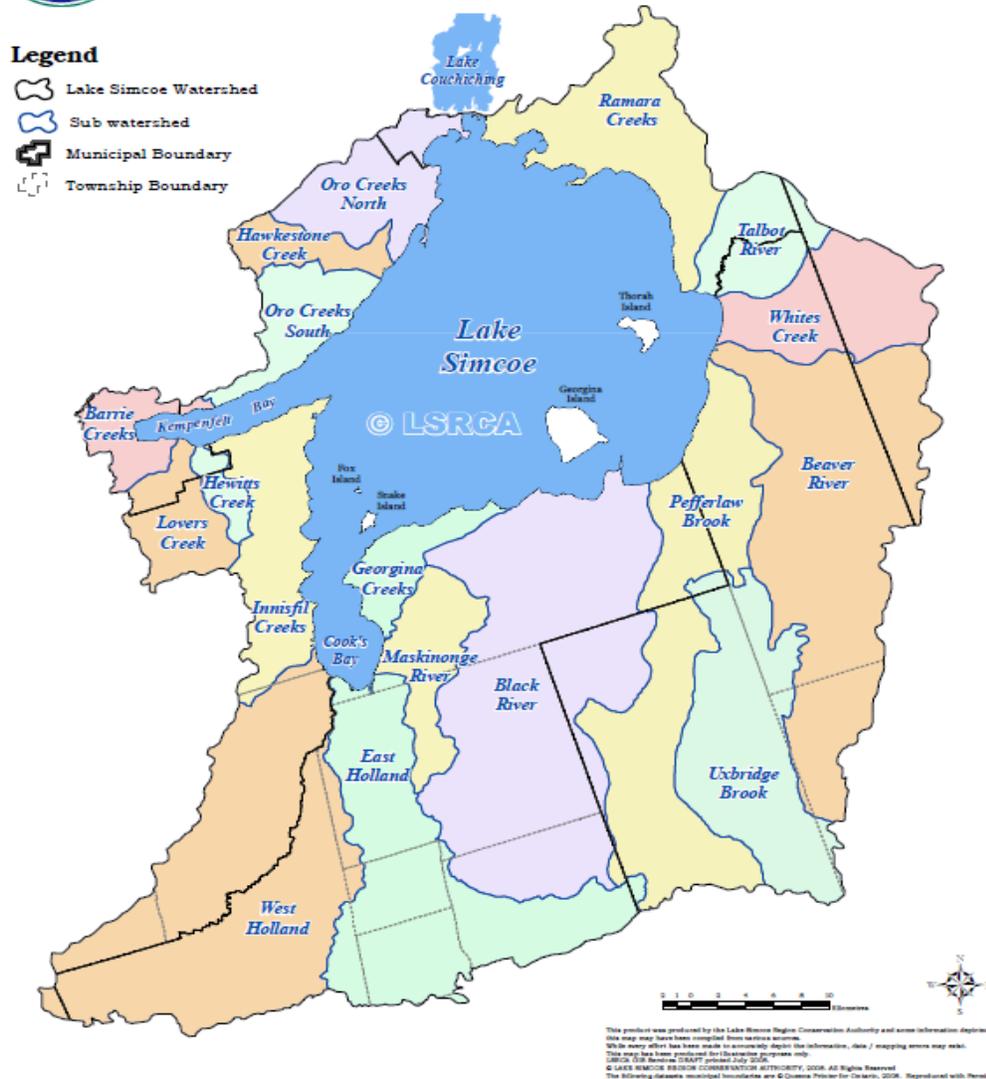


Figure 1.13. Lake Simcoe and its subwatersheds (LSRCA, 2008)

Paleozoic terrains are overlain by unconsolidated Quaternary sediments (Deane, 1950; Gravenor, 1957). The Lake Simcoe watershed was subjected to glaciation by the Laurentide Ice Sheet with predominantly south to southwest ice flow (Chapman and Putnam, 1984; Karrow, 1989; Barnett, 1992). Wisconsin deposits (undifferentiated tills with minor exposures of glaciofluvial ice-contact and outwash deposits (gravel and sand) and glaciolacustrine deposits (silt and clay, sand) cover bedrock in the western Lake Simcoe area, but they form a

relatively thin to discontinuous veneer over bedrock in the eastern Lake Simcoe area (Deane, 1950; Gravenor, 1957).

The Lake Simcoe watershed contains five major physiographical areas: the Oak Ridges Moraine, the Peterborough Drumlin Fields, Schomberg plains, the Simcoe Lowlands and the Oro Moraine. The Oak Ridges Moraine (Plate 1.1B) is an interlobate moraine composed of gravel, sand and silt material (Barnett et al., 1998) and occupies approximately 20% of the watershed (LSRCA, 2008). The peak of the moraine is a drainage divide between Lake Simcoe and Lake Ontario watersheds (Johnson 1997). The Schomberg Clay Plains (Plate 1.1D) are located immediately northwest of the Oak Ridges Moraine between the Towns of Schomberg and Newmarket, and form roughly 15% of the total watershed area. They consist of deep deposits of stratified clay and silt (Chapman and Putnam, 1984). The Peterborough Drumlin Field (Plate 1.1.E) is located to the north of the Oak Ridges Moraine and the Schomberg Clay Plains, and constitutes roughly 30% of the total watershed area. The general orientation of the drumlin axes in this field is from northeast to southwest (Meriano and Eyles, 2009). The Simcoe Lowlands occupy 35% of the watershed area (Plate 1.1. A). The lowlands are connected with Nottawasaga basin by a flat-floored valley at Barrie and by similar valleys among the upland plateaus farther north. Having been flooded by Lake Algonquin, transverse valleys are bordered by shorecliffs, beaches, and bouldery terraces of Lake Algonquin (Chapman and Putnam, 1984). The area south of Lake Simcoe is low and swampy; the Holland Marsh (Plate 1.1.F) extends southwestward from Cook's Bay and occupies 80 km². The marsh has been drained in 1925 - 1930. East of the marsh the Algonquin lake plain consists of level plains based on deep deposits of sand and silt. North of Lake Simcoe the lowland encompasses both the rivers and upland areas in the Mara Flats and extends to the western watershed divide north of Orillia (Chapman and Putnam, 1984). Only a small portion of the Oro Moraine lies on the edge of the Lake Simcoe watershed (Plate 1.1. C). The surface sediments of the Oro Moraine can be recognized as glaciofluvial material (Barnett, 1992).



Plate 1.1. Physiographical areas of Lake Simcoe watershed: A, the Simcoe Lowlands; B, Oak Ridges Moraine; C, Oro Moraine; D, Schomberg plains; E, the Peterborough Drumlin Fields; F, Holland Marshes.

The climate of the Lake Simcoe watershed can be described as humid continental (Koppen climate classification *Dfa*) with moderately cold winters, fairly

early springs, sunny warm summers and cool fall seasons (Sanderson, 2004). Winters have a mean temperature of -6.1°C to -8.3°C , and the summers have a mean temperature of 18.8°C (Environment Canada, 2012). Temperature differences between the north and south regions are greater in winter than in summer. The average annual rainfall is approximately 81.8 cm, and snowfall ranges from 152 cm to 279 cm (Environment Canada, 2012).

Before European settlement in the 1860s the Lake Simcoe basin was covered with mixed forest, but at present, much of the basin is dominated by non-arboreal vegetation (Johnson 1997). Undisturbed forests currently occupy about 11% of watershed, they belong to zone L1 (Rowe, 1972) and consist of maple (*Acer*), beech (*Fagus*), basswood (*Tilia*) ashes (*Alnus*), birch (*Betula*), oaks (*Quercus*), hemlock (*Tsuga*), pine (*Pinus*), fir (*Abies*), hickory (*Carya*). Agriculture is the dominant land-use in the Lake Simcoe watershed, occupying 48% of the area, and another 40% of the catchment is occupied by forest, wetlands and maintained, but non-agricultural, greenlands. The remaining 12% of the area belong to urban development and roads (LSRCA, 2003; Winter et al., 2007). The land use around the lake is not uniform, most of the watershed of West Holland River and Beaver River is used for agriculture, with the Holland River marsh being the largest (28 km^2) cultivated marsh in Ontario. In contrast, forests, wetlands and maintained greenlands occupy most of the Black River and Pefferlaw Brook watersheds. The largest proportions of urban development and roads can be found in the watersheds of East Holland River and Lovers Creek (Winter et al., 2007).

1.5. Lake Simcoe and its watershed: from last deglaciation to present

During the late Wisconsin, the Lake Simcoe basin was covered by the Simcoe Lobe of the Laurentide Ice Sheet; the late-glacial advance of the Simcoe Ice Lobe resulted in deposition of the Newmarket Till (Chapman and Putnam, 1984). As glacial ice advanced from the north, relatively little bedrock scouring took place on the hard crystalline rock, but when the ice moved onto a softer rock, its erosive efficiency increased dramatically. The ice plucked large quantities of

this soft bedrock material and ground it into finer particles (Johnson, 1997). One of these large depressional areas became today's Lake Simcoe basin.

Ice retreat from Lake Simcoe basin began around 14,000 cal yr BP (Lewis et al., 2008); as the Laurentide Ice Sheet retreated to the north, glacial lakes occupied the study area (Chapman and Putnam, 1984; Eschman and Karrow, 1985). Initially, glacial Lake Schomberg was formed in the southern part of Lake Simcoe basin (Eschman and Karrow, 1985; Mulligan, 2011), draining into the Lake Ontario basin, and later on into Early Lake Algonquin in the Huron basin (Eschman and Karrow, 1985; Barnett, 1992). Following the deglaciation of Kirkfield (Fenelon Falls) outlet, the onset of Kirkfield phase of Lake Algonquin took place (Eschman and Karrow, 1985; Lewis et al., 2008). At that time Lake Algonquin extended to the east, merging Lake Schomberg, and drained into the glacial Lake Iroquois (Eschman and Karrow, 1985), and eventually into the North Atlantic Ocean, probably via the Mohawk and Hudson River valleys (Lewis et al., 1994).

As ice retreated from the Lake Superior basin, Lake Algonquin extended to the west (Lewis et al., 1994). At about this time, the Thunder Bay outlet was opened enabling drainage of glacial Lake Agassiz into Lake Algonquin (Teller and Thorleifson, 1983; Teller et al., 2002; Tinkler et al., 1992; Thompson, 2002; Thorleifson, 1983; 1996). This inflow resulted in the Main Lake Algonquin phase and the highest water levels marked by former shoreline that can be found in Lake Simcoe basin (Deane, 1950; Chapman and Putnam, 1984). On the west side of Lake Simcoe from Orillia to Bradford the Algonquin shoreline is definite and continuous, although not as strongly developed as on the exposures facing Georgian Bay. Beaches are scarce between Orillia and Barrie, but they appear at frequent intervals south of Barrie. The shoreline is faint around the Holland Marsh, reappearing as prominent sandy beaches to the east (Chapman and Putnam, 1984).

Deglaciation of the North Bay outlet around 10,500 cal yr BP transferred drainage to the Ottawa River valley and Champlain Sea (Lewis et al., 1994; Lewis et al., 2008). After disintegration of the ice dam that supported Main Lake

Algonquin, water level fell through the Post Algonquin lake phases (Ardtrea, Upper and Lower Orillia, Wyebridge, Penetang, Cedar Point and Payette) (Lewis et al., 1994). These former shorelines were mapped and defined by Stanley (1936) and Deane (1950) in the southern Georgian Bay and Lake Simcoe areas. After the Lake Algonquin drawdown, water levels in the Huron Lake basin fluctuated dramatically: during the Mattawa highstands resulting from periodic inflow from Lake Agassiz (Teller et al., 2002) or from subglacial outburst floods (Breckenridge et al., 2004; Breckenridge, 2007). Water levels rose 40 to 60 m above the North Bay outlet and dropped to 25 - 30 m below the outlet during the lowstands (Lewis et al., 2007). After the Lake Algonquin drawdown, Lake Simcoe became a separate water body, and it has persisted as a separate water body to the present as water flow was unable to cut down through the Precambrian rock at the outlet at the north end of Lake Couchiching (Johnson, 1997).

The Nipissing Flood was one of the most notable events in the eastern Great Lakes region; however, it did not affect Lake Simcoe directly. The rise in water level resulted from a shift of upper Great Lakes outflow from the North Bay Outlet into the lower Great Lakes (Karrow and Calkin, 1985; Pengelly et al., 1997; Lewis et al., 2008; Thompson et al., 2011). According to Lewis (1969), the Nipissing phase consisted of three parts: the pre-Nipissing phase with single North Bay outlet; the Nipissing I phase with North Bay, Port Huron and Chicago outlets; the Nipissing II with Port Huron and Chicago outlets. There is a variation in reports of timing of these phases; for example, Lewis (1969) suggested 6,300 cal yr BP for the beginning of the Nipissing I phase and 5,400 cal yr BP for the Nipissing II; Larsen (1985) reported the maximum level of the Nipissing I phase around 5,100 cal yr BP, a low water level at 4,700 cal yr BP, and the maximum Nipissing II phase at 4,250 cal yr BP. However, most studies (Lewis, 1969; Larsen, 1985; Baedke and Thompson, 2000; Thompson et al., 2011) show that by 4,000 cal yr BP the lake level dropped initiating the Algoma phase (Figure 1.14).

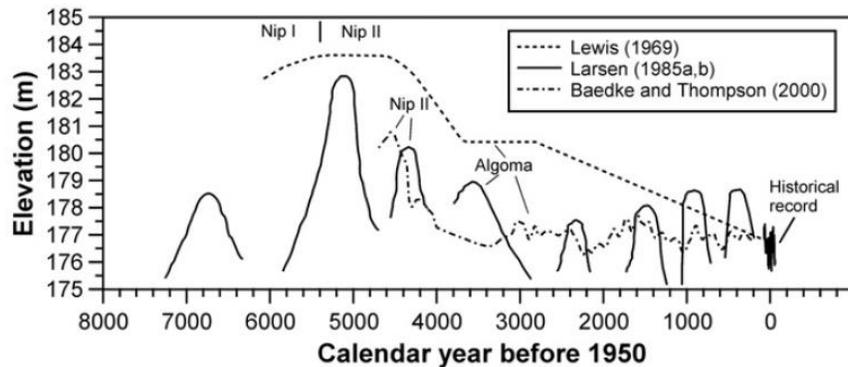


Figure.1.14. Changes in water level during mid- to late Holocene in the Lake Huron and Lake Michigan basins from Baedke and Thompson (2000), Larsen (1985a), and Lewis (1969) (Thompson et al., 2011)

Southern Ontario, including the Lake Simcoe watershed, became accessible to human occupation after the last deglaciation and the recession of the glacial lakes (12,000 - 11,500 cal yr BP) (Ellis and Deller, 1990). Several Early Paleo-Indian sites associated with the Lake Algonquin shoreline were reported from the southern part of the Lake Simcoe watershed (Storck, 1982). Paleo-Indians were followed by Archaic people (Dakin and Skibicki, 1994). The site of Laurentian Archaic peoples was found at Atherley Narrows near Orillia, and it is one of the earliest fish weirs in North America reported from the Middle Archaic (8,000 to 4,500 cal yr BP) (Ringer, 2008). Around 2,900 cal yr BP, southern Ontario was occupied by Woodland Indians (Dakin and Skibicki, 1994) who were later replaced by the Iroquois. The latter increased greatly and developed a marked footprint in the Lake Simcoe area since the 12th century, but were outnumbered and gradually replaced by Europeans in the 18th – 19th centuries (LSRCA, 2000). Before European settlement, the influence of humans on Lake Simcoe was relatively weak and didn't cause significant eutrophication. Nicholls (1995) established that the total pre-settlement P loading rate into Lake Simcoe was only ~32 t/ year.

Most European activity at the beginning of settlement in Upper Canada (17th century) was devoted to the fur trade, but later Europeans started to establish permanent agricultural and industrial settlements. In 1796, Iroquois trails connecting Toronto and Lake Simcoe were replaced by Yonge Street,

paving the way to establishing a few communities along it, with Aurora and Newmarket being the largest (LSRCA, 2000).

Immigrants from Europe began clearing the land around the lake in the 1820s. In 1853, a railway line was finished linking Toronto and Bradford. It played a substantial role in further development of the region, causing the first period of rapid population growth. For instance, the combined population of Newmarket and Aurora in 1841 was approximately 600 people, while in 1871 it reached approximately 3,350 (LSRCA, 2000). This land-clearing was mostly accomplished by the 1890s. As an unintended consequence, soil erosion rapidly increased, bringing more sediments into the lake, as well as nutrients, phosphorus in particular (Evans et al., 1996). Wilson (1986) calculated that erosional losses reached their peak between 1851 and 1891, averaging about 860 000 t/year. Later, cattle farming became more popular in the region, with relatively higher proportions of the land being used for hay and pasture the rate of erosion decreased since 1911 as a result. Nutrient load into Lake Simcoe increased between 1925 and 1930 when the Holland Marsh, a wetland in the Holland River valley situated south of Cook's Bay, was drained. Fifteen Dutch families settled on the marsh in 1934 forming the nucleus of the agricultural community that has kept growing (LSRCA, 2000).

In the mid-1940s a new source of eutrophication appeared, with the introduction of phosphate-based laundry detergents. As a result, P load increased steadily to a peak in excess of 100 t/year between 1940 and 1950 (Nicholls, 1995). In response to the decrease in water quality, federal legislation was introduced in 1971 and 1973, limiting the P content of laundry detergent to 5% (Evans et al., 1996). Since the early 1960s, corn and soybean farms became more popular, rising from 1.4% to 21% of total farmland, and erosion rate increased again, from the low of 1.73 t/ha in 1961 to 3.12 t/ha in 1981 (Wilson, 1989).

The second half of the 20th century was characterized by rapidly increasing population in Lake Simcoe watershed; for example after the World War II (WWII) the population of Newmarket and Aurora rose from around 6,750

(1941) to approximately 32,550 (1971) (LSRCA, 2000) and it is continuing to grow exponentially, especially for the past decade (133,180 in 2011 (Statistics Canada, 2012; Statistics Canada, 2012a)). Changes in agricultural practices and increased population caused significant eutrophication; according to Nicholls (1995) median P load into Lake Simcoe in mid-1980s reached values of about 90 t/ year.

The increased anthropogenic impact has caused drastic deterioration of the lake's ecological status. Demise of water quality became increasingly evident since the 1970s, prompting investigations of the causes and developing possible solutions for the problem (LSEMS, 2003). It was determined that these changes took place as a result of anthropogenic phosphorus inputs that promoted algal production. Five main sources of phosphorus entering the lake have been identified:

- 1) tributaries (urban and non-urban);
- 2) polders (East/West Holland Marsh);
- 3) sewage treatment plants;
- 4) septic systems;
- 5) the atmosphere (LSRCA and MOE, 2009) (Figure1.15).

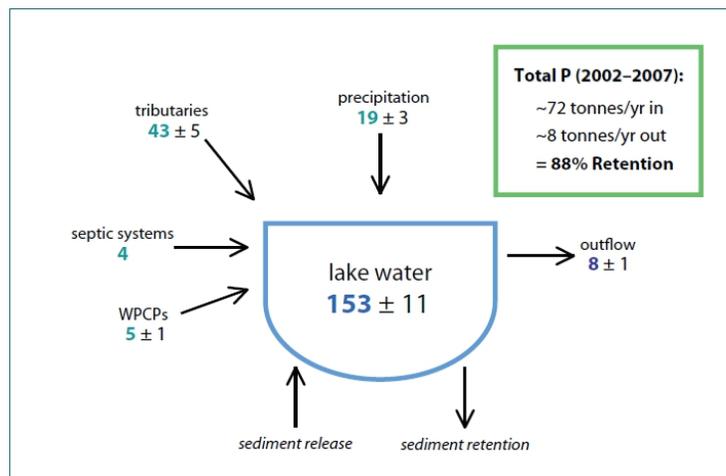


Figure1.15. Total P mass balance for Lake Simcoe averaged from 2002–2007. While approximately 72 tonnes of P are input into Lake Simcoe per year, only approximately 8 t/year leave through the outflow. Internal processes of uptake and sedimentation retain approximately 88% of P inputs within the lake. Tributaries are the single largest source, particularly the East and West Holland Rivers. WPCPs refer to water pollution control plants (Young et al., 2010).

In order to manage the eutrophication, the Lake Simcoe Environmental Management Strategy (LSEMS) was initiated in the 1980s, that later developed partnership with other organizations, including the Lake Simcoe Region Conservation Authority, the Ontario Ministries of the Environment, Natural Resources, Agriculture, Food and Rural Affairs, Municipal Affairs and Housing, and Public Infrastructure Renewal, the Federal Department of Fisheries and Oceans, the Chippewa of Georgina Island First Nation, Lake Simcoe watershed municipalities, and other stakeholders (LSEMS, 2008). This joint effort resulted in implementation of restrictions on total allowable phosphorus output from municipal sewage treatment plants, as well as establishment of more than 500 projects designed to reduce phosphorus inputs into the lake from agricultural and urban sources (Palmer et al., 2011). The success of this hard work can be seen in reduction of P wash-off into the lake by 30% over the past 20 years, from over 100 t/year in the 1990s to approximately 72 t/year in 2002–2007 (LSRCA and MOE, 2009; Winter et al., 2007).

1.6. This Study

1.6.1. Materials and methods

Three cores were collected from different parts of Lake Simcoe, from the highly impacted Cook's Bay with the highest level of eutrophication to the least impacted Smith's Bay near the Lake Couchiching inflow where the level of eutrophication is the lowest (Figure 1. 16).

A 775 cm-long sediment core (LS07PC5) was collected by the Geological Survey of Canada- Atlantic (Todd et al., 2004; 2008) from the main basin of Lake Simcoe (44.48730° N, 79.41692°W) at a water depth of 21 m using gravity corer. In 2011, the core was subsampled at Dr. Fred Longstaffe's Laboratory for Stable Isotope Science (University of Western Ontario) by Prof. Francine McCarthy and Olena Volik. Fifty nine sub-samples of 5 ml volume were taken every 5cm – 15 cm in the upper 350 cm and every 30 cm downcore to a depth of 750 cm for palynological analysis at Brock University. Forty five subsamples of 5 - 75 ml volume (see Appendix 2g) were taken every 5cm – 15 cm in the upper 200 cm

and every 30 cm downcore to a depth of 750 cm for thecamoebian analysis at Brock University. All subsamples were processed and analyzed by Olena Volik.

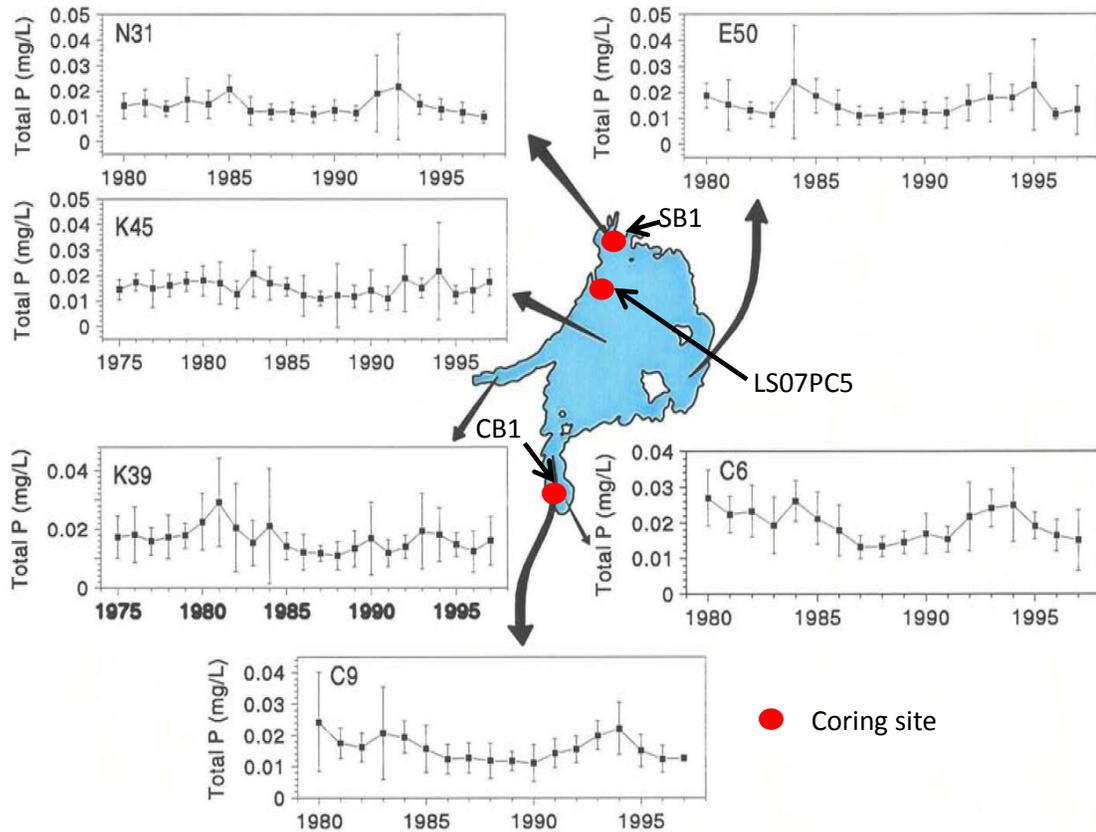


Figure 1.16. Phosphorus concentrations at six main lake sampling stations, October – May (LSEMS, 2003). Levels of eutrophication reflected in total phosphorous (TP) concentrations are the highest in Cook’s Bay, followed by Kempenfelt Bay and the main basin, and are the lowest near the outflow at the Atherley Narrows. Location of three coring sites: CB1 – the core taken by EnviroFix Corporation from Cook’s Bay (Danesh et al., 2013); LS07PC5 - the core collected by the Geological Survey of Canada- Atlantic from the main basin (Todd et al., 2004; 2008); SB1 – the core taken by Francine McCarthy, Volodymyr Sivkov, and Olena Volik from Smith’s Bay.

In August of 2010, a 102 cm-long sediment core (CB1) was collected using technology developed by EnviroFix Corporation at a water depth of 5.87m from the Cook’s Bay (44°10’31”, -79°30’16”) in a region of low dissolved oxygen (DO) (Danesh, 2011; Danesh et al., 2013). The core was subsampled and processed by Donya Danesh who performed initial NPP/pollen analyses. Fourteen sub-samples of 5 ml volume were taken every 5 cm down core and prepared for palynological analysis at Brock University. Six sub-samples of 2.5ml volume were

taken from different zones in the core and prepared for thecamoebian analysis by Matea Drlješan at Brock University (Danesh et al., 2013). For this study pollen analysis of the Cook's bay core was done by Prof. Francine McCarthy, and detailed NPP analysis was done by Olena Volik.

In October of 2012, an 80 cm-long sediment core (SB1) was taken from Smith's Bay (44°35'53.76"N - 79°22'37.87"W) at a water depth of 2.15 m using Rowley Dahl sampler (diameter 5 cm) by Francine McCarthy, Volodymyr Sivkov, and Olena Volik. Only the upper part (45 cm) of the core was used for palynological and thecamoebian analyses. Ten sub-samples of 5 ml volume were taken every 5cm down core and prepared for palynological analysis at Brock University. Ten sub-samples of 5 ml volume were taken every 5cm down core and prepared for thecamoebian analysis at Brock University. All subsamples were processed and analyzed by Olena Volik.

The volume of each sample was determined by water displacement (Bennett and Willis, 2001), and the samples were prepared for palynological analysis in the Palynology Laboratory at Brock University using a slightly modified procedure from that typically used to process Quaternary lacustrine sediments (e.g., Faegri and Iversen, 1975): muds were disaggregated using a weak base (0.02% sodium hexametaphosphate), and no acetolysis treatment was performed. Otherwise, processing was relatively standard: carbonates were dissolved using hot 10% HCl, and hot HF (48%) was used to dissolve silicates. A tablet containing a known number of *Lycopodium clavatum* spores was added during HCl treatment in order to quantify the concentration of palynomorphs (Benninghoff 1962). The elimination of the use of KOH and acetolysis, both of which are standard in the palynological processing of freshwater sediments, is in keeping with the recommendations of Mertens et al. (2009), and although a hot (not boiling) water bath was used during acid treatment, the exposures were relatively short (<30 minutes). Residues were sieved using 10µm *Nitex* mesh and mounted on slides using glycerin jelly.

The strew slides were examined using a Leica DMLB light microscope at 400X magnification and photographed using a Leica EC3 Digital Imaging

Camera. Pollen grains were identified following McAndrews et al. (1973). Concentration of pollen was calculated based on a sum of at least 200 tree pollen grains and 100 nonarboreal pollen grains (Bennett and Willis, 2001; Patterson and Fishbein, 1989).

Non-pollen palynomorphs were identified using a variety of sources (Beyens and Meisterfeld, 2001; John et al., 2002. Wehr and Sheath, 2003; Coesel and Meesters, 2007; Komárek and Jankovská, 2001, and other). A summary of taxonomic and ecological features of selected NPP (as reported in literature) is presented in Appendix 1. Following the suggestion by Jankovska and Komarek (2000), desmids and *Pediastrum* were identified to species level and this approach was crucial for this study.

Despite being a very important subject, counting procedure for NPP is unclear: even fundamental writings on NPP such as Van Geel (2001), Komárek and Jankovská (2001) don't provide definite suggestions how many NPP should be counted per one sample, how many NPP should be counted within one taxa and how to group NPP for counting. Even for the better known *Pediastrum* counting procedure varies from study to study. Whitney and Mayle (2012) counted a minimum of 30 identifiable coenobia in each sample, which they equated to the approximate abundance of *Pediastrum* coenobia per 300 terrestrial pollen grains in sediment samples; *Pediastrum* species abundance was calculated as a proportion of the sum of all identified *Pediastrum* in each sample. Bradshaw et al. (2005) counted at least 500 *Pediastrum* per sample, and percentage abundances for *Pediastrum* were calculated on the basis of the terrestrial pollen and spore sum. Sarmaja-Korjonen et al. (2006) counted 400 coenobia+ *Lycopodium* spores for most samples, but where colonies were very rare 400 *Lycopodium* spores+*Pediastrum* colonies were enumerated.

Taking into consideration discrepancies in counting procedure, NPP counts were performed in following way: 5 groups (desmids, *Pediastrum* spp, *Botryococcus* spp., dinoflagellates, ciliates) were divided and at least 50 palynomorphs in each group were counted. Number 50 was chosen following a suggestion by Patterson and Fishbein (1989) as a minimal statistically sufficient

count. Then concentration of each taxa was calculated, as the groups were not taxonomically equal to compare relative abundance. The calculations of concentration of palynomorphs (pollen and NPP) were performed according to the slightly modified equation from Bennett and Willis (2001):

$$C_P = \frac{\sum P \times N_L \div \sum C_L}{V},$$

where C_P is concentration of palynomorphs in the sample, $\sum P$ – the sum of counted palynomorphs in the sample, N_L – number of markers (*Lycopodium*) that were added to the sample, $\sum C_L$ – the number of markers that were counted in the sample, V – the volume of the sample.

For thecamoebian analysis 45 sub-samples of 5 – 25ml volume (depending on thecamoebian test concentrations) were sieved to retain the >45 μm fraction, although for ease of analysis and to allow comparison with a variety of published studies, the 45-63 μm fraction was analyzed separately from the >63 μm fraction. Thecamoebians were examined at 100X using a Leica ZOOM 2000 and identified primarily using the key of Dalby and Kumar (1998) and the monograph of Scott and Medioli (1983). Calculations of the concentration were performed using the following equation:

$$C_T = \frac{\sum T_T}{V},$$

where C_T is concentration of theca in the sample, $\sum T_T$ – the sum of counted theca in the sample, V – volume of the sample.

As preliminary results from Cook's Bay (Danesh et al., 2013) showed there is surprisingly little similarity in thecamoebian and ciliate protozoan assemblages identified in washed microfossil samples and in palynological preparations, thecamoebians were counted only in washed samples. However, photographs (Plate 2.2) were taken from pollen slides.

The Shannon-Weaver diversity index (SDI) was used to determine species diversity (Shannon and Weaver, 1949). SDI between 0.5 – 1.5 indicates harsh, unfavorable environmental conditions, SDI from 1.5 to 2.5 represents intermediate conditions, and the index above 2.5 points out favorable conditions

(Patterson and Kumar, 2002). The SDI is calculated using the following formula:

$$H = - \sum_{i=1}^{S_s} P_i \times \ln P_i,$$

where H - Shannon-Weaver diversity index (SDI);

S_s – total number of species;

$P_i = N_i/N_n$ - proportion of individuals of the total sample belonging to i th species;

N_i – number of individuals (N_n) belonging to i th species;

N_n – total number of individuals.

Pollen, NPP, and thecamoebian diagrams were divided into zones basing on stratigraphically constrained cluster analysis using PAST version 2.17 (Hammer et al., 2001). For chronology pollen diagrams were visually zoned following McAndrews (1994).

1.6.2. Study objectives

The main aim for this thesis was to evaluate the potential of NPP as proxies of paleoenvironmental and anthropogenic change in Lake Simcoe by comparing their downcore distributions with those of better-understood pollen and thecamoebians. A long core from the main basin (LS07PC5) was analyzed to determine variations in climate and limnological features such as lake level, trophic state, etc. Two short cores from Cook's and Smith Bays provide us with additional insights into changes in water quality associated with human impact.

The following questions were addressed:

- 1) Have NPP assemblages of Lake Simcoe changed since the late glacial?
- 2) How do the temporal and spatial distributions of NPP compare with the pollen and thecamoebian records?
- 3) What changes in climate (cooling, warming, drought, humidification etc.), limnology (increase/decrease in water levels, eutrophication, turbidity, etc.), and human impact (urbanization, agricultural practices, deforestation, industrialization) can be inferred from NPP, thecamoebian, and pollen assemblages?

4) Is there agreement between NPP inferred and diatom-inferred (Hawryshyn et al., 2012) water-quality changes in Lake Simcoe?

The results of pollen/NPP/thecamoebian analyses are presented in Chapter 2, with Chapter 3 devoted to discussion of evolution of the lake from late glacial to present, and temporal and spatial changes in anthropogenic impact inferred from microfossils from Lake Simcoe. Raw data is presented in Appendices 2-4.

Chapter 2: Results

More than 40 taxa of microfossils (excluding pollen) were identified in the sediment cores taken from Cook's Bay, Smith's Bay and, the main basin, of Lake Simcoe (Figure 1.15); the most abundant NPPs were algae (~ 20 species that belong to the genera *Pediastrum*, *Cosmarium*, *Euastrum*, *Staurastrum* and four species of Dinoflagellata: (*Parvodinium* [*Peridinium*] *inconspicuum*, *Peridinium willei*, *P. volzii*, *P. wisconsinense*) (Plates 2.1, 2.2), whereas protozoa were less common (>10 species of thecamoebians and one species of ciliates (*Codonella cratera*) (Plate 2.3). The upper 30 cm of core LS07PC5 from the main basin (Todd et al., 2004) was imperfectly recovered (being soupy, and the surface sediments may have been blown off with the piston corer), so more detailed information about the time frame it represents (the period of European settlement) was taken from the Cook's Bay and the Smith's Bay cores. Numbers of NPP become statistically significant only above 384 cm in the core from the main basin; the underlying glaciolacustrine and till are essentially barren.

Pollen data were used mostly for chronology, although some paleoclimatic inferences were made. The pollen diagram of the core from the main basin shows a typical succession for Southern Ontario, with pollen zones from 1 to 4 (McAndrews, 1994) (see Appendix 5). Although pollen grains were found throughout the core, the data below 490 cm is statistically insignificant because of very low pollen concentrations (~50 – 100 pollen grains per milliliter). The cores from Cook's Bay and Smith's Bay include pollen zones 3d and 4.

2.1 Palynological and thecamoebian analysis of the core from the main basin (LS07PC5)

Pollen diagrams were divided into zones following McAndrews (1994) and using PAST version 2.17 (Hammer et al., 2001) (Figure 2.1). Based on stratigraphically constrained cluster analysis using PAST version 2.17 (Hammer et al., 2001), the NPP and thecamoebian diagrams were divided into eleven and eight zones respectively (Figures 2.2, 2.3). The boundaries between the pollen, NPP and thecamoebian zones nearly match one another (Figure 2.4).

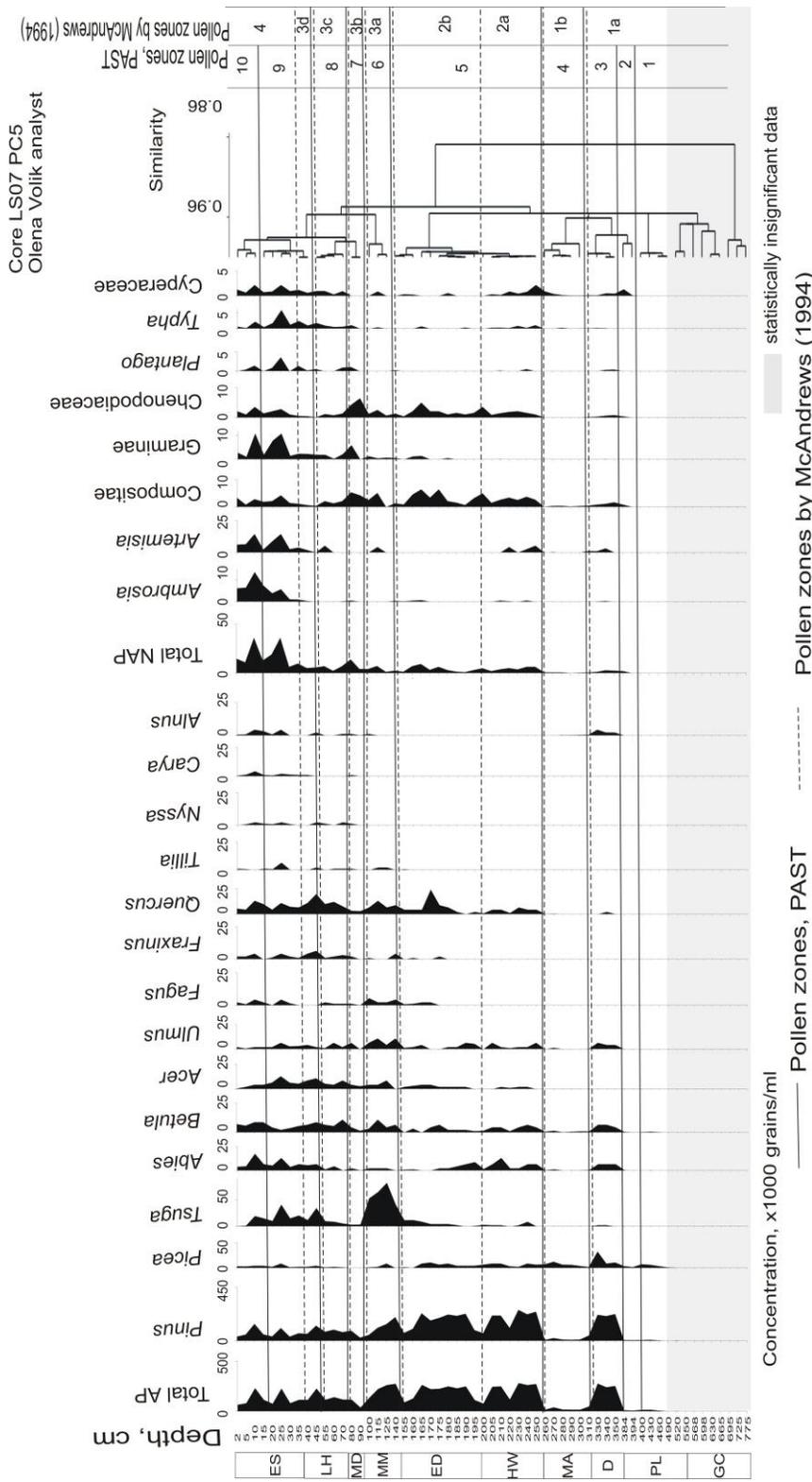


Figure 2.1. Pollen concentration identified per ml sediment measured using liquid displacement in core LS07 PC5. Pollen zones were divided using stratigraphically constrained cluster analysis using PAST version 2.17 (Hammer et al., 2001) (solid black line) and "by eyes" following McAndrews (1994) (dash line). The diagram shows typical succession for southern Ontario with pollen zone 1 to 4 by McAndrews (1994) identifying the most pronounced changes: GC – glacial conditions; PL – proglacial lake; D – deglaciation; MA – the Main Algonquin phase; HW – Holocene warming; ED – early Holocene drought; MM – mid- Holocene moist period; MD – mid – Holocene drought; LH – late Holocene climate amelioration; ES – European settlement. Sediments below 490 cm were barren of pollen

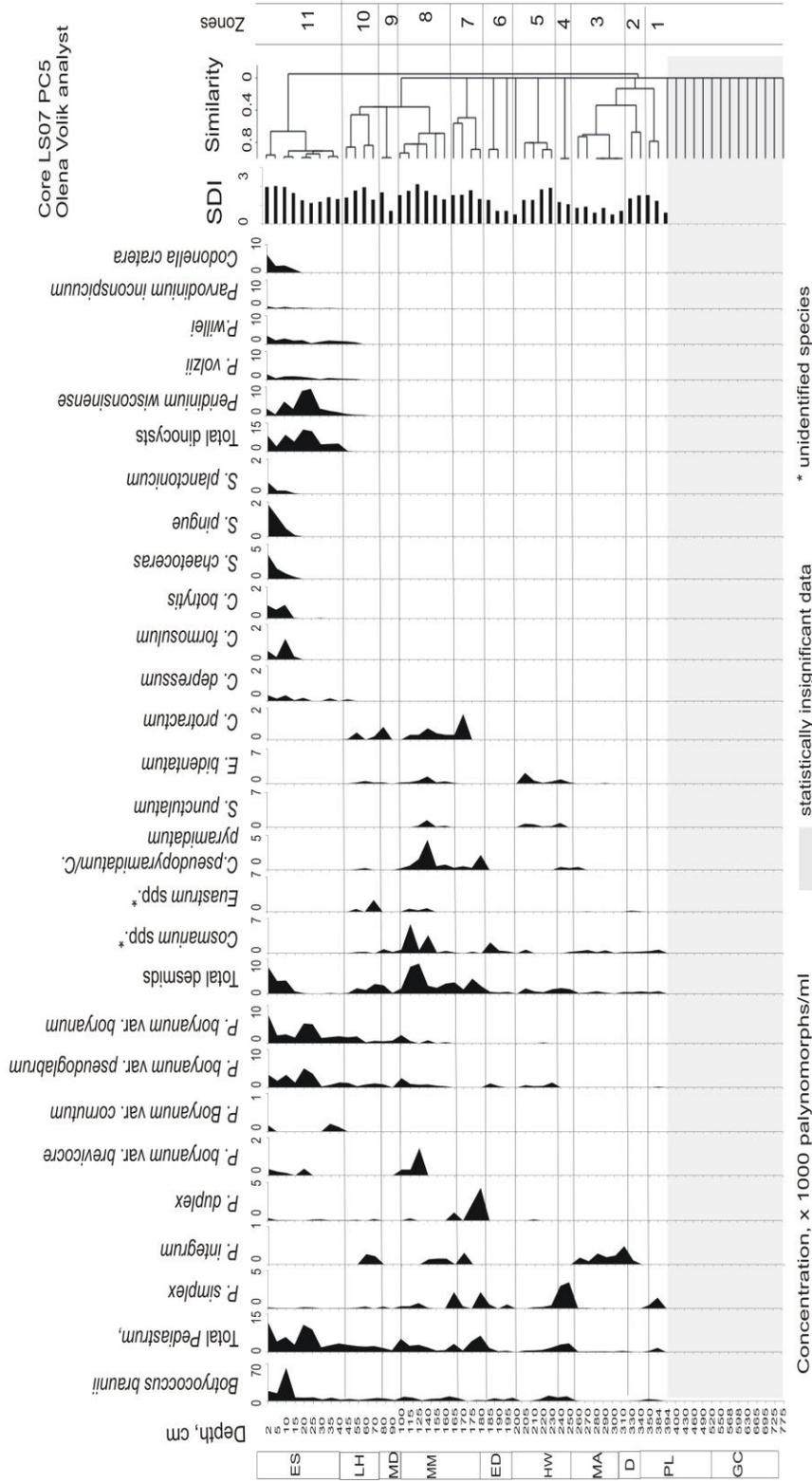


Figure 2.2. Concentration of NPP identified per ml sediment measured using liquid displacement in core LS07 PC5. Zones were divided using stratigraphically constrained cluster analysis using PAST version 2.17 (Hammer et al., 2001) (solid black line). Sediments below 384 cm were barren of NPP. Shifts in NPP assemblages indicate the most pronounced changes: GC – glacial conditions; PL – proglacial lake; D – deglaciation; MA – the Main Algonquin phase; HW – Holocene warming; ED – early Holocene drought; MM – mid- Holocene moist period; MD – mid – Holocene drought; LH – late Holocene climate amelioration; ES – European settlement.

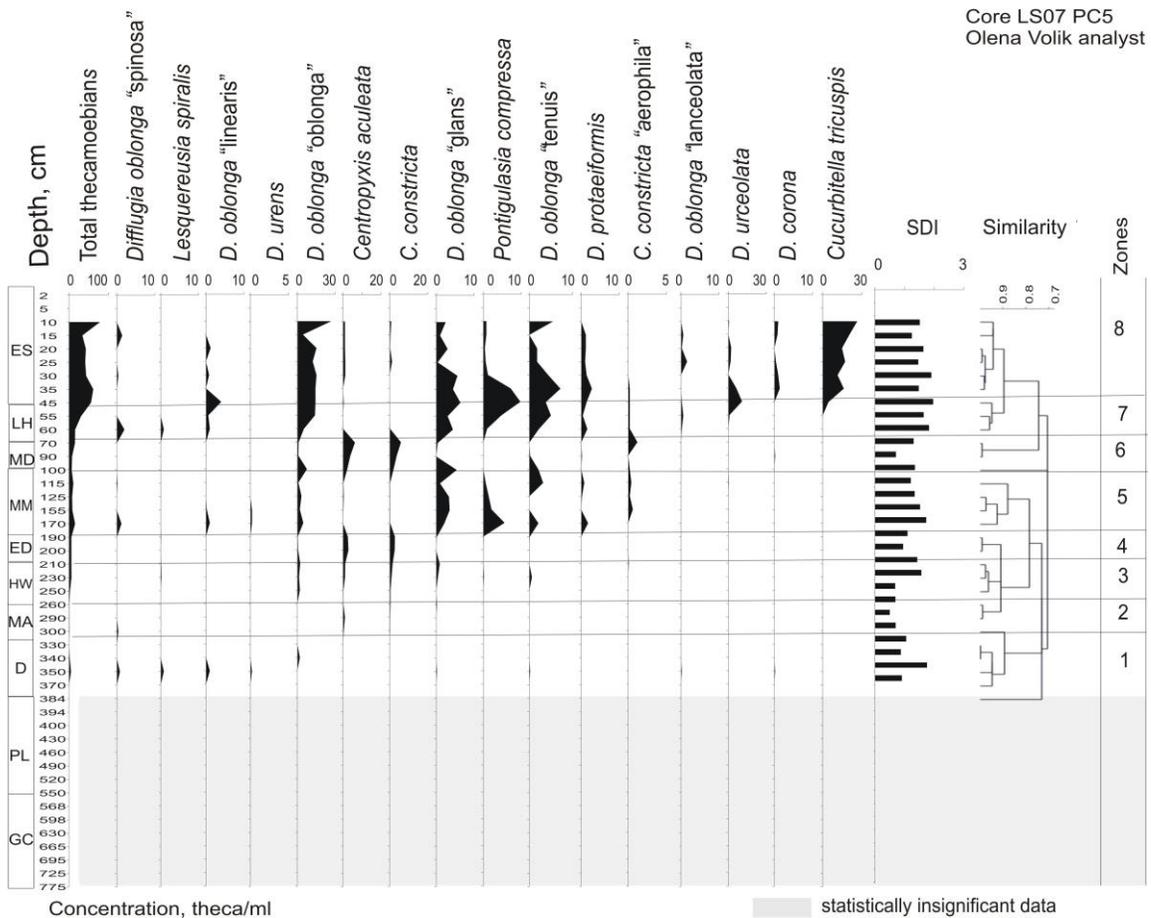


Figure 2.3. Concentration of thecamoebian thecae identified per ml sediment measured using liquid displacement in core LS07 PC5. Zones were divided using stratigraphically constrained cluster analysis using PAST version 2.17 (Hammer et al., 2001) (solid black line). The most common species is *Diffflugia oblonga*, and some taxa are essentially restricted to the upper 45 cm, where abundances increase by nearly an order of magnitude- *Cucurbitella tricuspsis*, *Diffflugia corona*, and *Diffflugia urceolata*. Sediments below 384 cm were barren of thecamoebians. Shifts in thecamoebian assemblages indicate the most pronounced changes: GC – glacial conditions; PL – proglacial lake; D – deglaciation; MA – the Main Algonquin phase; HW – Holocene warming; ED – early Holocene drought; MM – mid- Holocene moist period; MD – mid – Holocene drought; LH – late Holocene climate amelioration; ES – European settlement.

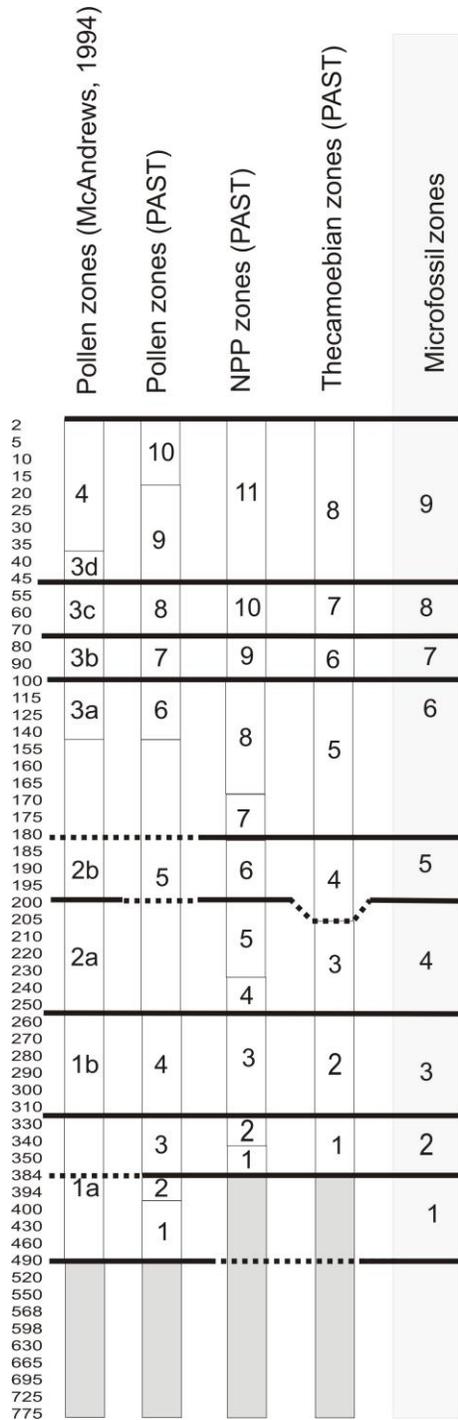


Figure 2.4. Microfossil zones in core LS07PC5. Zones were determined based on coincidence at least of two zones (pollen (McAndrews, 1994)/PAST, NPP or thecamoebian): matching boundaries are delineated by solid horizontal black lines. Nine microfossil zones were divided: 1) microfossil zone 1 includes bottom part of pollen zone 1a (McAndrews, 1994) and pollen zones 1 – 2 (PAST); 2) microfossil zone 2 includes upper part of pollen zone 1a (McAndrews, 1994) and pollen zone 3 (PAST), NPP zones 1 – 2, and thecamoebian zone 1; 3) microfossil zone 3 includes pollen zones 1b (McAndrews, 1994) and 4 (PAST), NPP zone 3, and thecamoebian zone 2; 4) microfossil zone 4 includes pollen zones 2a (McAndrews, 1994) and bottom part of zone 5 (PAST), NPP zones 4 - 5, and thecamoebian zone 3; 5) microfossil zone 5 includes pollen zone 2b (McAndrews, 1994) and upper part of pollen zone 5 (PAST), NPP zone 6, and thecamoebian zone 4; 6) microfossil zone 6 includes pollen zones 3a (McAndrews, 1994) and 6 (PAST), NPP zones 7 - 8, and thecamoebian zone 5; 7) microfossil zone 7 includes pollen zones 3b (McAndrews, 1994) and 7 (PAST), NPP zones 9, and thecamoebian zone 6; 8) microfossil zone 8 includes pollen zones 3c (McAndrews, 1994) and 8 (PAST), NPP zones 10, and thecamoebian zone 7; 9) microfossil zone 9 includes pollen zones 3d - 4 (McAndrews, 1994) and 9 - 10 (PAST), NPP zone 11, and thecamoebian zone 8.

Microfossil zone 1 (490–394 cm) 1 includes bottom part of pollen zone 1a (McAndrews, 1994) and pollen zones 1 – 2 (PAST) and is dominated by *Pinus* (> 50 %) and *Picea*; the concentration of pollen is very low (~2,000 – 8,000 grains/ml). NPP and thecamoebian are absent.

Microfossil zone 2 (384–330 cm) includes the upper part of pollen zone 1a of McAndrews (1994) and includes pollen zone 3 (PAST), NPP zones 1 – 2, and thecamoebian zone 1. This zone is dominated by *Pinus* (> 50 %), *Alnus*, *Betula* and herbs (Compositae, Chenopodiaceae, Cyperaceae). The presence of low abundances of *Tsuga*, *Acer*, and *Quercus* probably results from long distance transport. Pollen concentration is high (~250,000–270,000 grains/ml). NPP assemblages consist of algae (*Pediastrum simplex* (>60%), *Cosmarium* spp., *Botryococcus* spp.) and the thecamoebian assemblage is dominated by *Diffflugia oblonga*. In contrast to pollen, the concentration of NPP is low (> 4000/ml for algae and >10/ml for thecamoebians). Concentrations of *Pediastrum simplex* and thecamoebians peak at 384 and 350 cm respectively, and then decrease sharply; the highest concentration of *Cosmarium* spp. is at 384 cm and then declines gradually towards the end of the zone. Species diversity indices (SDI) vary from 1.0 to 1.5 for thecamoebians and from 1.0 to 2.0 for algae.

Microfossil zone 3 (310–260 cm) includes *Picea*–Cyperaceae pollen zones 1b (McAndrews, 1994) and 4 (PAST), NPP zone 3, and thecamoebian zone 2. The pollen and NPP concentrations are the lower than anywhere else in the upper 384 cm of the core. The thecamoebian assemblages are characterized by very low species diversity index (SDI ~0.5) and comprise only two species: *Centropyxis aculeata* (~80%) and *Centropyxis constricta* (almost 20%). Algae are presented by *Pediastrum integrum* (~ 60 %) and *Cosmarium* spp. (~40 %); the species diversity index ranges from 0.5 to 1.0.

Microfossil zone 4 (250 cm–200cm) includes pollen zones 2a (McAndrews, 1994) and bottom part of zone 5 (PAST), NPP zones 4 - 5, and thecamoebian zone 3. This zone is characterized by a dominance of *Pinus* (dominantly *P. banksiana* /*resinosa*->50%) and relatively high abundances of *Betula*, *Quercus*, *Abies*, Compositae and Chenopodiaceae. NPP assemblages are diverse: SDI for algae is 1.0–1.9, and for thecamoebians it is 1.4–1.5. Algal communities are dominated by *Pediastrum simplex* (>40%) that increases sharply at the beginning of the zone, reaching its absolute maximum at 250–240 cm, then declines abruptly at 230 cm, slowly tapering off by the end of the zone.

In the upper part of the zone, *Pediastrum boryanum* var. *boryanum* and *P. boryanum* var. *pseudoglabrum* appear for the first time, but the concentration of *Pediastrum boryanum* var. *boryanum* is very low (< 500 coenobia/ml). *Botryococcus braunii* numbers are maintained through the central part of the zone, and disappear near the top. The concentration of desmids is relatively stable throughout the zone with a slight decrease in the middle. Their assemblages are represented by *Euastrum bidentatum*, *Staurastrum* spp., *Cosmarium punctulatum*, *C. pyramidatum*, *C. pseudopyramidatum*. The concentration of thecamoebians is low, especially in the lower part of the zone; the dominant species is *Diffflugia oblonga* consisting of three strains (*D. oblonga* “oblonga”, *D. oblonga* “tenuis”, *D. oblonga* “glans”). Small numbers of *Pontigulasia compressa* and *Centropyxis constricta aerophila* are present in the middle and top of the zone, respectively. Low percentages of *C. constricta* and *C. aculeata* are found at the base of the zone, but they gradually increase in abundance through the zone.

Microfossil zone 5 (195– 185 cm) corresponds to bottom part of pollen zone 2b of McAndrews (1994) and upper part of pollen zone 5 (PAST), NPP zone 6, and thecamoebian zone 4. In this zone white pine (*Pinus strobus*) becomes dominant. The beginning of the zone is marked by peaks of Compositae and Chenopodiaceae. A shift to depleted NPP assemblages is observed; SDI for both thecamoebians and algae is <1. The algae are represented by *Cosmarium* spp., *Botryococcus braunii*, *Pediastrum simplex*, concentrations of which are low throughout the zone with slight increases at the end. The thecamoebian fauna consists of *Centropyxis constricta* and *C. aculeata*, and their concentrations gradually rise toward the end of the zone.

Microfossil zone 6 (180–100cm) (includes upper part of pollen zone 2b and zone 3a (McAndrews, 1994), zone6 (PAST), NPP zones 7 - 8, and thecamoebian zone 5. The pollen assemblages are characterized by the rise of *Tsuga* (with a maximum between 140 and 100 cm), and abundant *Betula*, *Fagus*, *Acer*, *Ulmus*, *Tillia*. The distribution of NPP shows a progression upcore from depleted assemblages to rich and abundant ones (SDI for this zone is 1-2 for

algae, and 1-1.5 for thecamoebians).

The bottom part (180 – 170 cm) is dominated by *P. simplex*, *P. duplex*, *Cosmarium* spp., *C. pyramidatum*, *C. pseudopyramidatum*, *E. bidentatum*, and later by *C. protractum*. Concentrations of *Pediastrum* and desmids more than double relative to zone 5, and peak at 180 cm and 175 cm respectively, but the concentration of *Botryococcus braunii* declines through this subzone. The thecamoebian fauna includes *Diffflugia oblonga* (consisting of 5 strains: *D. oblonga* “oblonga”, *D. oblonga* “tenuis”, *D. oblonga* “spinosa”, *D. oblonga* “linearis”, *D. oblonga* “glans”), *Diffflugia protaeiformis*, *Diffflugia urens*, and *Pontigulasia compressa*. Their concentration increases through the subzone peaking at the top. In the middle part (170 – 155 cm), there is a slight increase in *Botryococcus braunii* and a decline in concentrations of *Pediastrum* spp., desmids and thecamoebians despite small peaks at the base. *Pediastrum* is represented by 5 taxa (*P. simplex*, *P. duplex*, *P. boryanum* var. *boryanum*, *P. boryanum* var. *pseudoglabrum*, *P. integrum*); a remarkable increase in relative abundance of *P. integrum* occurs throughout this subzone. Desmids include *Euastrum bidentatum*, *Staurastrum* spp., *Cosmarium pyramidatum*, *C. pseudopyramidatum*, and *C. protractum*. The most prominent changes in thecamoebian assemblages are a dominance of *D. oblonga glans*, a decreased concentration of *P. compressa*, and an appearance of *Centropyxis constricta* “aerophila”. The upper part (155–100 cm) is marked by an increase in *Pediastrum* and desmid concentrations and a relative stability in thecamoebian and *Botryococcus* spp. concentrations. Algal assemblages are characterized by replacement of *P. integrum* by *P. boryanum* var. *brevicornis*, an increase in relative abundance of *P. boryanum* var. *boryanum* and *P. boryanum* var. *pseudoglabrum*, and by maxima of *E. bidentatum*, *S. punctulatum*, *C. pyramidatum* together with *C. pseudopyramidatum*.

Microfossil zone 7 (90–80 cm) includes pollen zones 3b (McAndrews, 1994) and 7 (PAST), NPP zones 9, and thecamoebian zone 7. This zone is characterized by *Tsuga* minimum together with relatively abundant herbs: Compositae, Chenopodiaceae, Gramineae) and like zone 5 is characterized by

depleted assemblages (SDI ~1 for algae and testate amoebae). *Cosmarium* spp., *Botryococcus braunii*, *Centropyxis constricta*, and *C. aculeata* are the dominant species.

Microfossil zone 8 (70–55 cm) includes pollen zones 3c (McAndrews, 1994) and 8 (PAST), NPP zones 10, and thecamoebian zone 7. This zone is characterized by *Tsuga* resurgence coupled with diverse NPP and thecamoebian assemblages (SDI for thecamoebians and algae varies from 1.5 to 2). The concentrations of *Botryococcus* spp. and *Pediastrum* are relatively stable within the zone; the dominant taxa are *P. boryanum* var. *boryanum* and *P. boryanum* var. *pseudoglabrum* although other species (*P. simplex*, *P. duplex*, *P. integrum*) are present. The highest concentration of desmids is observed at the base of the zone, decreasing towards the top of the zone; the assemblages include *Euastrum* spp., *Staurastrum* spp., *Cosmarium protractum*; the middle part of the zone also contains *E. bidentatum*, *C. pyramidatum* together with *C. pseudopyramidatum*. Thecamoebian concentrations rise rapidly, peaking at the end of the zone. *Diffflugia oblonga* (*D. oblonga* “oblonga”, *D. oblonga* “tenuis”, *D. oblonga* “spinosa”, *D. oblonga* “linearis”, *D. oblonga* “glans”), *Pontigulasia compressa*, *Diffflugia urceolata*, and *Diffflugia protaeiformis* are the dominant taxa.

Microfossil zone 9 (above 45 cm) coincides with pollen zones 3d and 4 of McAndrews (1994) and 9 - 10 (PAST), NPP zone 11, and thecamoebian zone 8. This zone is characterized by an increase in non-arboreal pollen, mainly *Ambrosia* and Gramineae). Bottom part (40 – 15 cm) is characterized by increased concentration of dinocysts, dominated by *Peridinium wisconsinense* that rises from 44% to 88% of total dinocysts. Total *Pediastrum* concentration shows a similar trend, and assemblages are dominated by *P. boryanum* var. *boryanum* and *P. boryanum* var. *pseudoglabrum* (together up to 90%), but also *P. simplex*, *P. duplex* and *P. integrum* are present. The concentration of *Botryococcus* is relatively stable through the subzone, but increases sharply in upper part. The concentration of desmids decreases, but number of thecamoebian rises. Thecamoebian assemblages are dominated by *D. oblonga* and *P. compressa* (>60%) in bottom part of the subzone, but above 25 cm

Cucurbitella tricuspis becomes dominant (>50%).

Upper part (above 15 cm) is characterized by a rise in desmid, dinocyst, *Pediastrum*, and thecamoebian concentrations, and a maximum in *Botryococcus* concentrations occurs. Algal communities are dominated by *P. boryanum* var. *boryanum* and *P. boryanum* var. *pseudoglabrum*, desmids (*Staurastrum chaetoceras*, *S. pingue*, *Cosmarium botrytis*, *C. formosulum*), and *Botryococcus* spp. The thecamoebian assemblage is dominated by *Cucurbitella tricuspis* and *Diffugia oblonga*, and the ciliate protozoan *Codonella cratera* first appears at 15 cm and rises sharply to the top of the core.

2.2 Palynological and thecamoebian analyses of the core from Cook's Bay (CB1)

Pollen (Figure 2.5; Appendix 5) is used for chronology; zone 1 (PAST) coincides with zone 3), and zones 2, 3 (PAST) coincide with zone 4 (McAndrews, 1994). Based on stratigraphically constrained cluster analysis using PAST version 2.17 (Hammer et al., 2001), NPP and thecamoebian diagrams were divided into four and two zones respectively (Figure 2.6; Figure 2.7); NPP zones 1 – 3 correspond to thecamoebian zone 1.

Microfossil zone 1 (below 70 cm) correlates with pollen zone 3d of McAndrews (1994). It is characterized by diverse NPP assemblages (SDI for algae varies from 1 to 1.5) and poor diversity of thecamoebians (SDI 0.2-0.9). Desmids are represented by *Staurastrum* spp., *Cosmarium* spp., and *Euastrum* spp.; although *C. formosulum*, *C. botrytis*, *C. depressum*, *E. bidentatum*, *E. denticulatum* are present, their concentrations are not high. Total desmid concentrations are the highest within the core (~100,000 half-cells/ml). Total *Pediastrum* concentration is the lowest in the core; the assemblages are dominated by *P. integrum* (47 – 49%) *P. boryanum* var. *boryanum* and *P. boryanum* var. *pseudoglabrum* (together ~ 40%). The total thecamoebian concentration is very low (< 20 tests/ml); *Centropyxis aculeata* and *C. constricta* are the dominant species here (> 80%). The first sporadic occurrence of cysts of dinoflagellates (*Peridinium wisconsinense*) is above 80 cm.

Microfossil zone 2 (64–55 cm) is characterized by a rise in *Ambrosia* and other non-arboreal pollen and correlates with pollen zone 4 of McAndrews (1994). Total desmid concentrations decrease towards the top of the zone. An increased concentration of dinoflagellate cysts is observed (10,000-11,000 cysts/ml). It is notable that gradual reduction (from 60% to 30%) in concentration of *P. wisconsinense* cysts occurs, with simultaneous increase of *Peridinium willei* and *P. volzii* cysts. SDI for algae in this zone ranges from 2 to 2.3. The concentration of desmids decreases reaching the minimum (approximately 10000 half cells/ml) at 70 cm, and then increases peaking at 64 cm. The species present are

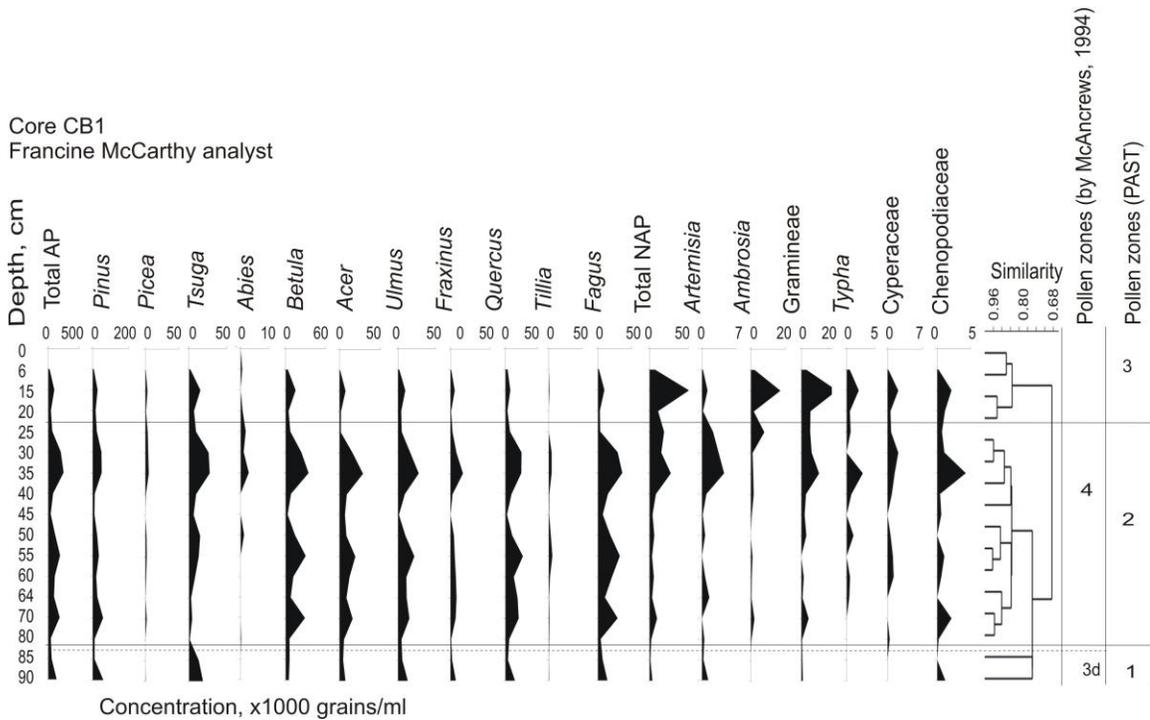


Figure 2.5. Pollen concentrations scaled by depth from a sediment core CB1 taken within Cook's Bay. Local pollen assemblage zones determined using PAST version 2.17 (Hammer et al., 2001) are delineated by a solid horizontal black line and pollen zones by McAndrews (1994) determined "by eyes" are delineated by a dash horizontal black line.

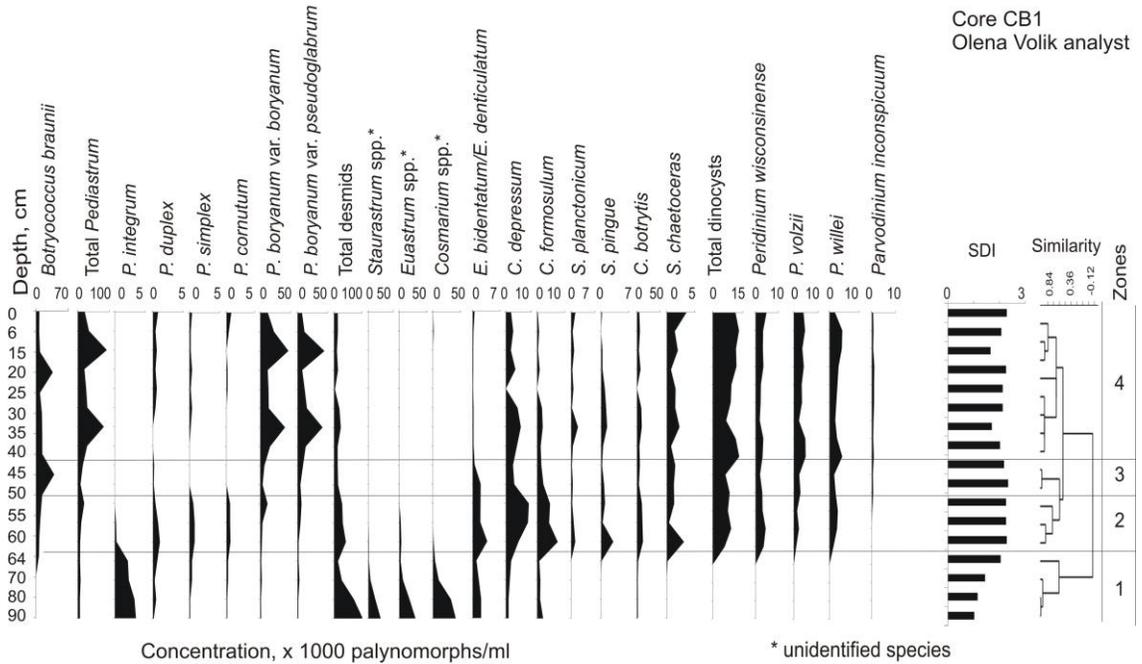


Figure 2.6. NPP concentrations scaled by depth from a sediment core CB1 taken within Cook's Bay. Local NPP zones were determined using PAST version 2.17 (Hammer et al., 2001)

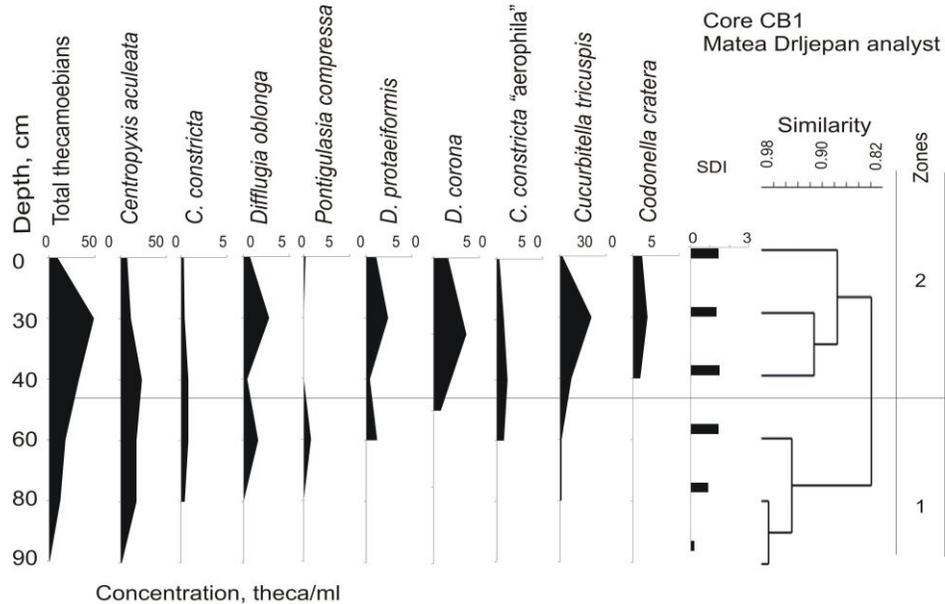


Figure 2.7. Protozoan concentrations scaled by depth from a sediment core CB1 taken within Cook's Bay, Lake Simcoe. Zones were determined using PAST version 2.17 (Hammer et al., 2001)

Staurastrum chaetoceras, *S. pingue*, *S. gracile*, *S. planctonicum*, *Cosmarium depressum*, *C. botrytis*, *C. formosulum*, *Euastrum bidentatum*. Above 65 cm *Pediastrum integrum* disappears completely; in turn the concentrations of *P. boryanum* var. *boryanum*, *P. boryanum* var. *pseudoglabrum* peak at 54-54 cm. The concentration of thecamoebians also gradually increases (approximately to 30 tests/ml), with SDI of 1.5; the concentration of *C. aculeata* and *C. constricta* tests stays almost the same, but relative abundances decrease (to 30%) due to notably higher quantities of *Diffflugia protaeiformis*, *Diffflugia oblonga*, *Diffflugia corona*.

Microfossil zone 3 (50–45 cm) is characterized by a sharp rise in *Ambrosia* and Gramineae (between ~ 50 cm and 40 cm). A sharp peak of dinocysts concentration (over 14000 cysts/ml is observed at 45 cm, with prevalence of *Peridinium willei* and *P. volzii* (together ~ 60%). The thecamoebian concentration rises to 40 theca/ml; the numbers of *Centropyxis aculeata* and *C. constricta* reach their maximum, and together they compose up to 45% of thecamoebian assemblage. It is notable that there is a 2.5-fold increase of *Diffflugia corona* as well. The concentration of desmids decreases to approximately 10,000 half-cells/ml; an increase in concentration of *Cosmarium botrytis*, and a decrease in concentration of *Euastrum bidentatum* is notable, with a general increase of eutrophic species on the background (up to 80%). The concentrations of *P. boryanum* var. *boryanum*, *P. boryanum* var. *pseudoglabrum* decrease at 45-50 cm, increasing only above 40 cm. *P. duplex* and *P. simplex* are absent at 45-50 cm, but they appear above 40 cm. SDI for algae in this zone remains high (2 - 2.3), and thecamoebians maintain their diversity index throughout (1.5).

Microfossil zone 4 (above 40 cm) is characterized by a rapid rise of *Ambrosia* between 30 cm and 25 cm, immediately followed by a second sharp rise in Gramineae (peaking at 15 cm). NPP assemblages are diverse, with SDI fluctuating from 2 to 1.6 and then back to 2 up-core. The numbers of dinocysts gradually increase, peaking at 6 cm; *Peridinium willei* and *P. volzii* dominate (up to 60%). An increased relative abundance of *P. wisconsinense* was found at 1 - 0

cm. Desmids are dominated by *Cosmarium botrytis* and *Staurastrum chaetoceras* (together >60%); the overall concentration of desmids remains more or less stable above 20 cm. There are two peaks in *Pediastrum* concentration, at 35 and 15 cm; *P. boryanum* var. *boryanum*, *P. boryanum* var. *pseudoglabrum* dominate (together > 80%), while the concentration of *P. duplex* and *P. simplex* remains stable low. Thecamoebian assemblages maintain SDI of 1.4 – 1.5, their concentration peaks at 30 cm (over 50 theca/ml); *Cucurbitella tricuspis* (60% at 30 cm) and *Centropyxis aculeata* (46% at 0 cm) are dominant species here. *Codonella cratera* appears at approximately 40 cm and its concentration reaches its maximum at the top of the core.

2.3 Palynological and thecamoebian analysis of the core from the Smith's Bay (SB1)

Pollen diagram (Figure 2.8) is used for timing; zone 1(PAST) coincides with zone 3d of McAndrews (1994)), and zone 2 (PAST) coincide with zone 4 (McAndrews, 1994). NPP and thecamoebian diagrams were divided into 2 zones with 3 subzones using PAST version 2.17 (Hammer et al., 2001) (Figure 2.9).

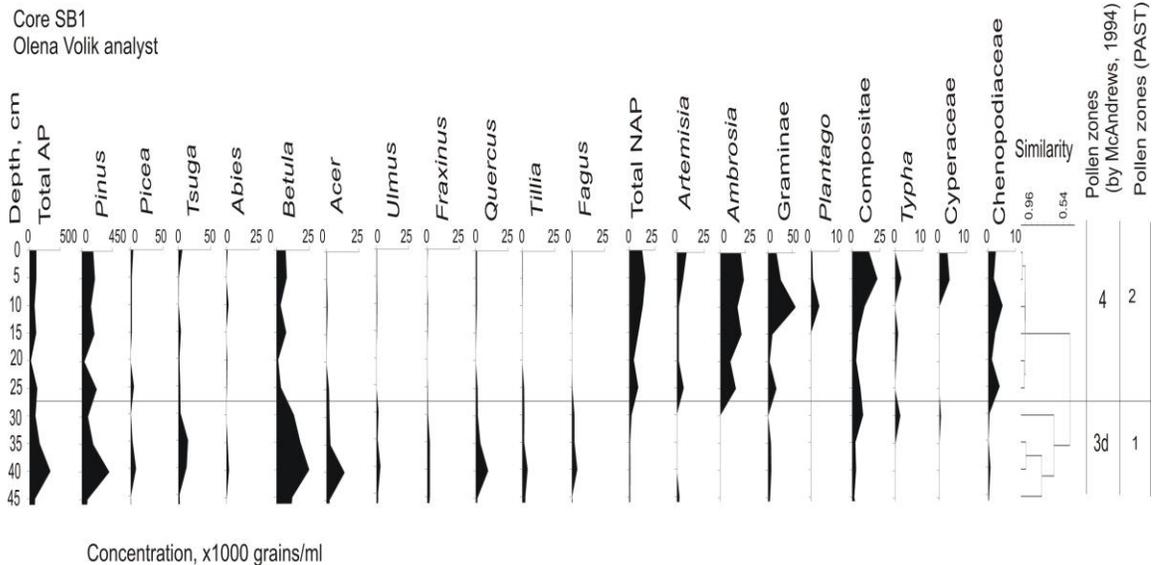


Figure 2.8 Pollen concentration scaled by depth from a sediment core SB1 taken within Smith's Bay, Lake Simcoe. Local pollen assemblage zones determined using PAST version 2.17 (Hammer et al., 2001) coincide with pollen zones by McAndrews (1994) determined "by eyes" (solid horizontal black line)

Core SB1
Olana Volik analyst

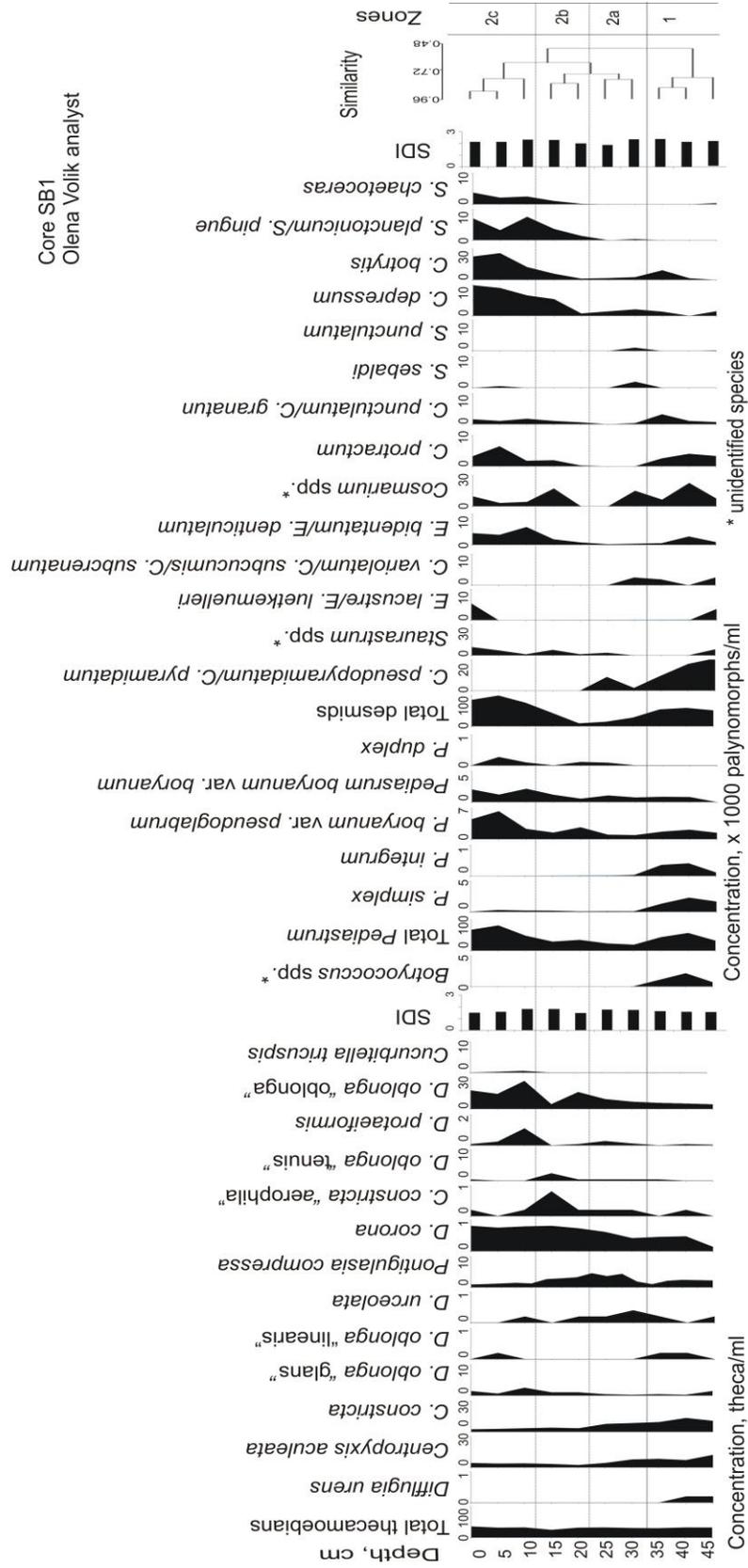


Figure 2.8. NPP and thecamoebian concentrations scaled by depth from a sediment core SB1 taken within Smith's Bay, Lake Simcoe. Local NPP zones were determined using PAST version 2.17 (Hammer et al., 2001)

Microfossil zone 1 (below 30 cm) includes pollen zones 3c (*Tsuga* recovery), and 3d (*Fagus* decline) of McAndrews (1994). NPP assemblages are diverse: SDI for algae ranges from 2.1 to 2.3, and for thecamoebians from 1.5 to 1.7. Algal communities are dominated by *Pediastrum simplex* and *P. boryanum* var. *pseudoglabrum* (up to 80 % in the lower part); *P. boryanum* var. *boryanum* and *P. integrum* increase at the upper part of the zone 1; a relative abundance of *P. integrum* is very low (1 – 8%) compared to *P. boryanum* var. *boryanum* (up to 20 % at the top of the zone). *P. integrum* is characterized by a sharp rise and decline while the concentration of *P. boryanum* var. *boryanum* is relatively stable. Total *Pediastrum* concentration reaches its maximum at 40 cm and then decreases sharply. Desmid assemblages are dominated by *Cosmarium pseudopyramidatum*, *C. pyramidatum* and *Euastrum bidentatum*, *E. denticulatum*, the concentrations of *Cosmarium protractum*, *C. punctulatum*, *C. granatum* and *C. botrytis* increase up-core. The total desmid concentration is relatively stable throughout the zone (between 55 and 35 cm). *Botryococcus* concentration is stable at the lower part, then declines at 45 cm and peaks at 40 cm. Thecamoebian assemblages are dominated by *Centropyxis aculeata*, *C. constricta*, *Diffflugia oblonga* and *Pontigulasia compressa* (>80%). Although *Diffflugia corona*, *D. urens*, *D. urceolata* and *D. protaeiformis* are present, their concentrations are very low (< 1 test/ml).

Microfossil zone 2 (0–30cm) matches pollen zone 4 (ragweed zone of McAndrews, 1994) and it can be divided into 3 subzones.

Subzone 2a (30 –25 cm) is characterized by a sharp increase in concentration of total non-arboreal pollen with a peak at 25 cm and a decline of arboreal pollen with absolute minimum at 20 cm. Algal assemblages are dominated by *Pediastrum boryanum* var. *pseudoglabrum* and *P. boryanum* var. *boryanum*. The total concentration of desmids decreases sharply; the most abundant are *Cosmarium depressum*, *C. botrytis*, *Euastrum bidentatum*, *E. denticulatum*, *C. variolatum*, *C. subcucumis*, *C. subcrenatum*. Total concentrations of thecamoebians are stable through the subzone; *Diffflugia*

oblonga, *Pontigulasia compressa*, *Centropyxis aculeata*, *C. constricta*, and *Diffflugia urceolata* are common species.

Within *subzone 2b* (20–15 cm) the absolute concentration of NAP increases 1.5 times; the concentration of *Ambrosia* and Gramineae peaks at the top of the subzone. Total *Pediastrum* concentration rises upcore; *P. boryanum* var. *pseudoglabrum* and *P. boryanum* var. *boryanum* are dominant taxa here (~ 90%). Desmid concentrations reach absolute minimum at 20 cm and then increase up core; the assemblages are dominated by *Cosmarium depressum*, *C. botrytis*, *Euastrum bidentatum*, *E. denticulatum*, *Staurastrum planctonicum*, *S. pingue*, and *S. chaetoceras*. Thecamoebian concentrations are stable through the subzone; *Diffflugia oblonga* and *Pontigulasia compressa* are dominant species, although *Centropyxis aculeata*, *C. constricta*, *Diffflugia urceolata*, *D. corona*, and *D. protaeiformis* are present; *Cucurbitella tricuspis* appears in small numbers (0.5 tests/ ml) at the top of the subzone.

Subzone 2c (10–0 cm) is characterized by an absolute maximum of total NAP concentration as well as maxima of *Ambrosia* and Compositae (at 5 cm), Graminae and Chenopodiaceae (at 10 cm), and *Artemisia* (at 0 cm). Total *Pediastrum* concentration increases upcore and reach the absolute maximum at 5 cm, *P. boryanum* var. *pseudoglabrum* (varies from 50 to >70%) is a dominant species, but *P. boryanum* var. *boryanum* (varies from 15 to 45%), *P. simplex* and *P. duplex* (together up to 10 %) are also present. Total desmid concentrations rise up core and the highest in the core are in *Subzone 2c*; the assemblages are dominated by *Cosmarium depressum*, *C. botrytis*, *Staurastrum planctonicum*, *S. pingue*, and *S. chaetoceras*, *C. punctulatum*, *C. granatum*. Although concentrations of *Euastrum bidentatum*, *E. denticulatum* and *E. lacustre*, *E. luetskemuelleri* are very low in the lower part of the subzone, they increase slightly at the top. Thecamoebian concentrations are stable through the subzone; *Diffflugia oblonga* and *Pontigulasia compressa* are the dominant species (60 – 70 %); *Centropyxis aculeata*, *C. constricta*, *Diffflugia urceolata*, *D. corona*, and *D. protaeiformis* comprise the rest. In the lower part of this subzone *Cucurbitella tricuspis* is present, but its concentration is very low (0.2 tests/ml). SDI for algae

and thecamoebian assemblages remains high throughout all three subzones, comprising 1.8-2.3 and 1.4-1.8 respectively.

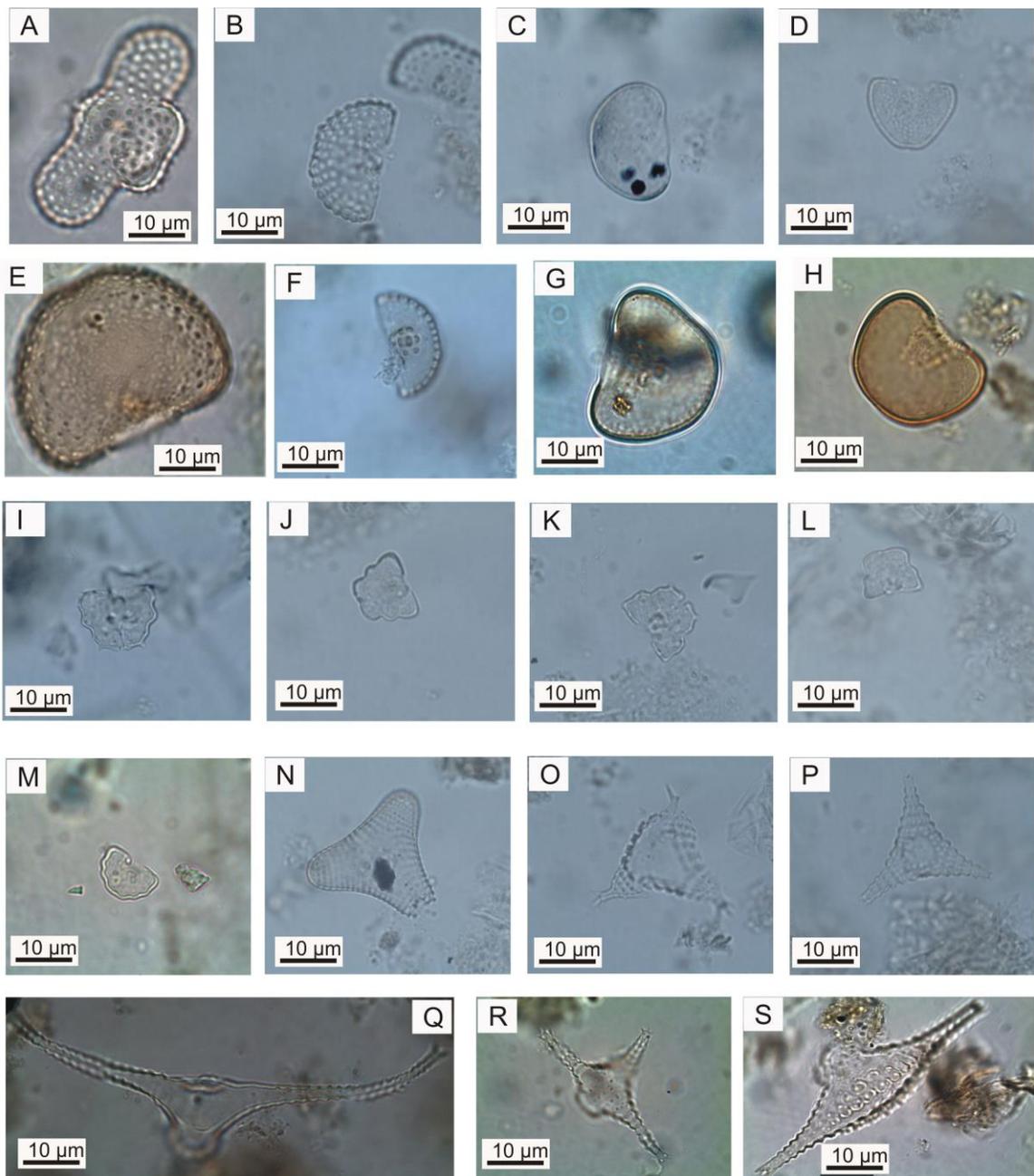


Plate 2.1. Selected desmids from the cores from Lake Simcoe:

- A, *Cosmarium protractum* (LS07 PC5, 175 cm, slide #4, England Finder reference C 53/3);
 B, *C. formosulum* (LS07 PC5, 5 cm, slide #1, England Finder reference S 36/1);
 C, *C. depressum* (LS07 PC5, 2 cm, slide #1, England Finder reference F 41/4);
 D, *C. pseudopyramidatum* (SB1, 40 cm, slide #1, England Finder reference K 27/1);
 E, *C. franzstonii?* (SB1, 15 cm, slide #1, England Finder reference G 52/4);
 F, *Cosmarium* sp.(unidentified) (SB1, 15 cm, slide #2, England Finder reference L 44/1);

G, *C. variolatum* (SB1, 15 cm, slide #1, England Finder reference Q 23/4);
H, *C. pyramidatum* (LS07 PC5, 125 cm, slide #1, England Finder reference K 22/1);
I, *Euastrum bidentatum* (LS07 PC5, 125 cm, slide #1, England Finder reference O 34/2);
J, *E. lacustre* (SB1, 15 cm, slide #1, England Finder reference M 37/1);
K, *E. denticulatum* (SB1, 25 cm, slide #2, England Finder reference F 31/4);
L, *E. luetkemulleri* (SB1, 25 cm, slide #1, England Finder reference K 29/1);
M, *Cosmarium* sp.(unidentified) (SB1, 35 cm, slide #2, England Finder reference D 49/4);
N, *Staurastrum punctulatum* (LS07 PC5, 125 cm, slide #3, England Finder reference S 45/1);
O, *Staurastrum* sp. (unidentified) (SB1, 35 cm, slide #2, England Finder reference H 54/2);
P, *Staurastrum* sp. (unidentified) (SB1, 25 cm, slide #2, England Finder reference K 39/3);
Q, *S. leptocladum?* (LS07 PC5, 5 cm, slide #3, England Finder reference O 54/1);
R, *S. anatinum?* (LS07 PC5, 5 cm, slide #1, England Finder reference G 40/1);
S, *S. sebalidii?* (SB1, 35 cm, slide #2, England Finder reference L 43/4)

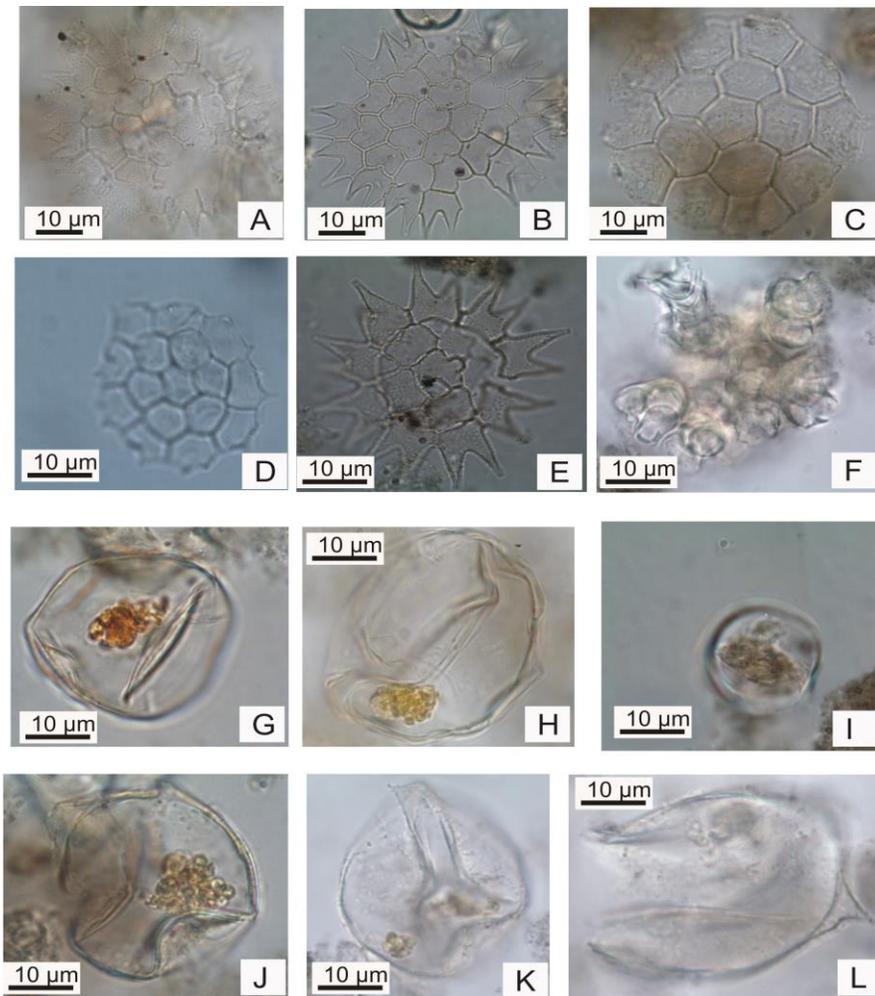


Plate 2.2. Selected algae from the cores from Lake Simcoe:

A, *Pediastrum boryanum* var. *boryanum* (LS07 PC5, 2 cm, slide #1, England Finder reference K 22/1);

B, *P. boryanum* var. *pseudoglabrum* (LS07 PC5, 2 cm, slide #2, England Finder reference M 28/1);

C, *P. integrum* (LS07 PC5, 280 cm, slide #3, England Finder reference F33/1);

D, *P. boryanum* var. *brevicorne* (LS07 PC5, 125 cm, slide #2, England Finder reference C 39/1);

E, *P. boryanum* var. *cornutum* (LS07 PC5, 2 cm, slide #2, England Finder reference K 25/3);

F, *Botryococcus braunii* (LS07 PC5, 2 cm, slide #1, England Finder reference K 47/2);

G, *Peridinium volzii* (CB1, 29-30 cm, slide# 3, England Finder reference P32/3);

H, *P. willei* (CB1, 29- 30 cm, slide# 5, England Finder reference L31/4);

I, *Parvodinium inconspicuum* (CB1, 14-15 cm, slide#3, England Finder reference M35/3);

J-L, *Peridinium wisconsinense* (J, CB1, 14-15 cm, slide#1, England Finder reference L 56/1;

K, LS07 PC5, 2 cm, slide #1, England Finder reference O 44/1; L, LS07 PC5, 2 cm, slide #1,

England Finder reference I 38/3).

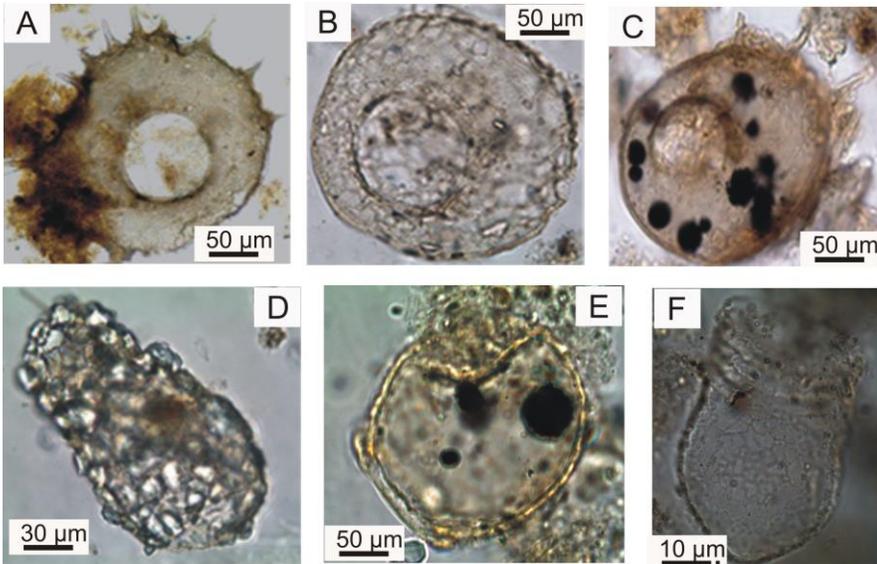


Plate 2.3. Selected protozoans from the cores from Lake Simcoe:

A, *Centropyxis* "aculeata" (CB1, 14 - 15 cm, slide #4, England Finder reference D 11/2);

B, *C. aculeata* "discoides" (CB1, 14 - 15 cm, slide #2, England Finder reference I 32/3);

C, *C. constricta* "spinosa" (LS07 PC5, 2 cm, slide #1, England Finder reference L 30/3);

D, *Diffflugia oblonga* "oblonga" (SB1, 25 cm, slide #3, England Finder reference M 23/1);

E, *D. urceolata* (LS07 PC5, 5 cm, slide #1, England Finder reference K 28/3);

F, *Codonella cratera* (LS07 PC5, 2 cm, slide #1, England Finder reference L 34/1).

N.B. Although the photographs were taken from pollen slides, thecamoebians were counted only in washed samples (see Chapter 1.6.1).

Chapter 3: Discussion

3.1. Late glacial to recent evolution of Lake Simcoe – insights from pollen, non-pollen palynomorphs and thecamoebians

Pollen, NPP and thecamoebian assemblages in sediment core LS07PC5 from the main basin of Lake Simcoe show several pronounced shifts over the last ~14,000 years that indicate a synchronous response between climate (recorded by upland vegetation) and limnology (evident in assemblages of planktonic and benthic algae and protozoans). Results are also similar to the response of aquatic assemblages to environmental and limnological changes since the last deglaciation elsewhere in southern Ontario, as documented in several studies (e.g., Boucherle et al., 1986; Hall and Smol, 1993; Duthie et al., 1996; St. Jacques et al., 2000), and they reflect known climatic and limnological changes in and around Lake Simcoe (e.g., Todd et al., 2008; McCarthy and McAndrews, 2012). Dramatic changes accompanying anthropogenic impact within the last several centuries are similar to those documented by Burden et al. (1986), McAndrews (1988), McAndrews and Boyko-Diakonow (1989), Campbell and Campbell (1994), Clark and Royall (1995), Ekdahl, et al. (2004), Turton and McAndrews (2006), Zippi et al. (1990; 1991), McCarthy et al. (2011), McCarthy and Krueger (2013), Hawryshyn et al. (2012) and others. These impacts are most evident in the short cores from shallower parts of Lake Simcoe (Cook's Bay and Smith's Bay) (see Chapter 3.2).

3.1.1. Late Glacial

During the last glacial, Lake Simcoe basin was covered by the Simcoe Lobe of the Laurentide Ice Sheet (Deane, 1950; Chapman and Putnam, 1984), and seismostratigraphic analysis of sediments beneath the lake identified two sequences corresponding to glacial conditions: the Red Sequence correlates with the Newmarket Till (interpreted as drumlins), and the Purple Sequence consists of sediments deposited in subglacial tunnel channels cut by rapid flows of meltwater (Todd et al., 2008). Lake Simcoe seismostratigraphic sequences,

reflection configuration, geological interpretation and geological correlation are presented in Appendix 5.

Extensive and thick ice cover prevented the survive of aquatic organisms so algal NPP and thecamoebians are absent in clay sediments below 490 cm in core LS07PC5 (Figure 3.1): traces, statistically insignificant numbers of pollen grains might have been present due to long - distance transport as shown by several studies (McAndrews, 1984; Fredskild and Wagner, 1974; Short and Holdsworth, 1985).

According to Lewis et al. (2008), after the Laurentide Ice Sheet retreated, around 13,850 cal yr BP, glacial lakes occupied the study area (Chapman and Putnam, 1984; Eschman and Karrow, 1985): initially, Lake Simcoe was a part of Lake Schomberg (Eschman and Karrow, 1985; Mulligan, 2011) and subsequently Lake Algonquin (Lewis et al., 2008). Very low abundances of pollen strongly dominated by *Pinus* in sediment devoid of aquatic microfossils (490 – 394 cm) are attributed to long-distance transport into glacial Lake Schomberg, which was almost entirely surrounded by glacier ice (Dyke, 2004; Lewis et al., 2008).

After deglaciation, terrestrial and aquatic ecosystems were established: tundra dominated by shrubs (*Alnus*, *Betula*) and herbs (Compositae, Chenopodiaceae, Cyperaceae) (recorded by pollen zone 1a of McAndrews (1994)) occupied the watershed (Figure 3.1). The climate was colder than present: based on pollen transfer functions for Tonawa Lake (44°51'N, 77°11'W), McAndrews and Campbell (1993) suggested mean July temperatures of 11 – 14° C, compared to present 12° (average low) to 25°C (average high) (Environment Canada, 2013a). Continued warming caused a spread of spruce woodland (Anderson, 1987) (pollen zone 1b of McAndrews, 1994) dominated by *Picea* and Cyperaceae) (Figure 3.1); pollen-inferred mean July temperatures for that period in Southern Ontario varied from 14 to 17 °C (McAndrews and Campbell, 1993).

Increased concentrations and higher diversity of NPP (NPP zones 1, 2) (Figure 3.1) and thecamoebians (thecamoebian zone 1) (Figure 3.2) indicate deglaciation and subsequent warming. In zone 1 (Figure 3.1) algal assemblages

Core LS07 PC5
Olena Volik analyst

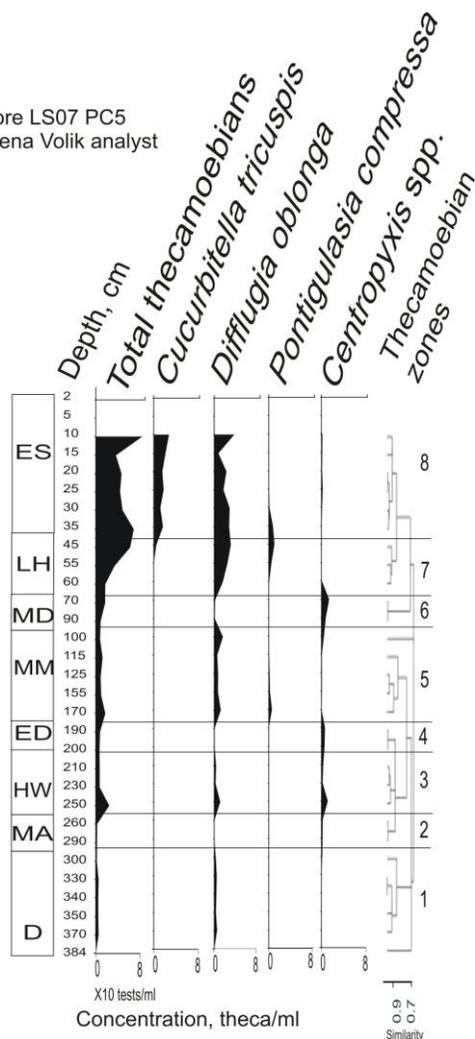


Figure 3.2. Summarized diagram of thecamoebian concentrations scaled by depth from a sediment core taken within the main basin, Lake Simcoe. Zones were determined independently using PAST version 2.17 (Hammer et al., 2001). Shifts in thecamoebian assemblages indicate following interval: D – deglaciation; MA – the Main Algonquin phase; HW – Holocene warming; ED – early Holocene drought; MM – mid- Holocene moist period; MD – mid – Holocene drought; LH – late Holocene climate amelioration; ES – European settlement

by presence of *Diffflugia oblonga* (Figure 3.2) (Plate 2.3, D); Kliza (1994) reported this species in high percentages in arctic lakes with organic matter-enriched sediment, where it replaced *Diffflugia globulus* when the organic content of the sediment increased. Kliza's observation was subsequently confirmed by Patterson et al. (1996) in their Ontario lakes study and by Burbidge and Schroder-Adams (1998) in their Lake Winnipeg study.

Abrupt decrease in NPP (NPP zone 3) (Figure 3.1) and thecamoebian concentrations (thecamoebian zone 2) (Figure 3.2) associated with very low pollen concentration in pollen zones 1b (by McAndrews) (Figure 2.1) records pronounced environmental changes. A significant shift in aquatic communities is reflected by dominance of oligotrophic species *Pediastrum integrum* (Plate 2.2, C), a very common alga in the pollen slides from the lake sediments of the Late Glacial and early Holocene (Whiteside, 1965; Janssen, 1968; Jankovska, 1980;

1983; 1988; Hielsen and Sørensen, 1992; Jankovska and Panova, 1992; Pasztaleniec and Poniewozik, 2004; Kaufman et al., 2010). Its common occurrence in lake sediments indicates oligotrophic and dystrophic cold and clear lakes (Komárek and Jankovská, 2001). Hielsen and Sørensen (1992) conclude that it is rare and relict, most frequently found in cold, clear waters (Komárek and Jankovská, 2001). The common presence of *Centropyxis aculeata* (Plate 2.3, A) and *Centropyxis constricta* (Plate 2.3, C) also confirms poor nutrient supply: McCarthy et al. (1995) and Schonborn (1984) considered *C. aculeata* to be a useful indicator of oligotrophic conditions. This species is quite tolerant of low algal productivity (Burbidge and Schroder, 1998) because it appears to feed on bacteria (McCarthy et al., 1995). *C. constricta* is opportunistic species that is widespread during intervals of cooler climate and low organic input, tolerant of high concentrations of total dissolved solids (McCarthy et al., 1995; McCarthy et al., 2012).

A dominance of oligotrophic species suggests nutrient depleted water that could result from changes in limnological regime at that time. Lake Simcoe was affected by the onset of the Main Lake Algonquin phase caused by influx from Lake Agassiz around 11,000 – 10,500 cal yr BP (Eschman and Karrow, 1985; Finamore, 1985; Larsen, 1987; Lewis et al., 1994; Lewis et al., 2008) (see chapter 1.5). The large influx of cold, turbid meltwater caused a decline in microfossils concentration due to low ecosystem productivity and high rates of sediment deposition. Low ecosystem productivity might also have resulted from climatic cooling associated with the sudden and conspicuous Younger Dryas Event- YD recorded by stable isotope analysis data in the eastern Great Lakes region between ~11,000 and 10,000 cal yr BP (e.g., Lewis and Anderson, 1992; Yu and Eicher, 1998; Yu, 2000, McFadden et al., 2005). However, Fritz et al. (1987), Lewis and Anderson (1992) suggested that limnological changes (e.g. meltwater dynamics) may complicate climatic signals in stable isotope data, and most pollen data did not indicate significant cooling during that time (Yu, 2000, Ellis et al., 2011) Yu (2000) summarized regional variation in evidence for the YD event and assumed that a geographic location and character of a particular

site affected its expression in paleoecological records.

NPP and thecamoebian response to the YD cooling should have been even less expressed for two reasons. First, according to Magnuson et al. (1997), aquatic communities are more sensitive to limnological changes than to climatic ones. Second, limnological changes did take place during the Main Algonquin Lake phase as it was described above. Consequently, YD cooling event could have some impact on aquatic assemblages reflected by NPP and thecamoebian, but it would not outweigh limnological changes.

3.1.2. Holocene warming

According to McAndrews and Campbell (1993), during the earliest Holocene July temperatures in southern Ontario rose to 19 – 21°C. The warming caused a shift from *Picea*-dominated woodlands to boreal forest dominated by *Pinus* (Anderson, 1987), predominantly diploxylon pine (*Pinus banksiana/resinosa*) (pollen zone 2a of McAndrews (1994) (Figure 2.1)). The base of this zone has been dated ~11,000 cal yr BP around 44°N in the Great Lakes region of Ontario (see Appendix 5). This warming also created favourable conditions for aquatic organisms by extending the growing season of phytoplankton (Smol and Boucherle, 1985). In addition, the decline in water level during the arid early Holocene coupled with the isolation of Lake Simcoe from Lake Huron led to nutrient enrichment and higher ecosystem productivity that is recorded by the shift from poor oligotrophic to diverse mesotrophic NPP (NPP zones 4, 5 (Figure 3.1)) and thecamoebian assemblages (thecamoebian zone 3 (Figure 3.2)). The presence of *Pediastrum simplex*, *Pediastrum boryanum* var. *boryanum*, *Pediastrum boryanum* var. *pseudoglabrum* and *Botryococcus braunii* records a climatically favorable period (Komarek and Jankovska, 2001) and suggests nutrient enrichment, as they are commonly distributed in deposits from naturally meso- to eutrophic waters during warmer periods of the Holocene (e.g., in the climatic optimum of the Atlantic period), and eventually for the warmer phases of interglacials (Janssen, 1968; Sebestyen, 1969; Pollinger, 1986; van Geel et al. 1986; Jankovska and Komarek, 2000; Pasztaleniec and Poniewozik,

2004). Intermediate nutrient enrichment is also confirmed by the presence of *Euastrum bidentatum* (Plate 2.1, I), a common mesotrophic species (Coesel and Meesters, 2007). Dominance of *Diffflugia oblonga* is consistent with these results; McCarthy et al. (1995) reported an increase in *D.oblonga* due to the accelerated climatic warming and higher level of nutrients during Holocene warming.

3.1.3. Early Holocene drought

Hydrologic deficit during the early Holocene is recorded by the dominance in pine (a xeric taxon), peaking with the shift from pollen zone 2a to pollen zone 2b of McAndrews (1994) which is dominated by drought-tolerant white pine (*Pinus strobus*) and herbs (Compositae, Chenopodiaceae) (Figure 2.1). This pollen zone boundary has been dated ~8500 cal yr BP in this region (Appendix 5). There is no shift in zones divided based on PAST (zone 6) because *Pinus banksiana*/*P. resinosa* and *Pinus strobus* were not systematically differentiated in the data presented, but a shift in dominance was noted within pollen zone 2 allowing zones 2a and 2b to be distinguished (Figure 2.1). Based on stable isotope data from southern Ontario lakes, Edwards et al. (1996) suggested low precipitation and effective humidity until 8,300 cal yr BP in the Great Lakes region and Hu et al. (1999) based on stable isotope data from Deep Lake MN, infer cooling between 8,900 and 8,300 cal yr BP which they attribute to increased outbreaks of polar air. McCarthy and McAndrews (2012) also suggested pollen-inferred precipitation of 65 – 90 cm/ year (only 66 – 81% of modern values) in the Lake Huron basin around 8,200 cal yr BP attributed to stronger polar air flow which could be related to the cold 8,200 cal yr BP event measured in the the Greenland Ice Sheet Project II (GISP2) core (Alley, 1997; Barber et al., 1999; Alley and Agustsdottir, 2005; Walker et al., 2012).

Several studies (e.g., Baker et al., 1992; Blasco 2001; Lewis et al., 2007; Croley and Lewis, 2008; Lewis and Anderson, 2012; McCarthy et al., 2012) reported lowstands and hydrologic closure of Lake Huron that have been attributed to the early Holocene drought (McCarthy and McAndrews, 2012). Evidence of low lake-level in Lake Simcoe was indicated by seismostratigraphic

analysis: the upper part of the Green Sequence (Lake Algonquin deposits) is eroded and overlain unconformably by the Blue Sequence (Lake Simcoe sediments) (Todd et al., 2004). A projection of locations and elevations of Green Sequence unconformities to the Lake Algonquin strand line diagram of the Lake Simcoe area (Deane, 1950) together with wave base calculations suggests wave abrasion during the lowest Penetang phase as an explanation of some occurrences of erosion (Figure 3.3).

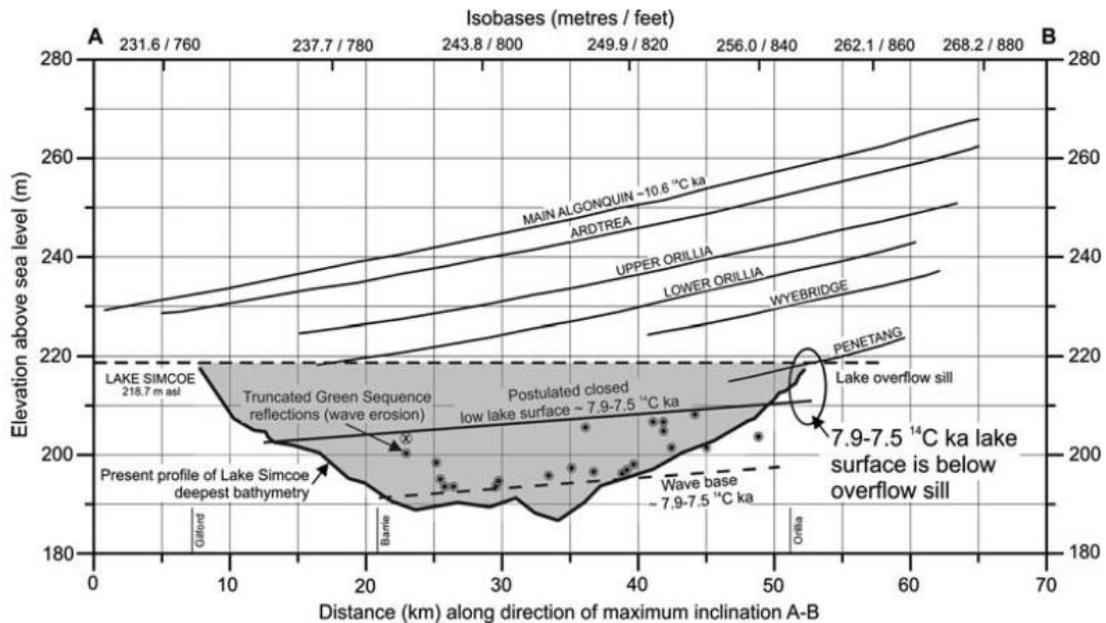


Figure 3.3. Strand line diagram of glacial Lake Algonquin in the Lake Simcoe area, extrapolated from Deane (1950). Grey area represents the present bathymetric profile of Lake Simcoe. The circled dots are projected locations of evidence of inferred wave abrasion erosion on Green Sequence sediments (modified from Todd et al., 2008)

To explain the deepest occurrences of erosion, Todd et al. (2008) computed a strand line slope for 7,900–7,500 ^{14}C (~8,700 – 8,300 cal yr BP) for the Lake Simcoe basin and assumed that a water plane of this slope could only explain them if it were positioned about 7.5 m below the sill near Orillia, in other words, at that time the lake would have been hydrologically closed (Figure 3.4).

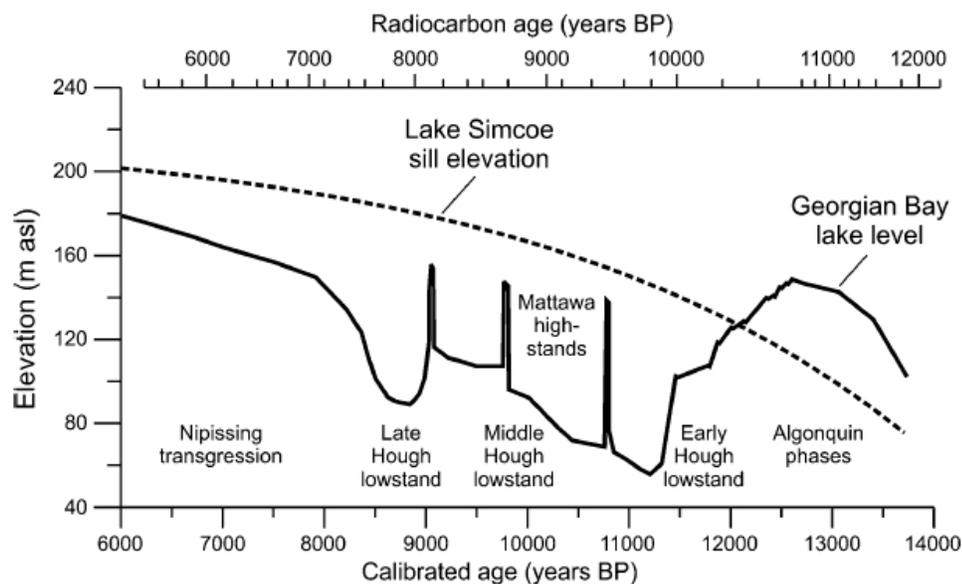


Figure 3.4. Elevation of the Lake Simcoe sill (dashed line) and the Georgian Bay lake level (solid line) and its identified phases (modified from Todd et al., 2004).

According to McCarthy et al. (2012), hydrologic closure together with arid climate during early Holocene affected the aquatic ecosystem of Georgian Bay: brackish conditions resulted from relative increase in total dissolved solids caused a shift from rich thecamoebian communities to a low-diversity centropyxid-dominated fauna (Figure 1.10). Similar evidence was found in the core from Lake Simcoe: rich NPP and thecamoebian assemblages were replaced by low-diversity assemblages composed of opportunistic testate amoebae (*Centropyxis aculeata*, *Centropyxis constricta*) (zone 4 (Figure 3.2)). These species seem to tolerate extreme conditions and usually are dominant in coastal lakes occasionally affected by salt spray (Scott et al., 2004). These organisms dominated the thecamoebian population in the interval representing the transition from marine to fresh water (Scott and Medioli, 1980; Patterson et al., 1985); in addition they can tolerate increased salinity in tailings ponds (Neville et al., 2011). Similarly, the dominance of *Botryococcus braunii* and *Pediastrum simplex* in algal assemblages in NPP zone 6 (Figure 3.1) is consistent with increased salinity. *B. braunii* has been reported in both fresh and saline waters

(Blackburn and Temperley, 1936; Moore and Carter, 1923; De Deckker, 1988). According to Rao et al. (2007), *B. braunii* can be cultivated in water with salinity 1.9 – 4.9‰. Similarly, *P. simplex* has been reported as one of the salt-tolerant species (Palmer, 1959). In other words, the distribution of NPP and thecamoebians shows a response of aquatic assemblages (both primary producers and consumers) to harsh conditions associated with the increased salinity and records a lowstand in Lake Simcoe during the early Holocene drought.

The subsequent shift in NPP (NPP zone 7 (Figure 3.1)) and thecamoebian assemblages (zone 4 (Figure 3.2)) records gradual improvement in climatic and limnological conditions: desmids and *Pediastrum* diversities increase; and indicators of favorable conditions such as *Pediastrum duplex* (Jankovska and Komarek, 2000), *Diffugia oblonga*, and *Pontigulasia compressa* (McCarthy et al., 1995) appear.

3.1.4. Mid-Holocene

During mid-Holocene, in the eastern Great Lakes region the climate was wet (except for a short interval from 4,800 to around 4,000 yr BP) (Silliman et al. 1996, McFadden et al., 2005, Yu and McAndrews, 1994; Yu et al., 1997) due to marked increase in humidity associated with increased dominance of the warm Tropical Air Mass of Bryson and Hare (1974) from the Gulf of Mexico. The warm and wet climate is recorded by transition from evergreen forests to mixed *Tsuga*-deciduous hardwood forests (Magnuson et al., 1997) similar to the modern vegetation Subzone L.1: Huron- Ontario, of the Great Lakes – St. Lawrence Forest of Rowe (1972). This climate-driven vegetation change resulted in the transition to pollen zone 3a of McAndrews (1994) ~8000 cal yr BP (Figure 2.1). McCarthy et al. (submitted) reconstructed mean July temperature ~21°C, mean January temperature ~-4°C, and mean annual precipitation ~ 900 mm/ year in pollen diagrams from small lakes near Lake Simcoe (Appendix 5). This represents an increase of precipitation 200 mm /year, 6°C warmer in January and 2°C warmer in July than during the preceding pollen zone 2b. The climate was

substantially wetter and with substantially warmer winters than today, but with similar mean July temperatures, producing the high snowfalls that allowed water levels in the region to rise rapidly following the early Holocene drought (McCarthy and McAndrews, 2012). The sharp increase in temperature and precipitation created favourable conditions for aquatic organisms and increased ecosystem productivity. Multi-proxy data (C:N, %C, %N, %TC, %TOM, $\delta^{13}\text{C}_{\text{OM}}$, and $\delta^{13}\text{C}_{\text{calcite}}$) from the eastern part of Lake Ontario (McFadden et al., 2004) record a rise in primary production during the mid-Holocene moist period. According to their study, the duration of summer growing season would have increased due to higher temperatures, thus accelerating erosion processes and causing greater influx of nutrients and sediments into the lake. The %TC data indicate a significant rise in precipitation of calcite from surface waters of eastern Lake Ontario during the mid-Holocene moist period, likely due to warmer summer temperatures.

NPP and thecamoebian assemblages from Lake Simcoe also record a flourishing aquatic ecosystem associated with optimal climatic conditions and sufficient nutrient input. Concentrations of microfossils and species diversity are high. It seems that assemblages of aquatic organisms reacted more quickly on environmental changes than the terrestrial vegetation: NPP assemblages show a shift at 165 cm whereas the shift in pollen assemblages appears only at 140 cm, consistent with the rapid generation time of protists and the lag time associated with vegetation change. The assemblages are dominated by mesotrophic species, but a few oligo- and eutrophic species are also present (zone 8 (Figure 3.1), upper part of thecamoebian zone 5 (Figure 3.2)). The aquatic flora is dominated by desmids (*Cosmarium pyramidatum*/ *Comarium pseudopyramidatum* (Plate 2.1, D), *Euastrum bidentatum*, *Staurastrum punctulatum* (Plate 2.1, N), *Cosmarium protractum* (Plate 2.1, A) and others), *Pediastrum* spp. (*P. simplex*, *P. duplex*, *P. brevicorne*, *P. boryanum* var. *pseudoglabrum*), *Botryococcus braunii*. The most prominent feature of the thecamoebian fauna is the dominance of *Diffflugia oblonga* and *Pontigulasia compressa*; these taxa record increased nutrient influx and climate warming

during the Hypsithermal (McCarthy et al., 1995)

Changes in atmospheric circulation patterns led to the onset of drought during late mid-Holocene in southern Ontario between 5,000 and 3,000 yr BP (McAndrews, 1981; Yu, 1995; Yu et al., 1997; Silliman et al., 1996, McFadden et al., 2005, Yu and McAndrews, 1994). A dry and warm climate resulted in the hemlock (*Tsuga*) crash (pollen zone 3b of McAndrews, 1994)(Figure 2.1)) (Fuller, 1997). Low lake levels during the late Mid-Holocene were reported from numerous sites: e.g., Rice Lake (Yu and McAndrews, 1994; Sonnenburg et al., 2012), Decoy Lake (Szeicz and MacDonald, 1991), Crawford Lake (Yu et al., 1997), Georgian Bay (McCarthy et al., 2003), Lake Ontario (McCarthy and McAndrews, 1988).

McCarthy et al. (2003) reported slightly brackish conditions in Georgian Bay recorded by a centropxyid-dominated thecamoebian fauna because of an increase in total dissolved solids, similar to the early Holocene drought fauna. In Lake Simcoe NPP/thecamoebian assemblages show a similar tendency, probably indicating low lake level and decreased ecosystem productivity during the mid-Holocene drought. Concentrations of NPP and thecamoebians decline in zones 9 and 6 respectively (Figures 3.1, 3.2); the species diversity is low, recording a stressed ecosystem and harsh conditions. Dominant thecamoebian species are the opportunistic *Centropxyxis constricta* and *Centropxyxis aculeata*, and algae are represented by *Botryococcus braunii* and *Cosmarium* spp.

3.1.5. Late Holocene

In the Great Lakes region, the climate became more moist around 3,500 cal yr BP (Anderson, 1989; Magnuson et al., 1997): this is recoded by the rise in Rice lake level (Yu and McAndrews, 1994; Sonnenburg et al., 2012). However, the cooling by about 0.5⁰C (McAndrews and Campbell, 1993) caused a decrease in lake ecosystem productivity: McFadden et al. (2004) reported lower primary production in the eastern Lake Ontario during the Neoglacial, compared to the Hypsithermal. The environmental changes during the late Holocene are reflected in the distribution of NPP and thecamoebians in the core from the main basin of

Lake Simcoe. The increase in microfossil concentrations coincides with the resurgence of *Tsuga* (pollen zone 3c of McAndrews (1994) (Figure 2.1)) and marks the gradual improvement of climatic conditions following the mid-Holocene drought. The aquatic ecosystem flourished, recorded by diverse NPP and thecamoebian assemblages dominated by *Pediastrum* spp. (*P. boryanum* var. *boryanum*, *P. boryanum* var. *pseudoglabrum*), desmids (*C. protractum*, *Euastrum* spp. *Staurastrum* spp.), *Botryococcus* spp., and thecamoebians (*Diffflugia oblonga*, *Pontigulasia compressa*, *Diffflugia urceolata*) (NPP zone 10 (Fig 3.1) and thecamoebian zone 7 (Figure 3.2)). The subsequent decrease in concentration of mesotrophic algae and appearance of oligotrophic *P. integrum* up-core may indicate a decrease in nutrient input associated with cooling coinciding with pollen zone 3d of McAndrews (1994) that reflects the onset of the Little Ice Age, the coldest recent period (16th – mid 19th century) (Campbell and McAndrews, 1991; Yu and McAndrews, 1994; Munoz and Gajewski, 2010). The decline in temperatures inferred from the shift in aquatic assemblages is also consistent with data from Lake Michigan (Colman et al. 1990) and Lake Ontario (Silliman et al., 1996; McFadden et al., 2005) suggesting declined input of terrigenous material due to lower temperatures.

Significant changes in land use associated with European settlement are reflected in the distribution of NPP and thecamoebian assemblages in the core from main basin; this is consistent with data reported from Cook's Bay by Danesh et al. (2013) (Figure 1.10). Cultural eutrophication is confirmed by a shift from meso-oligotrophic algal assemblages to eutrophic ones (*Staurastrum chaetoceras*, *Staurastrum pingue*, *Cosmarium botrytis*, *Cosmarium formosulum*, *Pediastrum boryanum* var. *boryanum*, *Pediastrum boryanum* var. *pseudoglabrum*) together with an increase in dinocysts (*Parvodinium inconspicuum*, *Peridinium wisconsinense*, *Peridinium willei*, *Peridinium volzii*), thecamoebians (especially *Diffflugia* spp., *Centropyxis* spp., *Cucurbitella tricuspis*), and ciliates (*Codonella cratera*) up-core (Figures 3.1 and 3.2).

3.2. Temporal and spatial changes in anthropogenic impact inferred from microfossils from Lake Simcoe

Several studies have documented dramatic changes in southern Ontario accompanying European settlement (~ 1850-1860 A.D.) (Burden et al., 1986; McAndrews, 1988; McAndrews and Boyko-Diakonow, 1989; Campbell and Campbell, 1994; Clark and Royall, 1995; Ekdahl et al., 2004; Turton and McAndrews, 2006; Zippi et al., 1990; 1991; McCarthy et al., 2011; McCarthy and Krueger, in press, and others). Due to increased nutrient-loading associated with land-clearing, agriculture, urbanization and industrialization, Lake Simcoe has been facing numerous water-quality issues (Johnson and Nicholls, 1989; Eimers et al., 2005; LSEMS, 2008.; LSRCA, 2009; LSPP, 2009; Hiriart-Baer et al., 2011). These changes are reflected in the distribution of aquatic microfossils. For example, diatom-based study indicated long-term changes in the water quality of Lake Simcoe over the last 200 years (Hawryshyn, 2010; Hawryshyn et al., 2012) with synchronous shifts in diatom assemblages in the cores from the main basin, Kempenfelt Bay and Cook's Bay. A preliminary study of core CB1 from Cook's Bay showed that NPP and thecamoebian assemblages responded to cultural eutrophication (Figure 1.10) (Danesh et al., 2013). More detailed studies of the core from Cook's Bay and additional studies of the cores from the main basin and Smith's Bay confirmed the previous results; moreover, not only temporal, but also spatial differences in eutrophication are evident.

Spatial differences in TP concentrations show that the level of eutrophication decreases gradually from Cook's Bay to the Atherley Narrows outflow due to natural features, differences in the extent of anthropogenic impact within the subwatersheds as well as to cumulative retention of phosphorus within sediments (Johnson and Nicholls, 1989; Eimers et al., 2005). In general, total phosphorous (TP) levels are the highest in Cook's Bay (~22.7 µg/L), followed by Kempenfelt Bay and the main basin (each ~13.3 µg/L), and they are the lowest in the outflow at the Atherley Narrows (~10.2 µg/L) (Eimers et al., 2005). NPP and thecamoebian assemblages in the cores from Cook's Bay and the main basin

show similar trends recording a higher level of eutrophication as well as stronger response to known episodes of human impact; in contrast, the core from Smith's Bay records a lower level of nutrient enrichment.

Based on palynological/theCAMOEBIAN analyses, four periods of anthropogenic influence on Lake Simcoe are identified.

1) The first period (to mid-19th century) corresponds with pollen zone 3d (decrease in *Tsuga* and *Fagus* together with increase in *Pinus*) of McAndrews (1994) (Figures 2.2, 2.5, 2.8) that record mixed forest covering the watershed during the Pre-European period. The increased relative abundance of Gramineae pollen in the upper part of the zone 3d may be associated with the initial invasion of the Iroquois Native settlements by Governor John Greaves Simcoe leading to establishment of York County in the Lake Simcoe region in the 1790s (LSRCA, 2000).

Several studies reported oligo-mesotrophic conditions in lakes in southern Ontario during the pre-European period although nutrient influx was slightly increased in the lake near aboriginal settlements (e.g., Turton and McAndrews, 2006; Krueger et al., 2011; McCarthy et al., 2011; McCarthy and Krueger, 2013). According to Nicholls (1995), during the pre-European period the natural background load of TP into Lake Simcoe was relatively uniform among the four main sedimentation basins, estimated at 32 t/year.

Relatively low nutrient influx into the lake before European settlement (beginning in the 1860s) is recorded by algal communities dominated by desmids (*Staurastrum* spp., *Cosmarium* spp., and *Euastrum* spp.) and *Pediastrum integrum* in all three cores (NPP zones 1 in the cores from Cook's (Figure 2.6) and Smith's Bay (Figure 2.9), and the bottom part (45 – 40 cm) of NPP zone 11 in the core from the main basin (Figure 3.1)). Low theCAMOEBIAN numbers and *Centropyxis*-dominated assemblages are also consistent with mesotrophic conditions. However, a modest increase in *Diffflugia oblonga* suggests gradual nutrient enrichment associated with Iroquois activities. It is also confirmed by an appearance of the first sporadic cysts of dinoflagellate (*Peridinium wisconsinense* (Plate 2.2, J-L)) at the upper part of pollen zone 3d in the cores from the main

basin and Cook's Bay (Figures 3.1, 2.6). Previous studies (Burden et al., 1986; McCarthy et al., 2011) found that this species was common prior to European settlement of the Severn Sound (Penetanguishene–Midland) region by both Wendat and Euro-Canadians. McCarthy and Krueger (Krueger et al., 2011; Krueger, 2012) also found this species being more common prior to Iroquois settlement of Crawford Lake (Figure 1.3).

2) The second period matches the time of European colonization in the 1850s – the 1920s). It is characterized by intensive land-disturbance, especially after completion of the Ontario, Simcoe, and Huron Railway in the 1850s when the first population boom in the south part of the watershed took place (LSRCA, 2000). Land clearing caused increase in total NAP concentration and sharp rise in *Ambrosia* (ragweed) that is recoded by pollen zone 4 (McAndrews, 1994) (Figures 3.1, 2.5, 2.8)).

Human activities such as deforestation and following settlement coupled with farming resulted in an increased level of soil erosion (Evans et al., 1996) and affected algal assemblages as it was shown for other lakes (e.g., Baker and Krumer, 1973; Burden et al., 1986; Zippi et al., 1991; McCarthy et al.). Moreover, Hawryshyn et al. (2012) reported a shift in diatom algal communities in Lake Simcoe during the 1800s due to increased nutrient availability and turbulence in the lake.

Increased anthropogenic influence on the lake and its watershed can be also traced by the changes in NPP and thecamoebian assemblages within microfossil zone 2 (Cook's Bay) (Figures 2.6), NPP zone 11 (35 – 25 cm) (Figure 3.1) and thecamoebian zone 8 (35 – 25 cm) (Figure 3.2) (the main basin), and subzone 2a (Smith's Bay) (Figure 2.9). An increase in dinocyst concentration, particularly *Peridinium willei* (Plate 2.2, H) and *P. volzii* (Plate 2.2, G), in the cores from Cook's Bay and the main basin records increased eutrophication of the lake (the concentration of TP in Cook's Bay sediments at this time shifts from 205 mg/kg to 280 mg/kg) (Danesh et al., 2013) (Figure 1.9). The concentration of thecamoebians, notably *Diffflugia protaeiformis*, *Diffflugia oblonga*, *Diffflugia corona*, also gradually increases in all three cores. The concentration of desmids

decreased, reaching their minimum in all the cores; desmids in these sediments are dominantly eutrophic species, e.g., *Staurastrum chaetoceras*, *Staurastrum pingue*, *Staurastrum gracile*, *Staurastrum planctonicum*, *Cosmarium depressum* (Plate 2.1, C), *Cosmarium botrytis*, *Cosmarium formosulum* (Plate 2.1, B) (Coesel and Meesters, 2007; Šťastný, 2010). A similar shift was found in *Pediastrum* assemblages: *Pediastrum integrum* disappears completely, and the concentration of meso- and eutrophic species increases (*Pediastrum boryanum* var. *boryanum* (Plate 2.2, A), *Pediastrum boryanum* var. *pseudoglabrum* (Plate 2.2, B), *Pediastrum duplex*, *Pediastrum simplex*). According to Komarek and Jankovska (2001), *P. boryanum* var. *boryanum* and *P. boryanum* var. *pseudoglabrum* are common in meso- to eutrophic usually slightly alkaline ponds, lakes, and swamps. The presence of *P. simplex* may indicate eutrophic or even polluted and relatively deep water (Janssen, 1968; Komarek and Jankovska, 2001); some studies, such as Bottema (1974), reported *P. simplex* from water bodies impacted by human activities, for example, fertilization by cattle.

3) The third period includes two crucial events – Dutch settlement coupled with draining of the Holland Marsh in the 1930-40's and Hurricane Hazel in 1954. It corresponds to NPP zone 3 (Cook's Bay) (Figure 2.6), NPP zone 11 (Figure 3.1) and thecamoebian zone 8 (20 – 15 cm) (the main basin) (Figure 2.4), and NPP/thecamoebian subzone 2b (Smith's Bay) (Figure 2.9). The increase in NAP concentrations is consistent with extensive deforestation and land clearing as Dutch settlers extensively drained, and then dammed the East and West Holland marshes in order to use the fertile soil to produce rich agricultural land (LSRCA, 2000). According to Nicholls (1995), during this period TP loading increased steadily peaking between 1940 and 1950 at 100 t/year.

Chemical analyses (Danesh, 2011; Danesh et al., 2013) record that the drainage of the Holland Marsh caused a significant influx of organic matter into Cook's Bay: TP content rose to approximately 420 mg/kg; in addition, a sharp increase of nitrates (to 14.3 mg/kg) and decrease of nitrites (to 2.9 mg/kg) indicate a depletion of dissolved oxygen levels (DO) due to increased biochemical oxygen demand (BOD), as aerobic bacteria had more organic matter

to process (Figure 1.9).

Hawryshyn (2010) identified a shift to eutrophic diatom communities associated with damming of the Holland River and the draining of the natural marshlands in the 1930s. In addition, evidence of water level rise after the Trent-Severn Canal construction in the 1920s was found in the shallow parts of Lake Simcoe.

The downcore distribution of NPP and thecamoebians also shows a response to significant changes in the aquatic ecosystem; moreover, differences in intensity of human impact can be traced across Lake Simcoe.. The shift from assemblages dominated by *Diffflugia oblonga* to assemblages dominated by *Cucurbitella tricuspis* in the cores from Cook's Bay and the main basin is evidence of cultural eutrophication and depleted DO, as *C. tricuspis* has a planktonic stage as reported in numerous studies (e.g., Scott and Medioli, 1983; Patterson et al., 2002; Reinhardt et al., 2005; Roe et al., 2010; McCarthy et al., 2012; Patterson et al., 2012).). Bottom water hypoxia and contamination are also confirmed by presence of *Diffflugia protaeiformis* and the ciliate *Codonella cratera* (Plate 2.3, F) reported from contaminated waters with low DO levels (Moore 1977; Barbieri and Orlandi, 1989; Patterson and Kumar, 2002; Reinhardt et al., 1998).

A 2.5-fold increase of *Diffflugia corona* in the core from Cook's Bay also indicates high nutrient influx and possible contamination as this species was present in eutrophic and contaminated ("mixed effect") sub-assemblages in several lakes within GTA (Roe et al., 2010) (Figure 1.7). A rise in concentrations of *Centropyxis aculeata* and *Centropyxis constricta* records heavy metal pollution, as *Centropyxis* sp. are tolerant to metal-rich waters (Scott et al, 2001; Reinhardt et al., 2005; Roe et al., 2010) and well as high eutrophication and low oxygen levels (Reinhardt et al. 1998; Reinhardt et al., 2005; Roe et al., 2010). In contrast, in the core from Smith's Bay the dominant species are *Diffflugia oblonga* and *Pontigulasia compressa*; concentrations of *C. aculeata*, *C. constricta*, *D. urceolata*, *D. corona*, and *D. protaeiformis* are very low. *C. tricuspis* appears only in small numbers (<0.5 tests/ ml) suggesting a low level of eutrophication.

In the cores from Cook's Bay and the main basin the concentrations of desmids decrease with human impact, and oligotrophic species are virtually absent; an increase in concentration of eutrophic taxa- e.g., *Staurastrum chaetoceras*, *Staurastrum pingue*, *Staurastrum planctonicum*, *Cosmarium botrytis*, *Cosmarium formosulum*- and a decrease of concentration of mesotrophic *Euastrum bidentatum* is evident. In contrast, the concentration of desmids in the core from Smith's Bay increases up core and the assemblages are more diverse, dominated by *Cosmarium depressum*, *Cosmarium botrytis*, *Cosmarium protractum*, *Euastrum bidentatum*/*Euastrum denticulatum* (Plate 2.1, K), *Staurastrum planctonicum*/*Staurastrum pingue*, and *Staurastrum chaetoceras*, suggesting lower levels of nutrient concentration and contamination. The presence of *C. protractum* is significant, as this species was reported from European eutrophic shallow lakes at the beginning of the 20th century, but disappeared due to progressive eutrophication and following loss of submerged vegetation (Coesel, 2001; 2003).

Total *Pediastrum* concentrations rise gradually in the core from the Smith's Bay, and form peaks in the cores from Cook's Bay and the main basin. It is also notable that in the core from Cook's Bay the numbers of eutrophic *P.boryanum var. boryanum* and *P.boryanum var. pseudoglabrum* decrease initially, and increase only above 40 cm, and meso- eutrophic *P. duplex* and *P. simplex* are absent at 40-50 cm, only to reappear above 40 cm. All this indicates pollution to which mesotrophic species can't adapt, and eutrophic taxa can only partially adapt to (Komarek and Jankovska, 2001). A sharp peak in *Botryococcus braunii* concentration in the Cook's Bay core confirms nutrient enrichment; this species can be found in oligotrophic conditions, but nutrient enrichment causes *B. braunii* to bloom (Haas et al., 2007, Levine et al., 2012).

A sharp peak of dinocyst concentration (predominantly *Peridinium willei* and *Peridinium volzii* (Figures 2.3, 2.6)) at the base of pollen zone 4 (~1860s) in the cores from Cook's Bay and the main basin is similar to the increase in anthropogenic impact in Georgian Bay (McCarthy, 2011) (Figure 1.2) and Crawford Lake (Krueger, 2012) (Figure 1.3). In contrast, dinocysts were virtually

absent in the core from Smith's Bay (Figure 2.9), indicating either low nutrient concentrations or taphonomic issues (McCarthy et al., 2011). Dinosporin is known to be sensitive to alkaline conditions (Kokinos et al., 1998), and the marly sediments in Smith's Bay may not have promoted the preservation of cysts. It is also possible that reduced DO is essential to the preservation of statistically significant numbers of dinocysts, consistent with the observations of McCarthy et al. (2011) and McCarthy and Kruger (2013).

Danesh et al. (2013) reported a dramatic peak in phytolith concentration above the zone corresponding to the draining of the Holland Marsh (Figure 1.10) that may record increased erosion due to flooding associated with Hurricane Hazel (October, 1954). At that time, the northern part of the Holland Marsh was flooded at 1.2 - 6.1 meters when water backed up into it from Lake Simcoe. A rise in water level in the south and west parts of the marsh varied between 6.1 and 9.0 meters due to water reverse from the bordering Holland River and Schomberg Creek (Environment Canada, 2013). Aquatic communities should also have responded to this event, but further research is required in order to confidently identify this response.

4) The fourth period starts in the mid- 20th century and corresponds to NPP zone 4 (Cook's Bay) (Figures 2.6), NPP zone 11 and thecamoebian zone 8 (above 15 cm) (the main basin) (Figures 2.3, 2.4), and NPP subzone 2c (Smith's Bay) (Figure 2.9). The post-WWII population boom, intensification of urbanization and industrialization are recoded by rise in *Ambrosia* and Gramineae in all the cores; however, the rise is sharper in Cook's Bay and in the main basin recording more intensive land disturbance. The sediments from Cook's Bay are characterized by increased TP content (to > 720 mg/kg at 6 cm) and a sharp increase of heavy metal concentrations (Figure 1.9) (Danesh, 2011).

Evidence of high level of eutrophication, bottom hypoxia and heavy metal contamination is most prominent in the NPP and thecamoebian records from Cook's Bay. This coincides with the highest population and most intense agriculture in subwatersheds draining into Cook's Bay relative to other subwatersheds of Lake Simcoe. For instance, combined population of Aurora

and Newmarket, the two urban centers situated within Holland River subwatershed, rose from ~6,750 in 1941 (LSRCA, 2000) to ~ 133,180 in 2011 (Statistics Canada, 2012; Statistics Canada, 2012a) that is more than 30% of total population of Lake Simcoe watershed; the area of urban areas and croplands in this watershed is more than 35% and 25% of total urban area and croplands of Lake Simcoe watershed respectively (LSRCA, 2010).

Continuous eutrophication and decreased DO caused an increase in dinocyst concentrations although the increased relative abundance of *Peridinium wisconsinense* at the top of the core from Cook's Bay correlates with a small decrease of TP up-core, which results from the government and public agencies' efforts to reduce phosphorus input into the watershed for the past 50 years (Danesh et al., 2013). Maximum concentrations of *Cucurbitella tricuspis* and *Codonella cratera* as well as an abundance of *Centropyxis aculeata* and *Centropyxis constricta* are significant also indicate oxygen depletion (Scott et al., 2001). Eutrophic species (*Cosmarium botrytis* and *Staurastrum chaetoceras*) dominate among desmids. *Botryococcus braunii* increases in the two cores reaching absolute maxima indicating the bloom associated with high nutrient availability. Total *Pediastrum* concentrations increase sharply with prevalence of eutrophic *P. boryanum* var. *boryanum* and *P. boryanum* var. *pseudoglabrum*. A sharp increase in total *Pediastrum* is consistent with the results of Patterson et al. (2002) who reported a dramatic increase in *Pediastrum* in Swan Lake (Ontario) after 1950 due to intensive erosion and introduction of high-yield chemical fertilizers in the post-World War II period. An appearance of the thermophile *P. boryanum* var. *brevicornis* (Komarek and Jankovska, 2001) matches the results of diatom-based analysis (Hawryshyn, 2010) that show a shift in algal communities due to increased temperatures and reduced ice cover at the end of the 20th and beginning of the 21st centuries.

The distribution of NPP and thecamoebians in the core from Smith's Bay (Figure 2.9) shows a lower level of eutrophication. Total desmids concentration rises up core and is maximal within the core; the assemblages are dominated by *Cosmarium depressum*, *Cosmarium botrytis*, *Staurastrum planctonicum*/

Staurastrum pingue, and *Staurastrum chaetoceras*, *Cosmarium punctulatum*/
Cosmarium granatum. Although concentrations of oligo-mesotrophic *Euastrum*
bidentatum/*Euastrum denticulatum* and *Euastrum lacustre*/*Euastrum*
luetkemulleri are low, they increase slightly upcore. Total *Pediastrum*
concentration increases up core and reaches its absolute maximum; the
dominant species is *Pediastrum boryanum* var. *pseudoglabrum*, but *Pediastrum*
boryanum var. *boryanum*, *Pediastrum simplex* and *Pediastrum duplex* are also
present. Thecamoebian assemblages are diverse, dominated by *Diffflugia*
oblonga and *Pontigulasia compressa*. *Cucurbitella tricuspis* is present, but its
concentration is very low (0.2 tests/ml), and *Codonella cratera* and dinocysts are
absent, consistent with relatively high DO. Diverse algal / thecamoebian
communities indicate favorable conditions: sufficient amounts of nutrients and
dissolved oxygen are available, and the level of contamination is still below the
critical level.

Chapter 4: Conclusion

Constrained cluster analysis identified synchronous changes in assemblages of non-pollen palynomorphs/ NPP (primarily algae) and agglutinated protozoans (primarily heterotrophic benthos) in three sediment cores from Lake Simcoe. Pollen stratigraphy allows these changes to be correlated from the southernmost Cook's Bay to the northernmost Smith's Bay core over the last several centuries, providing insights into the response of Lake Simcoe to anthropogenic impact. The most prominent changes in microfossil assemblages appear to record historic events such as land clearing and population growth at the end of 19th century, draining of the Holland Marsh (1925 - 1930) and post-WWII urbanization and industrialization. Cultural eutrophication is recorded by an increase in microfossil concentrations and a shift from oligotrophic assemblages to eutrophic assemblages rich in the desmids *Staurostrum chaetoceras*, *S. pingue*, *Cosmarium botrytis*, *C. formosulum*, various species of *Pediastrum* (*P. boryanum* var. *boryanum*, *P. boryanum* var. *pseudoglabrum*) and dinocysts *Parvodinium inconspicuum*, *Peridinium willei*, and *P. volzii*, thecamoebians (especially *Diffflugia* spp., *Centropyxis* spp., and *Cucurbitella tricuspis*), and ciliates (*Codonella cratera*). The virtual absence of *Cucurbitella tricuspis* and *Codonella cratera* in the core from Smith's Bay indicates oxygenated water at shallow depths at this site, consistent with spatial differences in TP concentrations within the lake that show a gradual decrease from Cook's Bay to the Atherley Narrows outflow due to differences in the extent of anthropogenic impact as well as to cumulative retention of phosphorus within sediments. The absence of dinocysts in the core from Smith's Bay is also consistent with continued high DO.

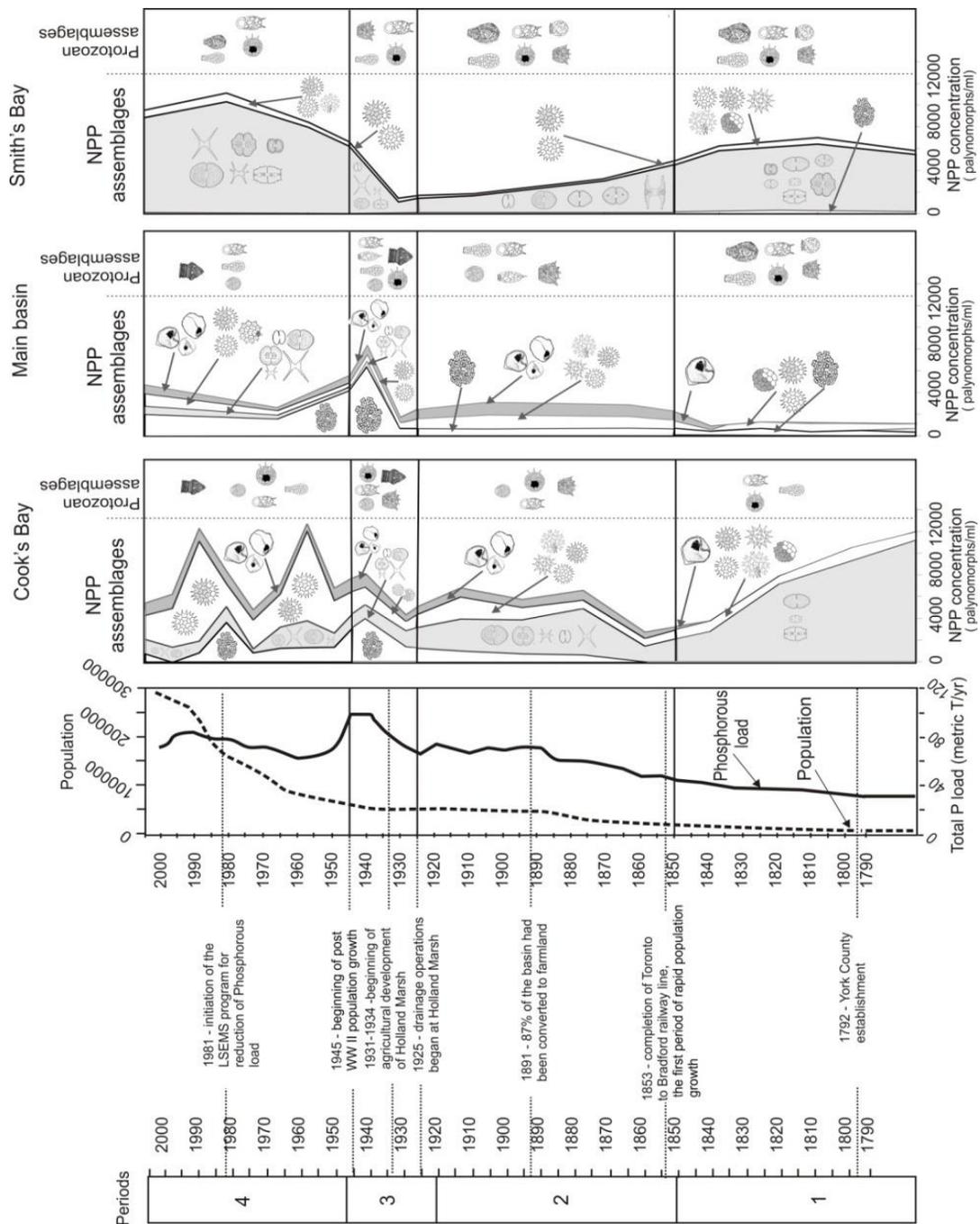


Figure 4.1. Summary of microfossil response to anthropogenic change. Phosphorous load and population (until 1990) are from Nichols (1995) and LSRCA, MOE (2009), and LSRCA (2010) (after 1990). Four periods of human impact were identified. The most prominent shifts in microfossil assemblages appear to record historic events such as land clearing and population growth at the end of 19th century, draining of the Holland Marsh (1925 - 1930) and post-WWII urbanization and industrialization. The distribution of NPP in cores from Cook's Bay and the main basin shows similar trends, but the distribution of NPP in core from Smith's Bay diverges from general trend showing rather gradual changes in trophic status, without dramatic peaks of NPP concentration found in other cores.

Up-core changes in the NPP and thecamoebians and ciliate protozoans from core LS07PC5 from the main basin correlate with vegetation changes in the watershed of Lake Simcoe, illustrating their sensitivity to large-scale environmental changes from the Late Glacial to present (Figure 4.2).

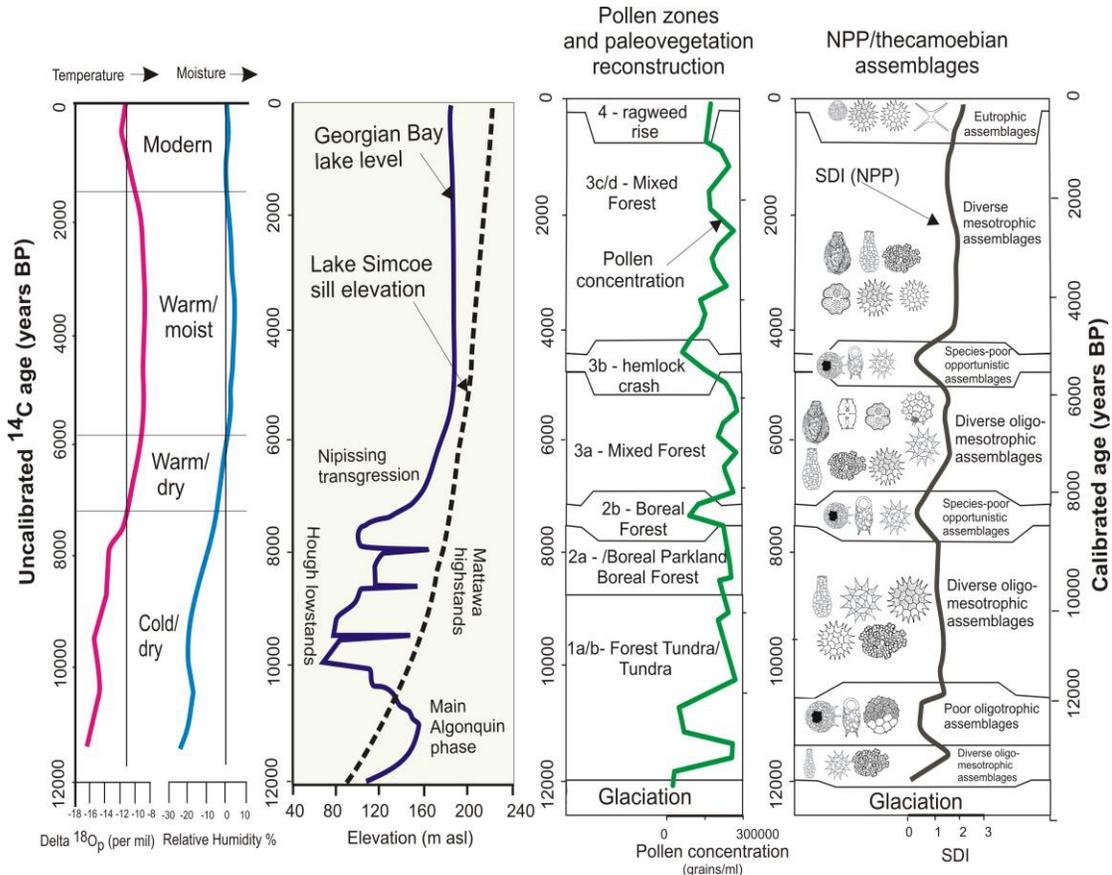


Figure 4.2. Summary of microfossil response to climatic, limnological, vegetation change. Temperature and moisture estimates from stable isotope analysis are from Edwards et al. (1996), Lake Simcoe sill elevation compared with lake level reconstruction of Lake Huron is from Todd et al. (2008). Until Euro-Canadian settlement and agriculture induced cultural eutrophication, Lake Simcoe supported a diverse and abundant assemblage of algae and protozoans dominated by oligotrophic to mesotrophic taxa, except for three intervals of sparse, oligotrophic assemblages attributed to 1) the influx of meltwater from Lake Agassiz during the Main Algonquin phase (11,000 – 10,500 cal yr BP; Lewis and Anderson, 1989), 2) the early Holocene drought that produced the late Lake Stanley/ Hough Lowstands in the Lake Huron. Georgian Bay basins (8,800 – 8,000 cal yr BP; McCarthy and McAndrews, 2012; McCarthy et al., submitted) and the mid-Holocene hemlock “crash” (4,800 – 4,000 cal yr BP; McCarthy et al., 2012).

Barren clays at the base of core LS07PC5 (from 775 to 384 cm) indicate glacial and postglacial conditions when the survival of aquatic organisms would

have been virtually impossible. Subsequent increased concentrations and higher diversity of NPP and thecamoebians reflect deglaciation and subsequent warming. Algal assemblages dominated by *Pediastrum simplex* and *Botryococcus braunii* and *Diffflugia oblonga*-dominated thecamoebian assemblages suggest improvement in trophic and climatic conditions. Influx of cold, turbid Lake Agassiz waters producing the Main Phase of Lake Algonquin is recorded by the abrupt decrease in NPP and thecamoebian concentrations associated with very low pollen concentration in the upper part of pollen zone 1b, and the dominance of the oligotrophic species *Pediastrum integrum* records cold, hyper-oligotrophic conditions. The subsequent increase in NPP concentration rich in *Pediastrum simplex*, *Botryococcus* spp., *Euastrum bidentatum*, and the thecamoebian *Diffflugia oblonga* is evidence of nutrient enrichment associated with Holocene warming. The establishment of a sparse *Centropyxis*-dominated thecamoebian fauna and the dominance of *Botryococcus braunii* and *Pediastrum simplex* records the development of slightly brackish conditions in Lake Simcoe during the early Holocene drought. The most diverse aquatic microfossil assemblages correspond to the mid-Holocene moist period (pollen zone 3a of McAndrews, 1994); the assemblages are dominated by desmids (*Cosmarium pyramidatum*, *C. pseudopyramidatum*, *Euastrum bidentatum*, *Staurastrum punctulatum*, *Cosmarium protractum*), *Pediastrum* spp. (*P. simplex*, *P. duplex*, *P. boryanum* var. *brevicorne*, *P. boryanum* var. *pseudoglabrum*), and thecamoebians (*Pontigulasia compressa*, *Diffflugia urceolata*, and *D. oblonga*). The subsequent decline in concentrations of NPP and thecamoebians together with predominance of *Centropyxis* spp. records decreased ecosystem productivity during the mid-Holocene drought. Subsequent gradual climatic amelioration during the late Holocene is recorded by diverse assemblages dominated by *Pediastrum* spp. (*P. boryanum* var. *boryanum*, *P. boryanum* var. *pseudoglabrum*), desmids (*C. protractum*, *Euastrum* spp. *Staurastrum* spp.), *Botryococcus* spp., and thecamoebians (*D. oblonga*, *P. compressa*, *D. urceolata*) until human settlement, particularly in the southwestern part of the Lake Simcoe

watershed, resulted in cultural eutrophication and associated bottom water anoxia resulting from BOD.

The well-documented history of human settlement in this region, together with geochemical analysis of heavy metals and nutrients in the core from Cook's Bay, illustrate that NPP analysis, especially when paired with the study of better-known microfossils such as thecamoebians and pollen, provide insights into the entire ecosystem of a lake and its watershed. This information can be used in managing our precious fresh water resources in a region facing increasing population pressure. In addition, the response of NPP to the well-documented paleoenvironmental changes from glacial Lake Algonquin to the present illustrate the potential of these little-known microfossils in paleolimnological studies. Future study should include determining the distribution of NPP in cores from other parts of the lake, preferably close to each significant tributary, in association with measurements of limnological variables (temperature, pH, DO, TP, N, heavy metals etc.) in the water column and on the lakebed at each site. Additional work is also needed on the taxonomy and taphonomy of these microfossils and to determine their sensitivity to environmental perturbations.

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Appendix 1a. Taxonomic and ecological features of selected desmids, as reported in the literature Taxonomy from Guiry and Guiry (2013)

Phylum Charophyta E.Möhn 1984

Class Conjugatophyceae Engler 1892

Order Desmidiaceae CE Bessey 1907

Family Desmidiaceae Ralfs 1848

Genus *Cosmarium* Corda ex Ralfs, 1848

Cells extremely variable in size, usually somewhat longer than broad, more or less compressed, usually with a fairly deep median constriction; cells variable in outline, without radiating processes or spines; vertical view usually oblong or elliptic, often with a central protuberance; chloroplasts usually axial, with one or two pyrenoids; cell wall varying from smooth to papillate, markings usually forming a definite pattern (Taft, 1945)

Cosmarium botrytis Meneghini ex Ralfs 1848

Chloroplasts axial with two pyrenoids (Taft, 1945).

Cosmarium depressum (Nägeli) P.Lundell 1871

Cell wall finely punctulate; chloroplasts axial, with one pyrenoid (Taft, 1945).

Cosmarium formulosum Hoff 1888

Chloroplasts axial, with two pyrenoids (Taft, 1945)

Cosmarium granatum Brébisson ex Ralfs 1848

Cell wall finely granulate; chloroplasts axial, with one pyrenoid (Taft, 1945).

Cosmarium protractum (Nägeli) De Bary 1858

Chloroplasts axial, with two pyrenoids (Taft, 1945).

Cosmarium pseudopyramidatum P.Lundell 1871

Cosmarium pyramidatum Brébisson ex Ralfs 1848

Cell round oval with flattened ends, deeply constricted in the middle; segments punctate, entire (Ralfs, 1848).

Cosmarium subcrenatum Hantzsch 1868

Chloroplasts axial, with one pyrenoid (Taft, 1945).

Cosmarium subcucumis Schmidle 1893

Cell wall smooth; chloroplasts axial, with two pyrenoids (Taft, 1945).

Cosmarium variolatum P.Lundell 1871

Chloroplasts axial, with one pyrenoid (Taft, 1945).

Genus *Euastrum* Ehrenberg ex Ralfs 1848

Cells variable in size, longer than broad, sometimes about as broad as long, strongly compressed, deeply constricted, sinus linear; semicells usually pyramidal, lateral margins variously lobed, center of semicell with one or more

protuberances, apex usually truncate with an incision (Taft, 1945).

Genus *Staurastrum* (Meyen) Ralfs 1848

Cells of variable size, usually as broad or broader than long, usually radially symmetrical, median constriction more or less deep; semicells variable in outline, with the angles frequently produced into elongate, hollow processes, 2-12 radiate in vertical view; cell wall smooth to granulate, or with variously arranged spines or verrucae; chloroplasts one per semicell, axial, with radiating lobes, and one pyrenoid (Taft, 1945).

Staurastrum chaetoceras (Schröder) G.M.Smith 1924

Cells fairly large, length (with processes) about equal to the breadth, deeply constricted, sinus obtuse-angled and with a blunt apex, isthmus narrow ; semicells obversely triangular, with the ventral margins sublinear and the apex flattened; angles continued in long divergent straight processes, the angle of divergence being a continuation of the angle of the sinus, processes slightly attenuated, delicate, with transverse concentric rings of minute granules and terminating in four minute teeth ; body of semicells with outline finely crenulate and with a few scattered subapical granules, at times with a transverse row of granules just above the isthmus. Vertical view narrowly elliptic (very rarely triangular) with the poles continued in straight processes whose ornamentation is as in the front view (Smith, 1924).

Staurastrum planctonicum Teiling 1946

Cells somewhat larger and broader than the type; angles of semicells more arcuate in front view and with terminal spine much smaller; cell wall finely granulate, with granules in concentric rings near the angles but scattered in the central portion of the cell. Vertical view with lateral margins very slightly retuse. (Euplankton.) Cells 35 μ long ; breadth with spines 45-54 μ, without spines (Smith, 1924).

Staurastrum punctulatum Brébisson 1848

Segments rough with puncta-like granules, elliptic, equal ; end view with broadly rounded angles and slightly concave sides (Smith, 1924).

List of desmids found in Lake Simcoe with their indicative notations (after Štastný, 2010)

Species	Trophic state of the habitat	Acidity	Life form
<i>Cosmarium botrytis</i>	mes–eu	aci–neu	ben
<i>Cosmarium depressum</i>	mes	aci–neu	ben
<i>Cosmarium formosulum</i>	eu–mes	aci–alk	ben–pla
<i>Cosmarium franzstonii</i>	No data available		
<i>Cosmarium granatum</i>	mes–eu	neu–aci	ben

<i>Cosmarium protractum</i>	eu	alk	ben
<i>Cosmarium pseudopyramidatum</i>	oli–mes	aci	ben
<i>Cosmarium punctulatum</i>	mes–eu	aci–alk	ben
<i>Cosmarium pyramidatum</i>	oli–mes	aci	ben
<i>Cosmarium reniforme</i>	eu–mes	aci–alk	ben
<i>Cosmarium subcrenatum</i>	mes	aci	ben–atm
<i>Cosmarium subcucumis</i>	mes	neu	ben
<i>Cosmarium subgranatum</i>	mes–eu	aci–alk	ben
<i>Cosmarium variolatum</i>	mes	aci	ben
<i>Euastrum bidentatum</i>	mes	aci–neu	ben
<i>Euastrum denticulatum</i>	mes	aci	ben
<i>Euastrum insulare</i>	mes	aci–neu	ben
<i>Euastrum luetkemuelleri</i>	oli–mes	aci	ben
<i>Euastrum lacustre</i>	No data available		
<i>Staurastrum anatinum</i>	No data available		
<i>Staurastrum chaetoceras</i>	eu	alk	pla
<i>Staurastrum pingue</i>	eu–mes	alk–neu	pla
<i>Staurastrum planctonicum</i>	eu–mes	alk–neu	pla
<i>Staurastrum punctulatum</i>	oli	aci	ben
<i>Staurastrum sebaldi</i>	mes	aci	ben

Appendix 1b. Taxonomic and ecological features of *Pediastrum* spp and *Botryococcus braunii*, as reported in literature

Phylum Chlorophyta A.Pascher 1914

Class Chlorophyceae Wille 1884

Order Sphaeropleales Luerssen 1877

Family Hydrodictyaceae Dumortier 1829

Genus *Pediastrum* Meyen 1829

Pediastrum boryanum var. *boryanum* (Turpin) Meneghini 1840

Coenobia usually circular, without holes between cells, with 16–32 cells. Marginal cells with two lobes ending in two narrow processi. Incision between processi V-shaped. Cell wall regularly granular. Dimensions: coenobia 84–92 µm in diameter, marginal cells up to 10–11 µm long, and 24 µm wide, inner cells up to 10–23 µm in diameter (Wolowski et al., 2002).

Species is typical for slightly alkaline, eutrophic, but not very polluted waterbodies (Komárek and Jankovská, 2001).

Pediastrum boryanum var. *pseudoglabrum* Parra Barrientos 1979

Coenobium circular without holes, with 14–32 cells. Incision between processi V-shaped. Cell wall very finely granular. Dimensions: coenobia 20–96 µm in diameter, marginal cells 8–14 x 8–11 µm, inner cells 8–10 x 8–11 µm (Komárek and Jankovská, 2001).

Species is typical for slightly alkaline, eutrophic, but not very polluted waterbodies (Komárek and Jankovská, 2001).

Pediastrum boryanum var. *brevicorne* A.Braun 1855

Coenobium circular without holes, 16-celled. Marginal and inner cells 10(–15) µm long and 20(–230) µm wide. Processi short (compare with *P. boryanum* var. *boryanum*, and *P. boryanum* var. *longicorne*). Incision between processi wide and shallow. Dimensions: coenobia ca. 76 µm in diameter. Cell wall granular. Recorded at 4.65, 420, and 3.40 m depth (Wolowski et al., 2002).

Thermophilic species, occurring in tropical up to warmer region of temperate zone (Komárek and Jankovská, 2001).

Pediastrum integrum Nägeli 1849

Coenobia circular or irregular in outline, without holes with 8(–31) cells. Marginal cells always with no incision. On the outline marginal cells with two very short, hyaline processi. Sometimes one of them may be reduced but invisible. Cell wall regularly granular. Dimensions: coenobia up to 60(–75) µm in diameter, marginal and inner cells up to 10–13 µm diameter. (Wolowski et al., 2002).

Species occurs in cold, oligo- and dystrophic waterbodies in northern and temperate regions (Komárek and Jankovská, 2001).

Pediastrum duplex Meyen 1829

Coenobia very deformed but a piece of coenobium enable determination of species. Marginal cells with internal incision 8–10 µm wide, and 7–10 µm long inner cells ca. 10 µm in diameter with incision of every side (Wolowski et al., 2002). Typical species of temperate zone, occurring in waterbodies with naturally increased nutrient level (Komárek and Jankovská, 2001).

Pediastrum simplex Meyen 1829

Colonies circular, of 4, 8, 16 or more cells, with large perforations between the cells. Inner half of the marginal cells obtuse to curved rectangular, outer half with a single, long horn-like process. Inner cells triangular, with concave sides. Cell wall smooth or granulate. Cells 7-13 μm in diameter, 19-30 μm long with the process (Wolowski et al., 2002).

Species occurs in neutral to slightly alkaline, eutrophic, but not polluted waterbodies (Komárek and Jankovská, 2001).

Phylum Chlorophyta A.Pascher 1914

Class Trebouxiophyceae Friedl 1995

Order Trebouxiales Friedl 1995

Family Botryococcace Wille 1909

Genus *Botryococcus* Kützing 1849

Botryococcus braunii Kützing 1849

Thalli microscopic, semi-microscopic to 1 mm in diameter, forming spherical, oval to irregular grape-like colonies. In some species (or when old) composed of subcolonies connected by thin to thick hyaline strands embedded in colorless mucilage. Cells elongate, oval, obovoid, conically narrowed towards the colony center or spherical, on the periphery of colonies arranged radially in one layer, partly or wholly immersed in compact mucilaginous central matrix or directly attached to it by their basal parts; in type species central matrix extremely elastic, sometimes cartilaginous, often impregnated with colorless or orange oil, in latter case colony brown to brick-red. In some species free parts of cells enveloped with collar to funnel like broadenings with wide apical openings, and the basal part of cells covered by brown precipitate. Cells 6-20 μm in diameter or length and 2.5-8 μm wide. Cells uninucleate; chloroplast parietal, cup-shaped, with one basal pyrenoid, sometimes indistinct because of the many oil droplets in the protoplast. Asexual reproduction by 2-4-8 (-16) autospores. Protoplast divides radially relative to colony center, alternately in two mutually perpendicular planes. The parental cell walls gelatinized and divided into two parts, later forming mucilage strands between cells or subcolonies. Zoospores and sexual reproduction unknown (Guiry and Guiry, 2013)

Modern *Botryococcus* is widely dispersed in temperate and tropical regions, and is known to tolerate seasonally cold climates. It generally lives in freshwater fens, temporary pools, ponds and lakes, where it may form a thick surface scum, but considerable abundances in variable salinity habitats are also known (van Geel, 2001).

Appendix 1c. Taxonomic features of selected dinoflagellates, as reported in literature

Phylum Dinoflagellata Butschli 1885

Class Dinophyceae F.E.Fritsch 1927

Order Peridiniales Haeckel 1894

Family Peridiniaceae Ehrenberg 1831

Genus *Peridinium* Ehrenberg 1832

Thecae range from ~10-100 μm in length, and contain ~20 plates with tabulation 4', 2-3a, 5-6c, 7'', 5''', 2'''' (Hansen and Flaim, 2007). Plate arrangement and ornamentation is used to identify dinoflagellates to species (Carty 2002), but phylogenetic surveys generally identify most taxa only to genus, identifying only a few very distinctive species, e.g. *Peridinium wisconsinense* Eddy. The identification of thecae is not straightforward because a wide range of morphotypes can occur within species (Popovsky and Pfiester, 1990). Kim *et al.* (2004), for instance, found greater genetic variation between the two populations of *Peridinium limbatum* (Stokes) Lemmermann within a single drainage basin in Wisconsin than that reported in the literature for some morphologically distinguishable microalgal species.

Peridinium volzii Lemmermann 1904

Cells are ovoid and slightly dorso-ventrally flattened. The cingulum is median or submedian and slightly displaced. Plate 1' is small and rhomboid to slightly elongate. The sulcus is narrow and the sa-plate extends onto the episome. Plate 4'' is large, rectangular and is only bordered by plate 2a at its anterior margin. The thecal plates are reticulated. Plate formula: 4', 3a, 7'', 5c, ?s, 5''', 2'''' . The cell contains brownish chloroplasts and an elongated red stigma within the sulcus. Length: 33-43 μm , width: 30-40 μm (Hansen and Flaim, 2007).

Cysts of *Peridinium volzii* Lemmerman are cavate and proximate, but lacking ornamentation. They are smaller (~38-45 μm by ~42-50 μm) than cysts of *P. willei*, which they resemble, but they have less pronounced shoulders and lack an apical flange (Krueger, 2012)

Peridinium willei Huitfeldt-Kaas 1900

The episome is hemispherical and slightly larger than the hyposome, which is somewhat conical. The submedian cingulum is displaced one cingular width. Plate 1' is rather large and wide. The sulcus is narrow. The thecal plates are reticulated. The epithecal plate borders often have wing-like extensions. The right and left sulcal borders also have well developed lists. Plate formula: 4', 3a, 7'', 5c, ?s, 5''', 2'''' . Length: 42-63 μm , width: 42-59 μm (Hansen and Flaim, 2007).

Cysts of *Peridinium willei* (Huitfeldt-Kaas) are cavate and proximate, with both layers closely appressed, although they sometimes can detach as noted in McCarthy *et al.* (2011). The inner layer is transparent, smooth and ellipsoidal, and the outer layer is slightly invaginated in the sulcal area forming two distinct shoulders. Where sutures can be discerned, the archeopyle can be seen to be transapical (McCarthy *et al.*, 2011). Cysts attributed to this genus in the varved

sediments from Crawford Lake range in size from 48 to 58 μm by 49 to 52 μm (stdev=2 μm) (Krueger, 2012).

Cysts of *Peridinium wisconsinense* Eddy 1930 easily identified by the presence of a rounded, sometimes bifurcated apical horn and a single, sharply pointed antapical horn. The cysts are cavate and proximate, with a smooth, transparent, slightly ellipsoidal inner layer, and an ornamented outer layer appressed to the inner layer in the equatorial region. The archeopyle, when observable, encloses an operculum, and is composed of the apical plates 2', 3' and 4' and part of the first apical plate (1). The length from apical to antapical horn of the outer layer of the cysts from varved sediments from Crawford Lake is 63 μm (stdev=4 μm) and the width is 50 μm (stdev=3 μm) (Krueger, 2012). Recent LSU and SSU rDNA analysis of single cysts demonstrated that this species is very different from other species of *Peridinium* Ehrenberg, and is close to the species *Chimonodinium lomnickii* Craveiro et al. (McCarthy et al., 2013), suggesting a possible need to reclassify this taxon. These very distinctive cysts are restricted to North American lakes, but this species may date back to the Miocene based on nearly identical cysts described from the nonmarine Tertiary of Alaska as *Geiselodinium tyonekensis* sp. nov. by Engelhardt (1976).

Genus *Parvodinium* Carty 2008

Freshwater dinoflagellate, small, ovoid to pentagonal cell, plates thin, plate pattern: apical pore, pore plate, canal plate, 4', 2a, 7", C6, S5, 5"', 2"', most photosynthetic with yellow-gold plastids, cingulum is wide, sub-median and the hypotheca is smaller than epitheca. Most species the sulcus enters the epitheca and spreads to the antapex; 3' and 4" plates may be in conjunctum, contactum or remotum positions (Carty, 2008).

Cysts of *Parvodinium* [*Peridinium*] *inconspicuum* (Lemmermann 1899) Carty 2008 are tiny ~ 15- 22 μm , spherical double-walled cysts lacking ornamentation and sometimes with a barely visible sulcal indentation. The red nuclei within the cyst indicate viable cell contents (Krueger, 2012).

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Appendix 2a. Raw arboreal pollen counts, Lake Simcoe, core from the main basin (LS07PC5).Olena Volik analyst

Depth, cm	Volume, ml	Lycopodium (spike)	<i>Pinus</i>	<i>Picea</i>	<i>Tsuga</i>	<i>Abies</i>	<i>Betula</i>	<i>Acer</i>	<i>Ulmus</i>	<i>Fraxinus</i>	<i>Quercus</i>	<i>Tilia</i>	<i>Nyssa</i>	<i>Carya</i>	<i>Alnus</i>	<i>Fagus</i>	Total AP
2	2,5	8	134	0	2	13	26	3	8	7	21	4	0	2	2	9	231
5	5	6	151	0	4	11	17	7	2	6	12	3	2	5	2	3	225
10	5	2	122	5	19	15	8	4	3	5	12.5	0	3	4	4	5	209.5
15	5	4	103	0	27	11	17	9	4.5	0	18	2	3	2	6	4	206.5
20	5	6	101.5	9	28	15	12	18	6	4	13	1	2	3	2	0	214.5
25	5	2	100	9	37	12	2	12	5	5	11	6	2	3	4	3	211
30	5	6	101	0	42	10	11	17	8	6	21	0	1	4	0	4	225
35	5	4	118	5	38	12	10	10	5.5	2	13	0	0	2	0	0	215.5
40	5	4	110	5	22	10	11	15	8	9	21	0	0	2	0	0	213
45	5	2	118	0	33	7	8	10	2	6	17	2	2	0	2	0	207
55	5	4	143	0	19	2	12	9	3	2	18	0	2	0	0	4	214
60	5	4	174	3	17.5	7	10	7.5	12	5	22	2	0	0	0	2	262
70	5	4	165	0	9	0	21	16	4	7	15	2	4	0	2	1	246
80	5	4	157	0	7	4	8	8	11	4	6	2	2	2	2	2	215
90	5	6	75	0	10	0	4	7.5	0	0	8	0	0	0	0	0	104.5
100	5	4	94.5	0	98	4	6	8	12	2	13	0	0	0	2	11	250.5
115	5	2	102	0	61	2	11	4	11	0	13	2	0	0	0	2	208
125	5	2	130	9	76	2	4	9	4	0	6	2	0	0	0	2	244
140	5	2	184	0	38	0	6	0	10	4	7	0	0	0	0	4	253
155	5	6	189	0	33	2	0	6	4	0	12	2	0	0	0	2	250
160	5	4	188.5	0	23	3	6	5	5	2	8	0	0	0	0	2	242.5
165	5	2	214	0	8	0	0	4	4	0	4	0	0	0	0	2	236
170	5	2	158	11	4	0	3	4	0	0	23	0	0	0	0	2	205
175	5	2	178	7	5	2	6	2	0	2	7	0	0	0	0	0	209
180	5	2	204	0	4	3	2	3	2	0	6	0	0	0	0	0	224
185	5	2	193	5	2	4	3	3	2	0	1	0	0	0	0	0	213
190	5	2	211	0	0	6	2	2	6	0	0	0	0	0	0	0	227
195	5	4	167	0	2	17	2	0	9	0	4	0	0	0	0	0	201
200	5	6	181	19.5	7	4	4	0	0	0	2	0	0	0	0	0	217.5
205	5	2	195	0	1	5	3	0	6	0	4	0	0	0	0	0	214
210	5	2	196	7	2	12	4	2	2	0	4	0	0	0	0	0	229
220	5	4	202	0	0	4.5	2	3	2	0	2	0	0	0	0	0	215.5
230	5	2	240	0	2	2	4	1	3	0	7	0	0	0	0	0	259
240	5	2	206	0	8	6	7	2	2	0	4	0	0	0	0	0	235

Depth, cm	Volume, ml	<i>Lycopodium</i> (spike)	<i>Pinus</i>	<i>Picea</i>	<i>Tsuga</i>	<i>Abies</i>	<i>Betula</i>	<i>Acer</i>	<i>Ulmus</i>	<i>Fraxinus</i>	<i>Quercus</i>	<i>Tilia</i>	<i>Nyssa</i>	<i>Carya</i>	<i>Alnus</i>	<i>Fagus</i>	Total AP
250	5	2	226	7	0	7	4	0	6	0	4	0	0	0	0	0	254
260	5	28	110	93	4	3	7.5	0	0	0	2	0	0	0	0	0	219.5
270	5	12	132	67.5	2	6	8	0	8	0	2	0	0	0	0	0	225.5
280	5	24	130	73	2	0	2	2	1	0	0	0	0	0	2	0	212
290	5	28	128	0	2	2	7	0	4	0	0	0	0	0	2	0	145
300	5	28	153	51	0	3	12	0	5	0	0	0	0	0	4	0	228
310	5	10	205	0	0	2	4	0	2	0	0	0	0	0	2	0	215
330	5	2	202	31	1	6	6	0	6	0	0	0	0	0	4	0	256
340	5	2	193	9	1	5	5	0	4	0	2	0	0	0	2	0	221
350	5	2	208	0	0	6	3	0	4	0	0	0	0	0	2	0	223
384	5	36	132	60.5	4	4	7	0	0	0	0	0	0	0	0	0	207.5
394	5	54	170	0	0	0	2	0	0	0	0	0	0	0	0	0	172
400	5	28	94	95	4	0	5	0	2	0	0	0	0	0	0	0	200
430	5	26	114	0	0	2	8	0	0	0	0	0	0	0	0	0	124
460	5	52	102	0	2	0	7	0	0	0	0	0	0	0	0	0	111
490	5	112	53	0	0	0	4	2	0	0	0	0	0	0	0	0	59
550	5	170	40	9	0	0	0	4	0	0	0	0	0	0	0	0	53
568	5	170	29	0	0	0	0	0	0	0	0	0	0	0	0	0	29
630	5	176	19	7	2	0	0	0	0	0	0	0	0	0	0	0	28
665	5	182	14	8	0	0	0	0	0	0	0	0	0	0	0	0	22
695	5	188	5	9	0	0	0	0	0	0	0	0	0	0	0	0	14
725	5	190	6.5	0	0	0	2	0	0	0	0	0	0	0	0	0	8.5
775	5	200	2	3	0	0	0	0	0	0	0	0	0	0	0	0	5

Appendix 2b. Raw non- arboreal pollen counts, Lake Simcoe, core from the main basin (LS07PC5). Olena Volik analyst

Depth, cm	Volume, ml	<i>Lycopodium</i> (spike)	<i>Artemisia</i>	<i>Ambrosia</i>	<i>Graminacea</i>	<i>Plantago</i>	<i>Compositae</i>	<i>Chenopodiaceae</i>	<i>Typha</i>	<i>Cyperaceae</i>	Total NAP
2	2,5	28	8	81	36	0	11	7	2	4	149
5	5	40	25	62	21	33	4	5	1	3	154
10	5	12	6	86	43	35	4	5	3	3	185
15	5	36	4	123	33	0	8	6	2	3	179
20	5	20	8	27	62	27	5	5	4	2	140
25	5	12	9	31	45	32	6	4	8	3	138
30	5	64	8	32	44	0	11	8	9	7	119
35	5	44	8	22	53	27	6	3	12	6	137
40	5	88	9	13	91	21	7	5	10	6	162
45	5	64	0	0	56	12	3	7	13	12	103
55	5	64	17	0	57	0	16	9	7	7	113
60	5	32	25	0	21	5	22	3	35	1	112
70	5	56	0	4	56	0	14	9	14	6	103
80	5	16	7	5	43	9	21	13	2	2	102
90	5	16	28	0	27	0	39	33	0	0	127
100	5	43	30	0	27	0	68	7	0	0	132
115	5	20	4	0	10	3	27	6	38	12	100
125	5	54	5	0	53	1	21	1	46	1	128
140	5	64	0	1	32	8	38	12	43	2	136
155	5	56	0	4	21	0	34	3	21	24	107
160	5	58	0	7	32	0	28	9	35	3	114
165	5	36	0	9	19	0	19	15	42	1	105
170	5	83	0	0	21	0	37	21	23	1	103
175	5	41	11	0	35	0	43	12	12	2	115
180	5	96	0	0	42	0	41	21	6	1	111
185	5	87	0	0	21	0	43	35	1	1	101
190	5	53	21	0	34	0	74	3	1	0	133
195	5	78	8	0	32	0	79	23	0	0	142
200	5	86	5	0	12	0	76	13	0	0	106
205	5	72	1	0	31	0	48	19	15	4	118
210	5	52	0	12	27	4	34	17	5	3	102
220	5	75	12	3	36	0	36	9	1	4	101
230	5	64	4	0	53	0	25	12	6	6	106
240	5	61	4	7	67	9	44	6	1	3	141

Depth, cm	Volume, ml	<i>Lycopodium</i> (spike)	<i>Artemisia</i>	<i>Ambrosia</i>	<i>Graminacea</i>	<i>Plantago</i>	<i>Compositae</i>	<i>Chenopodiaceae</i>	<i>Typha</i>	<i>Cyperaceae</i>	Total NAP
250	5	68	3	0	55	0	21	15	7	4	105
260	5	96	7	0	61	0	32	5	1	24	130
270	5	98	3	0	7	0	27	8	3	61	109
280	5	103	2	0	16	0	23	12	2	53	108
290	5	100	9	0	11	0	14	13	1	57	105
300	5	111	3	0	10	0	23	21	5	41	103
310	5	115	4	0	52	0	61	11	1	1	130
330	5	80	4	4	21	0	54	34	1	1	119
340	5	61	18	9	33	1	58	37	1	3	160
350	5	32	6	0	15	3	64	21	8	21	138
384	5	100	7	0	12	0	52	21	2	12	106
394	5	100	12	0	0	0	67	37	0	1	117
400	5	108	7	0	5	0	65	23	0	0	100
430	5	91	5	0	4	0	100	1	0	0	110
460	5	104	12	0	1	0	94	4	0	0	111
490	5	95	53	0	4	0	56	1	0	0	114
520	5	93	8	0	5	0	4	10	0	0	37
550	5	102	5	0	6	0	6	5	0	0	21
568	5	111	0	0	0	0	0	0	0	0	0
598	5	107	0	0	0	0	0	0	0	0	0
630	5	100	0	0	0	0	0	0	0	0	0
665	5	100	0	0	0	0	0	0	0	0	0
695	5	100	0	0	0	0	0	0	0	0	0
725	5	100	0	0	0	0	0	0	0	0	0
775	5	100	0	0	0	0	0	0	0	0	0

Appendix 2c. Row counts of *Pediastrum*, Lake Simcoe, core from the main basin (LS07PC5). Olena Volik analyst

Depth, cm	Volume, ml	<i>Lycopodium</i> (spike)	<i>P. boryanum</i> var. <i>boryanum</i>	<i>P. boryanum</i> var. <i>pseudoglabrum</i>	<i>P. boryanum</i> var. <i>cornutum</i>	<i>P. boryanum</i> var. <i>brevicorne</i>	<i>P. integrum</i>	<i>P. duplex</i>	<i>P. simplex</i>	Total <i>Pediastrum</i>
2	2,5	13	45	20	1	2	0	2	1	71
5	5	32	31	26	0	3	0	1	1	62
10	5	33	36	51	0	2	0	1	1	91
15	5	50	35	30	0	0	0	1	1	67
20	5	12	29	28	0	2	0	0	1	60
25	5	15	35	25	0	0	0	1	1	62
30	5	63	41	8	0	0	0	5	1	55
35	5	42	32	14	4	0	0	1	1	52
40	5	36	31	22	2	0	0	1	1	57
45	5	45	33	25	0	0	0	1	1	60
55	5	57	47	9	0	0	0	3	4	63
60	5	80	11	30	0	0	10	0	10	61
70	5	50	16	31	0	0	2	2	0	51
80	5	80	21	30	0	0	0	0	11	62
90	5	150	51	0	0	0	0	0	0	51
100	5	28	26	63	0	5	0	0	4	98
115	5	49	14	20	0	6	0	7	7	54
125	5	39	0	12	0	26	0	0	12	50
140	5	80	31	29	0	0	5	0	5	70
155	5	210	0	46	0	0	15	0	0	61
160	5	140	21	22	0	0	11	0	0	54
165	5	40	0	0	0	0	0	21	40	61
170	5	270	0	0	0	0	31	0	30	61
175	5	50	0	0	0	0	0	53	0	53
180	5	20	0	0	0	0	0	41	21	62
185	5	80	0	41	0	0	0	0	22	63
190	5	300	0	25	0	0	0	0	26	51
195	5	200	0	0	0	0	0	0	53	53
200	5	100	0	0	0	0	0	0	0	0

Depth, cm	Volume, ml	<i>Lycopodium</i> (spike)	<i>P. boryanum</i> var. <i>boryanum</i>	<i>P. boryanum</i> var. <i>pseudoglabrum</i>	<i>P. boryanum</i> var. <i>cornutum</i>	<i>P. boryanum</i> var. <i>brevicorne</i>	<i>P. integrum</i>	<i>P. duplex</i>	<i>P. simplex</i>	Total <i>Pediastrum</i>
205	5	170	0	43	0	0	0	0	9	52
210	5	190	0	30	0	0	0	16	14	60
220	5	150	16	27	0	0	0	0	15	58
230	5	175	0	42	0	0	0	0	19	61
240	5	40	0	0	0	0	0	0	56	56
250	5	35	0	0	0	0	0	0	54	54
260	5	240	0	0	0	0	20	0	11	31
270	5	300	0	13	0	0	15	0	24	52
280	5	300	0	0	0	0	41	0	0	41
290	5	340	0	10	0	0	30	0	11	51
300	5	370	0	0	0	0	41	0	0	41
310	5	270	0	0	0	0	47	0	0	47
330	5	200	0	5	0	0	27	0	0	32
340	5	100	0	0	0	0	0	0	0	0
350	5	250	0	0	0	0	0	0	51	51
384	5	72	0	9	0	0	0	0	49	58
394	5	27	0	0	0	0	0	0	0	0
400	5	14	0	0	0	0	0	0	0	0
430	5	13	0	0	0	0	0	0	0	0
460	5	26	0	0	0	0	0	0	0	0
490	5	56	0	0	0	0	0	0	0	0
520	5	50	0	0	0	0	0	0	0	0
550	5	85	0	0	0	0	0	0	0	0
568	5	85	0	0	0	0	0	0	0	0
598	5	50	0	0	0	0	0	0	0	0
630	5	88	0	0	0	0	0	0	0	0
665	5	91	0	0	0	0	0	0	0	0
695	5	94	0	0	0	0	0	0	0	0
725	5	95	0	0	0	0	0	0	0	0
775	5	100	0	0	0	0	0	0	0	0

Appendix 2d. Raw counts of desmids, Lake Simcoe, core from the main basin (LS07PC5). Olena Volik analyst

Depth, cm	Volume, ml	<i>Lycopodium</i> (spike)	<i>Cosmarium depressum</i>	<i>C. botrytis</i>	<i>C. formosulum</i>	<i>C. protractum</i>	<i>C. pyramidatum/pseudopyramidatum</i>	<i>Cosmarium</i> spp*.	<i>Staurastrum planctonicum</i>	<i>S. pingue</i>	<i>S. chaetoceras</i>	<i>S. anatinum</i>	<i>S. seabaldi</i>	<i>S. punctulatum</i>	<i>Staurastrum</i> spp*	<i>E. bidentatum</i>	<i>Euastrum</i> spp*.	Total desmids
2	2,5	13	3	6	4	0	0	0	5	13	22	0	0	0	0	0	0	53
5	5	32	2	8	2	0	0	0	3	17	22	0	0	0	0	0	0	54
10	5	33	5	13	18	0	0	0	3	7	12	0	0	0	0	0	0	58
15	5	151	3	2	13	0	0	0	3	8	22	0	0	0	0	0	0	51
20	5	220	11	12	0	0	0	0	0	18	11	0	0	0	0	0	0	52
25	5	100	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
30	5	100	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
35	5	100	8	0	0	0	0	3	0	0	0	0	0	0	0	0	0	11
40	5	100	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
45	5	100	5	0	0	3	0	4	0	0	0	0	0	0	1	0	0	13
55	5	19	0	0	0	4	1	2	0	0	0	0	0	0	2	0	5	14
60	5	82	0	0	0	0	11	18	0	0	0	0	0	0	21	0	0	50
70	5	50	0	0	0	5	0	0	0	0	0	0	0	0	6	0	56	67
80	5	49	0	0	0	18	0	17	0	0	0	12	0	0	7	0	0	54
90	5	180	0	0	0	0	0	21	0	0	0	0	0	0	0	0	0	21
100	5	70	0	0	0	0	11	30	0	0	0	0	0	0	12	0	0	53
115	5	14	0	0	0	2	5	38	0	0	0	0	0	0	3	0	5	53
125	5	15	0	0	0	6	26	11	0	0	0	0	0	5	10	0	6	64
140	5	64	0	0	0	4	25	20	0	0	0	0	0	8	9	0	4	70
155	5	70	0	0	0	15	21	5	0	0	0	0	0	6	11	0	0	58
160	5	42	0	0	0	6	16	9	0	0	0	0	0	7	9	4	0	62
165	5	40	0	0	0	21	20	21	0	0	0	0	0	0	1	0	0	63
170	5	100	0	0	0	46	15	0	0	0	0	0	0	0	0	0	0	61
175	5	100	0	0	0	0	26	27	0	0	0	0	0	0	0	0	0	53
180	5	50	0	0	0	0	52	0	0	0	0	0	0	0	0	0	0	52
185	5	200	0	0	0	0	0	51	0	0	0	0	0	0	0	0	0	51
190	5	300	0	0	0	0	0	52	0	0	0	0	0	0	0	0	0	52
195	5	200	0	0	0	0	0	51	0	0	0	0	0	0	0	0	0	51
200	5	100	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Depth, cm	Volume, ml	<i>Lycopodium</i> (spike)	<i>Cosmarium depressum</i>	<i>C. botrytis</i>	<i>C. formosulum</i>	<i>C. protractum</i>	<i>C. pyramidatum/pseudopyramidatum</i>	<i>Cosmarium</i> spp*.	<i>Staurastrum planctonicum</i>	<i>S. pingue</i>	<i>S. chaetoceras</i>	<i>S. anatinum</i>	<i>S. seabaldi</i>	<i>S. punctulatum</i>	<i>Staurastrum</i> spp*	<i>E. bidentatum</i>	<i>Euastrum</i> spp*.	Total desmids
205	5	70	0	0	0	0	0	11	0	0	0	0	0	10	31	0	0	52
210	5	190	0	0	0	0	0	0	0	0	0	0	0	31	30	0	0	61
220	5	250	0	0	0	0	0	0	0	0	0	0	0	24	27	0	0	51
230	5	100	0	0	0	0	0	0	0	0	0	0	0	21	44	0	0	65
240	5	80	0	0	0	0	11	0	0	0	0	0	11	19	21	0	0	62
250	5	100	0	0	0	0	21	20	0	0	0	0	0	0	20	0	0	61
260	5	240	0	0	0	0	11	10	0	0	0	0	0	0	0	0	0	21
270	5	200	0	0	0	0	0	28	0	0	0	0	0	0	0	0	5	33
280	5	150	0	0	0	0	0	52	0	0	0	0	0	0	0	0	0	52
290	5	340	0	0	0	0	0	41	0	0	0	0	0	0	11	0	0	52
300	5	150	0	0	0	0	0	5	0	0	0	0	0	0	0	0	0	5
310	5	200	0	0	0	0	0	53	0	0	0	0	0	0	0	0	0	53
330	5	260	0	0	0	0	0	27	0	0	0	0	0	0	0	0	25	52
340	5	190	0	0	0	0	0	45	0	0	0	0	0	0	0	0	12	57
350	5	250	0	0	0	0	0	51	0	0	0	0	0	0	0	0	0	51
384	5	180	0	0	0	0	0	59	0	0	0	0	0	0	0	0	0	59
394	5	27	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
400	5	14	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
430	5	13	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
460	5	26	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
490	5	56	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
520	5	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
550	5	85	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
568	5	85	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
598	5	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
630	5	88	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
665	5	91	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
695	5	94	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
725	5	95	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
775	5	100	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

* unidentified species

Appendix 2e. Raw counts of *Botryococcus braunii* and *Codonella cratera* (in pollen slides), Lake Simcoe, core from the main basin (LS07PC5). Olena Volik analyst

Depth, cm	Volume, ml	<i>Lycopodium</i> (spike)	<i>Botryococcus braunii</i>	<i>Lycopodium</i> (spike)	<i>Codonella cratera</i>
2	2,5	7	62	26	75
5	5	10	69	51	52
10	5	3	87	52	54
15	5	36	58	10	6
20	5	5	58	0	0
25	5	16	51	0	0
30	5	40	59	0	0
35	5	22	66	0	0
40	5	41	60	0	0
45	5	33	62	0	0
55	5	30	51	0	0
60	5	40	75	0	0
70	5	29	76	0	0
80	5	25	53	0	0
90	5	61	60	0	0
100	5	15	57	0	0
115	5	19	53	0	0
125	5	58	59	0	0
140	5	29	51	0	0
155	5	28	65	0	0
160	5	12	50	0	0
165	5	15	62	0	0
170	5	60	0	0	0
175	5	51	50	0	0
180	5	24	61	0	0
185	5	28	51	0	0
190	5	42	50	0	0

Depth, cm	Volume, ml	<i>Lycopodium</i> (spike)	<i>Botryococcus</i> <i>braunii</i>	<i>Lycopodium</i> (spike)	<i>Codonella</i> <i>cratera</i>
195	5	16	51	0	0
200	5	58	50	0	0
205	5	96	51	0	0
210	5	71	58	0	0
220	5	11	53	0	0
230	5	11	51	0	0
240	5	17	64	0	0
250	5	81	61	0	0
260	5	51	0	0	0
270	5	50	0	0	0
280	5	34	0	0	0
300	5	37	0	0	0
310	5	18	0	0	0
330	5	120	51	0	0
340	5	134	50	0	0
350	5	128	50	0	0
384	5	133	50	0	0
394	5	27	0	0	0
400	5	14	0	0	0
430	5	13	0	0	0
460	5	26	0	0	0
490	5	56	0	0	0
520	5	2	0	0	0
550	5	85	0	0	0
568	5	85	0	0	0
598	5	3	0	0	0
630	5	88	0	0	0
665	5	91	0	0	0
695	5	94	0	0	0

Appendix 2f. Raw counts of dinocysts, Lake Simcoe, core from the main basin (LS07PC5). Olena Volik analyst

Depth, cm	Volume, ml	<i>Lycopodium</i> (spike)	<i>Peridinium volzii</i>	<i>P. willei</i>	<i>P. wiconsinense</i>	<i>Parvodinium inconspicuum</i>	Total dyncysts
2	2,5	13	12	18	15	5	50
5	5	44	12	28	10	5	55
10	5	14	8	13	32	4	57
15	5	30	18	18	33	3	72
20	5	12	6	8	48	2	64
25	5	12	4	2	52	1	59
30	5	32	4	13	37	2	56
35	5	28	9	17	23	3	52
40	5	36	8	19	21	2	50
45	5	71	13	33	21	2	69
55	5	19	3	6	3	0	12
60	5	8	0	0	1	0	0
70	5	10	0	0	1	0	0

Appendix 2 g. Raw counts of thecamoebians, Lake Simcoe, core from the main basin (LS07PC5). Olena Volik analyst

Depth, cm	Volume, ml	<i>Cucurbitella tricuspsis</i>	<i>Diffugia oblonga</i> "oblonga"	<i>D. oblonga</i> "glans"	<i>D. oblonga</i> "tenuis"	<i>D. oblonga</i> "spinosa"	<i>D. oblonga</i> "linearis"	<i>D. oblonga</i> "bryophila"	<i>D. oblonga</i> "lanceolata"	<i>D. protaeiformis</i>	<i>D. corona</i>	<i>D. urens</i>	<i>D. urceolata</i>	<i>Lagenodiffugia vas</i>	<i>Pontigulasia compressa</i>	<i>C. constricta</i> "aerophila"	<i>C. constricta</i>	<i>C. aculeata</i>	<i>Lesquerusia spiralis</i>	Total thecamoebians
10	2	53	54	12	11	0	0	0	0	0	5	0	3	0	4	0	4	5	0	151
15	5	102	22	5	0	7	0	0	3	6	4	0	0	4	4	0	2	5	0	164
20	5	74	76	15	9	0	6	0	1	6	0	0	11	3	2	0	1	5	0	209
25	5	86	61	2	9	0	0	0	8	5	2	0	9	0	3	0	6	6	0	197
30	5	57	76	28	22	2	4	2	0	7	5	0	0	3	6	0	0	6	0	218
35	5	81	72	22	36	0	0	0	0	14	7	0	31	8	36	1	0	0	0	308
45	5	22	72	32	19	0	20	0	1	7	0	0	54	0	49	1	0	2	0	279
55	5	0	70	15	25	0	3	0	3	2	0	0	5	5	24	1	0	0	0	153
60	10	0	52	44	22	4	10	1	1	8	0	0	0	2	5	1	1	1	4	156
70	10	0	10	4	4	0	0	0	0	0	0	0	0	0	0	12	59	63	0	152
90	20	0	4	0	1	0	0	0	0	1	1	0	0	0	0	0	73	76	0	156
100	25	0	76	54	21	0	0	0	0	0	0	0	0	0	0	1	10	11	0	173
115	15	0	94	10	48	1	0	0	0	4	0	0	2	0	3	2	1	1	0	166
125	20	0	65	67	0	0	0	1	0	1	0	0	0	0	21	1	1	2	0	159
155	20	0	39	71	0	0	4	4	0	0	0	4	0	4	43	3	1	1	0	174
170	10	0	47	21	21	12	10	1	0	9	0	1	0	4	28	0	1	0	0	155
190	25	0	9	3	3	0	0	0	0	0	0	0	0	0	3	0	87	64	3	172
200	25	0	15	0	0	0	0	0	0	0	0	0	0	0	0	0	65	71	0	151
210	25	0	56	23	0	0	0	0	0	0	0	0	0	0	1	2	45	33	3	163
230	25	0	72	11	15	0	0	0	0	0	0	0	0	0	5	0	23	27	5	158
250	40	0	53	0	0	0	0	0	0	0	0	0	0	0	0	0	23	33	0	109
260	75	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	45	21	0	67
290	75	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	37	27	0	64
300	50	0	11	0	0	2	0	0	0	0	0	0	0	0	0	0	29	11	0	53
330	60	0	112	5	0	1	0	0	0	1	4	0	2	0	0	0	1	0	0	126
350	30	0	65	6	5	8	5	0	1		1	1	0	4	0	0	1	0	23	120
370	60	0	140	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	142
384	30	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	1

Appendix 3a. Raw pollen counts, Lake Simcoe, core from the Cook's Bay (CB1).
Francine McCarthy analyst

Depth (cm)	6	14	20	24	30	34	40	44	50	54	60	65	70	75	80	95
Volume, ml	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5
<i>Cupress</i>	0	0	1	0	0	0	0	0	0	0	1	0	0	1	0	1
<i>Pinus</i>	32.5	51	83	64	45.5	35	27	64	40.5	32	32	55	54	49	38.5	97
<i>Picea</i>	3.5	6	5.5	10	4	3.5	2	0	3	2	2	0.5	2	0.5	0.5	1
<i>Abies</i>	3	0	3.5	5	1	2	0	0	2	0	0	0	0	1	0	0
<i>Tsuga</i>	10	28	34	26	24	19	22	40	24	12	13	6	4	5	45	30
<i>Betula</i>	18	28	23	20	22	24	19	20	23	28	19	16	27	26	21	8
<i>Ostrya</i>	5	5	3	0	4	2	8	4	3	1	1	1	3	7	2	5
<i>Corylus</i>	0	4	1	4	2	1	0	0	0	0	0	1	0	1	0	1
<i>Carya</i>	3	2	3	0	4	2	2	4	2	1	2	5	3	3	1	0
<i>Tilia</i>	1	2	0	0	4	3	2	4	5	5	3	1	1	3	1	1
<i>Ulmus</i>	10	18	22	14	15	19	21	9	16	20	18	24	14	21	20	21
<i>Alnus</i>	2	4	3	0	5	5	2	0	4	2	6	5	7	7	4	0
<i>Juglans</i>	1	0	1	0	0	1	4	0	0	2	0	1	0	0	0	2
<i>Quercus</i>	18	14	16	20	23	17	22	16	17	25	21	39	19	26	14	24
<i>Acer</i>	5	14	10	5	15	20	21	44	14	18	20	18	15	25	16	12
<i>Salix</i>	0	1	6	2	1	4	4	3	2	1	2	0	1	0	2	3
<i>Fraxinus</i>	5	10	4	7	7	11	6	0	7	5	11	16	6	4	7	11
<i>Fagus</i>	9	18	16	10	27	25	35	48	30	30	34	22	27	19	25	23
<i>Nyssa</i>	3	0	0	6	3	3	9	2	3	4	7	6	5	5	8	3
<i>Liquidambar</i>	1	0	0	0	0	0	0	0	0	0	2	0	1	1	0	0
<i>Cornus</i>	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0
<i>Ambrosia</i>	12	32	9	22	1	1	4	4	0	1	1	1	2	2	0	0
<i>Artemisia</i>	1	2	1	6	3	3	2	1	1	0	1	3	0	2	1	2
<i>Chenopod</i>	1	4	6	2	1	3	1	4	0	1	1	0	2	1	0	2
<i>Gramineae</i>	20	48	34	18	7	9	8	16	6	0	3	2	5	3	3	2
<i>Cyperaceae</i>	1	4	3	2	2	1	2	0	1	1	2	0	0	2	0	0
<i>Typha</i>	3	4	3	2	0	2	2	0	2	0	1	1	0	0	0	0
<i>Nuphar</i>	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
<i>Compositae</i>	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0
<i>trilete spore</i>	0	4	1	0	1	1	1	2	0	0	0	0	0	1	0	0
<i>Dryopteris-type</i>	0	5	1	0	1	0	0	0	0	1	0	0	1	0	0	0
<i>Potamogeton</i>	0	0	1	0	2	0	0	0	0	0	0	0	0	0	0	1
<i>Lycopodium (spike)</i>	23	8	22	12	4	3	10	28	7	4	7	9	4	19	15	7
TOTAL POLLEN SUM	169	308	293	245	224.5	216.5	226	285	207.5	192	202	223.5	200	215.5	209	249
TOTAL ARBOREAL SUM	130	205	235	193	206.5	196.5	206	258	195.5	188	194	216.5	189	204.5	205	243

Appendix 3b. Raw counts of *Pediastrum*, Lake Simcoe, core from Cook's Bay (CB1). Olena Volik analyst

Depth, cm	Volume, ml	<i>Lycopodium</i> (spike)	<i>Pediastrum boryanum</i> var. <i>boryanum</i>	<i>Pediastrum boryanum</i> var. <i>pseudoglabrum</i>	<i>Pediastrum integrum</i>	<i>Pediastrum duplex</i>	<i>Pediastrum cornutum</i>	<i>Pediastrum simplex</i>	Total <i>Pediastrum</i>
0	2.5	20	58	34	0	4	4	2	102
6	2.5	20	105	54	0	2	2	1	164
15	2.5	20	215	205	0	3	0	1	424
20	2.5	20	57	36	0	2	1	2	98
24	2.5	20	63	55	0	3	1	1	123
30	2.5	20	65	72	0	2	0	2	141
34	2.5	20	189	191	0	0	0	1	381
40	2.5	20	75	63	0	0	0	0	138
44	2.5	20	32	42	0	1	0	0	75
50	2.5	30	27	33	0	1	0	0	61
54	2.5	20	56	31	0	2	3	3	95
60	2.5	20	17	23	1	4	3	4	52
64	2.5	30	19	14	2	8	5	6	54
70	2.5	30	12	13	15	5	2	3	50
80	2.5	30	18	23	16	2	2	3	64
85	2.5	32	10	11	24	4	1	1	51
90	2.5	31	12	11	25	1	1	1	51

Appendix 3c. Raw counts of desmids, Lake Simcoe, core from Cook's Bay (CB1).
Olana Volik analyst

Depth, cm	Volume, ml	<i>Lycopodium</i> (spike)	<i>Cosmarium depressum</i>	<i>C. botritus</i>	<i>C. formosulum</i>	<i>Cosmarium</i> spp*	<i>Staurastrum planctonicum</i>	<i>S. pingue</i>	<i>S. chetoceras</i>	<i>Staurastrum</i> spp*.	<i>Euastrum bidentatum</i>	<i>Euastrum</i> spp*.	Total desmids
0	2.5	17	8	20	1	1	5	1	14	0	2	1	53
6	2.5	18	12	27	3	6	2	0	6	0	1	1	58
15	2.5	24	11	24	2	1	5	2	11	0	1	1	58
20	2.5	23	20	41	5	1	2	2	4	0	1	0	76
24	2.5	63	1	2	0	0	10	14	23	0	2	0	52
30	2.5	17	18	37	7	0	1	5	6	0	1	1	76
34	2.5	17	23	41	8	0	8	6	9	0	1	0	96
40	2.5	17	17	21	5	0	2	2	3	0	1	0	51
44	2.5	17	11	25	6	0	1	1	6	0	2	0	52
50	2.5	17	13	17	9	0	2	3	5	0	8	1	58
54	2.5	13	27	32	14	0	1	3	4	0	6	1	88
60	2.5	11	22	30	11	0	2	1	1	1	5	7	80
64	2.5	7	8	21	12	2	2	5	5	2	6	6	69
70	2.5	27	13	17	5	25	0	1	1	7	6	15	90
80	2.5	11	4	5	3	27	0	0	0	11	4	17	71
85	2.5	4	1	2	1	30	0	0	0	13	2	17	66
90	2.5	4	1	2	2	38	0	0	0	23	2	27	95

* unidentified species

Appendix 3d. Raw counts of *Botryococcus braunii*, Lake Simcoe, core from Cook's Bay (CB1). Olana Volik analyst

Depth, cm	0	6	15	20	25	30	35	40	45	50	55	60	65	70	75	80	85	90
Volume, ml	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5
<i>Lycopodium</i> (spike)	34	37	25	23	63	17	17	17	17	17	27	32	36	27	11	30	30	30
<i>Botryococcus braunii</i>	61	58	51	195	127	51	53	54	155	53	61	56	55	0	0	0	0	0

Appendix 3e. Raw counts of dinocysts, Lake Simcoe, core from Cook's Bay (CB1). Olena Volik analyst

Depth, cm	Volume, ml	<i>Lycopodium</i> (spike)	<i>Parvodinium inconspicuum</i>	<i>Peridinium volzii</i>	<i>P. willei</i>	<i>P. wisconsinense</i>	Total dinocysts
0	2.5	70	5	32	15	39	91
6	2.5	70	6	37	35	27	105
15	2.5	70	5	28	34	26	93
20	2.5	70	9	33	25	28	95
25	2.5	70	8	26	22	19	75
30	2.5	70	8	27	19	18	72
35	2.5	70	6	17	16	15	54
40	2.5	70	5	38	21	28	92
45	2.5	70	7	39	35	25	106
50	2.5	70	4	18	13	16	51
55	2.5	70	5	22	17	24	68
60	2.5	70	2	11	23	25	61
65	2.5	70	0	17	21	36	74
70	2.5	74	0	8	11	29	50
75	2.5	70	0	0	0	0	0
80	2.5	70	0	0	0	0	0
85	2.5	70	0	0	0	0	0
90	2.5	70	0	0	0	0	0

Appendix 3f. Raw counts of thecamoebians and *Codonella cratera*, Lake Simcoe, core from Cook's Bay (CB1). Matea Drijepan, analyst

Depth, cm	Volume, ml	<i>Cucurbitella tricuspis</i>	<i>Diffugia oblonga</i> "oblonga"	<i>D. protaeiformis</i>	<i>D. corona</i>	<i>Pontigulasia compressa</i>	<i>C. constricta</i> "aerophila"	<i>C. constricta</i>	<i>C. aculeata</i>	Total thecamoebians	<i>Codonella cratera</i>
0	2.5	24	7	11	0	2	3	3	43	93	10
30	2.5	86	7	6	4	0	2	1	17	123	4
40	2.5	31	1	1	9	0	3	2	35	82	2
60	2.5	4	4	3	2	2	2	2	26	45	0
80	2.5	4	0	0	0	0	0	1	26	31	0
90	2.5	0	0	0	0	0	0	0	2	2	0

Appendix 4a. Raw arboreal pollen counts, Lake Simcoe, core from Smith's Bay (SB1). Olena Volik analyst

Depth, cm	Volume, ml	<i>Lycopodium</i> (spike)	<i>Pinus</i>	<i>Picea</i>	<i>Tsuga</i>	<i>Abies</i>	<i>Betula</i>	<i>Acer</i>	<i>Ulmus</i>	<i>Fraxinus</i>	<i>Quercus</i>	<i>Tillia</i>	<i>Nyssa</i>	<i>Carya</i>	<i>Alnus</i>	<i>Fagus</i>	Total AP
0	5	3	104	6	9	3	23	2	2	2	3	2	0	0	2	2	160
5	5	3	119	3	2	0	27	2	1	0	3	2	0	0	0	3	162
10	5	3	84	3	1	5	11	3	2	2	3	1	1	1	1	2	120
15	5	3	112	3	6	0	25	2	2	1	2	0	0	0	0	0	153
20	5	12	98	0	10.5	9	20	2	2	0	1	1	0	1	3	2	149.5
25	5	2	91	5	3	1	8	4	0	1	3	3	0	0	0	1	120
30	5	3	57	1	5	0	45	7	5	2	5	5	0	1	0	6	139
35	5	2	70	3	14	2	41	6	2	4	7	3	0	0	0	4	156
40	5	1	83	4	6	2	28	13	3	2	9	4	1	0	0	4	159
45	5	3	53	1	3	1	41	7	4	6	4	7	1	0	1	1	130

Appendix 4b. Raw non- arboreal pollen counts, Lake Simcoe, core from Smith's Bay (SB1). Olena Volik analyst

Depth, cm	Volume, ml	<i>Lycopodium</i> (spike)	<i>Artemisia</i>	<i>Ambrosia</i>	<i>Graminacea</i>	<i>Plantago</i>	<i>Compositae</i>	<i>Typha</i>	<i>Cyperaceae</i>	<i>Chenopodiaceae</i>	Total NAP
0	5	12	15	68	14	2	24	0	13	9	145
5	5	8	6	51	15	2	25	6	9	4	118
10	5	8	2	39	29	9	12	0	0	10	101
15	5	15	5	47	15	0	13	6	1	14	101
20	5	12	7	67	6	0	12	5	0	9	106
25	5	12	11	53	14	0	13	0	0	12	103
30	5	44	0	0	2	0	57	27	11	7	104
35	5	98	0	0	41	3	42	6	4	4	100
40	5	103	0	0	49	0	50	0	0	23	122
45	5	121	41	0	37	0	34	0	0	12	124

Appendix 4c. Raw counts of desmids, Lake Simcoe, core from Smith's Bay (SB1).
 Olena Volik analyst

Depth, cm	Volume, ml	<i>Lycopodium</i> (spike)	<i>C. depressum</i>	<i>C. botrytis</i>	<i>C. formosulum</i> / <i>C. reniforme</i>	<i>C. protractum</i>	<i>C. variolatum</i> / <i>C. subcucumis</i> / <i>C. subcrenatum</i>	<i>C. punctulatum</i> / <i>C. granatum</i>	<i>C. pseudopyramidatum</i> / <i>C. pyramidatum</i>	<i>C. franzstonii</i> ?	<i>Cosmarium</i> spp.*	<i>S. planctonicum</i> / <i>S. pingue</i>	<i>S. chaetoceras</i>	<i>S. sebaldi</i>	<i>S. punctulatum</i>	<i>Staurastrum</i> spp.*	<i>E. lacustre</i> / <i>E. luetkemulleri</i>	<i>E. bidentatum</i> / <i>E. denticulatum</i>	Total desmids
0	5	2	11	28	0	7	0	3	0	0	12	13	7	0	0	5	1	3	79
5	5	2	10	32	13	6	0	2	0	0	24	6	4	1	0	3	0	1	92
10	5	3	11	23	21	16	0	5	0	0	10	21	7	0	0	1	0	2	106
15	5	3	9	11	4	5	0	3	0	0	11	10	3	0	0	5	0	8	60
20	5	14	6	11	0	10	0	8	0	0	7	18	2	0	0	5	0	0	61
25	5	10	8	11	6	2	0	0	41	0	0	0	0	0	0	8	0	0	68
30	5	6	7	10	12	2	14	2	5	0	0	2	0	11	6	0	0	14	78
35	5	4	3	23	16	2	7	12	18	0	19	0	0	0	0	0	0	4	101
40	5	2	0	2	8	5	0	2	16	0	15	0	0	0	0	0	0	7	55
45	5	6	5	0	2	5	14	4	58	0	37	0	2	0	1	11	2	7	143

* unidentified species

Appendix 4d. Raw counts of *Pediastrum*, Lake Simcoe, core from Smith's Bay (SB1). Olena Volik analyst

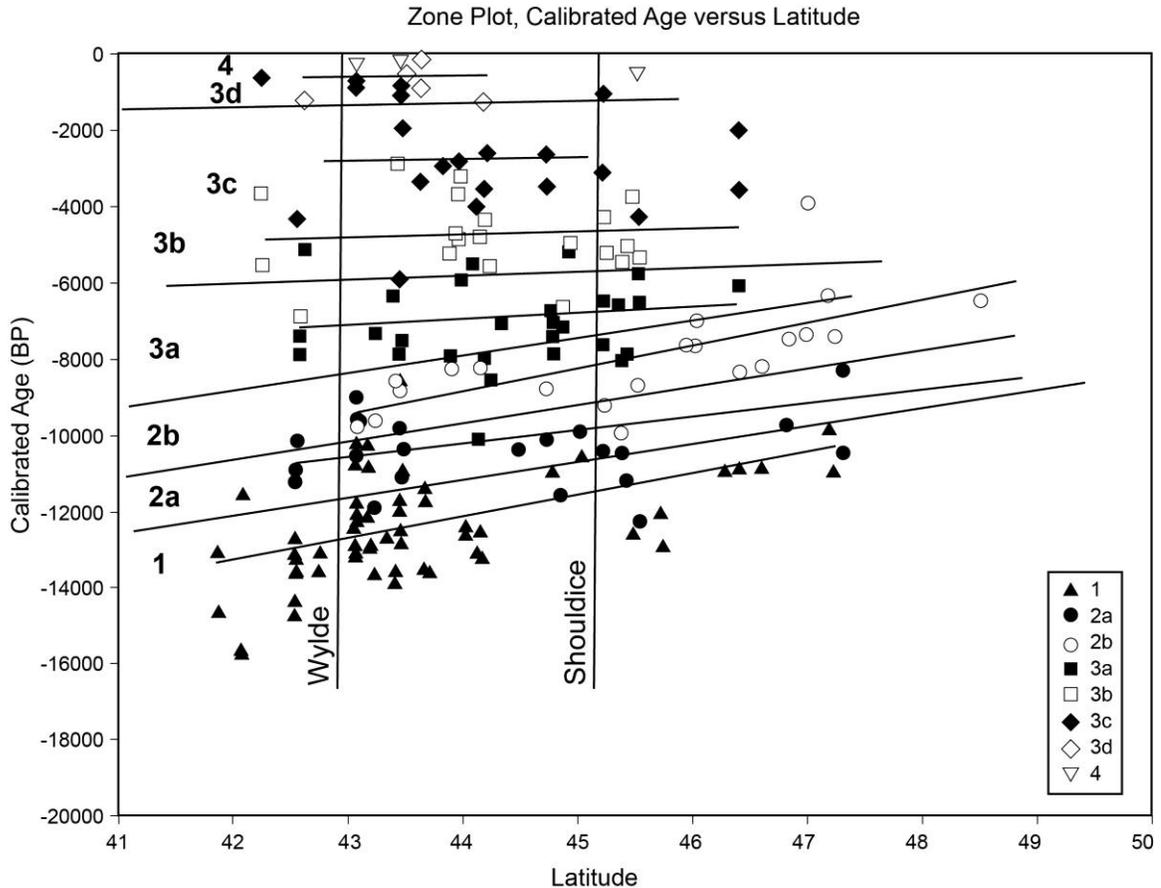
Depth, cm	Volume, ml	<i>Lycopodium</i> (spike)	<i>P. boryanum</i> var. <i>boryanum</i>	<i>P. boryanum</i> var. <i>pseudoglabrum</i>	<i>P. integrum</i>	<i>P. duplex</i>	<i>P. simplex</i>	Total <i>Pediastrum</i>
0	5	20	19	42	0	0	1	62
5	5	16	9	47	0	2	2	60
10	5	23	23	25	0	1	2	51
15	5	40	22	28	0	0	3	53
20	5	39	10	49	0	2	1	62
25	5	50	25	24	0	2	2	53
30	5	60	21	26	1	2	2	52
35	5	30	12	24	5	1	18	60
40	5	21	8	21	4	0	22	55
45	5	37	0	25	2	0	28	55

Appendix 4e. Raw counts of thecamoebians, Lake Simcoe, core from Smith's Bay (SB1). Olena Volik analyst

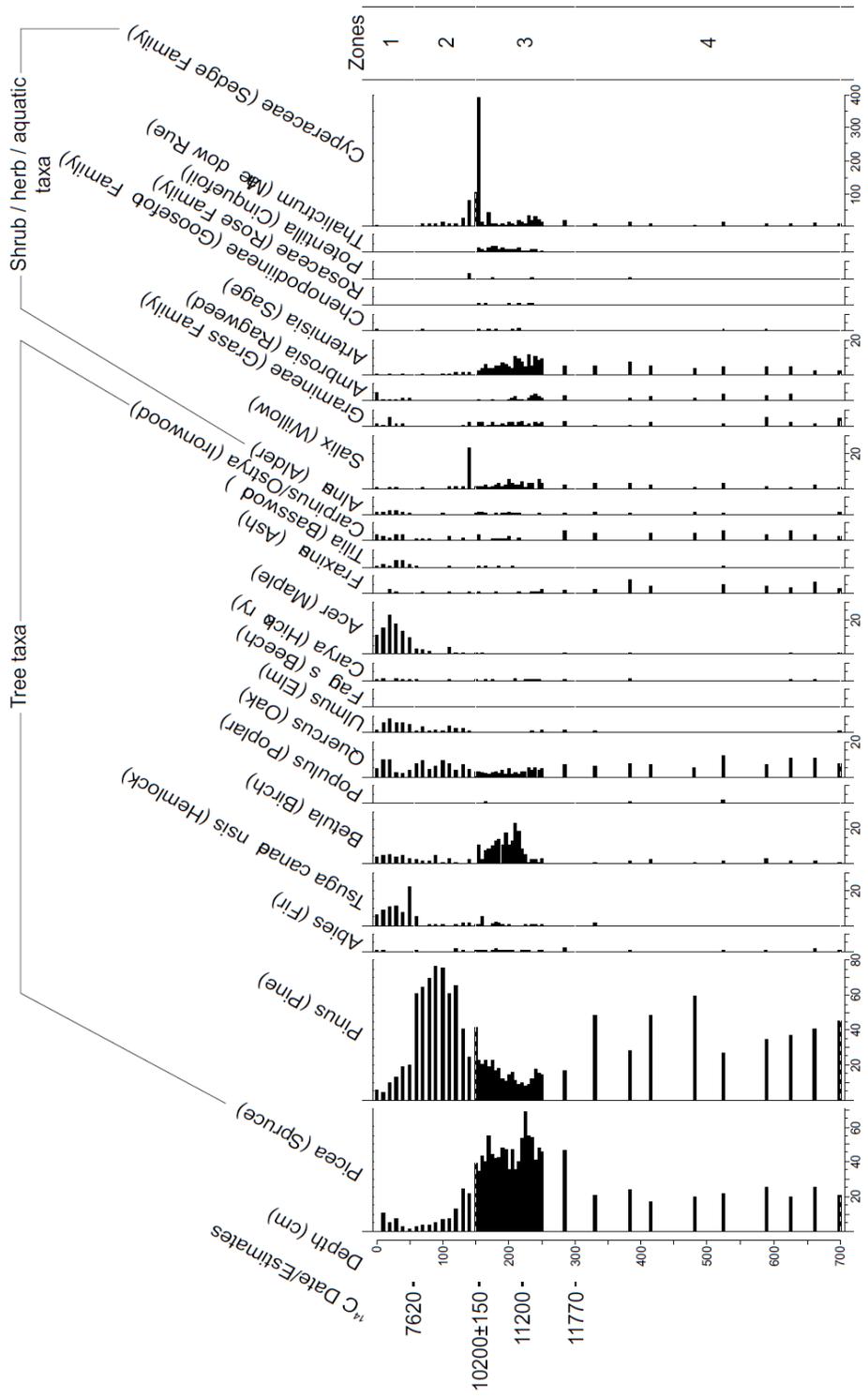
Depth, cm	Volume, ml	<i>Cucurbitella tricuspis</i>	<i>Diffugia oblonga "oblonga"</i>	<i>D. oblonga "glans"</i>	<i>D. oblonga "tenuis"</i>	<i>D. oblonga "linearis"</i>	<i>D. protaeiformis</i>	<i>D. corona</i>	<i>D. urens</i>	<i>D. urceolata</i>	<i>Pontigulasia compressa</i>	<i>C. constricta "aerophila"</i>	<i>C. constricta</i>	<i>C. aculeata</i>	<i>Lesquerusia spiralis</i>	Total thecamoebians
0	5	0	89	7	2	0	1	1	0	0	41	6	13	21	1	182
5	5	1	72	3	6	1	0	0	0	0	38	8	15	18	0	162
10	5	1	54	12	11	0	0	1	0	1	40	9	18	19	0	166
15	5	0	22	5		0	6	4	0		41	11	21	16	1	127
20	5	0	81	5	2	0	1	1	0	1	37	5	18	11	0	162
25	5	0	47	2	7	0	1	1	0	1	31	15	39	21	0	165
30	5	0	34	1	3	0	1	1	0	2	21	12	43	38	0	156
35	5	0	28	2	0	1	1	0	0	1	23	8	48	41	0	153
40	5	0	25	1	2	1	0	1	1	0	24	7	68	35	0	165
45	5	0	21	7	1	0	0	0	1	1	7	12	54	60	0	164

Appendix 5. Chronological Control and Correlation

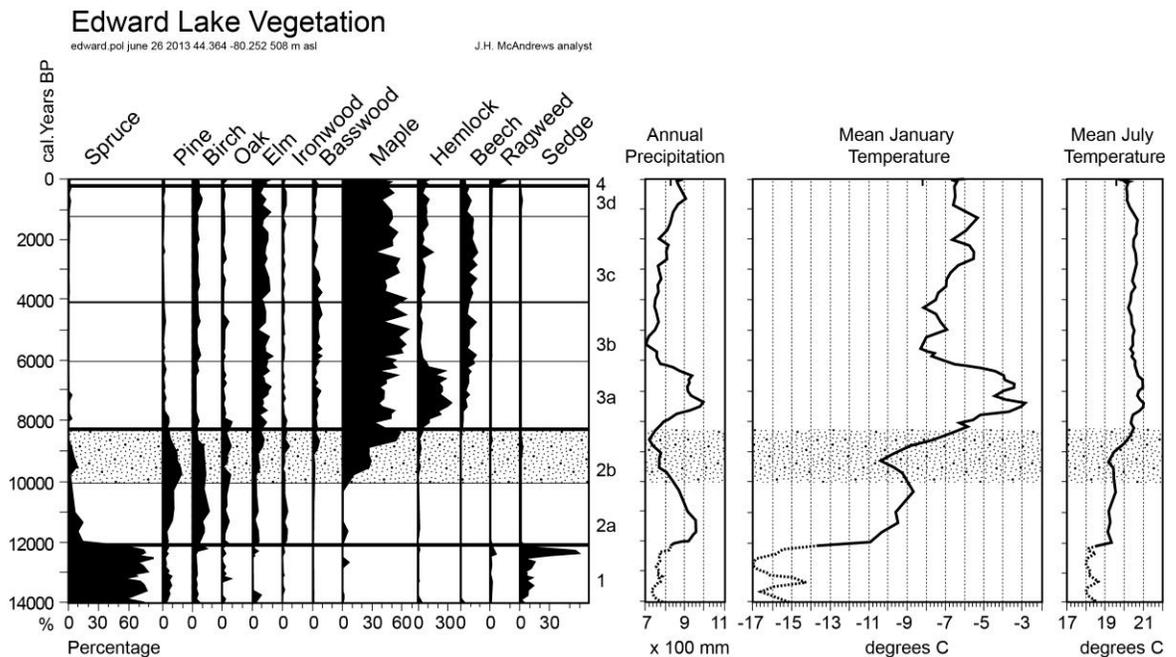
Although no radiometric ages are available to date, the well-dated pollen zone boundaries of McAndrews (1994) provide age control (Appendix Fig. 5.1), allowing correlation between sites within Lake Simcoe and comparison with other sites in southern Ontario, e.g. Cookstown Bog from Todd et al., (2004) and Edward Lake from McCarthy et al. (submitted) (Appendix Figs. 5.2 and 5.3). Seismic stratigraphy allowed correlation across Lake Simcoe and with the surficial geology in the surrounding region (Appendix Fig. 5.4).



Appendix Figure 5.1 Calibrated ages of the pollen zones of McAndrews (1994) from well-dated Ontario lakes between 41 and 49° latitude (modified from McCarthy et al., submitted). These ages were used to provide age control for core LS07 PC5 in the absence of radiocarbon dates. The greater latitudinal diachroneity in Zones 1 and 2 records a steeper climate gradient during the late glacial – early Holocene.



Appendix Figure 5.2. Pollen stratigraphy from Cookstown Bog and underlying Lake Algonquin sediments. The basal 2.5 cm of the peat bog was radiocarbon dated at 10,200 ± 150 cal yr BP. The ¹⁴C estimates are based on pollen concentration (Todd et al., 2004).



Appendix Figure 5.3 Reconstruction of vegetation based on pollen analyzed from a Livingstone core from Edward Lake, west of Lake Simcoe (from McCarthy et al., submitted; J.h. McAndrews, analyst)). Stippling identifies pollen Subzone 2b of McAndrews (1994), the most arid part of the early Holocene. Transfer functions for area "G" of Bartlein and Webb (1993) reconstruct a sharp increase in annual precipitation around 7500 yr cal BP following a sharp increase in mean January temperature ~8000 yr cal BP that led to the succession of the boreal woodland (Subzone 2b) by the hemlock-maple-beech mixed forest (Subzone 3a). Mean annual precipitation during the driest part of the early Holocene drought, ~8200yr cal BP in Subzone 2b, is reconstructed ~72 cm/y, which is only ~62% of the modern measured value in nearby Chatsworth.

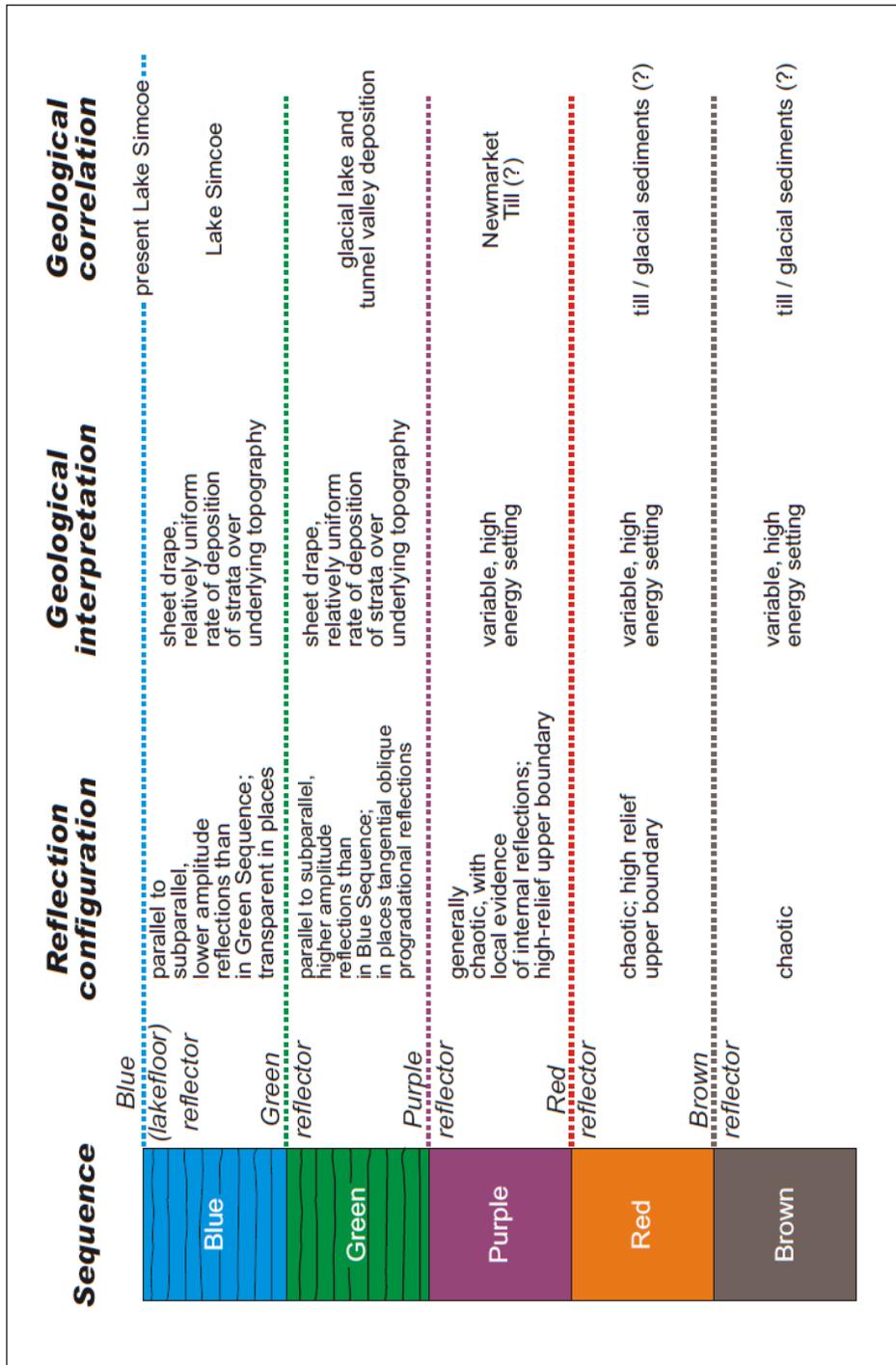


Figure Appendix 5.4 Lake Simcoe seismostratigraphic sequences, reflection configuration, geological interpretation and geological correlation (Todd et al., 2004)

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