Environ Earth Sci (2013) 68:1823–1834
DOI 10.1007/s12665-012-1870-1

ORIGINAL ARTICLE

The paleolimnology of Haynes Lake, Oak Ridges Moraine, Ontario, Canada: documenting anthropogenic and climatic disturbances

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Received: 4 July 2011 / Accepted: 24 July 2012 / Published online: 19 August 2012

Abstract Haynes Lake is a small kettle lake located on the Oak Ridges Moraine, and is within the Greater metropolitan area of Toronto, Ontario; Canada's most populous region. Lake sedimentation, flux rates, diatoms and thecamoebians extracted from a benthic core were used as biological proxies to evaluate changes in water quality through time as a function of anthropogenic activity and changing climate. There were two periods of disturbance to the Haynes Lake ecosystem from ca 8,500 years before present (YBP) through to ca A.D. 2003, which were significant enough to cause changes in lake sedimentation, the diatom flora, and thecamoebian fauna. The first disturbance was concomitant with the decline in global temperatures following the Hypsithermal Climate Optimum (ca. 4,700 YBP). The most significant disruption to Haynes Lake over the last 8,500 years, however, was the settlement of Europeans and subsequent urban development (ca. A.D. 1875), including the construction of a road immediately adjacent to the lake. Anthropogenic disturbance of inorganic clays in the recent paleosediment record (<5 cm) is indicative of more recent eutrophication events.

Keywords Haynes Lake · Ontario · Paleolimnology · Diatoms · Thecamoebians · Anthropogenic change · Hypsithermal

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Introduction

The degree of anthropogenic disturbances in eastern Canada due to land use change and population growth on both short term and long term ecosystem stability is a subject of much debate (e.g. Burden et al. 1986b; Ekdahl et al. 2007; Patterson and Kumar 2000, 2002; Watchorn et al. 2008; Whitelaw and Eagles 2007). In eastern North America, two distinct recent anthropogenic disturbance events through the Holocene have been identified. The first is associated with land clearing activities of indigenous peoples, and the second was the recent migration of European settlers (e.g. Burden et al. 1986a; Patterson and Kumar 2002; Ekdahl et al. 2007; McAndrews and Turton 2007; Watchorn et al. 2008).

Prior to A.D. 1825, Ontario was sparsely populated by Europeans. In 1795, construction of the first highway in the area was started, and was completed over 25 years. It followed an existing Amerindian trail, and opened a route between Lake Ontario and Lake Huron, thus opening the area to settlement (Stamp 1991). This new road was located within 0.5 km of a previously inhabited Iroquoian settlement (the Esox site; see Fig. 1), and only 3 km from Haynes Lake (Austin 1994). More roads were built between A.D. 1825 and A.D. 1851, and as a direct result, Ontario experienced rapid population growth (Gentilcore and Wood 1978). By A.D. 1878, the land immediately surrounding Haynes Lake had been cleared and was being farmed by several landowners (Canniff 1869; McGill University 2001).

Previous research has indicated that it is possible to predict past water quality variables in this part of Canada using a model based on the relationship between diatoms extracted from surface sediments and current water quality variables (Anderson 1995; Dixit et al. 2002; Enache and

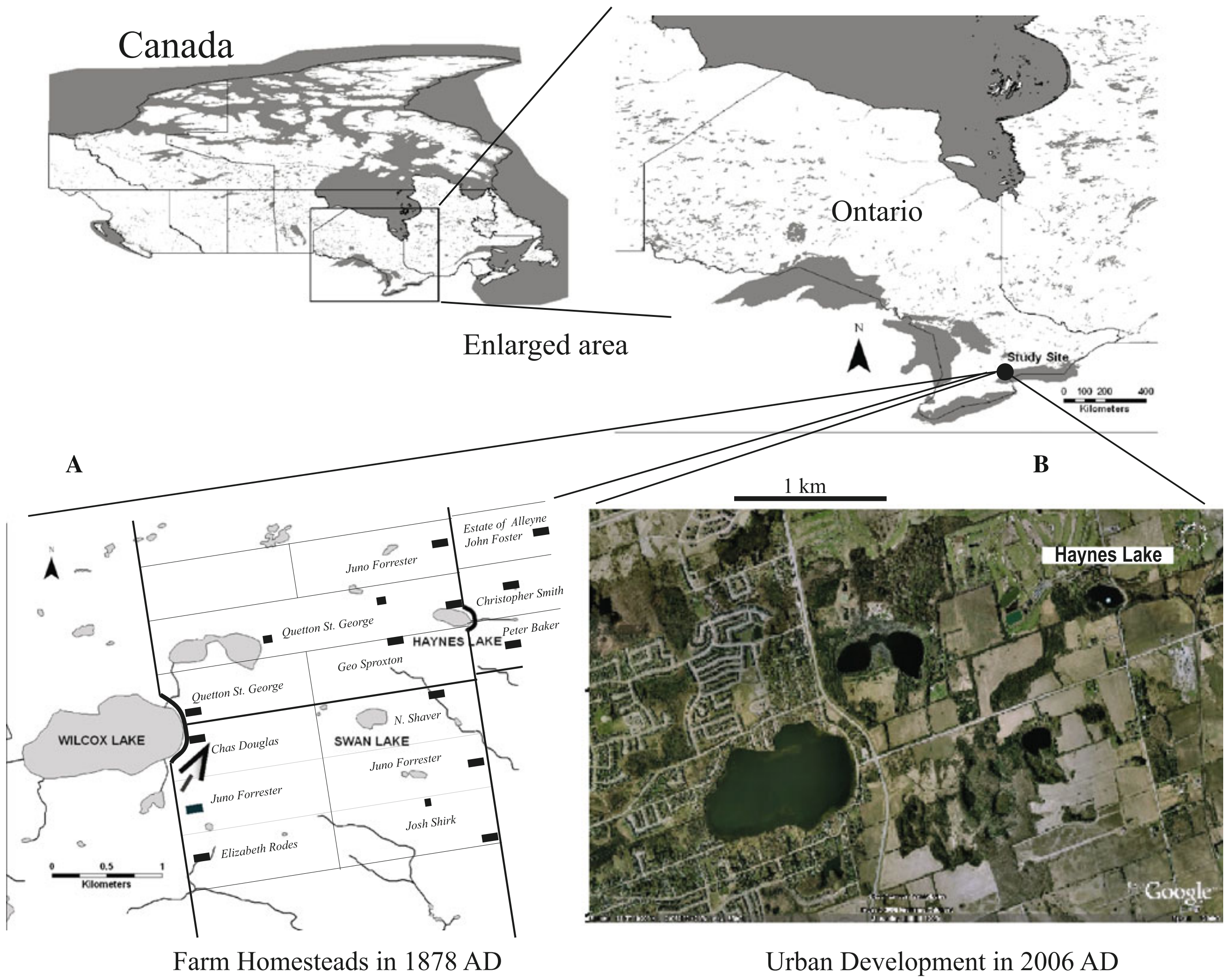


Fig. 1 Map of Canada and the province of Ontario. *Inset* **a** Location of Haynes Lake Ontario, ~1 km to the west, and the Iroquoian settlement, Esox Site, 300 m to the east of Wilcox Lake, indicated with an *arrow*. Farmhouse and barnyard areas marked with *dark boxes*. *Inset* **b** Google map of urban development in 2006. (DMTI Spatial Inc. 2003; Google Earth™ Mapping Service 2007; Natural Resources Canada 2002; Stamp 1991; Statistics Canada 2001)

Prairie 2002; Reavie and Smol 2001; Siver 1999; Watchorn et al. 2008). Similarly, many thecamoebian taxa have been shown to have preferences for particular environmental variables and, as such, analysis of changes in their populations provide important paleolimnological information (Kumar and Patterson 2000; Patterson and Kumar 2002; Patterson et al. 2002; Roe et al. 2010). The main purpose of this study was to utilize diatom and thecamoebian paleorecords to assess temporal changes, both natural and anthropogenic, on the biological diversity in Haynes Lake. The consistency, or inconsistency, of reported findings between paleolimnological and archaeological anthropogenic reconstructions was evaluated for this region of Canada. In addition, the impact of changing climatic conditions and settlement activities on lake water quality and ecosystem stability for Haynes Lake were assessed. In addition, finally, the paleolimnological predictive consistency of two adjacent lakes (Swan and Haynes Lakes) within the city of Toronto, on the Oak Ridges Moraine, was evaluated.

Materials and methods

Study area

Haynes Lake (43°57′57″N; 79°24′42″W) is a kettle lake located on the Oak Ridges Moraine (ORM) (Fig. 1). The ORM area extends 160 km from the Trent River in the east to the Niagara Escarpment in the west. It is a >100 m thick, till–glaciofluvial–glaciolacustrine sediment complex deposited as an inter-lobate moraine between about 13,000 and 15,000 years BP (Karrow 1989; Sharpe et al. 2004). This moraine acts as a recharge and discharge area for groundwater, supporting some 65 watercourses, and is a drinking water source for local communities (Gerber and Howard 2002; Whitelaw and Eagles 2007). The ORM also provides natural habitat for a large number of plant and animal species (Whitelaw and Eagles 2007). The ORM, with a growing population of >100,000 residents, is situated within the Greater Toronto Area (GTA), which has a population of more than 5.6 million people (2006 Census, Statistics Canada 2007; Whitelaw and Eagles 2007).

Haynes Lake is one of many kettle depressions in the moraine (Fig. 1). It is a small lake, at 0.4 km long by 0.13 km wide, with a maximum depth of 16 m, and is approximately 255 m above sea level. The surrounding land is level with the lake to the east, while land on the south and north sides lies about 20 m above water level. From mid-way between Wilcox Lake and Haynes Lake, the land on the west side slopes gently towards Haynes Lake. There is a road (Regional Road 12) located immediately adjacent to the lake and within the floodplain of Haynes Lake. When water levels are high, particularly in the spring, a portion of the regional road is often submerged. One house is situated on the north side of Haynes Lake, and a recreational center is just to the north of the house. The Diamond Back Golf and Country Club is located up a slope just northwest of the lake. The rest of the lake is surrounded by mixed deciduous and coniferous forest, with roads, farmland, and residential areas beyond. There were Common Cattails (*Typha latifolia* L.), Eurasian Water Milfoil (*Myriophyllum spicatum* L.), and zebra mussels (*Dreissena polymorpha* Pallas) observed in the littoral zone along the east side of the lake. Populations of Canada Geese (*Branta canadensis* L.) were also observed on the lake during spring and fall.

Sedimentology and stratigraphy

Haynes Lake core HYC1 (43°57′55″N; 79°24′48″W) was obtained using a Livingstone corer (Deevey 1965) on August 20, 2005. The core was collected in three sections (HYC1-1 [94.5 cm], HYC1-2 [96.0 cm] and HYC1-3 [81.0 cm]). The total amount of sediment was 269.5 cm.

The core sections were X-rayed to identify distinct layers with a Kevex X-ray machine at 40 kV, and 27–44 mA, with exposure times ranging from 90 to 180 s. The images were captured on erasable phosphor plates and digitally recovered using an OREX scanner with Video-Ren® software (version 1.0).

Chronology

Radiocarbon and lead-210 dating

Radiocarbon dates were provided by Beta Analytic and the Chrono Centre using the ^{14}C calibration program (Stuiver and Reimer 1993; Stuiver et al. 1998a, b). Calibration was carried out using IntCal09 dendrochronological database for terrestrial material (Reimer et al. 2009). Thirteen samples subsampled from the 0–36.5 cm interval of the core were dated for ^{210}Pb at the St. Croix Watershed Research Station using the alpha spectrometry method. This methodology was used to determine age and sediment accumulation rates for the past 100–150 years (Eakins and Morrison 1978). Dates and sedimentation rates were calculated according to the c.r.s. (constant rate of supply) model (see Appleby and Oldfield 1978) with confidence intervals determined by first-order error analysis of counting uncertainty (Binford 1990).

Diatom preparation and enumeration

Diatoms deposited in Haynes Lake sediment were extracted from twenty-two 1 cm thick subsamples from Core HYC1, corresponding to a range of sample depths from 1 to 188.5 cm. Approximately 1 cc of wet sediment was extracted, weighed and freeze-dried from each of the subsamples. The subsamples were prepared for diatom analysis by weighing out 0.020–0.058 g of dry sediment. A 10 ml solution of 50:50 nitric/sulfuric acid was added to each sediment sample and heated for approximately 20 min to remove organic material. The acid mixture was then diluted with distilled water and sonicated to disaggregate the diatom frustules into single valves. Subsequently, the acid was removed from the samples through centrifugation and a series of at least five distilled water dilutions. Finally, washed samples were stored for further processing in 45 ml of distilled water.

Aliquots of 0.5 ml from the washed diatom solution were pipetted onto 18 mm × 18 mm coverglasses and allowed to air-dry. The coverglasses were fixed onto microscope slides with Naphrax® mountant. Two microscope slides were prepared for each sample; one for analysis with a Leica DMR® light microscope with phase contrast optics, and the others as reserve slides for cross-reference and verification. Prior to diatom counting, two scanning electron microscope stubs were prepared from two samples to identify small diatoms using an FEI XL Environmental Scanning Electron Microscope (ESEM). All of the quantified prepared microscope slides, the remaining subsample material, associated notes and photomicrographs were archived in the National Collection at the Canadian Museum of Nature, in Ottawa (CANA 81172–81204).

At least 600 diatom valves were counted at 1,600× magnification from each slide using a transect counting protocol (Pappas and Stoermer 1996; Watchorn et al. 2008). The number of valves per gram dry weight (total valves g^{-1} dwt) and percent abundance were subsequently calculated for each taxon. Diatom sedimentation rates were determined using ^{210}Pb and sediment accumulation measures for the top 60 cm of the core. The diatoms were identified using standard taxonomic references for northeastern North America and Europe (Krammer 1997a, b, 2000, 2002; Krammer and Lange-Bertalot 1986, 1988, 1991a, b; Lange-Bertalot 2001; Patrick and Reimer 1966, 1975; Round et al. 1990). A more comprehensive list of taxonomic references used in establishing current taxonomic identifications and nomenclature can be found at http://www.nature-cana.ca.

Thecamoebian preparation and enumeration

Twenty samples for thecamoebian analysis were obtained from the same Haynes Lake subsamples as were used for diatom analysis. Each 1 cc sample prepared for thecamoebian study was screened with a 43 µm sieve to retain thecamoebians and to remove silts and clays. Wet aliquots were then examined under an Olympus binocular stereomicroscope at 40× and 80× magnification and counted until statistically significant populations were obtained (Patterson and Fishbein 1989). Taxa identification followed Kumar and Dalby (1998). Relative fractional abundance was subsequently calculated for each taxonomic unit.

Data analysis

A diatom-water quality transfer function for Haynes Lake was developed following the format of Watchorn et al. (2008) using the program C2 version 1.5 (Juggins 2005). Fifty lakes from the Reavie and Smol (2001) calibration set that had complete data for spring growing conditions, including pH, and total phosphorus (TP), were used as the calibration model to infer past water chemistry values in Haynes Lake. Lakes used in the calibration set are located <275 km to the east of Haynes Lake and are situated on bedrock formations of limestone (Trenton and Beekmantown formations), granitic (Precambrian Shield) rock, or a mixture of the two (Chapman and Putnam 1966). Reconstruction of past water chemistry values for Haynes Lake were generated using 32 taxa from the fossil assemblage that were present in the calibration set. The species relative abundance data were square-root transformed for weighted averaging (WA) analyses to reduce the effect of dominant taxa, as previously described in Reavie and Smol (2001).

Primer 6 version 6.1.11 software was used to establish Bray–Curtis similarity comparisons for the diatom and thecamoebian communities among the core sections. A hierarchical cluster analysis incorporating a group average linkage cluster mode was used to establish clusters of community similarities and a SIMPROF test was selected to evaluate the significance of these associations. The relative abundance data were square-root transformed for these analyses (Clarke and Gorley 2006).

Results

Sediment core details and chronology

X-ray analysis indicated distinctive laminations and changes in sedimentology in Haynes Lake sediments through time (Fig. 2). The top 30 cm of the core was composed of dense, finely layered clay, with small amounts of organic matter. In order to capture a clear X-ray image of this very dense section, the top 30 cm of the core was subjected to the longest exposure times and highest amperages of any section of the core. There was a distinctive change in sedimentology at 30 cm core depth, with layers higher in organic material (appearing as dark areas on the X-ray images) alternating with layers higher in clay content below this core depth. A thick, distinctive region of high organic content was observed at approximately 70 cm, with frequent changes in bedding orientation beginning at this horizon and continuing to about 135 cm depth. Bedding orientation returned to a horizontal orientation at 135 cm depth, similar to that observed in the top 70 cm of sediments. In the region from 135 to 153 cm depth, the sediment laminations were mainly composed of organic matter. From 153 to 165 cm, there was fine layering, with 4 thicker (2.5–7.4 mm) clay bands interspersed through this section. The bottom of this core section (165–188 cm) showed fine and consistent banding comprised of alternating organic and clay layers.

Radiocarbon and ^{210}Pb dating methods indicated that the sediments recovered in the examined core spanned from ~13,000 years before present (YBP) (calibrated age range for 241.5 cm; see Fig. 3; Table 1) to ca A.D. 2003 (1 cm; see Fig. 3; Table 2). The sedimentation rate for the portion of the core deposited below 32 cm was ~0.02 cm/year. The calibrated bulk organic dates obtained from the top 150 cm of the core were not used in the determination of the sedimentation rate as an ~1,500 age offset with calibrated dates obtained from two plant macrofossil samples (UBA017176, UBA17177) through this interval suggested that "old carbon" may have influenced the bulk dates.

Fossil diatom assemblages

Ninety-six different diatom taxa were identified from twenty-five genera in the Haynes Lake sediment core. Of these taxa, sixteen were present at >5 % abundance in at least one sample, and were deemed present in statistically significant enough numbers for subsequent analysis. Species assemblages changed as sediment depth decreased,

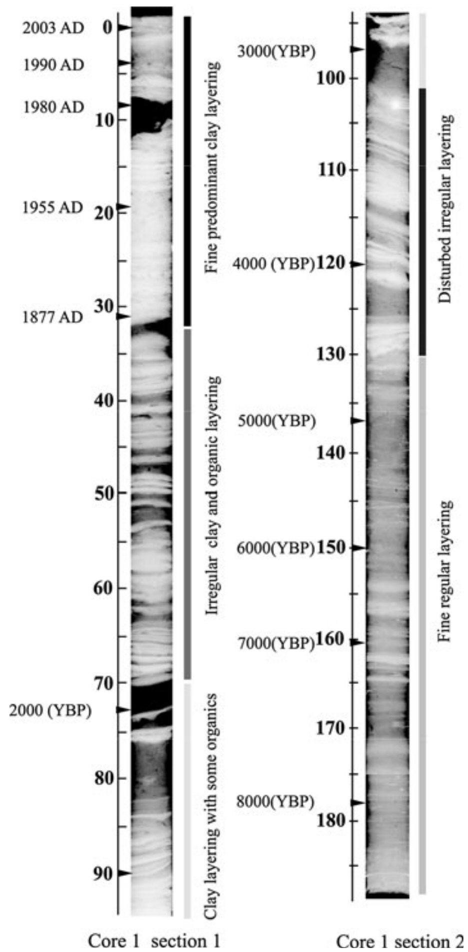


Fig. 2 Haynes Lake Core X-ray. Downcore scale measures are in cm. The *single arrow* indicates disturbance areas in the core resulting from processing. Age estimates (YBP) based on the age-depth model established for Haynes Lakes are presented next to the depth scale

with particularly distinct changes noted through the top 30 cm and below 130 cm in the core (Fig. 4). Diatom sedimentation rates for the period from ca. 1875 AD to present varied from 9.66×10^6 to 5.1×10^7 valves cm^{-2} $year^{-1}$.

At the base of the core (188.5–140 cm), the dominant species were *Cyclotella comensis* Grunow 1882, *Cyclotella michiganiana* Skvortzow 1937, and *Discostella pseudostelligera* Houk & Klee 2004 (Fig. 4). Other prominent species included *Encyonema silesiacum* Bleisch 1861, *Nitzschia amphibia* Grunow 1862, *Fragilaria capucina* Desmazieres 1825 sensu lato and *Navicula cryptotenella* Krammer & Lange-Bertalot 1985. The diatom community changed at ~130 cm core depth, with *Fragilaria nanana* Lange-Bertalot 1993 temporarily increasing in abundance along with *Encyonema silesiacum*, *Achnanthidium minutissimum* (Kützing) Czarnecki 1994 (at 135 cm), and *Fragilaria capucina* sensu lato. From 130 to ~30 cm, there was a general decline in *Encyonema silesiacum* and *Nitzschia amphibia*, with successional increases in *D. pseudostelligera* (120 cm), *C. comensis* (100 cm), *Cyclotella bodanica* Grunow 1878 sensu lato (75 cm) and *C. michiganiana* (60 cm). From 30 to 2 cm, a clay layer was present with a successional shift in the diatom flora from *Fragilaria capucina*, *Navicula cryptotenella* and *Nitzschia amphibia* to *D. pseudostelligera* (30 cm), *Fragilaria nanana* (15 cm), *Cyclotella michiganiana* (11 cm), and *Achnanthidium minutissimum* (5 cm). At the top of the core (<5 cm) *Asterionella formosa* Hassall 1850 and *Stephanodiscus medius* Håkansson 1986, became more prominent in conjunction with a decline in the relative abundance of *A. minutissimum*. *Asterionella formosa* was absent down-core, but at the top of the core represented the third most dominant species, at 14.5 % abundance. *Stephanodiscus medius* was also absent below 25 cm, but in the top 5 cm composed 12.9 % of the assemblage.

Diatom-inferred pH (DI-pH) and total phosphorus (DI-TP)

There were distinct changes in spring diatom-inferred pH (Fig. 4) recognized throughout the Haynes Lake sediment core. The inferred pH ranged from 7.8 to 8.1 in the deepest part of the core (188.5–110 cm). The highest DI-pH (8.3) occurred at 100 cm core depth, and fluctuated between 7.8 and 8.2 from 80 cm core depth to 40 cm. At 30 cm core depth, the DI-pH dropped to 7.6, the lowest DI-pH, and fluctuated between 7.7 and 7.9 to 1 cm depth, where it rose to 8.0. Direct measurements of pH from Haynes Lake water samples provided values of 7.97 (August 2005), and 8.13 (September 2007).

Diatom-inferred total phosphorus (DI-TP) was subject to large error, and changes through time were not significant (Fig. 4). Interestingly, however, DI-TP at 1 cm core depth was determined to be 0.010 mg L^{-1}, while instrument measured TP ranged from 0.011 to 0.012 mg L^{-1}. The highest DI-TP values corresponded to 45 cm core depth at 0.012 mg L^{-1}, while the lowest values were modeled for the 110–120 cm core depth (~0.007 mg L^{-1}).

Fossil Thecamoebian assemblages

Twelve taxa were identified in the Haynes Lake core. Of these taxa, eight were present at >5 % abundance in at least one sample (Fig. 5). In the lowermost core section (176–75 cm), the dominant species was *Arcella vulgaris* (Ehrenberg, 1830). At 116 cm core depth, a change in the composition of the less dominant species was noted, when *Cucurbitella tricuspis* (Carter, 1856) became the second most dominant species at 18 % abundance with the decline of *Centropyxis aculeata* Ehrenberg 1832 "discoides". At 60 cm core depth, *A. vulgaris* and *C. tricuspis* became

Fig. 3 Age-depth model for Haynes Lake core HL3. Age models are based on ^{14}C dates from plant macrophytes (UBA-17176, UBA-17177), a bulk organic sample from near the base of the core (C1-3-53-54) and ^{210}Pb data. Other ages (Beta-260149, Beta-260148 and Beta-275540) based on bulk organic samples are plotted passively. The 95 % confidence interval of the regression line is based on the error in ^{14}C ages (*solid line bounding gray region*). The ^{210}Pb age model for the upper 32 cm of the core where sedimentation rate is higher is presented in *right* hand figure, the base of which corresponds to the *dotted horizontal line* in the *left* hand figure

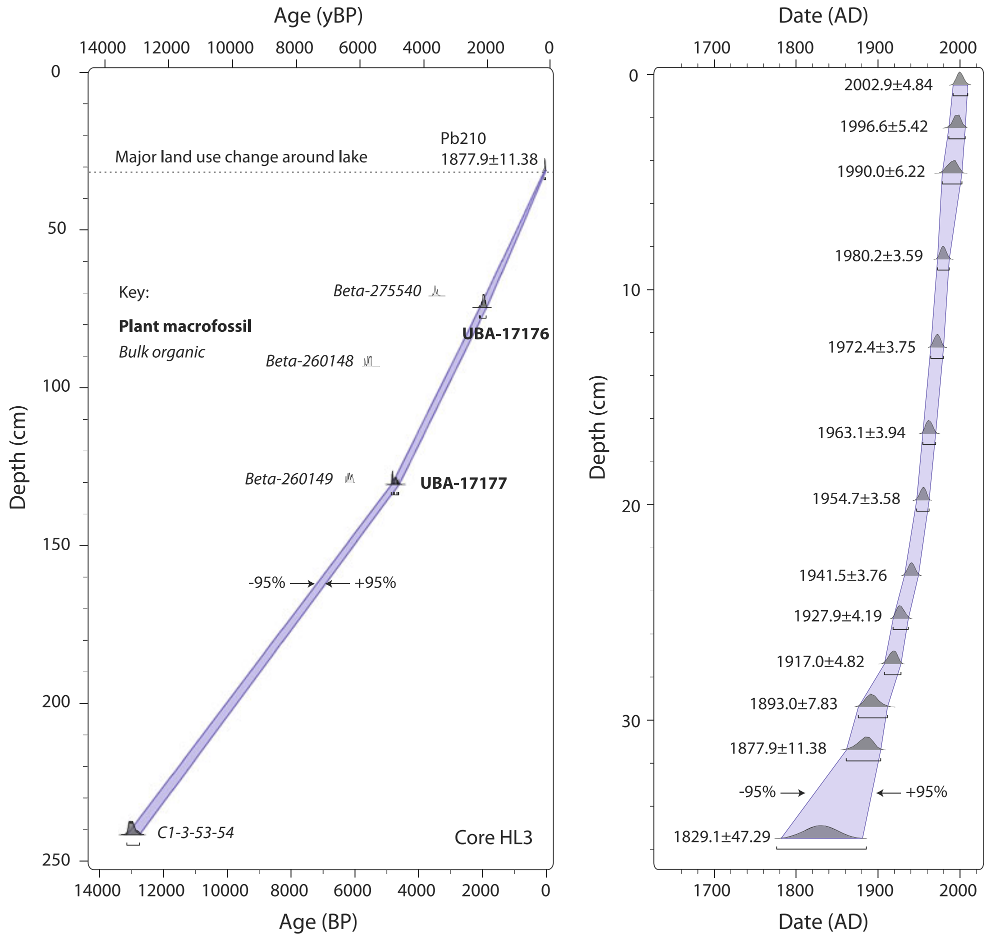


Table 1 Radiocarbon ages obtained from Haynes Lake

Sample ID	Laboratory number	Description	Depth (cm)	^{14}C age	Calibrated age ranges (year BP) IntCal09
HYNL_69-70 cm	Beta-275540	Bulk organic	69–70	3,330 ± 40	3,553 ± 89
DC969	UBA-17176	Plant macrofossil	74–75	2,017 ± 35	1,972 ± 88
C1-2-3-5	Beta-260148	Bulk organic	97	4,900 ± 40	5,652 ± 66
C1-2-36-38	Beta-260149	Bulk organic	130	5,350 ± 40	6,108 ± 108
DC971	UBA-17177	Plant macrofossil	130–131	4,226 ± 37	4,695 ± 68
C1-3-53-54		Bulk organic	241–242	11,110 ± 60	12,955 ± 197

OxCal v4.1.7 Bronk Ramsey (2011); r:5; Atmospheric data from Reimer et al. (2009)

co-dominant. However, from 50 to 15 cm the community changed dramatically to one dominated by *Centropyxis aculeata* ‘aculeata’ with either *A. vulgaris* or, in the more recent sediments, *C. tricuspis* as the second most dominant species. In the upper 11–0 cm section, *C. tricuspis* was the clear dominant species with *Centropyxis aculeata ‘aculeata’* the second most important taxon.

Cluster analysis

Cluster analysis using diatom community similarity data resulted in the recognition of three main clusters with >50 % similarity (Fig. 6). The most distinctive cluster group comprised samples from the top 30 cm of the core. Within this top 30 cm cluster, SIMPROF analysis, with a conventional 5 % significance level, determined 3 sub-groups; 1, 1–15 cm; 2, 20–25 cm and 3, 30 and 110 cm. The immediate upper sections of the core (1–15 cm) were different from all other core sections. In contrast, the 30 cm section was more aligned with the deeper 110 cm section. The two other cluster groups (4 and 5) were significant groupings based on SIMPROF analysis, but did not represent complete contiguous sections of the core. Cluster group 4 showed a general grouping from 100 to 140 cm

Table 2 ^{210}Pb dates obtained from Haynes Lake Core C3-1

Sample depth (cm)	^{210}Pb date (AD)
0.5	2002.9 ± 4.84
2.5	1996.6 ± 5.42
4.6	1990.0 ± 6.22
8.6	1980.2 ± 3.59
12.7	1972.4 ± 3.75
16.7	1963.1 ± 3.94
19.8	1954.7 ± 3.58
23.3	1941.5 ± 3.76
25.3	1927.9 ± 4.19
27.4	1917.0 ± 4.82
29.4	1893.0 ± 7.83
31.4	1877.9 ± 11.38
35.5	1829.1 ± 47.29

Atmospheric data from Reimer et al. (2009); OxCal v4.1.7 Bronk Ramsey (2011); r:5

(except 120 and 160 cm) and 40–45 cm sections. Cluster group 5 was a mix of sample sections from 50 to 189 cm, which showed no contiguous patterns. Cluster analysis using thecamoebian community similarity data resulted in three groups, with Bray Curtis similarities >60 %. The upper most cluster comprised samples from the top 30 cm of the core minus the 11 cm section (Fig. 7). A second cluster was composed of sediments between 40 and 50 cm, and was aligned with the upper sediments (<30 cm). Below 60 cm, the thecamoebian communities were in one large cluster with >65 % similarity. The 130–188 cm sample sections were within a subgroup of cluster 3 (also including 75 and 80 cm), while a second subgroup contained 60, 110, and 120 cm.

Discussion

Interpretation of the microfossil and sedimentary record from a core collected from Haynes Lake, Ontario, spanning the period from ca. 8,500 YBP to the present decade indicated there were two periods of disturbance to the lake ecosystem. Changes in sedimentology, diatom flora assemblages and thecamoebian fauna assemblages through this time period can be linked to documented climate events, and to human-induced alteration of the surrounding landscape.

Frequent changes in bedding orientation of the sediments observed through X-ray analysis commencing at <135 cm core depth (Fig. 2) provided the earliest suggestion that conditions in the lake were altered. The sediment layering through this section was sporadic, with multiple bands of clay. The inconsistent changes in inorganic sediment loading likely caused the lake pH changes through this period (Fig. 2). A change in the diatom flora at ~130 cm core depth (~4,200 YBP macrofossil estimate vs. ~5,350 YBP bulk estimate) was also indicative of changes to the lake ecosystem. For example, *Fragilaria capucina* sensu lato, *Fragilaria nanana* and *Achnanthidium minutissimum* (starting at 135 cm depth), were found to increase in abundance at this horizon, and they are epiphytic species that can tolerate a broad range of disturbance conditions (Beaver 1981; Potapova and Hamilton 2007). In contrast, *Cyclotella bodanica* decreased in abundance in comparison to assemblages found in older sediments in the core. One thecamoebian species, *Arcella vulgaris*, dominated the lower section of the core (176–74 cm); however there was a shift between 125 and 115 cm in the second dominant taxon from *Centropyxis aculeata* 'discoides' to *Cucurbitella tricuspis*. The transition to *Cucurbitella*

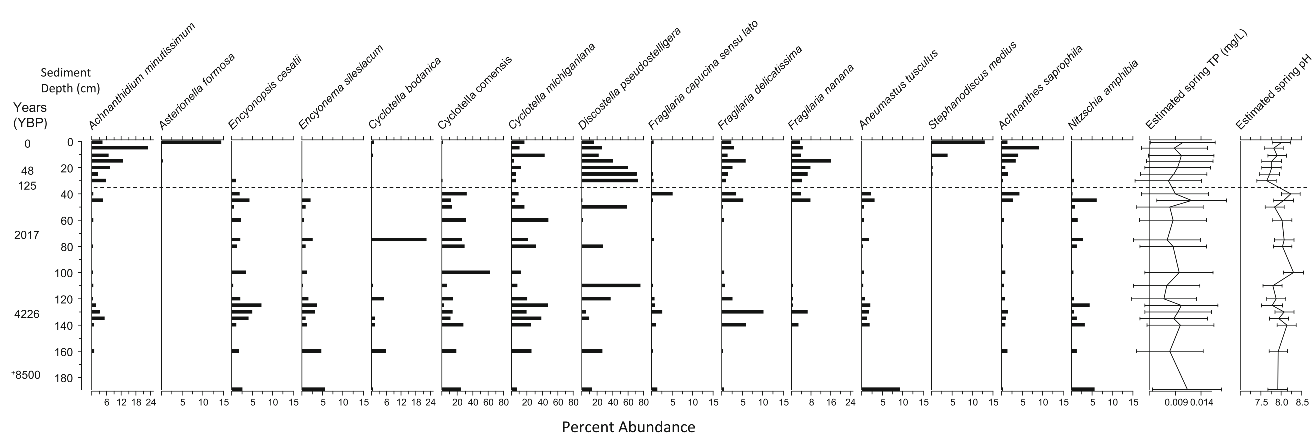


Fig. 4 Diatom percent abundance, Diatom-Inferred spring TP (DI-TP), and Diatom-Inferred spring pH (DI-pH) from Haynes Lake, Ontario. Taxa are represented if they are present in >5 % abundance in at least one sample. *Dash line* indicates period of European settlement. Samples were recovered from Core HYC1-1 and HYC1-2

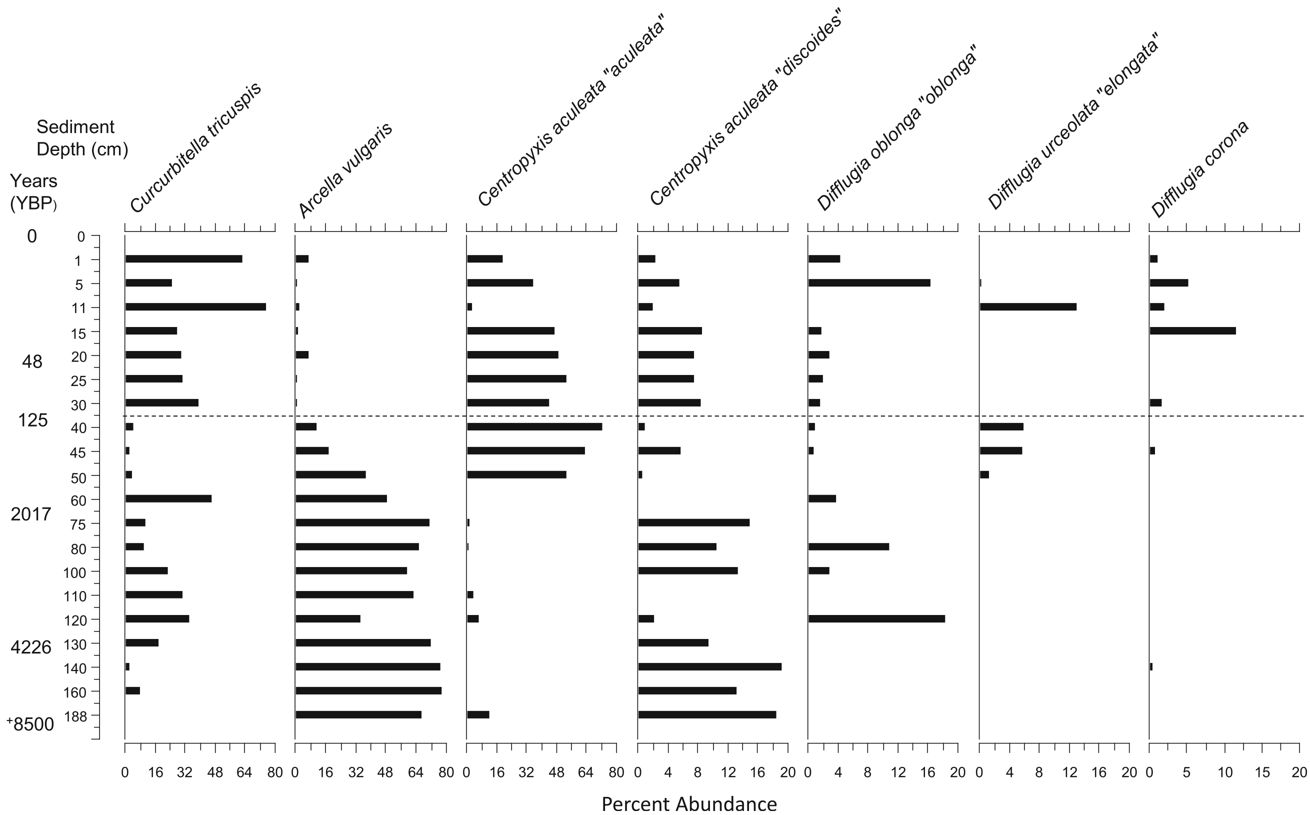


Fig. 5 Thecamoebian stratigraphic diagram from Core HYC1 Haynes Lake, Ontario. Taxa are represented if they are present in >5 % abundance in at least one sample. *Dash line* indicates period of European settlement. Samples were recovered from Core HYC1-1 and HYC1-2

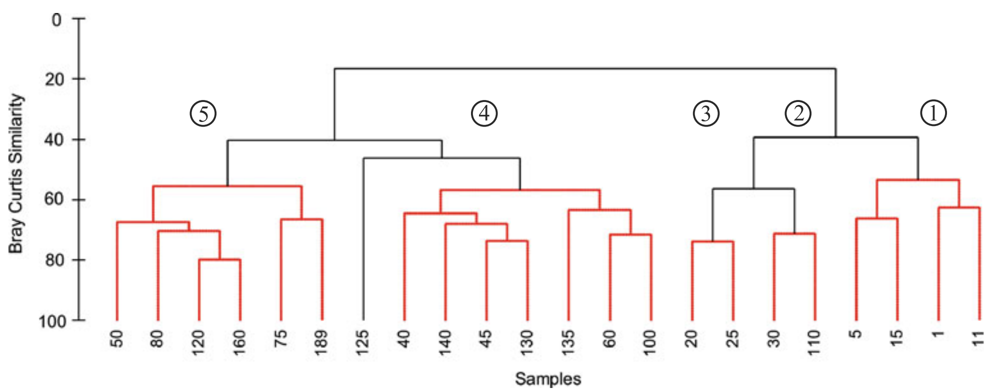


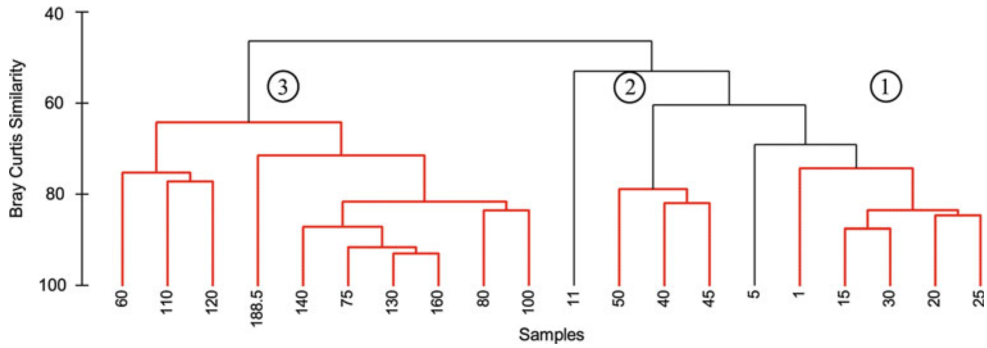
Fig. 6 Bray–Curtis similarity of diatom species percent abundance from Haynes Lake, Ontario using a complete linkage model. The sample depths in cm are across the *x*-axis. Five significant clusters were determined by SIMPROF analysis and are presented in *red*. Samples were recovered from Core HYC1-1 and HYC1-2

tricuspis was associated with the introduction of disturbance conditions (Patterson et al. 2002; Roe et al. 2010).

The changes in sedimentation and biotic composition correlate with cooler, drier, climatic conditions following the reported Hypsithermal Climate Optimum (McFadden et al. 2005; Yu 2003), suggesting a link between the two. A significant alteration in thecamoebian community structure suggest water quality changes <2,000 YBP, whereas changes in diatom community structure were less consistent, but notable at >5,000 YBP. The limnological changes observed in Haynes Lake were mirrored in changes in the landscape surrounding Crawford Lake ~70 km to the west, on the Niagara Escarpment. Observed changes through that time period (ca. 4,800–2,000 YBP) in the Crawford Lake area were linked to changing climatic conditions (Yu 2003).

Other studies from the Ontario region have linked changes in the environment to cooling conditions following

Fig. 7 Bray–Curtis similarity of thecamoebian species percent abundance from Haynes Lake, Ontario. The sample depths in cm are across the *x*-axis. Complete linkage model. Three significant clusters were determined by SIMPROF analysis and are presented in *red*. Samples from Core HYC1-1 and HYC1-2



the Hypsithermal Climate Optimum. Sediment collected from James and Granite Lakes, located in the Temagami region of Northeastern Ontario, showed decreases in white spruce, aspen and birch pollen, and increases in *Abies* pollen at ~4,116 YBP. These changes in tree species abundance were linked to the onset of cooler, moister conditions (Boudreau et al. 2005). Additionally, a multi-proxy study of deep-water sediment from eastern Lake Ontario showed a marked decrease in lake sedimentation rates, and a significant increase in biogenic silica occurred ~5,300 YBP, concomitant with the cooling trend (McFadden et al. 2005).

A shift from organic to more inorganic sediments was observed at the 70 cm section (~2,000 YBP macrofossil estimate) of the core (Fig. 2). There were changes in diatom and thecamoebian assemblages through the 70–49 cm section of the core. A single species and sample shift in the truly plankton dominated diatom assemblage through the 75–60 cm interval provided biological evidence of changing water quality and community composition. *Cyclotella michiganiana* was the dominant species by 60 cm core depth. This followed a transitional change from *Discostella pseudostelligera* in the deeper sections of the core to *Cyclotella bodanica*, which was present in significant numbers for the first time at the 75 cm horizon. The change in water quality was also observed in the thecamoebian community. There was a transition between 75 and 49 cm from *A. vulgaris* dominance to *A. vulgaris* and *Cucurbitella tricuspis* co-dominance, with a final transformation to *Centropyxis aculeata* 'aculeata'. As a stressed environment indicator, *Centropyxis aculeata* 'aculeata' provided further evidence of change in the area around the lake. These observations indicate that the indirect impact of the Hypsithermal Climate Optimum on the sedimentology and biology of Haynes Lake extended thousands of years.

Paleolimnological evidence of anthropogenic disturbances ~AD 1300–1400 have been documented from Crawford Lake, Ontario, which had a known Iroquoian village adjacent to the lake (Ekdahl et al. 2007; McAndrews and Turton 2007). Haynes Lake is <1.5 km away from another documented Iroquoian 1.2 ha village in southern Ontario. Current local knowledge indicates that Amerindians inhabited the Haynes Lake area with the occurrence of arrow head artifacts in the lake (per. comm. J. Schweizer). Changes in thecamoebian composition and possible changes in diatom composition indicated by the Bray Curtis Similarity results during the predicted period of Iroquoian settlement (40–45 cm) suggest change in the ecology of Haynes Lake. However, it is not clear from the sedimentology record and the pH reconstruction that it was caused by anthropogenic activity. The non-significant results from the TP reconstructions also suggest that eutrophication in Haynes Lake was not significant compared to more recent geochemical alterations. Although anthropogenic disturbances by Amerindians have been documented in southern Ontario, the degree of disturbance was much less than that associated with European settlement (Ekdahl et al. 2007).

The top 30 cm of the Haynes Lake sediment core, which encompassed the interval from ca. AD 1875 to present day, correlated with the mass introduction of European settlers into the area (Canniff 1869). More precisely, clearance of the land around Haynes Lake began soon after parcels were granted to two settlers. The first was granted to William Bond, (Concession II, Lot 7, Whitchurch Township) in 1798 (Archives of Ontario 1979), who developed his land into a nursery and fruit farm (Guillet 1946). The second was William Wilcocks (Concession II, Lot 6, Whitchurch Township), who was granted land in 1802. The clay content in the core increased dramatically around 32 cm, and remained high up to 12 cm core depth, as indicated by the 10-fold increase in the sedimentation rate during this time (Fig. 2). The clay observed in these upper lake sediments were introduced as a consequence of erosion due to deforestation for housing and agriculture. Further erosion would have resulted from the construction of Regional Road 12 along the edge of the lake (Gentilcore and Wood 1978; Langman 1971).

At 30 cm core depth (~A.D. 1875), changes in diatom species assemblage were also noted when *Cyclotella comensis*, and *Nitzschia amphibia* both decreased in abundance. Also, *C. comensis*, a species associated with oligotrophic conditions (Sorvari and Korhola 1998), and *N. amphibia* did not appear in the assemblage above this core depth. The DI-pH ratio declined to 7.7 at 30 cm depth, and further declined to 7.6 at 15 cm depth, which was indicative of the clastic deposition of clay. The X-ray results from this section confirm there was an influx of clay into the lake at this time. Similar changes in diatom floral makeup have been observed with road construction and resultant clay input in other lakes (e.g., Third Sister Lake, Michigan; Hammer and Stoermer 1997). The reconstructed lake pH changes we observed were not linked to post-industrial acidification as reported from lakes in the Killarney region just 300 km to the north-west (Dixit et al. 2002). This result highlights the importance of local disturbances (e.g. soil erosion) which often override any ecoregion or global impacts such as acid rain deposition.

Changes in the diatom species assemblage in Haynes Lake in the post-European settlement phase were not as significant as those noted to have occurred in nearby Swan Lake during this same time period (Watchorn et al. 2008). Swan Lake sediments inferred the highest DI-TP levels during the European settlement period (Watchorn et al. 2008), whereas changes in DI-TP across the European settlement horizon in Haynes Lake were equivocal, with large error estimates. However, the DI-pH ratio (Fig. 4) provided a good proxy to explain temporal changes in the diatom species assemblages in Haynes Lake.

Thecamoebian data from the top 30 cm of the Haynes Lake sediment core were consistent with the diatom results from the same sample depths. Cluster analysis of both diatom and thecamoebian data, in collaboration with the X-ray data, indicated that this portion of the core was undergoing sedimentation and water quality changes that were distinctly different from the rest of the lake holocene paleohistory (Figs. 6, 7). *Centropyxis aculeata* '*aculeata*' was dominant at 30 cm depth, with *C. tricuspis* the second most important taxa. In recent times ($\sim$AD 1986–2003), there was a further transition, with *C. tricuspis* becoming the dominant taxon. Changes in thecamoebian assemblage were also noted in nearby Swan Lake from the European settlement period, with *C. aculeata* and *A. vulgaris* present in higher proportions than that observed in older sediments (Patterson et al. 2002).

The results from Haynes Lake provide evidence of past and current temporal changes in water quality and aquatic community stability in regional lakes of southern Ontario as a direct result of anthropogenic disturbances. Within this geographic region of North America, other aquatic studies have documented significant changes to lake ecosystems as a result of erosion due to deforestation and land development since human settlement (e.g. Ekdahl et al. 2007; Hammer and Stoermer 1997; Patterson et al. 2002; Watchorn et al. 2008). The recent (<10 years) introduction of *Asterionella formosa* and relative abundance decline of *Discostella pseudostelligera* and *Cyclotella* spp. was further indicative of recent eutrophication pressures on Haynes Lake, although large errors in our TP reconstruction limit discussion on the significance of this change (Reynolds 1984). It is worth noting that a similar species transformation was also correlated with community changes in nearby Crawford Lake (Ekdahl et al. 2007). With a limited dataset ($n = 7$) covering the last 110 years we were not able to find any correlations between local average summer air temperature, average winter air temperature, average yearly temperature and diatom-inferred water temperature using climate data from Watchorn et al. (2008). Likewise there were no correlations between total cell accumulation rates and any measured estimates of local air temperature over the same 110 year period. At this time, the proxy records of Haynes Lake show no lake changes due to recent regional changes in climate.

Conclusions

Analysis of this multiproxy dataset indicates that a range of disturbances occurred in the Haynes Lake ecosystem through the period from ca. 8,500 YBP to ca. A.D. 2003. Both climatic changes (2,000 to >5,000 YBP) and European settlement (ca 1875 A.D.) had an impact on lake water quality and sedimentation. The most significant disturbance indicated by the diatom flora, the thecamoebian fauna, and sedimentology represented the period from ca. A.D. 1875 to the present. European anthropogenic disturbances had a stronger influence on lake health and diversity than did climate, even when compared to the Hypsithermal Climate Optimum. An additional period of disturbance may have occurred during a period of Iroquoian population growth (ca. A.D. 1300); however, this cannot be confirmed. The changes in water quality (limnological impact) in Haynes Lake due to European settlement (ca. 1875 to present) were not as significant as that observed in nearby Swan Lake, or Crawford Lake, which were clearly nutrient-enriched. However, the same anthropogenic-induced alterations of the landscape (soil erosion) caused a pH disturbance to the aquatic ecosystem in Haynes Lake, and these effects remain evident in the modern lake habitat today. Extensive inorganic sediment loading, likely from road construction adjacent to the lake, is the determining factor in observed alterations to the health of Haynes Lake. However, the dramatic increase in *Asterionella formosa* in the recent sediments indicates that nutrient loading has had an impact on Haynes Lake in the last 20 years. In contrast, Swan Lake, which is <1 km away, showed a clear farming nitrification signal over the last $\sim$50 years. The paleosediments of these two lakes highlight the significance of, and changes in, recent local anthropogenic activities. This study highlights the importance of incorporating all proxies (including documented human history and local knowledge) when reconstructing the paleohistories of urban environments.

Acknowledgments This research was supported by a Natural Sciences and Engineering Research Council Discovery Grant to RTP. Assistance in the field was provided by B. Boudreau, D. Carter, I. Clark, C. Black, H. Roe and T. Ziten.

References

Anderson NJ (1995) Using the past to predict the future: lake sediments and the modelling of limnological disturbance. Ecol Model 78:149–172

Appleby PG, Oldfield F (1978) The calculation of lead-210 dates assuming a constant rate of supply of unsupported ^{210}Pb to the sediment. Catena 5:1–8

Archives of Ontario (1979) Ontario Archives land record index township listing

Austin SJ (1994) The Wilcox Lake site (AlGu-17): Middle Iroquoian exploitation of the Oak Ridges Moraine. Ont Archaeol 58:49–84

Beaver J (1981) Apparent ecological characteristics of some common freshwater diatoms. Ontario Ministry of the Environment, Don Mills, p 513

Binford MW (1990) Calculation and uncertainty analysis of ^{210}Pb dates for PIRLA project lake sediment cores. J Paleolimnol 3:253–267

Boudreau RE, Galloway JM, Patterson RT, Kumar A, Michel F (2005) A paleolimnological record of Holocene climate and environmental change in the Temagami region, northeastern Ontario. J Paleolimnol 33:445–461

Bronk Ramsey C (2011) OxCal 4.1. http://c14.arch.ox.ac.uk/oxcal

Burden ET, McAndrews JH, Norris G (1986a) Palynology of Indian and European forest clearance and farming in lake sediment cores from Awenda Provincial Park, Ontario. Can J Earth Sci 23:43–54

Burden ET, Norris G, McAndrews JH (1986b) Geochemical indicators in lake sediment of upland erosion caused by Indian and European farming, Awenda Provincial Park, Ontario. Can J Earth Sci 23:55–65

Canniff W (1869) History of the settlement of Upper Canada, (Ontario) with special reference to The Bay of Quinte. Dudley and Burns Printers, Victoria Hall

Chapman LJ, Putnam DF (1966) The physiography of southern Ontario. University of Toronto Press, Toronto

Clarke KR, Gorley RN (2006) PRIMER v6: User Manual/Tutorial. PRIMER-E, Plymouth

Deevey ESJ (1965) Sampling lake sediments by use of the Livingstone Sampler. In: Kummel B, Raup D (eds) Handbook of Paleontological Techniques. W.H. Freeman and Company, San Francisco

Dixit SS, Dixit AS, Smol JP (2002) Diatom and chrysophyte transfer functions and inferences of post-industrial acidification and recent recovery trends in Killarney lakes (Ontario, Canada). J Paleolimnol 27:79–96

DMTI Spatial Inc (2003) Esri Data and Maps. Canada Water Bodies. Redlands California, USA

Eakins JD, Morrison RT (1978) A new procedure for the determination of lead-210 in lake and marine sediments. Int J Appl Radiat Isot 29:531–536

Ekdahl EJ, Teranes JL, Wittkop CA, Stoermer EF, Reavie ED, Smol JP (2007) Diatom assemblage response to Iroquoian and Euro-Canadian eutrophication of Crawford Lake, Ontario, Canada. J Paleolimnol 37:233–246

Enache M, Prairie YT (2002) WA-PLS diatom-based pH, TP and DOC inference models from 42 lakes in the Abitibi clay belt area (Quebec, Canada). J Paleolimnol 27:151–171

Gentilcore RL, Wood D (1978) A Military Colony in a Wilderness: the Upper Canada Frontier. In: Wood JD (ed) Perspectives on landscape and settlement in Nineteenth Century Ontario. The MacMillan Company of Canada Ltd., Toronto, pp 32–42

Gerber RE, Howard K (2002) Hydrogeology of the Oak Ridges Moraine aquifer system: implications for protection and management from the Duffins Creek watershed. Can J Earth Sci 39(9):1333–1348

Google Earth™ Mapping Service (2007). http://downloading-now.com/googleearth/1/. Accessed 24 February 2008

Guillet EC (1946) Pioneer life in the county of York. Hess-Trade Typesetting Company, Toronto

Hammer BK, Stoermer EF (1997) Diatom-based interpretation of sediment banding in an urbanized lake. J Paleolimnol 17:437–449

Juggins S (2005) C2 Version 1.5: Software for ecological and paleoecological data analysis and visualization. http://www.campus.ncl.ac.uk/staff/Stephen.Juggins/software/C2Home.htm. Accessed 14 January 2008

Karrow PF (1989) Quaternary geology of the Great Lakes Subregion. In: Fulton RJ (ed) Quaternary geology of Canada and Greenland. Geological Survey of Canada, Geology of Canada, No. 1, pp 326–350

Krammer K (1997a) Die Cymbelloiden Diatomeen: Eine Monographie der wetweit bekannten Taxa Teil 1. Allgemeines und Encyonema Part. J. Cramer, Stuttgart

Krammer K (1997b) Die cymbelloiden Diatomeen Eine Monographie der weltweit bekanten Taxa Teil 2. *Encyonema* part., *Encyonopsis* and *Cymbellopsis*. J. Cramer, Stuttgart

Krammer K (2000) Diatoms of Europe: diatoms of the European Inland Waters and Comparable Habitats. In: Horst Lange-Bertalot ARG (ed) The genus Pinnularia, vol. 1. Gantner Verlag K.G, Germany

Krammer K (2002) Diatoms of Europe: diatoms of the European Inland Waters and Comparable Habitats. In: Horst Lange-Bertalot ARG (ed) Cymbella, vol 3. Gantner Verlag K.G, Germany

Krammer K, Lange-Bertalot H (1986) Bacillariophyceae Süβwasserflora von Mitteleuropa, 2/1. Teil: Naviculaceae. Gustav Fischer Verlag, Stuttgart

Krammer K, Lange-Bertalot H (1988) Bacillariophyceae Süβwasserflora von Mitteleuropa, 2/2. Teil: Bacillariaceae, Epithemiaceae, Surirellaceae. Gustav Fischer Verlag, Stuttgart

Krammer K, Lange-Bertalot H (1991a) Bacillariophyceae Süβwasserflora von Mitteleuropa, 2/3. Teil: Centrales, Fragilariaceae, Eunotiaceae. Gustav Fischer Verlag, Stuttgart

Krammer K, Lange-Bertalot H (1991b) Bacillariophyceae Süβwasserflora von Mitteleuropa, 2/4. Teil: Achnanthaceae, Kritische Ergänzungen Zu Navicula (Lineolatae) und Gomphonema Gesamtliteraturverzeichnis Teil 1–4. Gustav Fischer Verlag, Stuttgart

Kumar A, Dalby AP (1998) Identification key for holocene lacustrine arcellacean (thecamoebian) taxa. http://palaeo-electronica.org/1998_1/dalby/issue1.htm

Kumar A, Patterson RT (2000) Arcellaceans (thecamoebians): new tools for monitoring long- and short-term changes in lake bottom acidity. Environ Geol 39:689–697

Lange-Bertalot H (2001) Diatoms of Europe: Diatoms of the European Inland Waters and Comparable Habitats. In: Horst Lange-Bertalot ARG (ed) Navicula sensu stricto, 10 Genera

Separated from Navicula sensu lato, Frustulia, vol 2. Gantner Verlag K.G., Germany
Langman RC (1971) Patterns of settlement in Southern Ontario. McClelland and Stewart Limited, Toronto
McAndrews JH, Turton CL (2007) Canada Geese dispersed cultigen pollen grains from prehistoric Iroquoian fields to Crawford Lake, Ontario, Canada. Palynology 31:9–18
McFadden MA, Patterson WP, Mullins HT, Anderson WT (2005) Multi-proxy approach to long- and short-term Holocene climate-change: evidence from eastern Lake Ontario. J Paleolimnol 33:371–391
McGill University (2001) The Canadian County Atlas Digital Project. http://digital.library.mcgill.ca/CountyAtlas/SearchMapframes.php. Accessed 13 January 2008
Natural Resources Canada (2002) GeoBase Geopolitical boundaries—Level 1. Ottawa, Ontario, Canada
Pappas JL, Stoermer EF (1996) Quantitative methods for determining a representative algal count. J Phycol 32:693–696
Patrick R, Reimer CW (1966) The diatoms of the United States Exclusive of Hawaii. Vol. 1. Fragilariaceae, Eunotiaceae, Achnanthaceae, Naviculaceae, vol 1. The Academy of Natural Sciences of Philadelphia, Philadelphia
Patrick R, Reimer CW (1975) The Diatoms of the United States Exclusive of Alaska and Hawaii. Vol. 2 Part 1. Entomoneidaceae, Bymbellaceae, Gomphonemaceae, Epithemiaceae. The Academy of Natural Sciences of Philadelphia, Philadelphia
Patterson RT, Fishbein E (1989) Re-examination of the statistical methods used to determine the number of point counts needed for micropaleontological quantitative research. J Paleontol 63:245–248
Patterson RT, Kumar A (2000) Assessment of arcellacean (thecamoebian) assemblages, species, and strains as contaminant indicators in James Lake, northeastern Ontario, Canada. J Foram Res 30:310–320
Patterson RT, Kumar A (2002) A review of current testate rhizopod (thecamoebian) research in Canada. Palaeogeogr Palaeoclimatol Palaeoecol 180:225–251
Patterson RT, Dalby A, Kumar A, Henderson LA, Boudreau REA (2002) Arcellaceans (thecamoebians) as indicators of land-use change: settlement history of the Swan Lake area, Ontario as a case study. J Paleolimnol 28:297–316
Potapova M, Hamilton PB (2007) Morphological and ecological variation within the *Achnanthidium minutissimum* (Bacillariophyceae) species complex. J Phycol 43:561–575
Reavie ED, Smol JP (2001) Diatom-environmental relationships in 64 alkaline southeastern Ontario (Canada) lakes: a diatom-based model for water quality reconstructions. J Paleolimnol 25:25–42
Reimer PJ, Baillie MGL, Bard E, Bayliss A, Beck JW, Blackwell PG, Bronk Ramsey C, Buck CE, Burr GS, Edwards RL, Friedrich M, Grootes PM, Guilderson TP, Hajdas I, Heaton TJ, Hogg AG, Hughen KA, Kaiser KF, Kromer B, McCormac FG, Manning SW, Reimer RW, Richards DA, Southon JR, Talamo S, Turney CSM, van der Plicht J, Weyhenmeyer CE (2009) IntCal09 and Marine09 radiocarbon age calibration curves, 0–50,000 years - cal BP. Radiocarbon 51:1111–1150
Reynolds CS (1984) The ecology of freshwater phytoplankton. Cambridge University Press, Cambridge, pp 185–186
Roe HM, Patterson RT, Swindles GT (2010) Controls on the contemporary distribution of lake thecamoebians (testate amoebae) within the Greater Toronto Area and their potential as water quality indicators. J Paleolimnol 43:955–975
Round FE, Crawford RM, Mann DG (1990) The Diatoms: Biology and Morphology of the Genera. Cambridge University Press, New York
Sharpe D, Pugin A, Pullan S, Shaw J (2004) Regional unconformities and the sedimentary architecture of the Oak Ridges Moraine area, southern Ontario. Can J Earth Sci 41:183–198
Siver PA (1999) Development of paleolimnological inference models for pH, total nitrogen and specific conductivity based on planktonic diatoms. J Paleolimnol 21:45–59
Sorvari S, Korhola A (1998) Recent diatom assemblage changes in subarctic Lake Saanajärvi, NW Finnish Lapland, and their paleoenvironmental implications. J Paleolimnol 20:205–215
Stamp RM (1991) Early Days in Richmond Hill: A History of the Community to 1930. Richmond Hill Public Library Board, Ch. 1 & 2. http://edrh.rhpl.richmondhill.on.ca/default.asp?ID=s2.2. Accessed 17 Feb 2008
Statistics Canada (2001) Province of Ontario Data Spatial Files. Statistical Reference Centre. National Capital Region, Ottawa
Statistics Canada (2007) Population and dwelling counts, for Canada, census metropolitan areas census agglomerations and census subdivisions (municipalities), 2006 and 2001 censuses. http://www12.statcan.ca/english/census06/data/popdwell/Table.cfm?T=303&CMA=535&S=0&O=A&RPP=25#FootCSDType. Accessed 4 Nov 2007
Stuiver M, Reimer PJ (1993) Extended ^{14}C database and revised CALIB radiocarbon calibration program. Radiocarbon 35:215–230
Stuiver M, Reimer PJ, Bard E, Beck JW, Burr GS, Hughen KA, Kromer B, McCormac FG, Plicht J, Spurk M (1998a) INTCAL 98 Radiocarbon age calibration 24,000–0 cal BP. Radiocarbon 40:1041–1083
Stuiver M, Reimer PJ, Braziunas TF (1998b) High-precision radiocarbon age calibration for terrestrial and marine samples. Radiocarbon 40:1127–1151
Watchorn MA, Hamilton PB, Anderson TW, Roe HM, Patterson RT (2008) Diatoms and pollen as indicators of water quality and land use change: a case study from the Oak Ridges Moraine, Southern Ontario, Canada. J Paleolimnol 39:491–509
Whitelaw GS, Eagles PFJ (2007) Planning for long, wide conservation corridors on private lands in the Oak Ridges Moraine, Ontario, Canada. Conserv Biol 21:675–683
Yu Z (2003) Late Quaternary dynamics of tundra and forest vegetation in the southern Niagara Escarpment, Canada. New Phytol 157:365–390