J Paleolimnol (2008) 39:491–509
DOI 10.1007/s10933-007-9126-x

ORIGINAL PAPER

Diatoms and pollen as indicators of water quality and land-use change: a case study from the Oak Ridges Moraine, Southern Ontario, Canada

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Received: 10 February 2007 / Accepted: 2 June 2007 / Published online: 17 July 2007

Abstract Swan Lake is a small kettle lake located on the Oak Ridges Moraine; a moraine that is recognized as an important source of ground water for the nearby and rapidly expanding Greater Toronto Area. A paleolimnological reconstruction using pollen and diatoms from the lake sediments showed significant changes in biological community composition through the last ~400 years. Alterations in the diatom and pollen assemblages were most dramatic ca. A.D. 1850, correlating with the highest sediment flux in the lake between the period ca. A.D. 1850 and A.D. 1870. These changes were directly linked to regional deforestation and agricultural activities associated with European settlement. The pollen record from ca. A.D. 1850 to present day indicated that tree species (e.g. *Pinus* spp., *Tsuga canadensis*) were declining, while grass (Poaceae) and invasive species (e.g. *Ambrosia*) were increasing. Around A.D. 1850, the diatom flora changed from an assemblage dominated by large, benthic species (e.g. *Sellaphora pupula*, *Pinnularia* cf. *maior*, and *Stauroneis phoenicenteron*) to an assemblage characterized by smaller, tychoplanktonic (e.g. *Fragilaria tenera, Staurosirella pinnata*) and epiphytic (e.g. *Achnanthidium minutissimum, Rossithidium linearis*) taxa. This diatom community change supports the intermediate disturbance hypothesis which predicts a high level of diversity and richness following an intermediate to intense disturbance of short duration. Phosphorus concentrations in Swan Lake were inferred using a diatom-based regional calibration model, and the results indicated marked changes in lake water chemistry through time (from below detection limits before land clearance and settlement to 19.3 $\mu g\ l^{-1}$ in the current sediments), which were concurrent with episodes of regional deforestation and land-use change. Although the sediment and biological records indicate that the lake ecology has stabilized over the last 30–50 years, paleolimnological records show that the water quality and biology of Swan Lake has changed dramatically and not returned to pre-settlement conditions. Swan Lake presents a detailed record of the impact created by deforestation and urban development with a population of <50 individuals per km^2. Detailed paleolimnological studies like Swan Lake, in tandem with global

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human footprint studies, can create realistic estimates of land-use impacts at the global scale.

Keywords Swan Lake · Oak Ridges Moraine · Ontario · Anthropogenic impacts · Paleolimnology · Diatoms · Pollen · Sediment flux · Climate change

Introduction

Water quality can change radically in short intervals of minutes and hours to longer intervals of decades and centuries, producing temporary or often temporally-constrained permanent changes in ecosystem stability. Although natural events such as volcanic activity cause significant, short- and long-term environmental change, in regions with large populations it is short-term anthropogenic activities that dominate environmental concerns. Anthropogenic disturbances relating to population growth, industrialization and land-use development are consistently highlighted as the primary factors controlling water quality (Wissmar 1982; Tarling 1997; Garrison and Wakeman 2000; Arnell and Liu 2001; Tong and Chen 2002; Fluteau 2003; Interlandi and Crockett 2003; Atasoy et al. 2006).

At the global scale, terrestrial based anthropogenic activities have resulted in the conversion of pristine land to cropland and urban development at an alarming rate. Global satellite imaging and current human footprint estimates show that 83% of the terrestrial earth surface is directly influenced by human activity (Sanderson et al. 2002). In A.D. 1850, there were ~537 million ha of cropland, whereas in A.D. 1999 this had increased to ~1,501 million ha (Groombridge and Jenkins 2002). In North America, more specifically the USA, the largest changes in land use since 1982 (ca. 25 million acres) have been in regions of both urban and rural industrial development (USDA-NCRS 2001). Historical anthropogenic deforestation activities for settlement and industrialization in central Canada have also caused significant changes in the landscape, and in water quality (e.g. Burden et al. 1986; McAndrews 1988; McAndrews and Boyko-Diakonow 1989; Hall and Smol 1996; Patterson et al. 1996; Patterson and Kumar 2000).

Many biological proxies have been used to independently assess anthropogenic disturbances and regional climate change (Hall and Smol 1999), although few studies have linked paleolimnological events with present-day ecological theory. In paleolimnological studies it is important, where possible, to complete multiproxy analyses in order to accurately reconstruct paleolimnological conditions of lakes, to ensure the validity of the results, and to develop robust predictive models (Finsinger et al. 2006; Lotter et al. 1997; Birks et al. 2000; Campbell et al. 2000; Woodward and Shulmeister 2006; Valero-Garcés et al. 2006).

Paleolimnological studies in central Canada, using diatoms and pollen indicators, have shown clear changes in general water quality and historical land use through time. Hall and Smol (1996), using diatoms as the biological indicator, found that inferred phosphorus levels increased in Basshaunt and Buck lakes following shoreline development for cottages and logging in south-central Ontario. They, along with others, have also suggested changes in water quality due to atmospheric acid deposition (Hall and Smol 1996; Dixit et al. 2002). Similarly, the clearance of land for farming by aboriginals (ca. A.D. 1450) was shown by changes in the palynology and lake sediment ion composition in Crawford, Second and Grignac lakes, Ontario (Burden et al. 1986; Ekdahl et al. 2004, 2007). In the same area, approximately 200 years later, these aboriginal farming activities were abandoned, the forest reclaimed the cultivated land, and a second period of deforestation was observed ca. A.D. 1870. Anthropogenic activities were again indicated in lake sediments by pollen assemblage changes and an increase in ion influx associated with erosion (Burden et al. 1986).

Within our study region (City of Toronto and the Greater Toronto Area, [GTA]) micropaleontological records of the flora (pollen) and fauna (arcellaceans) from Swan Lake demonstrated that regional land use changes (ca. A.D. 1850) had an almost immediate impact on the biology of the lake (Patterson et al. 2002). Arcellaceans changed from an equitable distribution of species indicating healthy lake conditions to higher proportions of stressed environment indicators such as *Cucurbitella tricuspis* (Patterson et al. 2002).

In this study of Swan Lake, we use the same lake sediment core analyzed by Patterson et al. (2002), but this time we examine multiproxy records of diatoms, absolute and relative pollen densities, sediment flux, regional air temperature data and the historical land acquisition records, to determine: (1) the level of anthropogenic land-use change within a typical North American urban city with a high population, (2) evaluate if these changes follow Disturbance Theory hypotheses for aquatic biological life, and (3) confirm that the results obtained using diatoms (primary producers) agree with thecamoebian (first order consumers) population changes from Swan Lake (Patterson et al. 2002).

Study site

The Oak Ridges Moraine (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 area for groundwater, is a drinking water source for local communities (Gerber and Howard 2002), and contains the largest concentration of headwater streams in the GTA (Government of Ontario 2004). The ORM also provides natural habitat for sensitive and threatened plant and animal species not found elsewhere in the GTA (Government of Ontario 2004).

Swan Lake (43°57′00″ N; 79°24′51″ W) is one of many kettle depressions in the moraine (Fig. 1). It is a small, 0.5 km long by 0.13 km wide lake that presently has a maximum depth of 6 m and lies within the headwaters of the Rouge River at about 300 m ASL. The local topography is flat, with Swan Lake lying within a depression approximately 7 m lower than the surrounding landscape. The soils surrounding Swan Lake are grey brown podzols of Peel Clay, and a small vein of alluvium till is located <500 m to the east (Hoffman and Richards 1955). The Peel Clay deposit is constructed of a thin layer of decomposed leaves and organic matter, covering a 0–15 cm layer of dark grayish brown clay with a pH around 6.8 (Hoffman and Richards 1955). This lake is situated in the GTA region, which had a population of 4,883,800 recorded in 2001 (Robinson and Schwartz 1999; Statistics Canada 2005).

At present, Swan Lake is located in a small, relatively undeveloped area (<50 individuals km^{-2}), immediately north of the urbanized metropolitan core, but within the next decade will be in the expansion and development zone of the GTA (Fig. 1). The town of Oak Ridges lies <5 km to the west of Swan Lake and scattered suburban development is a short distance away (<1 km) in all directions. There is presently one homestead situated adjacent to the lake with an associated boathouse right on the water. Immediately behind the boathouse, there is an apple orchard and the rest of the lake is surrounded by a thin 10–50 m wide buffer of mixed forest including red maple (*Acer rubra*), sugar maple (*Acer saccharum*), white birch (*Betula papyrifera*), white pine (*Pinus strobus*), poplar (*Populus* spp.), spruce (*Picea* spp.), oak (*Quercus* spp.), speckled alder (*Alnus incana*) and willow (*Salix* spp.), with open arable farmland on the higher elevations to the south and east.

Historical records indicate that land within the region of Swan Lake was not fully cleared until around A.D. 1850 (Riley and Mohr 1994). More specifically, land immediately surrounding Swan Lake was first granted to a Mary Chambers by the English government in A.D. 1797 (Archives of Ontario 1979). She had gained title to the land by A.D. 1800 after fulfilling obligatory settlement duties which included clearing 5 acres of the 200 acres of land granted, building a house, and opening a road a quarter of a mile in length across the front of the grant (Canniff 1869; Archives of Ontario 1979). In the interval from A.D. 1797 to A.D. 1878, this land (then owned by N. Shaver) and adjoining properties, were changed from virgin forest into 10 working farms (lands within concession II, sector 1 of Whitchurch Township, Fig. 1) (McGill University 2001). From 1878 to present, the homestead has been reconstructed several times, but the watershed immediately surrounding the lake has not dramatically changed and is still maintained as crop-based farmland.

Methods

Laboratory methods

The sediment samples from Swan Lake examined in this study came from two sources. The first was the upper part of a 16.4 m complete sediment core (AP-94-04) recovered from the center of the lake by the

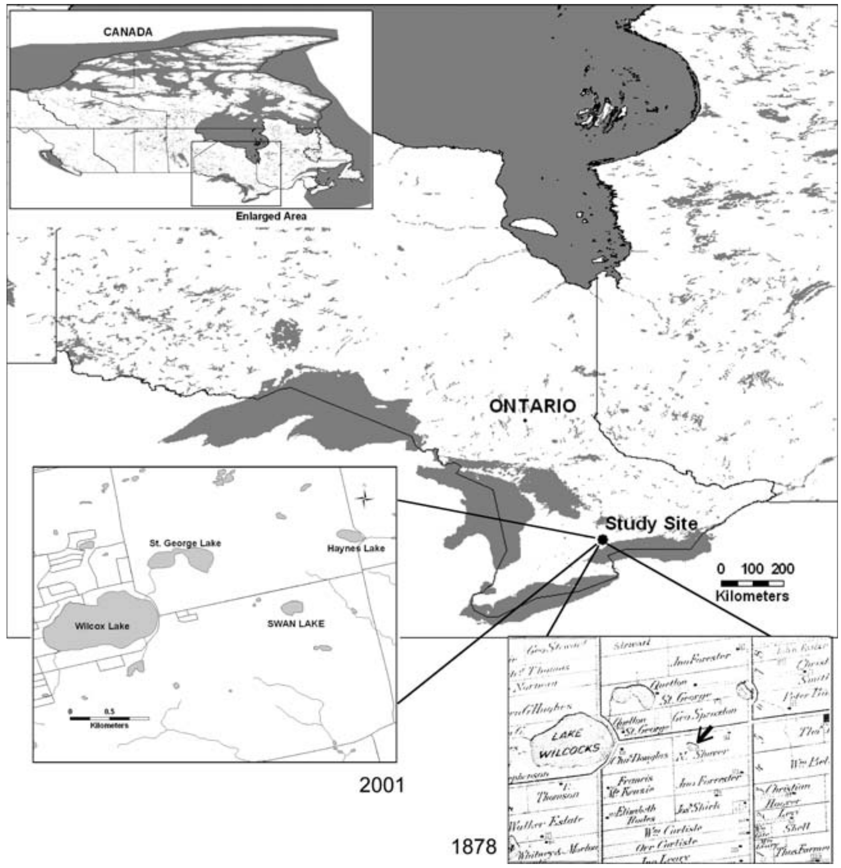

Fig. 1 Location of study area (Natural Resources Canada 2002; DMTI Spatial Inc. 2003). The A.D. 1878 inset shows Swan Lake (indicated by arrow), property boundaries (single lines), and concession roads (double lines) (McGill University 2001a). The A.D. 2001 inset indicates the location of Swan Lake relative to other lakes in the area (Statistics Canada 2001)

Geological Survey of Canada in 1994 using a modified Livingstone corer. Samples from this core are archived in the National Collection at the Canadian Museum of Nature (CANA 68814–69582). Second, four surface sediment samples were collected from the lake (water depths 0.5–4.2 m) in August 2003 with an Ekman grab sampler. These samples, which span the upper 2 cm of the sedimentary infill, were collected to gain insight into diatom distribution in the modern lake environment. The contemporary surface sample (0 cm) from 4.2 m water depth was examined in detail to provide information about water quality from post-1994 to present lake conditions, while the other three samples were used as replicates to evaluate spatial colonization patterns and verify the information obtained from the first sample.

One cubic centimeter (cc) wet sediment samples were extracted from depth levels between 0.5 cm and 270 cm in core AP-94-04 and freeze dried prior to diatom analysis. Subsamples from selected sections of the core were prepared by weighing out 0.015–0.054 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 mins to remove organic material. The acid mixture was then diluted with distilled water and sonicated at a frequency of 50 KHz with a benchtop Edmund Scientific Company Ultrasonic Cleaner No. 71-003, to disaggregate the diatom frustules into single valves. Subsequently, the acid was removed from the samples through centrifugation with a series of at least five distilled water dilutions. Finally, washed samples were stored for further processing in 45 ml of distilled water. The integrity of diatom frustules and valves after this digestion was evaluated using LM observations, which confirmed that breakage due to sonication was minimal. The contemporary surface samples were prepared in the same manner.

Aliquots of 0.4 ml from the washed diatom solution were pipetted onto 18 mm × 18 mm cover slips and allowed to air-dry. The cover slips were fixed onto microscope slides with Naphrax® mountant. Two or three microscope slides were prepared for each sample; one for analysis with a Leica DMR® or Olympus BH2® light microscope with phase contrast and brightfield optics, and the others as reserve slides for replicate verification. Prior to diatom counting, a scanning electron microscope stub was prepared from one sample to identify small diatoms using an FEI-XL Environmental Scanning Electron Microscope (ESEM). To provide reference material for future verification, representative specimens of the dominant taxa including *Achnanthidium minutissimum* (Kützing) Czarnecki, *Eolimna minima* (Grunow) Reichardt, *Neidium hitchcockii* (Ehrenberg) Cleve and *Stauroneis phoenicenteron* (Nitzsch) Ehrenberg were circled using a diamond marker on microscope slides CANA 77948 and CANA 77963. All of the quantified prepared microscope slides, associated notes and photomicrographs are archived in the National Collection at the Canadian Museum of Nature in Ottawa (CANA 77947–77963).

At least 600 diatom valves were counted at 1600× magnification from each slide using a transect counting protocol (Pappas and Stoermer 1996). Forty-seven different taxa were identified from 15 genera using standard taxonomic references (Patrick and Reimer 1966, 1975; Krammer and Lange-Bertalot 1986, 1988, 1991a, b; Reichardt 1999; Krammer 1997a, b, 2002; Lange-Bertalot 2001). The number of valves per square centimeter of sediment per year (corrected for lake influx, see pollen analysis below) and percent abundance were subsequently calculated for each taxon.

One cubic centimeter (cc) wet sediment samples were extracted at 26 depth levels from 0.5 cm to 290 cm in core AP-94-04 for pollen analysis. These subsamples were then processed using the standard HF/acetolysis procedures (Faegri and Iversen 1964). A known quantity of exotic pollen (*Eucalyptus*) was added to the samples prior to chemical processing and these were tabulated along with the fossil pollen. Counts of at least 200 tree, shrub and herb pollen provided the basic sum, and concentrations of fossil pollen per square centimeter per year (corrected for lake influx) were calculated from the proportionate number of *Eucalyptus* to fossil pollen in each sample. Eighteen pollen taxa-complexes, including pine (*Pinus*), hemlock (*Tsuga canadensis*), grass (Poaceae) and ragweed (*Ambrosia*) were selected to illustrate the pollen changes associated with deforestation and the beginning of farming at the time of settlement.

Chronology

Pollen studies were undertaken on the surface sediments (0–290 cm interval) in the Swan Lake core to obtain a record of pollen change that can be tied to European settlement, to establish time boundaries, and to derive sedimentation rates (Fig. 2). Based on excellent correlation between this lake and

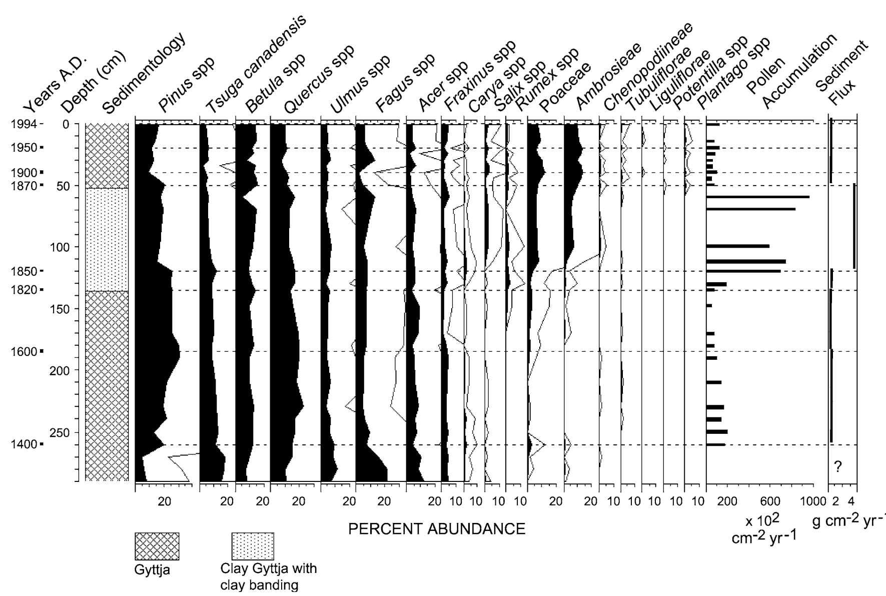

Fig. 2 Sedimentation, pollen percent abundances, total pollen accumulation per cm^2 of sediment per year and sediment influx rate in g cm^{-2} $year^{-1}$ for Swan Lake, Ontario from core AP-94-04

a similar pollen record at Crawford Lake, located about 75 km southwest of Swan Lake, several ages can be assigned to specific levels in the Swan Lake core. Annual varves deposited in Crawford Lake provide a precise chronology for pollen studies and land use and climate changes in the vicinity of the lake dating back to 1000 A.D. (Ekdahl et al. 2004; McAndrews and Boyko-Diakonow 1989; Campbell and McAndrews 1993).

The base of the Swan Lake record shows high *Fagus* (beech) giving way upward to first *Quercus* (oak) and then *Pinus* (pine). The change from beech to oak is interpreted as cooling brought on by the Little Ice Age (Campbell and McAndrews 1993). Based on this pollen change, and correlation with Crawford Lake, an age of 1400 A.D. is placed at the 260 cm depth level. The decline in *Carya* (hickory) higher up in the record at 185 cm depth is dated at 1600 A.D. The next dated pollen boundary is the rise in *Rumex* (sorrel) (at 135 cm depth) which represents the first signal of settlement, dated 1820 A.D. at Crawford Lake. Coinciding with the *Rumex* rise is a sediment change from gyttja to an increase in clay content marked by distinct clay layers at 136, 131 and 122 cm depths. The *Rumex* rise is succeeded by major increases in Poaceae (grass), *Ambrosia* (ragweed) and Chenopodiaceae (pigweed) (at 120 cm depth) and a compensating decrease in *Pinus* which McAndrews and Boyko-Diakonow (1989) relate to land clearing and onset of farming associated with European settlement during the mid 1800's. Clay deposition continues up to about 50 cm depth, where it reverts to gyttja deposition again. At this point, *Pinus* decreases a second time and Poaceae, *Ambrosia* and other weed pollen, i.e., the composites (Tubuliflorae, Liguliflorae), *Potentilla* and *Plantago* show significant increases. The interval above 50 cm is distinguished by three dated levels that can be tied to post-settlement changes in land use around the time of intense cultivation (McAndrews and Boyko-Diakonow 1989); i.e., the first increase in *Plantago* dated at ca. 1870 A.D., peak percentages of Poaceae dated at ca. 1900 A.D. and the highest *Ambrosia* percentages, which peak at ca.1950 A.D.

Data analysis

Reavie and Smol (2001) documented water quality and relative abundance of diatom taxa from 64 lakes in southeastern Ontario and produced a calibration model relating specific diatom assemblages to water quality conditions. Using canonical correspondence analysis (CCA), they determined that environmental variables important to lake water management such as spring pH (r^2 = 0.702; RMSE = 0.208; R^2_{boot} = 0.485; $RMSE_{boot}$ = 0.234) and spring TP (r^2 = 0.637; RMSE = 0.007 mg l^{-1};r^2_{boot} = 0.466; $RMSE_{boot}$ = 0.01 mg l^{-1}) were significant in explaining variance in surface sediment diatom assemblages. The lakes studied had a pH range of 6.99–8.65, and a total phosphorus gradient of 0.004–0.054 mg l^{-1}. Swan Lake has pH ranging from 7.59 (spring 2006 lab measurement) to 8.2 (spring 2006 field measurement) and total phosphorus of 0.021 mg l^{-1} (spring 2006 lab measurement) to 0.019 mg l^{-1} (summer 1995 lab measurement) (see Table 1). The close proximity of the Reavie and Smol (2001) calibration set (<200 km) combined with the similarity in lake chemistry allows for paleolimnological reconstructions of Swan Lake water conditions using the environmental transfer functions.

Updated diatom-water quality transfer functions were developed with the program C2 version 1.4 (Juggins 2005) using 50 lakes that had complete summer data from the Reavie and Smol (2001) calibration set with new data supplied by E. Reavie (personal communication). The diatom inference model for summer TP provided a robust model (r^2 = 0.673; RMSE = 0.00367 mg l^{-1}; r^2_{boot} = 0.214; $RMSE_{boot}$ = 0.0061 mg l^{-1}). The diatom inference model for pH was also robust (r^2 = 0.707; RMSE = 0.163;r^2_{boot} = 0.486; $RMSE_{boot}$ = 0.232). Inference models for other environmental variables, like TN and water depth, were calculated using summer water chemistry data but found to be weak environmental predictors. The new transfer functions were developed following the same protocol as that published by Reavie and Smol (2001) using weighted averaging (WA) with inverse deshrinking and performance verification was done using bootstrapping. The diatom inference model for summer TP using only benthic/tychoplanktonic taxa was similar and even slightly better compared to the complete diatom community model (r^2 = 0.637; RMSE = 0.016; r^2_{boot} = 0.313; $RMSE_{boot}$ = 0.025), however taxa sample size across the environmental gradient was substantially reduced. Mississagua Lake was removed from the pH calibration set after an explor-

Table 1 Swan Lake water chemistry representing ions, predominant metals and nutrients

Date	Al^{3+} (µg l^{-1})	Ba^{2+} (µg l^{-1})	Mn^{2+} (µg l^{-1})	Sr^{2+} (µg l^{-1})	Zn^{2+} (µg l^{-1})	Ca^{2+} (mg l^{-1})	Mg^{2+} (mg l^{-1})	K^{+} (mg l^{-1})	Si^{4+} (mg l^{-1})	Na^{+} (mg l^{-1})	TP (mg l^{-1})	TKN (mg l^{-1})	Cond µS cm^{-1}	pH
14/04/2006	13.0	4.7	9.5	21.0	1.0	16.0	1.37	1.20	0.003	2.1	21.0	0.77	96	7.59
03/08/1995	30.0	9.2	0.2	42.0	2.0	21.0	1.90	2.20	0.130	2.1	19.0	0.97	110	8.20
27/02/1995	4.7	9.6	0.6	39.0	56.0	23.0	1.90	2.70	0.100	2.6				
22/09/1994	14.0	11.0	0.4	43.0	3.2	23.0	1.90	2.50	0.470	2.2			120	
13/04/2006														7.96[a]

[a] Note this measurement was taken in the field. All other pH measurements were completed at a laboratory facility

atory survey of these data indicated that the two dominant species *Achnanthidium minutissimum* and *Tabellaria flocculosa* strain-3P were distinct outliers in the calibration model due to uncertain water chemistry measures from this lake. The transfer function for total phosphorus [TP] was developed, with two lakes (Sturgeon and Upper Rideau) being removed from the sample set due to missing data, leaving a final dataset size of n = 47 lakes. See Rippey et al. (1997) and Köster et al. (2004) for a summarization of techniques and associated errors.

Reconstruction of past water chemistry values for Swan Lake were generated using 22 primarily benthic taxa from the fossil assemblage that were also found in the surface water calibration set. The species relative abundance data was square-root transformed for WA analyses to reduce the effect of dominant taxa, as previously described in Reavie and Smol (2001).

Q-mode cluster analysis was used to determine the biological similarities among the sediment intervals using 17 diatom subsamples and 26 pollen subsamples. Pollen taxa were selected based on their significance in dating the core sediments (see dating methods above). Percent abundance data for the diatom samples was first square-root transformed to produce a normal distribution (Zar 1974). Systat (version 11.00.01) was then used to calculate Euclidean distances using Ward's minimum variance method (Ward 1963). To assess the significance of interspecies relationships, the 23 diatom taxa that were present in at least 5% abundance in at least one sample were analyzed (Patterson and Fishbein 1989).

The Shannon Diversity Index (SDI) was also calculated for the 17 diatom subsamples (using diatom accumulation rates adjusted for sedimentation rates determined through pollen analysis) since it is a general measure of diversity for the lake ecosystem (Patterson et al. 2002).

To further assess the relationship between changes in water quality and changes in the landscape, a comparison between biotic changes in the terrestrial and aquatic environments was explored. PCA factor analyses were run separately on the pollen and diatom relative abundance assemblages, and the resultant samples scores for the first two factors were compared using a simple correlation analysis with Bonferroni significance testing (Systat, version 11.00.01). Although in natural systems delayed responses to disturbances are often observed, the specific use of common tree and grass pollen in this analysis temporally brackets the primary period of possible terrestrial input on the ecology and water quality of Swan Lake.

Since diatom growth is affected by water temperature (Patrick 1977; Weckström et al. 1997; Anderson 2000; Bigler and Hall 2003), it was important to establish whether air temperature correlated with water temperature in the study area. It was necessary to link these two variables because little data is available examining ground-water influences and water temperature changes through time, while there is considerable air temperature data available from the immediate area for the past 100 years (Environment Canada 2005a–c). The average of 10 water temperature measurements per day for Swan Lake from June 9, 1995 to October 14, 1995 (Hipwell et al. 1995) were used to document summer growing conditions and fall lake turn-over. These measurements were compared to air temperature data (collected once daily) for the same time period from the Richmond Hill weather station, which is within 10 km of Swan Lake (Environment Canada 2005c).

Simple Pearson Product Moment correlations, (Listwise approach) using the program Systat (version 11.00.01), with a Bonferroni test for significance at the 95% probability level were carried out to determine whether there was a relationship between water temperature and air temperature. A statistically significant positive correlation would indicate that changes in air temperature were linked to changes in lake water temperature, which would in turn, possibly affect diatom productivity (Anderson 2000).

Air temperature data from two stations, Toronto Agincourt and Richmond Hill, both within 23 km of Swan Lake, were obtained from Environment Canada (Environment Canada 2005a, b) to study the historical climate in the area, and to establish if regional changes in temperature affected diatom productivity over the last 100 years. Temperature data for 1897–1959 was obtained from the Toronto Agincourt station (43°46′ N; 79°16′ W), and with the exception of the values for 1908 and 1909, when the station was not in operation, this data set was complete and unaltered (Environment Canada 2005a). Temperature data for 1960–2003 were obtained from the Richmond Hill (43°52′ N; 79°27′ W) weather station. This weather station was periodically not operational (1995, 2001 and 2002) therefore only estimated temperature values were available for those 3 years. In addition, the data for 1971 and 1992 was incomplete (Environment Canada 2005b) and therefore eliminated from the study. Mean spring, summer, fall and winter air temperatures were determined by calculating the average of the weather data (Environment Canada 2005a, b) around the estimated dates for each of the diatom sediment samples counted between ca. A.D. 1897 and ca. A.D. 2003. Mean spring air temperatures were calculated as the average of data from March to May. Mean summer air temperatures were averages from June to August, mean fall air temperatures were averages from September to October and winter air temperatures were calculated as averages from November to April. Simple correlations between diatom percent abundance and average air temperature were developed for six sediment depths between 0 cm and 40 cm using a Pearson product moment correlation, (listwise approach) with a Bonferroni test for significance at the 95% probability level.

Results

Present water quality and core sedimentology

Swan Lake is mesotrophic (TP 19–21 μg l^{-1}) and phosphorus limited (TN:TP 33:1–51:1). The lake is weakly buffered with specific conductance levels of <150 μS cm^{-1} and has a poor ion balance between the common cations (Ca^{2+}, Na^{+}, Mg^{2+}, K^{+}) and the anions. Calcium carbonate is the primary ion-buffering complex, while higher levels of the less common cations aluminum, strontium and barium can account for a small part of the imbalance of the anions (Table 1). As a result of weak buffering, pH levels varied from 7.6 to 8.2. Although data are limited and not replicated, there is some suggestion that Swan Lake has annual fluctuations in water chemistry (Table 1, see zinc and aluminum concentrations). A groundwater well within 0.8 km of Swan Lake had well surface waters with an alkalinity level of 251 (mg $CaCO_3$ l^{-1}) and Cl^{-} and SO_4^{2-} levels ranging from 1,000 to 22,000 μg l^{-1}. In contrast, Swan Lake had alkalinity levels <20% (39 μg $CaCO_3$ l^{-1}) of the well water.

The sedimentology of the 290 cm sediment core highlights three distinct zones of sedimentation (Fig. 2). The profile shows fairly uniform sedimentation rates in the lower part of the profile, but these rates increase over twofold at 135 cm depth and then sevenfold at 120 cm. Sedimentation rates become stabilized again above the 50 cm level. At the bottom of the core (290–130 cm depth) sediments were predominantly gyttja. Sediments from 135 cm to 50 cm were a composite of clay-gytjja and clay banding, while the upper zone (50–0 cm) was again gyttja. Sediment influx rates ranged from 0.23 g cm^{-2} $year^{-1}$ to 0.38 g cm^{-2} $year^{-1}$ in the lowest zone, 3.5 g cm^{-2} $year^{-1}$ in the clay-gyttja clay banded zone and 0.33–0.45 g cm^{-2} $year^{-1}$ in the more recent upper sediments (Fig. 2).

Fossil assemblages

Pollen relative abundances were dominated by tree pollen, in order in decreasing importance by *Pinus* spp., *Quercus* spp., *Tsuga canadensis*, *Betula* spp., *Fagus* spp., *Ulmus* spp., *Acer* spp. and *Fraxinus* spp. (Fig. 2). The vascular plant pollen, excluding the trees, was composed primarily of grasses (Poaceae) and ragweed (*Ambrosieae*). The pollen spectra can be subdivided into three zones based on assemblage changes over the period 1600 A.D.–1994 A.D. The interval between 1600 A.D. and 1850 A.D. was characterized by the highest abundance of *Pinus* and *Tsuga canadensis* but at 1850 A.D., *Pinus* and *Tsuga canadensis* decreased upward and pollen of Poaceae and *Ambrosia* increased and remained relatively stable to 1870 A.D. Above 50 cm depth (or since about 1870 A.D.), relative abundance levels of both Poaceae and *Ambrosia* pollen increased, whereas *Pinus* and *Tsuga canadensis* dropped to their lowest levels. The greatest change in the pollen record was observed immediately after 1850 A.D. with the dramatic decline in conifers and introduction of grasses and ragweed. Q-mode cluster analysis confirmed that pollen assemblages found at 0.5–112 cm grouped together and were separated from assemblages found below those depths (Fig. 3).

Forty-seven diatom taxa were identified from 15 genera in the samples analyzed. Of the 47 taxa, 23 were present at >5% abundance in at least one sample. Species assemblages and accumulations changed significantly as sediment depth decreased (Fig. 4). Diatom accumulations were lowest in the oldest section of the core analyzed (120–190 cm), becoming significantly higher during the period of deforestation and initial settlement (120–50 cm), followed by reduced accumulation levels during recent times (<50–0 cm). Although the recent sediments had reduced diatom accumulations, they were still higher than the 130–190 cm portion of the core (Fig. 4). There were also shifts observed in species composition and abundance, with dominant species changing during periods of changing sediment influx.

Through the 130–190 cm interval, flux rates and diatom accumulations were low. A significant change occurred between 120 cm and 130 cm which was reflected in observed changes in relative abundance for the dominant species. *Sellaphora pupula* (Kützing) Mereschkowksy was dominant at 190 cm (18% abundance), and still dominant at 160 cm (12%), but declined at 130 cm to 2.5% (Fig. 4). Similarly,

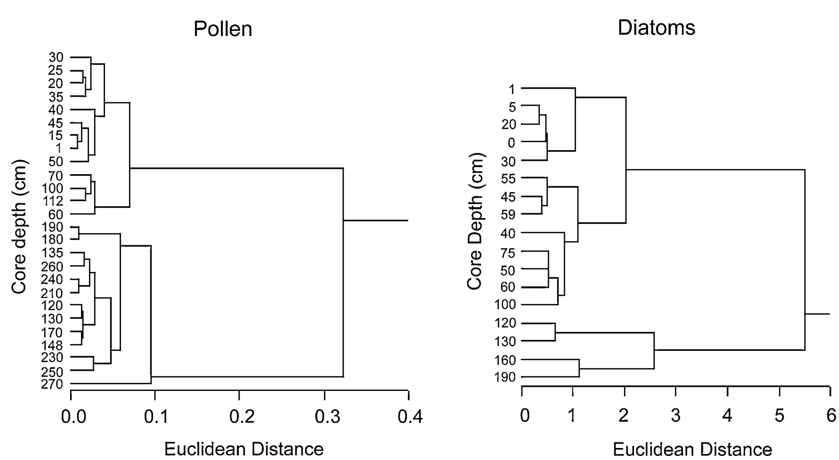

Fig. 3 Q-mode cluster dendrograms: pollen and diatom assemblage relationships with reference to sediment depth

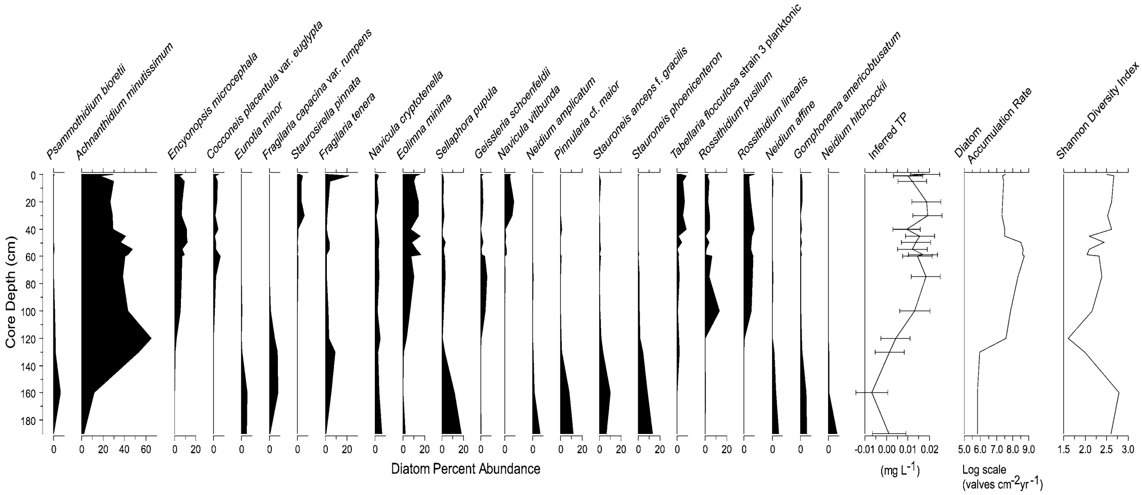

Fig. 4 Diatom species percent abundance, diatom-inferred phosphorus levels (TP), number of diatom valves cm^{-2} year^{-1} and Shannon Diversity Index (SDI) for Swan Lake, Ontario (from core AP-94-04)

Stauroneis phoenicenteron (Nitzsch) Ehrenberg, at 13% abundance was the second most dominant species at 190 cm, but decreased to 8% at 160 cm, and to 4% at 130 cm. Other species that were present in significant percentages at the lower depths and decreased at 130 cm include *Eunotia minor* (Kützing) Grunow, *Stauroneis anceps* f. *gracilis* Rabenhorst, *Neidium affine* (Ehrenberg) Pfitzer, and *Gomphonema americobtusatum* Reichardt and Lange-Bertalot. *Fragilaria tenera* (W. Smith) Lange-Bertalot increased in percent abundance at 130 cm and then became less abundant above this depth. *Achnanthidium minutissimum* (Kützing) Czarnecki increased to 53% abundance at 130 cm, and then to 65% abundance at 120 cm.

Using palynological evidence, the core depth at 120 cm was dated at A.D. 1850. Slightly above this horizon, at 100 cm, there were significant changes in diatom species composition with *A. minutissimum* declining to 43% relative abundance, and the appearance of *Rossithidium pusillum* (Grunow) Round and Bukhtiyarova at 13% (Fig. 4). Other taxa, such as *Encyonopsis microcephala* (Grunow) Krammer, *Eolimna minima* (Grunow) Lange-Bertalot, *Geissleria schoenfeldii* (Hustedt) Lange-Bertalot and Metzeltin, and *Rossithidium linearis* (W. Smith) Round and Bukhtiyarova, previously not observed in abundance in the lower portions of the core, also became more dominant (Fig. 4). In contrast, *Sellaphora pupula* and *Stauroneis phoenicenteron* numbers further declined at this depth.

Contemporary surface samples (0 cm) from 0.5 m to 4.2 m water depths show similar diversities emphasizing a littoral/benthic dominated lake system with highest numbers at 2.2 m depth and lowest numbers at 0.5 m depth. When comparing the contemporary surface samples with sediments from 190 cm depth, there were obvious changes in diatom numbers, as well as species assemblages. The taxa *S. phoenicenteron*, *Neidium hitchcockii* (Ehrenberg) Cleve, and *N. affine* were found in significant quantities in the oldest samples analyzed at the bottom of the core (190 cm) but absent in the contemporary surface sample (0 cm). Similarly, taxa such as *Navicula vitabunda* Hustedt, and *Cocconeis placentula* var. *euglypta* Ehrenberg were evident in significant percentages at 0 cm, but non-existent at 190 cm.

Q-mode cluster analysis confirms that species assemblages present at the bottom of the core were different than those at the top of the core (Fig. 3). The mean linkage of base pair comparisons has a Euclidean distance of 0.5. The cluster of species assemblages from 0 cm to 30 cm depth were linked to their nearest neighbour group (40–100 cm depths) at a Euclidean distance roughly two times the mean base linkage distance. Both of these clusters were further separated from the species assemblages at the bottom of the core (120–190 cm), clustering at a Euclidian distance five times the mean base-pair linkage distance.

The Shannon Diversity Index (SDI) values showed that samples found in the lower sections examined were more taxonomically diverse than samples recovered from the top of the core (Fig. 4). SDI values were highest at 160 cm (2.79) and the lowest value was observed at 120 cm (ca. 1850 A.D.). Above 120 cm, there was an improvement in species diversity, with the highest post-settlement values observed at 1 cm (SDI = 2.67).

Disturbance correlations

Current diatom-inferred TP (DI-TP) concentrations are slightly lower than measured values (by 2–3 μg l^{-1}) although well within error estimates (Fig. 4). Inferred TP concentrations in Swan Lake show significant changes in lake water conditions over time. Total phosphorus concentrations were lowest at 160 cm depth. Between 160 cm and 75 cm, inferred total phosphorus concentrations rose steadily to a maximum of 19.1 μg l^{-1} (Fig. 4). Above 75 cm depth, phosphorus concentrations followed a general downward trend; with a temporal increase around 30 cm. The 2003 surface sample indicates that current DI-TP concentrations are estimated around 19.3 μg l^{-1} (actual measured TP 21 μg l^{-1}). Inferred TP (DI-TP) using a more confined benthic/tychoplanktonic taxa inference model with a reduced taxa set gave the same temporal trends, although DI-TP estimates were approximately 3–4 μg l^{-1} lower (but still within error limits).

PCAs for the pollen and diatom assemblages had explained variances of 44% and 35% for the first factor and 15% and 13% for the second factor, respectively. Simple correlations of the factor scores between pollen and diatoms showed a strong correlation between pollen and diatoms for the first factor (Bartlett Chi-square statistic = 9.363; df = 1; $P = 0.002$) and no correlation was found for the second factor comparison (Bartlett Chi-square statistic = 0.028; df = 1, $P = 0.867$).

Temperature correlations

Regression analysis of air temperature data from the Swan Lake area (Environment Canada 2005a, b) shows a significant warming trend in spring, summer and winter monthly air temperatures, while average fall air temperatures generally declined from A.D. 1897 to A.D. 2003. Analyzed on a yearly basis, there is a general warming trend in the area (Fig. 5a). During the summer of 1995, water temperatures were collected every 2.5 h throughout each day from Swan Lake. There was a positive correlation ($r^2 = 0.632$, $P < 0.001$) between summer air and water temperatures, suggesting a direct link between regional climate patterns, water temperature and lake productivity (Fig. 5b). However, a simple Pearson product moment correlation showed no significant correlations between annual, spring, summer, fall and winter monthly air temperatures and individual diatom species abundance, relative abundances, or total diatom abundance.

Discussion

Fossil diatom assemblages and DI-TP concentrations

There has been a significant anthropogenic-induced change in water quality within Swan Lake from the pre-settlement period prior to A.D. 1797 to present day (Figs. 2 and 4). Prior to land settlement (160–190 cm section of core), the diatom flora was biologically diverse with relatively low numbers and low diatom productivity (Langman 1971; Garrison and Wakeman 2000; Patterson et al. 2002). Through the settlement and land clearing period, total diatom accumulations and species diversity showed dramatic increases over a short period from ca. A.D 1850 to A.D. 1870. After the establishment of the farm around Swan Lake (ca. A.D. 1879, Fig. 1), the biological diversity of the diatom flora returned, and numbers stabilized. The intermediate disturbance hypothesis (Connell 1978; Shea et al. 2004) predicts that environments under disturbance stressors (factored by frequency, extent, intensity, duration) will create more variable living conditions (available niche space, food resources, competition), which are congenial to high levels of species diversity. Although this hypothesis has received both positive and negative support on an ecosystem scale, it has been shown that, at the community scale, species diversity is typically higher under moderate

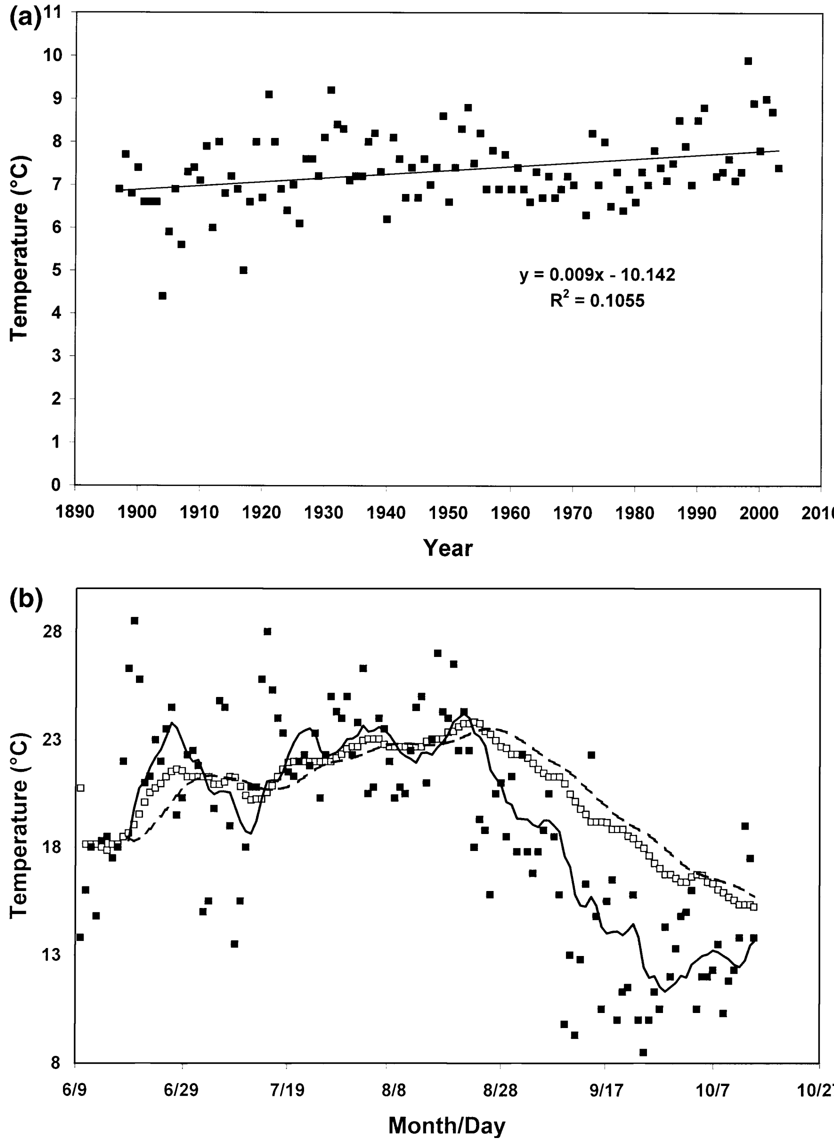

Fig. 5 Temperature relationships for Swan Lake and the immediate region: (**a**) Mean annual temperatures for Toronto Agincourt (A.D. 1897–1959) (43°46′ N; 79°16′ W) (Environment Canada 2005a) and Richmond Hill (A.D. 1960–2003) (43°52′ N; 79°27′ W) (Environment Canada 2005b). The *closed squares* represent the yearly mean temperature (°C), and the straight line is the linear regression line. (**b**) Average daily water temperatures (°C) (*open square* symbol) in Swan Lake (Hipwell et al. 1995) and average daily air temperature (*closed square* symbol) for Richmond Hill (Environment Canada 2005c) for June 9, 1995 to October 14, 1995. The solid line represents the 10-day running mean for air temperature and the dashed line represents the 10-day running mean for water temperature

disturbances (e.g., Sousa 1979, physical disturbances; Lubchenco 1978, biological disturbances). In Swan Lake, the physical disturbance of clear cutting and increased allochthonous sedimentation caused an initial drop in diatom diversity (high disturbance) followed immediately by a dramatic increase in diversity as the impact changed to a moderated or "intermediate" disturbance. Although estimates of diversity can be prone to error as a result of dilution effects in paleosediment records (Smol 1981), it is clear that increased influx levels changed pelagic and benthic habitats and only the observed taxa (taxa enumerated in comparible counts) can be considered successful survivors. Approximately 20 years later, at the end of the disturbance period, there was still instability in the diatom community although diversity metrics returned to pre-deforestation levels shortly thereafter. The higher levels of diversity shown before and after the massive deforestation disturbance are indicative of the temporal changes, or on-going moderate disturbances, that have affected Swan Lake. As would be predicted from an environmental disturbance, inferred total phosphorus concentrations increased first around A.D. 1820 (along with nitrogen) and supplied the nutrients for the subsequent increase in diatoms (Fig. 4) (Garrison and Wakeman 2000; Tong and Chen 2002). After ca. A.D. 1870, TP levels remained elevated (>15 μg l^{-1}) but through time have shown a general declining trend until present day (Fig. 4). This pattern in TP change after an anthropogenic disturbance had also been documented in lakes from Europe (Finsinger et al. 2006) and from North American lakes with altered drainage patterns (Ripley et al. 1997). The 3–4 μg l^{-1} difference in predicted versus actual DI-TP between whole community and the benthic/tychoplankton taxa models (Fig. 4; Table 1) reflects a poorer environmental gradient at higher TP levels using the benthic/tychoplankton model.

Inferred TP concentrations of <2 μg l^{-1} (below analytical detection limit) suggest that Swan Lake was ultra- to oligotrophic prior to ca. A.D. 1800. Prior to A.D. 1825, only three communities in Ontario had populations of 1000 or more inhabitants, and Toronto, then known as York, was one of them. The demographic composition of the province changed dramatically between A.D. 1825 and A.D. 1851 as the military encouraged settlement in the area by clearing land for agriculture and roads. As a result, Ontario's population soared from ~158,000 to ~952,000 in this short 26 year interval (Gentilcore and Wood 1978). The rapid removal of forest cover created erosional conditions for this type of soil (Hoffman and Richards 1955). Evidence of this population growth (anthropogenic erosion disturbance) is clearly indicated in the paleolimnological diatom record preserved in Swan Lake following the initial clearing of 5 acres adjacent to the lake by Mary Chambers between A.D. 1797 and A.D. 1800 (Archives of Ontario 1979). In the 130–120 cm depth interval (ca. A.D. 1835–A.D. 1850), diatom numbers increased 40-fold in association with a twofold increase in DI-TP. These drastic changes over such a short time interval highlight the degree of impact created by the settlers, more specifically the erosional influx increase to the lake, and the subsequent change in biology and water chemistry.

Between A.D. 1861 and A.D. 1891, Southern Ontario experienced further population growth, and roads were extended through this fertile agricultural area all the way to the Precambrian Shield to the north (Langman 1971). By 1878, the land surrounding Swan Lake was part of a subsistence farm owned by N. Shaver (Fig. 1), and all the adjacent properties had been cleared and were being actively farmed (Canniff 1869; McGill University 2001). This change in land use from A.D. 1850 to 1870 (i.e. elevated farming activity) was reflected in increased diatom accumulation, diversity and inferred TP levels reaching ~19 μg l^{-1}. Through this short 20-year period, Swan Lake had changed from oligotrophic to mesotrophic (TP > 15 μg l^{-1}), diatom numbers increased fivefold and Shannon Diversity was recovering after the initial settlement disturbance (at ca. A.D. 1850). This pattern of change in species diversity precisely matches that predicted by the intermediate disturbance hypothesis for an intense disturbance over a short period of time.

By the late 19th century, the settlers recognized that soil erosion problems were related to the almost complete removal of trees from the area, which in turn, was affecting farm productivity. Many farmers subsequently replanted trees as breaks to facilitate soil stabilization (Kelly 1978). This change in agricultural practice correlates with the decline in sediment influx (ca. A.D. 1870, Fig. 2) and the decline in species diversity and diatom numbers (ca. A.D. 1870–1880, Fig. 4). The young forest (<150-years-old) that immediately surrounds Swan Lake (CMN archived images) supports these results. From ca A.D. 1900 to 1950, inferred TP levels showed an increasing trend, while diatom accumulation and diversity remained stable. Through the latter years (ca. A.D. 1950–1970) the use of phosphate and manure-based fertilizers in southern Ontario increased significantly (150,000–300,000 tonnes per year; Bruulsema et al. 2004). The inferred TP concentration in the contemporary sediment samples (2003), estimated at 19 μg l^{-1}, is aligned with present TP levels and error estimates over the last 30 years, suggesting that TP level declines in recent times are at best minimal. Although we imply that changes in DI-TP concentrations in Swan Lake were solely the result of anthropogenic phosphorus loading, increased pelagic biological activity also enhanced the retention of nutrients (Reynolds 1984). The increasing presence of true planktonic diatoms in the recent sediments (especially *F. tenera* and *Tabellaria flocculosa* strain 3 planktonic) confirms that planktonic algal activity is capturing and maintaining a phosphorus pool in the water column.

Evidence of water quality changes in Swan Lake was also found when diatom assemblages and accumulations recovered from sediment before ca. A.D. 1850 were compared to those found after ca. A.D. 1850. Q-mode cluster analysis confirmed that diatom community associations from sediments at the bottom of the core were distinctly different from communities analyzed at the top of core (Fig. 3). R-mode cluster analysis further confirmed this trend (Fig. 4), with clear diatom species associations from the bottom to the top of the core. Larger, benthic, acid tolerant species including *Neidium* spp., *Eunotia minor*, *Pinnularia* spp., *Stauroneis* spp. and *Sellaphora pupula* were found in abundance at the bottom of the core. In the early phase of the settlement disturbance, *A. minutissimum* dominated the flora. *Achnanthidium minutissimum* is an opportunistic cosmopolitan invasive species that can tolerate a broad range of nutrient and disturbance conditions (Beaver 1981; Potapova and Hamilton 2007). As the disturbance continued and nutrients increased (A.D. 1850–A.D. 1870), other more alkaline, epiphytic and littoral species (i.e. *Encyonopsis microcephala*, *Cocconeis placentula* var. *euglypta*, *Eolimna minima*, *Geissleria schoenfeldii*, *Rossithidium* spp.) appeared in the lake. Over the last ~130 years the planktonic species *Tabellaria flocculosa* has increased in relative abundance and tychoplanktonic taxa like *Fragilaria pinnata*, *F. tenera* and *Navicula vitabunda* have become more prominent, thereby documenting the changing ion, pH and nutrient composition of the lake (Siver et al. 2004).

Land-use disturbances versus climate (A.D. 1897–A.D. 2003)

Diatom productivity is affected by water temperature (Patrick 1977; Weckström et al. 1997; Anderson 2000), and summer air temperatures are typically correlated with lake water temperatures (Livingstone and Lotter 1998). For the present study, differences between ground-water and lake-water chemistry, along with a high positive correlation between air and water temperature (Pearson product moment correlation of 0.632, $r > 0.999$) during the spring and summer of A.D.1995 confirmed that water temperatures in Swan Lake are primarily influenced by local air temperatures and not ground waters. This indirectly suggests that the productivity of Swan Lake, as measured by diatom accumulation levels and community composition, could be linked to changing regional temperatures. Regression analysis of mean air temperature data from 1897 to 2003 (Environment Canada 2005a, b) has shown a weak local decadal warming trend in winter temperatures ($y = 0.0119x - 26.53$; $r^2 = 0.071$; $P = 0.01$; df = 106), spring temperatures ($y = 0.0122x - 18.02$; $r^2 = 0.074$; $P = 0.005$; df = 106) and to a lesser extent in summer ($y = 0.0073x + 5.35$; $r^2 = 0.050$; $P = 0.025$; df = 106). This warming trend poses the possibility that regional climate may be having an impact on Swan Lake. However, as might be predicted (based on proximity to a large urban city [Toronto] and current water chemistry), the generally warmer regional air (and implied water) temperatures over the last century (ca. 1.3°C increase in air temperature) are presently not enough to change the biology of Swan Lake as indicated by the lack of any correlation with diatom species composition, accumulations or relative abundances. Even with a one-step correction for a possible time-delayed response, we could not find any associations. Therefore, the benthic diatom floras observed in the Swan Lake sediment do not indicate significant changes in lake biology and inferred water chemistry as a result of water temperature changes. The absence of specific data on winter/summer diatom growth and winter water temperatures limits the resolution of these findings to longer decadal or even century level measures of biological change. Moreover, any changes resulting from recent warming may have been masked by extensive land-use changes occurring over the same period.

Comparisons with other proxies and studies

The strong correlation between diatoms and pollen for the first factor in the PCA analyses link terrestrial and aquatic environment changes to a single environmental factor, or selected set of factors. PCA biplots clearly separate *Pinus* and *Tsuga* pollen (mature forest), from *Ambrosia* and Poaceae (grassland) across factor 1, which represents logging and land clearing by European settlers. Other environmental stressors which are captured in factor 2 are not linked between the terrestrial and aquatic systems. Therefore, it must be concluded that the primary factor changing both terrestrial and aquatic environments is deforestation and agricultural development. More specifically, marked increases in *Ambrosia* pollen densities at 130 cm depth (just prior to ca. A.D. 1850) indicated that logging and burning of forest in the area (Caniff 1869; Bradbury and Waddington 1973) was the main factor that changed water quality and diatom biodiversity. Further, the significant reduction of tree pollen in the lake sediment record also clearly matches the documented historical deforestation records for the region (Gentilcore and Wood 1978).

The sedimentology of the core clearly highlights a significant influx to the lake between ca. A.D. 1820 and 1870. The influx material was predominantly clay, which is also the dominant soil below the 15 cm thick leafy litter. Destabilization of the thin leaf litter layer through deforestation and agriculture easily freed subsurface clays for migration into Swan Lake and the clay sediment record in the lake is linked precisely with the arrival of European settlers who undertook widespread logging and land clearing to make space for farming (Fig. 1). Prior to ca. 1820, sediment influx was low (0.38–0.23 cm year^{-1}) and the composition of the sediment was predominantly gyttja. After ca. A.D. 1870, sedimentation returned to gyttja, although influx levels were higher than before European settlement. This sedimentation pattern has also been observed in other lakes across eastern North America, highlighting the significance of the range and degree of land disturbance experienced during the 1800s (Hill 1976; Moore et al. 1997; Francis and Foster 2001).

Previous work in Lake St. George (Fig. 1, immediately adjacent to Swan Lake) has shown that the introduction of herbicides and pesticides resulted in rapid shifts in species assemblages (Hamilton et al. 1988; Solomon et al. 1992). These almost immediate changes (within hours and days) indicate that local land use practices can rapidly alter the community structure of local lakes. Another study on Swan Lake has also detected changes in arcellacean (thecamoebian) and pollen assemblages from pre- A.D. 1850 to present day (Patterson et al. 2002), indicating alterations in biology and lake water quality.

The most significant changes in land use observed in Swan Lake using arcellaceans (thecamoebians) as biological indicators was recorded around 1850 when a species shift from *Difflugia oblonga* to *Cucurbitiella tricuspis* was observed (Patterson et al. 2002). The thecamoebian change correlates with changes in historical land use, diatom biodiversity and accumulation rates, and regional deforestation (Gentilcore and Wood 1978). This correlation indicates that aquatic taxa within the thecamoebians and diatoms are powerful indicators of terrestrial land use disturbances and urbanization.

Another important alteration in species composition noted by Patterson et al. (2002) occurred ca. A.D.1950 (around 20 cm depth) when *Pediastrum*, a planktonic freshwater algae, showed a dramatic increase, which concurs with the appearance of the planktonic *Tabellaria flocculosa* strain 3. In addition, the high inferred TP levels ($\sim$18 μg l^{-1}) from this research (A.D. 1930–A.D. 1950) correlates with the dominance of the thecamoebian *Cucurbitella tricuspis* (Carter), a species characteristic of nutrient enriched conditions (Torigai et al. 2000; Patterson and Kumar 2002). Patterson et al. (2002) interpreted the dominance of *C. tricuspis* to be indicative of high yield fertilizer use on adjacent fields. Interestingly, DI-TP concentration showed a fluctuating trend, moderately declining from A.D. 1950 to 1994 with present day estimates showing peak levels (19 μg l^{-1}) (Fig. 4; Table 1).

With recent advancements of the human footprint model, it is more evident than ever that most of the global landmass has been impacted by land-use development (Sanderson et al. 2002). Large areas classified as undisturbed land now number less than 10, and include areas in northern North America, western North America, central South America, north-central Africa, southwestern Africa, northern and central Asia, northern Scandinavia, Australia and south-eastern Saudi Arabia. This study of Swan Lake, and many other studies like it, clearly indicate that significant human impacts on aquatic lake systems can occur with <50 individuals km^{-2}, and can happen in a short span of less than a decade. As experienced in Swan Lake, recovery to a stable state is slow, and Swan Lake will likely not return to pre-disturbance conditions.

Conclusions

Swan Lake has undergone significant anthropogenically-induced changes in water chemistry and biology through time, as directly indicated by changes in diatom assemblages, thecamoebian assemblages (Patterson et al. 2002), and indirectly by changes in land-use records, sediment flux, and pollen concentrations. With rapid influx changes (i.e. anthropogenic disturbance) diatom species diversity initially decreased, immediately followed by an increase as predicted by the intermediate disturbance hypothesis. Species showing a competitive advantage as a result of the habitat and nutrient disturbance (like *Achnanthidium minutissimum*) quickly filled the niche. Inferred TP concentration changes corresponded with changing land-use practices (deforestation, reforestation, fertilizer application) from ca. A.D. 1850 to the 1980's. The results of this study explicitly imply that in the post-settlement period, anthropogenic impact on lakes within the Oak Ridges Moraine have been significant. The biological record indicates that limnological conditions within Swan Lake have stabilized through the last 30–50 years and are presently being driven primarily by planktonic biological processes. The lake has not returned to pre-settlement water conditions. Since all of these proxies show the same trends, this multiproxy dataset must be considered significant and detailed paleolimnological studies like this one of Swan Lake, in tandem with global human footprint studies, can be utilized to realistically estimate land-use impacts on a global scale.

Acknowledgements This study was funded by an NSERC Discovery Grant awarded to Dr. R. T. Patterson, by two RAC grants awarded to P. B. Hamilton (2005–2006) from the Canadian Museum of Nature, and research funding supplied to Dr. T. Anderson from the Geological Survey of Canada (NR Can). We gratefully acknowledge Dr. Dörte Köster and one anonymous reviewer for comments that greatly improved the manuscript.

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