

# An Assessment of Environmental Changes in Three Lakes from King's County (Nova Scotia, Canada) Using Diatom-Based Paleolimnological Techniques

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Paleolimnological approaches using sedimentary diatom assemblages were used to assess water quality changes over the last approximately 200 years in three lakes from King's County, Nova Scotia. In particular, the role of recent shoreline development in accelerating eutrophication in these systems was assessed. Sediment cores collected from each lake were analyzed for their diatom assemblages at approximately 5-year intervals, as determined by  $^{210}\text{Pb}$  dating. Analyses showed that each system has changed, but tracked different ecosystem changes. Tupper and George lakes recorded shifts, which are likely primarily related to climatic warming, with diatom assemblages changing from a preindustrial dominance by *Aulacoseira* spp. to present-day dominance by *Cyclotella stelligera*. In addition to the recent climatic-related changes, further diatom changes in the Tupper Lake core between approximately 1820 and 1970 were coincident with watershed disturbances (farming, forestry, and construction of hydroelectric power infrastructure). Black River Lake has recorded an increase in diatom-inferred total phosphorus since about 1950, likely due to impoundment of the Black River system for hydroelectric generation and subsequent changes in land runoff. Before-and-after (i.e., top-bottom) sediment analyses of six other lakes from King's County provided further evidence that the region is being influenced by climatic change (decreases in *Aulacoseira* spp., increases in planktonic diatom taxa), as well as showing other environmental stressors (e.g., acidification). However, we recorded no marked increase in diatom-inferred nutrient levels coincident with shoreline cottage development in any of the nine study lakes. Paleolimnological studies such as these allow lake managers to place the current limnological conditions into a long-term context, and thereby provide important background data for effective lake management.

**Key words:** paleolimnology, eutrophication, Nova Scotia, diatoms, climate change, acidification

## Introduction

Many aquatic ecosystems are being threatened by multiple large-scale environmental stressors such as acidification, nutrient inputs, and climatic change. While monitoring changing limnological conditions is essential for proper ecosystem management, most systems lack detailed long-term data which are required to place current limnological conditions into a broader temporal context. Fortunately, these missing instrumental data can often be inferred using paleolimnological techniques (Smol 2008).

Paleolimnology uses the physical, chemical, and biological information preserved in lake sediments to reconstruct past limnological conditions (Smol 2008). By studying changes in biological assemblages and other indicators from sections of dated sediment cores, and comparing these with current limnological conditions, environmental changes can be assessed and put into a long-term perspective. Paleolimnology can be used to track a wide range of environmental conditions including changes in acidic deposition (e.g., Battarbee et al. 1990; Cumming et al. 1994; Ginn et al. 2007a), climate (e.g.,

Smol and Cumming 2000; Rühland and Smol 2002; Laird et al. 2003; Smol and Douglas 2007), lake depth (e.g., Moos et al. 2005), fish populations (e.g., Sweetman and Finney 2003; Gregory-Eaves et al. 2004), mining effects (e.g., Salonen et al. 2006), urban development (e.g., Meriläinen et al. 2003), nutrient inputs (e.g., Tibby 2004; Reid 2005), as well as contaminant transport (e.g., Donahue et al. 2006). While a wide variety of chemical and biological indicators have been used in paleolimnological studies, diatoms (Bacillariophyceae), a dominant algal group in many freshwater systems, are the most widely used because they are well preserved in lake sediments, are ecologically diverse, and show quantifiable responses to environmental change (Stoermer and Smol 1999).

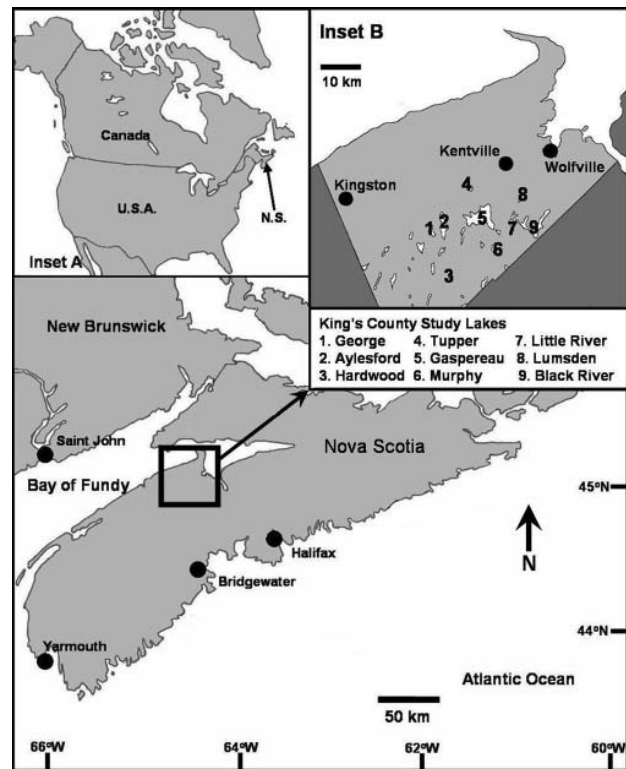
The majority of studies on eutrophication have focused on lakes with large-scale nutrient inputs (Schindler 1987), however the role of smaller-scale increases in nutrient levels, such as those following moderate shoreline development, are less well studied. Previous paleolimnological investigations of the effect of lakeshore cottage development on trophic status in Canada have focused on lakes in central Ontario, where cottage development has been particularly intense. These studies have addressed concerns of lake managers, such as nutrient inputs from cottages (e.g., Hall and Smol 1996; Wilkinson et al. 1999), taste and odour problems

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(Paterson et al. 2004), and decreases in hypolimnetic oxygen (Clerk et al. 2000; Quinlan and Smol 2002). These paleolimnological studies have shown a variety of responses by lakes to diffuse inputs of nutrients associated with seasonal cottages. However, to date, no long-term studies have been undertaken on the effect of cottage development in Atlantic Canada.

Nova Scotia, located on the Atlantic coast of Canada (Fig. 1), has approximately 9,400 lakes larger than 1 ha. The province was first settled by Europeans in 1605 and traditional land use has centered on forestry and agriculture, both of which continue today. Due to this relatively long North American settlement history, most lakes have been impacted, to varying degrees, by anthropogenic changes. One region of Nova Scotia that has undergone a recent increase in the amount of shoreline development, and the focus of this investigation, is King's County (Fig. 1). Located on the Bay of Fundy coast and approximately 100 km from the city of Halifax, King's County has historically been the primary agricultural region of the province with 526 km<sup>2</sup> (or 25% of the county area) under cultivation, resulting in an estimated benefit of about \$378 million to the provincial economy (Statistics Canada 2001). However, since the mid 1980s, the number of seasonal and permanent homes has increased, especially on lakefront properties, and lake managers have expressed concern that shoreline development has affected water quality and may be responsible for algal blooms, excessive macrophyte growth, problems with taste and odour, and changes in fish stocks. Monitoring efforts, however, have only been in place for the past decade and lack information on pre-disturbance (preindustrial or presettlement) conditions.

While previous paleolimnological studies in Nova Scotia have primarily focused on tracking the effects of acidic deposition (Ginn et al. 2007a, 2007b), other studies have assessed changes in drinking water quality (Tropea et al. 2007), impacts of road construction (Ginn et al. 2008a), and the overriding influence of climatic change (Ginn et al. 2008b). The objectives of this current study were to track long-term environmental changes in three lakes from King's County, Nova Scotia, that have undergone varying degrees of shoreline development and other watershed disturbances. Before-and-after (or top-bottom) analyses of sediment cores from six other lakes were added to the three detailed primary study lakes to provide a better overall assessment of possible environmental changes in the greater King's County region. While the level of cottage development is not as high as in central Ontario, these catchments represent some of the highest levels of cottage development in Nova Scotia. In the three detailed studies, we track which environmental stressors have affected the water quality of these systems.



**Fig. 1.** Maps showing the location of study lakes in King's County, Nova Scotia, Canada. Inset A shows the location of Nova Scotia (N.S.) within the context of North America; Inset B shows the study lake locations in King's County.

## Materials and Methods

### Site Descriptions

The three detailed study lakes (George, Black River, and Tupper) are located in the Municipality of King's County, Nova Scotia (Fig. 1), on South Mountain, a long elevated ridge running along the south of the Annapolis River Valley (Davis and Browne 1996). In addition to these three primary study lakes, six other King's County lakes (Aylesford, Hardwood, Gaspereau, Murphy, Little River, and Lumsden lakes; Fig. 1) were studied in a before-and-after approach to compare current limnological conditions (Table 1) with those before cottage development. The area around all nine study lakes was twice settled by Europeans, first during the Acadian period (~1680 to 1755) and continuously since the arrival of Loyalist refugees following the United States Revolutionary War (~1780s). The area has traditionally been used for farming and logging, with the forests being cleared several times since settlement. Current forests are classified as Acadian mixed forests (coniferous-deciduous) with dominant tree species being spruce, hemlock, pine, aspen, oak, and maple (Davis and Browne 1996). Soils are thin, well drained, and glacially derived, whereas the bedrock is sandstones, slates, and granites (Davis and Browne 1996).

**TABLE 1.** Selected physical and chemical data for nine study lakes in King's County, Nova Scotia

Lake	Latitude	Longitude	Depth (m)	Elevation (m)	Surface area (ha)	pH	DOC <sup>a,b</sup> (mg/L)	Alkalinity <sup>a</sup> (mg/L)	TP <sup>c,d</sup> ( $\mu\text{g/L}$ )
George	44°55'N	64°42'W	9.0	231	153	6.3	5.3	2.8	17.5
Black River	44°58'N	64°23'W	19.0	170	668	6.9	8.4	2.4	19.0
Tupper	45°01'N	64°35'W	3.0	201	36	6.3	5.3	4.0	7.2
Aylesford	44°57'N	64°40'W	12.0	216	532	5.9	7.0	1.8	10.1
Murphy	44°54'N	64°31'W	6.8	207	121	6.8	4.0	8.3	n/a <sup>e</sup>
Lumsden	45°01'N	64°28'W	15.5	126	88	6.2	7.8	2.9	15.2
Little River	44°57'N	64°28'W	4.5	189	520	6.0	8.2	2.7	11.5
Gaspereau	44°58'N	64°33'W	10.9	175	2200	6.0	7.3	2.1	n/a
Hardwood	44°51'N	64°39'W	7.0	208	120	6.2	8.2	2.8	27.5

<sup>a</sup> Average values from monthly sampling, May through October 2004–2007, courtesy King's County Lake Monitoring Program.

<sup>b</sup> DOC = dissolved organic carbon.

<sup>c</sup> Integrated sample from the epilimnion in midsummer, courtesy Peter Dillon (Trent University).

<sup>d</sup> TP = total phosphorus.

<sup>e</sup> n/a = not available.

**Lake George.** Lake George (44°55.0'N, 64°41.9'W, elevation: 231 m above sea level) has extensive development in its catchment, including seasonal cottages and year-round homes, a public access beach, a vacation trailer park, and the waterfront recreation area for the Lake George Provincial Park. The lake has a maximum depth of 9 metres, a surface area of 153 ha, is circumneutral (pH = 6.3) (Table 1), and drains into the Gaspereau River. Forestry is the main historical use of the land in this area (Davis and Browne 1996). Despite having a higher elevation than other systems used for hydroelectric generation in the Gaspereau watershed, Lake George has no history of impoundment.

**Black River Lake.** Black River Lake (44°58.3'N, 64°22.7'W, elevation: 170 m above sea level) was dammed in 1930 and again in 1950 by Nova Scotia Power to provide hydroelectric power generation. While some cottage development has occurred along the shoreline, the area was traditionally used for farming or logging since European settlement, and approximately 45% of the catchment is currently cleared (Davis and Browne 1996). The lake is relatively large for this area, with a surface area of 668 ha. The lake has a maximum depth of 19 metres, and thermal stratification occurs in the deepest regions. Due to wetlands and coniferous forests in the catchment, as well as drowned trees (due to dam construction), the lake is coloured by chromophoric dissolved organic carbon (DOC = 8.6 mg/L, colour = 65 relative units, 2005 to 2006 means) but is circumneutral (lake water pH = 6.9) (Table 1).

**Tupper Lake.** Tupper Lake (45°01'N, 64°35.4'W, elevation: 201 m above sea level) is the smallest of the three main study lakes (surface area = 36 ha, maximum depth = 3 m) and the least cottage-developed with few homes in an otherwise forested catchment. In contrast to George and Black River lakes, Tupper Lake drains into the Cornwallis River. The catchment has been logged several times throughout its history, and, in the 1950s, a

sawmill (which operated until the early 1970s) was built on the shoreline. Currently, the lake is circumneutral (pH = 6.3) and oligotrophic (total phosphorus [TP] = 7.2  $\mu\text{g}\cdot\text{L}^{-1}$ ) (Table 1).

**Other King's County Lakes.** The six lakes analyzed using the top-bottom (before-after) approach have a range of limnological conditions (Table 1) as well as a variety of development histories. Many of the forests in the region were cut to support the local shipbuilding industry in the region in the early 1900s, which may have included those around these lake systems. Like Black River Lake mentioned above, several other systems in the Gaspereau watershed have been impacted by impoundment for hydroelectric generation. Water levels in Gaspereau Lake were elevated during the 1930s, and again during the 1950s at the same time as Black River Lake. Lumsden Pond was created in 1941 by the flooding of a river valley, and connects to Black River Lake via an 8.4-km long canal, which is controlled by a hydroelectric generating station. The flooding of this river valley submerged a large area, including forests and a road, the remains of which were still visible when Lumsden Pond was drained temporarily in 1996.

The degree of current shoreline development from cottages and permanent dwellings varies in these six lakes. Aylesford and Murphy lakes have moderate to heavy shoreline development, including public beaches, while Little River and Hardwood lakes have few dwellings, with their catchments being primarily forested. Finally, Gaspereau and Lumsden lakes have limited shoreline development, with these systems being used primarily for hydroelectric means by Nova Scotia Power.

### Sediment Core Collection

Sediment cores were collected from the nine study lakes in July 2005 using a Glew gravity corer (internal diameter = 7.6 cm) equipped with a 50-cm long Lexan core tube (Glew 1989; Glew et al. 2001). The cores were

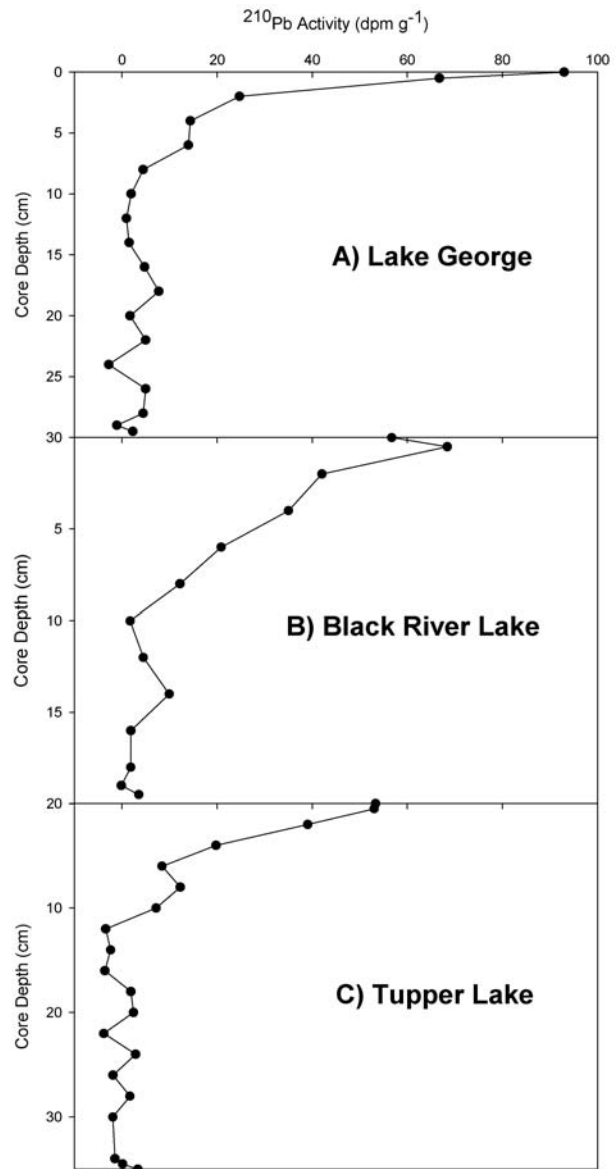
sectioned at 0.5-cm intervals using a Glew (1988) vertical extruder, placed in individual Whirl-Pak sample bags, and stored at approximately 4°C. The sediment cores obtained from the three detailed core lakes (George, Black River, and Tupper) were analyzed every 2.0 cm throughout the length of the core, an integrated sample with a resolution of approximately 5 years of sediment accumulation (as established by  $^{210}\text{Pb}$  dating). The detailed core analyses provide a full picture of the history of the lake throughout the time period represented by the gravity sediment core (between approximately 100 to 200 years). The remaining six study lakes were processed for before-and-after (or top-bottom) analyses where surface sediments (representing the past few years) were compared with those from a core depth of below 15.0 to 15.5 cm (which were analyzed to infer precottage development environmental conditions). In the case of Aylesford, Murphy, and Gaspereau lakes, a third sample from 25.0 to 25.5 cm was analyzed, which represented conditions approximately 150 years before the primary predisturbance sample at 15.0 to 15.5 cm. Thus, the two predisturbance samples can be used to assess natural environmental changes and directly compare these to changes since cottage development began. From these sediment intervals a snapshot of the environmental changes that have occurred from predisturbance times to the present can be compared.

### Diatom Preparation and Analysis

Diatoms were isolated from the sediment using a 1:1 molar ratio of  $\text{HNO}_3$  and  $\text{H}_2\text{SO}_4$ , as outlined in Battarbee et al. (2001), and mounted on slides using Naphrax. A minimum of 300 diatom valves were enumerated per sample using a 100X oil immersion objective (numerical aperture = 1.3) on a Leica DMRB microscope equipped with differential interference contrast (DIC) optics. Diatoms were identified to the lowest taxonomic level possible using Patrick and Reimer (1966, 1975), Krammer and Lange-Bertalot (1991, 1997, 1999, 2000), Round et al. (1990), Camburn and Charles (2000), and other references fully described in Ginn et al. (2007c). In addition, the number of chrysophyte stomatocysts was enumerated since an increase in the ratio of stomatocysts to diatom valves can be a useful index of increasing trophic status (Smol 1985).

### Radiometric Dating

Sediment samples from each of the three detailed core lakes were dried using a Virtis freeze dryer, and approximately 0.5 g of sediment from each interval was placed in individual plastic test tubes for  $^{210}\text{Pb}$  dating following the procedures of Schelske et al. (1994) and Appleby (2001). Radioactive decay was analyzed using an Ortec germanium (Ge) crystal detector for 80,000 s.  $^{210}\text{Pb}$ ,  $^{214}\text{Bi}$ , and  $^{137}\text{Cs}$  activities (Fig. 2) were calculated using procedures outlined in Schelske et al. (1994). Sediment core chronologies were calculated using the

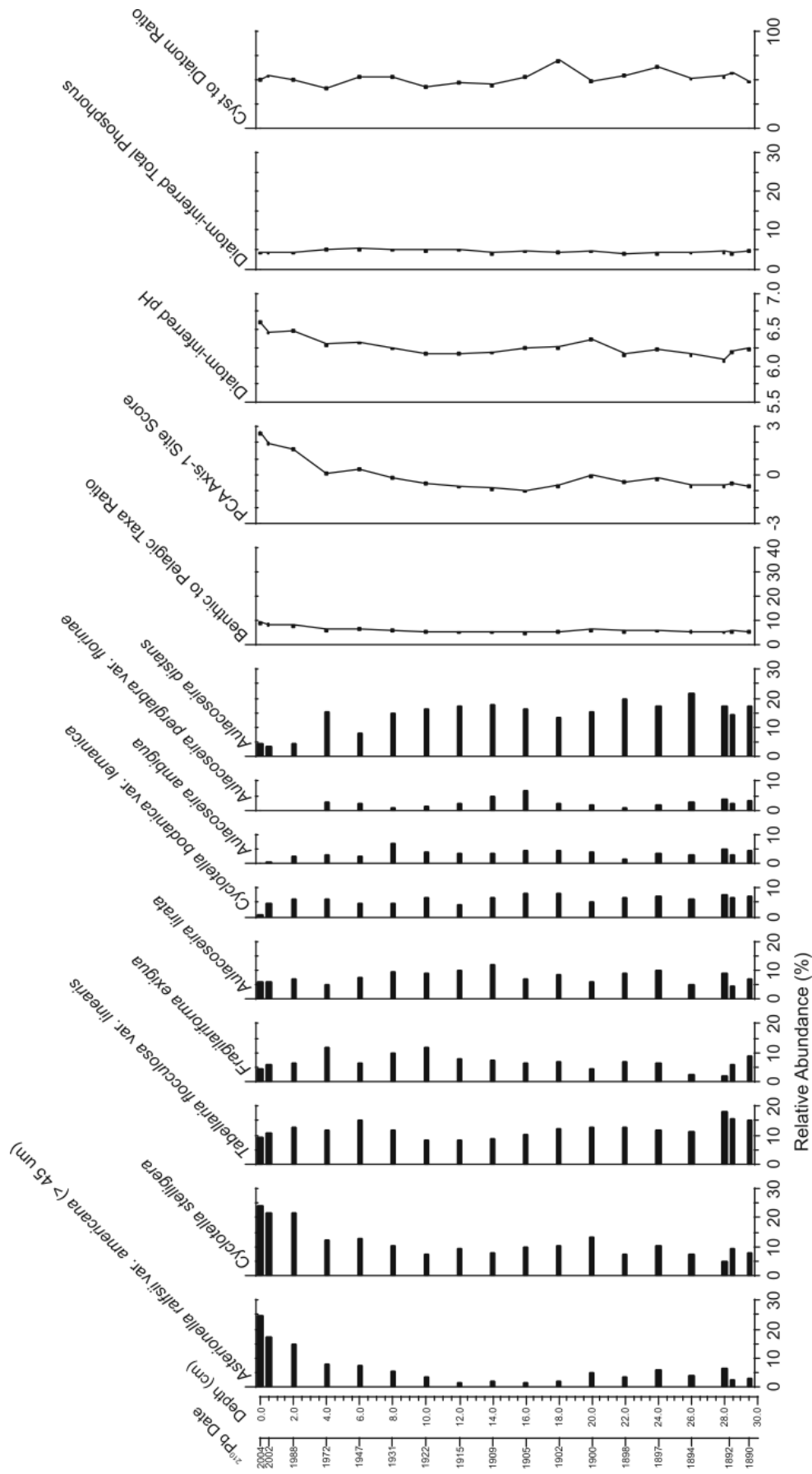


**Fig. 2.**  $^{210}\text{Pb}$  activity (disintegrations per minute per gram dry sediment) plotted versus core depth (cm) for A) Lake George; B) Black River Lake; C) Tupper Lake.

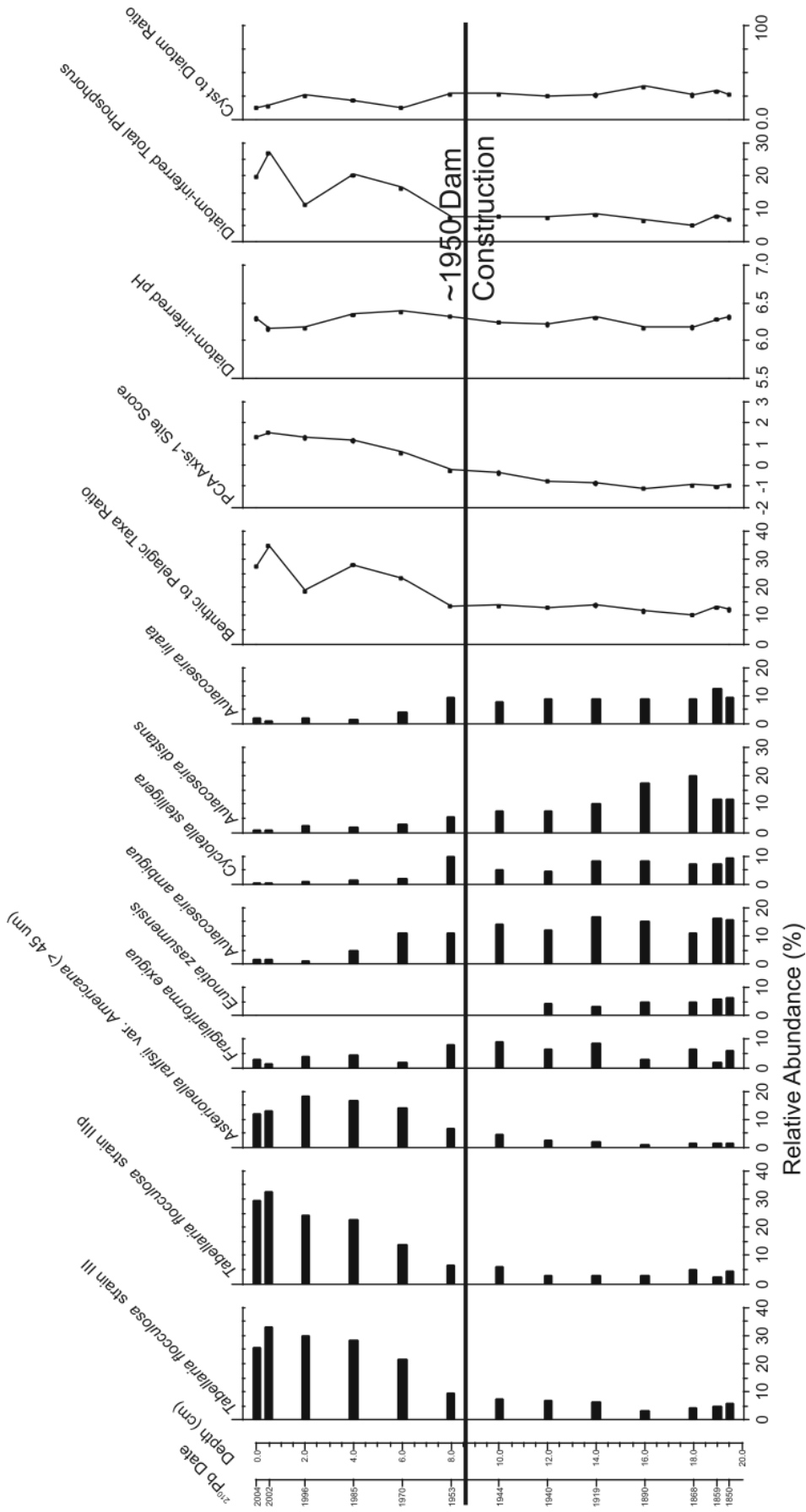
constant rate of supply (CRS) model (Appleby and Oldfield 1978) using the computer program developed by M.W. Binford (1990, University of Florida).

### Statistical Analysis and Inference of Limnological Variables

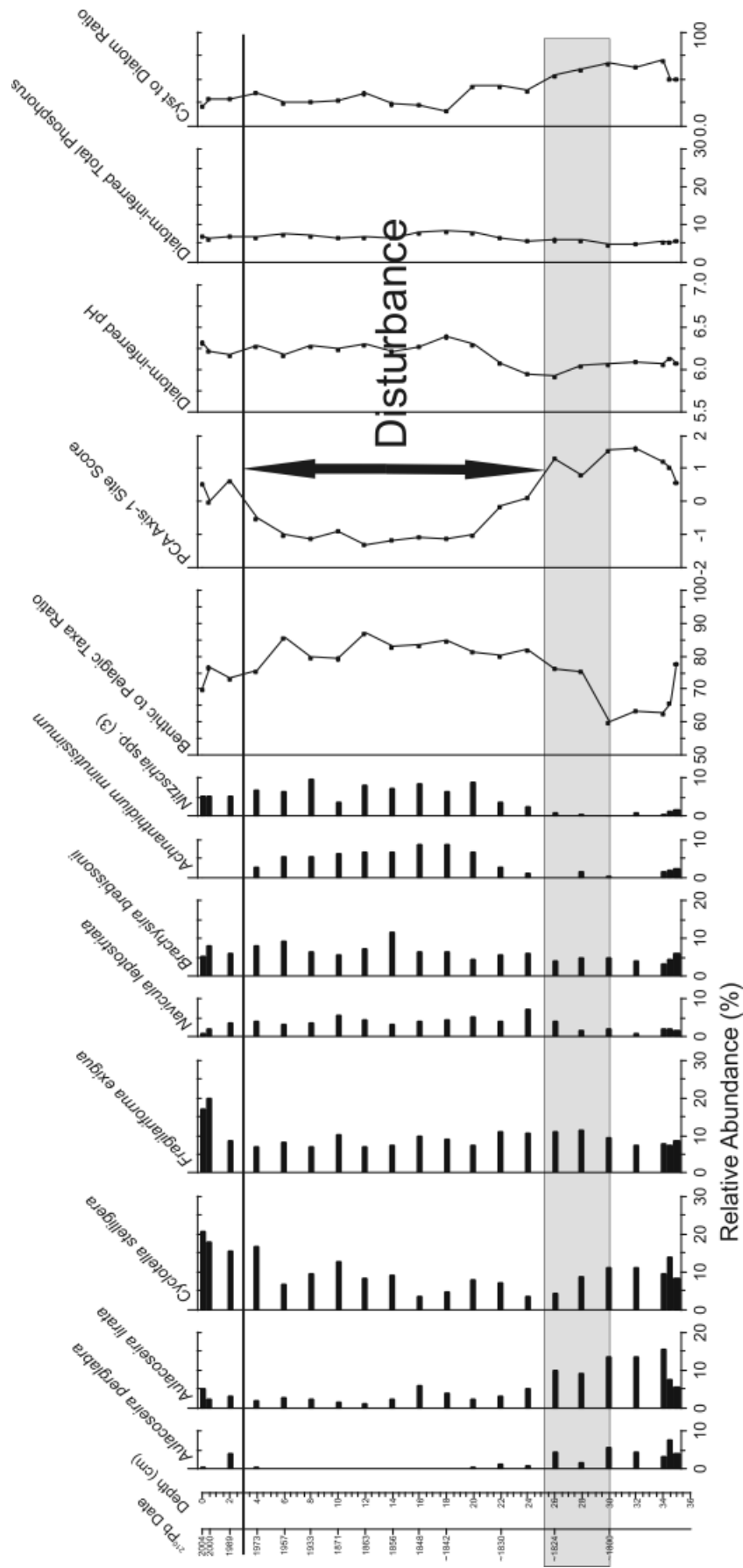
Relative abundances of diatom taxa were analyzed by principal components analysis (PCA) using the computer program CANOCO v.4.5 (ter Braak and Šmilauer 2002). PCA axis-1 site scores were used to compare the main direction of variation in the diatom assemblages. The diatom-based transfer function for Northeastern North America (NENA) developed by Ginn et al. (2007c) was used with the maximum likelihood model to infer the TP



**Fig. 3.** Relative abundance of the dominant diatom taxa (>5%) and diatom-inferred limnological variables from Lake George, King's County, Nova Scotia. Abbreviations: PCA = principal components analysis sample scores; cyst to diatom ratio = ratio of chrysophyte cysts to diatom frustules.



**Fig. 4.** Relative abundance of the dominant diatom taxa (>5%) and diatom-inferred limnological variables from Black River Lake, King's County, Nova Scotia. Abbreviations: PCA = principal components analysis sample scores; cyst to diatom ratio = ratio of chrysophyte cysts to diatom frustules. The timing of hydroelectric dam construction (1950), known from historical records, is indicated by the solid line.



**Fig. 5.** Relative abundance of the dominant diatom taxa (>5%) and diatom-inferred limnological variables from Tupper Lake, King's County, Nova Scotia. Abbreviations: PCA = principal components analysis sample scores; cyst to diatom ratio = ratio of chrysophyte cysts to diatom frustules. The grey zone corresponds to the approximate timing of the onset of disturbance (between ~1800 and ~1820), likely related to logging and farming in the catchment. The solid line indicates the end of the inferred period of catchment disturbance, based on changes in the diatom assemblage.

and pH. The strength and significance of the pH model was similar to other studies (RMSEP = 0.45,  $r^2_{\text{boot}} = 0.88$ ), while the TP model had a lower predictive ability (RMSEP = 0.46,  $r^2_{\text{boot}} = 0.24$ ) (Ginn 2006; Ginn et al. 2007a, 2007c). Correlations of PCA axis-1 scores with inferred limnological variables were determined using the computer program SYSTAT v.11.0. Figures of  $^{210}\text{Pb}$  activity were generated using SigmaPlot v.10.0. Relative frequency diagrams of the dominant diatom taxa (>5% abundance) and inferred limnological variables were generated using the computer programs TGView v.2.0.2 (Grimm 2004) and C2 (v.1.4, S. Juggins, University of Newcastle, U.K.), with diatom taxa arranged by their PCA axis-1 species scores.

## Results

### Lake George

Diatom assemblages from Lake George were relatively stable from the 1850s to about 1970, during which time the most abundant diatom taxa were the tychoplanktonic *Aulacoseira distans* (Ehrenberg) Simonsen and the planktonic *Tabellaria flocculosa* var. *linearis* J.D. Koppen (Fig. 3). Since about 1972 (core depth = 4 cm), the diatom assemblage has been dominated by *Cyclotella stelligera* Cleve et Grunow in Cleve and *Asterionella ralfsii* var. *americana* (>45  $\mu\text{m}$ ) Körner (McIntyre and Duthie 1993) (Fig. 3). This notable change is reflected in the PCA axis-1 site scores. While there were minor fluctuations, overall diatom-inferred pH and diatom-inferred TP were relatively stable throughout the core. The ratio of chrysophyte stomatocysts to diatom frustules did not change throughout the length of the core.

### Black River Lake

The diatom assemblages in Black River Lake record a marked change in species assemblages in about 1950 (core depth = 8 cm) (Fig. 4); before then, the diatom assemblage was dominated by *Aulacoseira* spp., with benthic diatom taxa making a contribution to the assemblage. Since about 1950, the abundance of *Aulacoseira* spp. *C. stelligera* and benthic taxa have decreased, and the assemblage is now dominated by *Tabellaria flocculosa* strains III and IIIp (Roth) Kützig *sensu* J.D. Koppen. Similarly, there has been an increase in diatom-inferred TP from 8.0 to 10.0  $\mu\text{g}\cdot\text{L}^{-1}$  before 1950, to a postimpact maximum of 28  $\mu\text{g}\cdot\text{L}^{-1}$  (current measured TP = 19.0  $\mu\text{g}\cdot\text{L}^{-1}$ ). The increase in diatom-inferred TP was highly correlated with PCA axis-1 scores ( $r = 0.88$ ,  $p < 0.01$ ). The ratio of chrysophyte stomatocysts to diatom frustules decreased at the top of the core (~1996) and was strongly negatively correlated ( $r = -0.82$ ,  $p < 0.01$ ) to diatom-inferred TP throughout the time period represented by this sedimentary record. The diatom-inferred pH remained stable throughout the core at approximately 6.3 units.

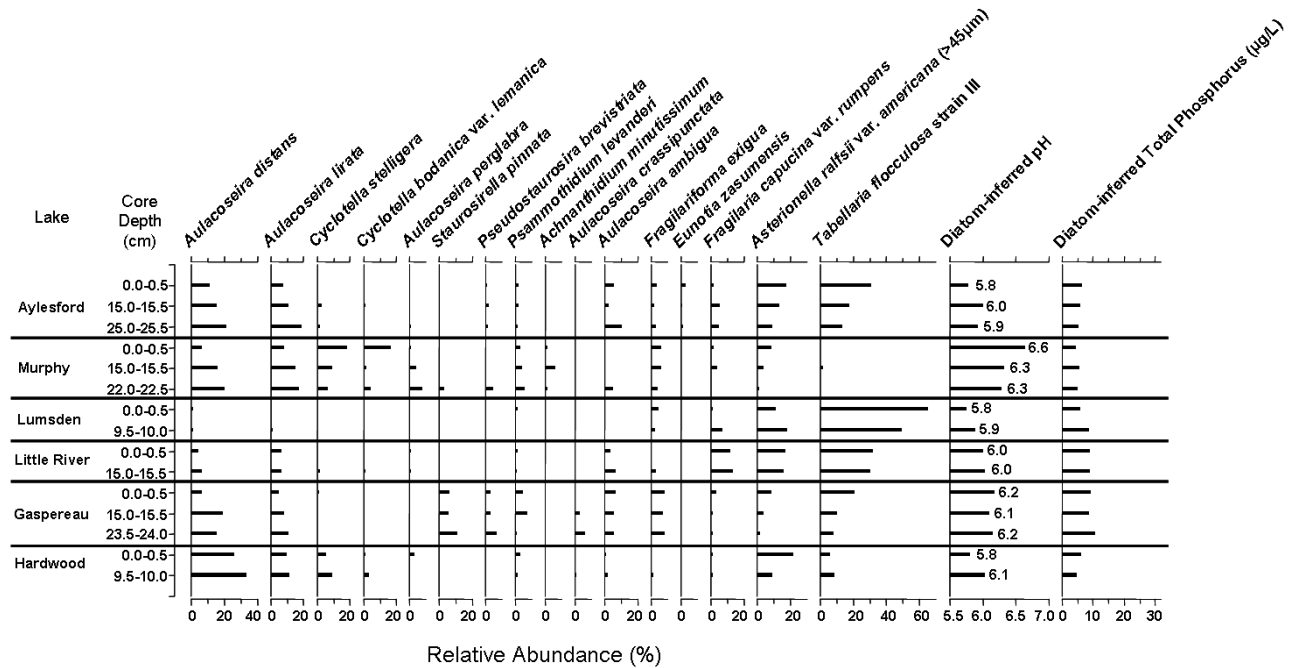
### Tupper Lake

The diatom assemblages in the Tupper Lake sediment core have undergone a number of changes during the last approximately 200 years (Fig. 5). Prior to about 1828 (core depth = 22.0 cm), the assemblages were dominated by *Aulacoseira lirata* (Ehrenberg) R. Ross, *C. stelligera*, and *Fragilariforma exigua* (Grunow) Krammer and Lange-Bertalot. In around 1800, the relative percentage of the assemblage made up of benthic taxa increased, however the relative abundances of these dominant taxa did not change at that point. Between about 1828 and 1973, these abundant taxa were replaced in dominance by several benthic species, including *Navicula leptostriata* Jørgensen, *Nitzschia* spp., and notably *Achnantheidium minutissimum* (Kützig) Czarnecki. During this time, there was also an increase in the diatom-inferred TP from 4.0 to 5.0  $\mu\text{g}\cdot\text{L}^{-1}$  to approximately 8.0  $\mu\text{g}\cdot\text{L}^{-1}$ . This increase in diatom-inferred TP is strongly and negatively correlated to the PCA axis-1 scores ( $r = -0.81$ ,  $p < 0.01$ ). Since about 1973, these taxa (*N. leptostriata*, *Nitzschia* spp., and *A. minutissimum*) have declined in relative abundance, with the current diatom assemblage being dominated by *C. stelligera* and *F. exigua*, while the diatom-inferred TP has remained at close to 6.0  $\mu\text{g}\cdot\text{L}^{-1}$  (measured midsummer TP is currently 7.2  $\mu\text{g}\cdot\text{L}^{-1}$ ). It is interesting to note that, unlike *C. stelligera* and *F. exigua*, *A. lirata* was not observed to return to the same dominance in the core after about 1973 as was observed prior to about 1828. Despite the importance of planktonic species, such as *C. stelligera*, the majority of the diatoms recorded in the sedimentary record of Tupper Lake, for about the last 200 years, were benthic, with between 60 and 90% of the assemblage being made up of benthic, pennate taxa (Fig. 5). When comparing the ratio of chrysophyte stomatocysts with diatom frustules, the ratio was found to decrease since preindustrial times, with the decrease corresponding to the observed increase in the ratio of benthic to pelagic taxa in about 1800 (core depth 30.0 cm). This decrease, as in Black River Lake, correlated negatively to the inferred TP level ( $r = -0.79$ ,  $p < 0.01$ ). The diatom-inferred pH increased slightly from a predisturbance value of 6.0 to 6.3 in about 1828.

### Present-Day versus Predisturbance Assemblages

Before and after (i.e., top-bottom) sediment core analyses of the remaining six study lakes also showed a number of changes between present-day and precottage development sedimentary diatom assemblages (Fig. 6). Two lakes (Aylesford and Hardwood) have recorded a change in diatom assemblage dominance by *Aulacoseira* spp. to present-day dominance by *Asterionella ralfsii* var. *americana* (>45  $\mu\text{m}$ ), although only Hardwood Lake showed a significant decrease in diatom-inferred pH (0.3 units). Murphy Lake showed a decrease in *Aulacoseira* spp. in surface sediments relative to bottom sediments, as well as a concurrent increase in the abundance of *C. stelligera* and *A. ralfsii* var. *americana* (>45  $\mu\text{m}$ ), similar





**Fig. 6.** Relative abundance of the dominant diatom taxa (>5%) and diatom-inferred limnological variables in a before-and-after (i.e., top-bottom) sediment survey of six lakes from King's County (Nova Scotia, Canada), which compares current diatom assemblages, diatom-inferred pH, and diatom-inferred TP to those from precottage development time periods.

to the assemblage shift observed in Lake George. Diatom assemblages in Lumsden Pond and Gaspereau Lake show a similar trend to those in Black River Lake, with an increase in the relative abundance of *T. flocculosa* strain III in the upper portion of the sediment archive. Little River Lake recorded no major changes in sedimentary diatom species assemblages as determined by before and after analyses.

## Discussion

### Lake George

The changes in diatom assemblages in Lake George (Fig. 3) are consistent with primarily climate-related changes over about the past 110 years. Heavily silicified, tychoplanktonic *Aulacoseira* spp., especially *Aulacoseira distans*, were the dominant taxa and represented as much as 40% of the relative diatom abundance below 4.0 cm (before ~1970). After about 1970 (core depth = 4.0 cm), the relative abundance of *A. distans* decreased markedly, and *A. distans* was replaced by *Cyclotella stelligera* and *Asterionella ralfsii* var. *americana* (>45 µm) as codominant taxa. While the timing of this *C. stelligera* increase began in about the 1940s, *C. stelligera* became the dominant taxon since the 1980s, and *A. distans* decreased in relative abundance to below 5%. The likely cause of this change is an increasing temperature trend, which results in reduced ice cover and a longer period of lake thermal stratification (e.g., Harris et al. 2006; Ginn et al. 2008b; Rühland et al. 2008). Based on instrumental temperature records from nearby Halifax, mean annual temperatures

have increased by 1.5°C since 1870, with a 0.8°C increase in mean summer temperature since 1948 (see Ginn et al. 2008b). Heavily-silicified *Aulacoseira* spp. require more frequent mixed water in order to survive in the photic zone, whereas the planktonic and more lightly-silicified *Cyclotella* spp. can survive in stratified waters and out-compete *Aulacoseira* spp. (Rühland et al. 2008). This 20<sup>th</sup> century warming trend has been observed in other lakes in Nova Scotia (Ginn et al. 2008a, 2008b), nearby New Brunswick (Harris et al. 2006), and numerous other lakes around the world (Smol et al. 2005; Rühland et al. 2008).

Observations by local residents of algal blooms in Lake George during summers since the mid 1970s do not appear to be due to increased nutrient inputs, based on paleolimnological data, as the diatom-inferred TP has remained relatively stable over about the past 110 years. However, the inferred increased thermal stratification caused by warmer waters may have enhanced the competitive abilities of blue-green algae (Cyanobacteria), which also thrive in warmer, stratified waters (Paerl and Huisman 2008). Modelling studies have also concluded that cyanobacteria have the potential to dominate phytoplankton communities under increased temperature regimes (Elliott et al. 2006). Algal blooms have been reported primarily during the late summer, when the lake is more strongly stratified and warmest.

### Black River Lake

Sedimentary diatom assemblages from Black River Lake (Fig. 4) show that the system has also been

affected by environmental changes that are most likely a result of changes in the watershed (e.g., forestry and dam construction), which would mask other changes (e.g., climate). The change in approximately 1950 in diatom assemblages and the concomitant increase in diatom-inferred TP coincide with the construction of a hydroelectric dam and major changes in the watershed (Mackay P., personal communication [Nova Scotia Power]). Black River Lake has a history of hydroelectric generation that dates back to the early 1930s when the first dam was constructed (Fig. 4); however, major environmental changes likely began in the late 1940s when drainage from Gaspereau Lake was routed into the Black River system. This change in drainage pattern involved flooding an area that was previously forested (the remains of submerged trees still pose a threat to local boat traffic) and impoundment of the river, and resulted in an increase in both the lake's surface area and water residence time. The flooding of and changes in land runoff in an agricultural catchment led to increases in the nutrient input. In addition, the decomposition of inundated vegetation, as well as leaching of nutrients from flooded soils, has been shown to cause increased nutrient flux to reservoir systems (Kennedy and Walker 1990). The changed hydrology of the system following its impoundment (e.g., longer residence time) would also have likely changed the nutrient fluxes, enhancing the probability of eutrophication. The shift to the strains of *T. flocculosa* in Black River Lake likely also reflects hydrological changes, since the depths of the water was increased following dam construction (maximum depth is currently 19 m). The observed decrease in the relative abundance of *C. stelligera* likely also reflects this eutrophication as a result of hydroelectric impoundment, as *C. stelligera* is recognized as an oligotrophic taxon (Wunsam et al. 1995; Ginn et al. 2007c), which would be less able to compete under higher nutrient conditions.

When examining the ratio of chrysophyte stomatocysts to diatom frustules, the ratio of cysts to diatoms decreased as diatom-inferred TP increased (Fig. 4). This relationship was strongly and negatively correlated ( $r = -0.82$ ,  $p < 0.01$ ). This follows the conclusions made by Smol (1985) who suggested that a greater ratio of cysts to diatoms indicates more oligotrophic conditions in Ontario lakes. Our data indicate that the timing of the construction of hydroelectric generating stations, and associated changes in Black River Lake, were linked to this change in the cyst to diatom ratio, and this provides further evidence that the system eutrophied at this time.

### Tupper Lake

The sediment core from Tupper Lake (Fig. 5) represents the longest history of the three lakes, with the deepest sediments in the core estimated to have been deposited in about 1790. Over this time period, the diatom assemblages have undergone several changes. Around 1820, *Achnanthydium minutissimum* increased to about 8 to 9% relative abundance, which we infer

to represent the onset of watershed development, as *A. minutissimum* has been shown to occur following catchment development (e.g., Garrison and Wakeman 2000). The timing of this disturbance may have begun as early as 1800 based on the observed increase in the percentage of benthic taxa and the decrease in the ratio of chrysophyte cysts to diatom frustules (Fig. 5). This approximately 150- to 170-year long watershed disturbance is likely related to several historically known periods of logging followed by the cleared area being used for a series of small farms (Griffiths J. personal communication [Municipality of King's County]), which likely added nutrients to the lake as shown by a slight ( $4.0 \mu\text{g}\cdot\text{L}^{-1}$ ) increase in diatom-inferred TP. In 1922, a small hydroelectric generating station was constructed on the lake (Mackay P., personal communication [Nova Scotia Power]), which likely caused additional disturbances, as well as the approximately 1950 construction of a sawmill to process trees harvested in the catchment. The close to 1970 decrease in *A. minutissimum*, along with the decrease in inferred TP, indicate the system had likely recovered from these disturbances. It is known that the local sawmill closed at approximately this time. Currently the watershed is forested and has very few (~10) seasonal cottages. In addition, most of the diatom taxa have returned to predisturbance abundances with the exception of the *Aulacoseira* taxa.

The diatom assemblages from the Tupper Lake core may also track a warming trend, similar to that described for Lake George. The predisturbance diatom assemblage was dominated by *Aulacoseira* spp. and *C. stelligera*, both of which decreased in abundance during the disturbance between about 1822 and 1970. However, following recovery from the disturbance, the assemblage was again dominated by *C. stelligera*. The lack of a return of the *Aulacoseira* spp. complex (particularly *A. lirata*) can also likely be attributed to increased temperatures in the water body as a result of 20<sup>th</sup> century warming trends (similar to our discussion of Lake George). However, due to the shallow nature of the system, which undergoes continual mixing throughout the ice-free season, better adaptation to thermally stratified waters cannot explain the dominance of *C. stelligera*, as the lake does not undergo thermal stratification. It is likely that *C. stelligera* dominance is due to less ice cover, which allows *C. stelligera* to persist later into the fall/winter (Smol 1988; Rühland et al. 2008). However, the timing of the onset of climate influence in this system is difficult to assess due to the watershed disturbances described above, which resulted in a decreased abundance of *C. stelligera*, and therefore blurred the timing of the onset of climate warming.

Therefore, based on sedimentary diatom assemblages, we conclude that Tupper Lake has been influenced by both disturbances in its catchment, as well the recent (post-1950) climate warming that has affected the region.

## Present-Day versus Predisturbance Diatom Assemblages

In addition to the detailed paleolimnological analyses described above, other environmental changes were inferred using the before-and-after (i.e., top-bottom) approach in six King's County lakes (Fig. 6). Murphy Lake showed a shift in dominance from a preimpact assemblage of *Aulacoseira* spp. to an assemblage dominated by *C. stelligera*, similar to the shifts described for lakes George and Tupper. This is also further evidence that the lakes of this region have been affected by 20<sup>th</sup> century climate warming. The increase in *Cyclotella* is not observed in all lakes due to the masking effect by other, more pronounced environmental stressors (e.g., acidification in Hardwood Lake, watershed disturbance in Gaspereau, Lumsden, Aylesford, and Black River lakes). Two lakes (Aylesford and Hardwood) have undergone changes in diatom assemblages that may also reflect the impact of a decrease in lake water pH (Fig. 6), although only Hardwood Lake shows a significant acidification signal. In these lakes, the diatom assemblage changed from dominance by *A. distans* and *A. lirata* to a present-day dominance by *A. ralfsii* var. *americana* (>45 µm). This change has been recorded in other Nova Scotia lakes that contain high (>5 mg/L) amounts of chromophoric dissolved organic carbon and have been affected by acidic deposition (Ginn et al. 2007a, 2007b). These lakes have an acidic preindustrial pH due to the presence of organic acids from dissolved organic carbon with diatom-inferred lake water pH values of 5.7 to 6.0 units. These lakes have become more acidic, likely due to deposition of sulphate from long-range transport (Clair et al. 2001).

Diatom assemblage changes in Lumsden Pond and Gaspereau Lake show similar trends to those observed in Black River Lake, and also likely reflect their history of use for hydroelectric generation. The flooding of a river valley in the case of Lumsden Pond, and the increase in the surface area of Gaspereau Lake following dam construction led to changes in the hydrology of these systems, which seems to have favoured the planktonic diatom *T. flocculosa* strain III, as was also observed in the detailed core analysis from Black River Lake. Based on the diatom assemblages determined in the top-bottom portion of this investigation, it appears that only Little River Lake has not been affected by some form of environmental change in about the last 100 years. However, detailed core analyses might provide further evidence for environmental changes in all of these six systems, as the top-bottom approach provides only a snapshot of conditions from which to interpret diatom-inferred changes.

## Recent Shoreline Development

The original goal of this investigation was to determine what (if any) impact recent (post-1970) shoreline development, in the form of seasonal cottages, has had

on the water quality of lakes in the King's County region, several of which are heavily used for these recreational purposes. While diatom assemblages have inferred environmental changes in all but one system in the region over about the last 150 years, the timing and type of assemblage shifts we observed are not consistent with any marked eutrophication trends that could be related to increased shoreline development. Eutrophication, which was inferred to have occurred only in Black River Lake, predates the establishment of cottages. On the contrary, detailed core studies of three of the nine lakes in the region show a trend towards slightly decreased TP in about the last 10 years, a trend that has been described previously in Ontario lakes (Hall and Smol 1996). This trend towards recent decreases in TP can likely be attributed to several factors, including decrease in the runoff of nutrient-rich materials from farms, better lake management by local residents, as well as decreased nutrient availability as a result of recent climate warming (e.g., Hall and Smol 1996).

## Conclusions

Despite the fact that this investigation found no evidence of marked recent eutrophication as a result of shoreline development, diatom assemblages have shown that lakes in King's County have been affected by a variety of environmental stressors over the last one to two centuries. While the sedimentary diatom assemblages recorded changes consistent with climate warming in three lake systems, and no significant environmental changes in one King's County lake (Little River), based on these findings it appears clear that climate warming has affected lakes in King's County, as has been documented through other paleolimnological investigations in the Maritimes (e.g., Harris et al. 2006; Ginn et al. 2008a, 2008b). Lack of similar changes in diatom species assemblages in all of the study sites may be due to differences in lake depth (Table 1), or masking by other environmental changes (e.g., landscape disturbance, acidification). In addition to climate as an environmental stressor, hydrological alterations to facilitate hydroelectric generation have resulted in changes in water quality in three lake systems in this region.

Using paleolimnological techniques, we were able to establish precottage development reference conditions for these lakes, which were lacking predisturbance instrumental data. From our results, lake managers will be able to put current conditions into better perspective. These data will facilitate environmental planning in response to future changes in these systems.

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