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PRIMARY RESEARCH PAPER

Glasgow Lake: an early-warning sentinel of lake acidification in Cape Breton Highlands National Park (Nova Scotia, Canada)

Alexandra M. Gerber · Brian K. Ginn ·
Colin J. Whitfield · Peter J. Dillon ·
Brian F. Cumming · John P. Smol

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Abstract In contrast to other lakes studied in Cape Breton Highlands National Park (Nova Scotia, Canada), our paleolimnological results indicated that Glasgow Lake has been impacted by acidic deposition starting in the early 1900s. Based on analysis of diatom assemblages, the lake experienced a decrease in diatom-inferred lakewater pH from a pre-industrial pH of $\sim$5.8 to a current pH of 5.3 (2000–2002 measured mean pH = 5.0) as well as a decrease in diatom-inferred Gran-alkalinity. In this study, diatom-based paleolimnological techniques were used in conjunction with a dynamic biogeochemical model (MAGIC) to assess both the timing and extent of the acidification trend, as well as determine a probable explanation as to why this lake, and none of the other 15 Cape Breton Highlands lakes studied for paleolimnology thus far, acidified under a peak non-marine sulphate deposition load of 43.6 $\text{mmol}_c\ \text{m}^{-2}\ \text{year}^{-1}$ in the mid-1970s. Steady-state models estimate that Glasgow Lake had the lowest buffering capacity of six study lakes and estimated critical sulphate loading of $<1\ \text{mmol}_c\ \text{m}^{-2}\ \text{year}^{-1}$. MAGIC also estimated a loss of charge balance alkalinity from a pre-1850 value of 38 $\mu\text{mol}_c\ \text{l}^{-1}$ to a low of 12 $\mu\text{mol}_c\ \text{l}^{-1}$. While no evidence of biological recovery has been recorded, MAGIC estimates an increase in charge balance alkalinity to 27 $\mu\text{mol}_c\ \text{l}^{-1}$ in 2002 in response to decreased SO_2 emissions. Of the five other lakes that were modelled, all showed trends towards more acidic states and subsequent increases in charge balance alkalinity; however, the empirical paleo-diatom approach applied to these lakes showed no evidence of acidification. Thus, Glasgow Lake has the lowest buffering capacity among the Cape Breton Highland study lakes and serves as a sentinel of potential acidification trends and recovery in this region.

Keywords Nova Scotia · Acidification · Diatoms · Paleolimnology · MAGIC · Biogeochemical modelling

Introduction

Surface-water acidification due to deposition of anthropogenic-sourced strong acid anions has affected the ecology and chemistry of lakes in Nova Scotia, a

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A. M. Gerber · B. K. Ginn (✉) · B. F. Cumming ·
J. P. Smol
Paleoecological Environmental Assessment and Research Laboratory (PEARL), Department of Biology, Queen's University, Kingston, ON, Canada K7L 3N6
e-mail: b.ginn@lsrca.on.ca

C. J. Whitfield
Watershed Ecosystems, Trent University, Peterborough, ON, Canada K9J 7B8

P. J. Dillon
Department of Environment and Resource Studies, Trent University, Peterborough, ON, Canada K9J 7B8

province in the Atlantic region of Canada. In this province, sulphate (SO_4^{2-}) deposition is generally highest in the southwest [~39.5 mmol$_c$ m^{-2} year^{-1} (19.0 kg ha^{-1} year^{-1}) (2000–2002), with peak deposition estimated at 63.6 mmol$_c$ m^{-2} year^{-1} (30.5 kg ha^{-1} year^{-1}) in 1973], a region that is closest to major emission sources (in central Canada, midwestern USA and northeastern USA), and thus receives higher levels of SO_4^{2-} deposition introduced by long-range atmospheric transport (Clair et al., 2001). Sulphate deposition decreases towards the northeast of the province with the exception of an area east and downwind of local SO_4^{2-} sources at the city of Halifax (Clair et al., 2001). Previous studies by Ginn et al. (2007a, b, c) and Tropea et al. (2007) identified major environmental changes due to acidic inputs in lakes in Kejimkujik National Park and around Halifax, but little evidence of widespread lake acidification in other areas of the province. In these studies, before-and-after paleolimnological techniques (i.e. top–bottom sediment analysis, see Smol, 2008 and Cumming et al., 1992) were used to compare current biological assemblages of diatoms and associated inferences of pH with pre-industrial (i.e. pre-1850) assemblages (Ginn et al., 2007a). Of the 16 paleolimnology study lakes in Cape Breton Highlands National Park, Glasgow Lake was the only study site that recorded evidence of diatom-inferred acidification since the 1800s (Ginn et al., 2007a). In addition to the 16-site before-and-after paleolimnological studies, six of these lakes were used for a decadal-scale detailed analysis, although changes in the diatom assemblages of these lakes were related to climatic influences rather than surface-water acidification (Ginn et al., 2007b). Paleolimnological techniques have not only been used to assess impacts from acidification, but also a wide variety of environmental issues such as drainage from mine sites (Salonen et al., 2006), increased nutrient loading (e.g. Miettinen et al., 2005), climatic changes (e.g. Laird et al., 2003; Moos et al., 2005; Smol & Douglas, 2007), fish populations (e.g. Gregory-Eaves et al., 2003), organic pollutants (e.g. Krümmel et al., 2005) and other lake management issues (e.g. Ginn et al., 2008).

In addition to the paleolimnological analyses, biogeochemical modelling techniques were used to assess the impact of acidic deposition across Nova Scotia, including six lakes in Cape Breton Highlands National Park. Whitfield et al. (2006a) presented critical loadings of SO_4^{2-} for the region where Glasgow Lake was demonstrated to have the lowest critical load among the six modelling study lakes. Additionally, the dynamic Model of Acidification of Groundwater In Catchments (MAGIC: Cosby et al., 1985) was used to reconstruct pre-acidification chemical conditions of the lakes, as well as to estimate temporal changes during the period 1850–2100 (Whitfield et al., 2007).

The objectives of this study were to examine the timing and nature of acidification trends recorded in Glasgow Lake, which had previously only been inferred based on an estimate of pre-industrial and present-day pH inferences from diatom assemblages (Ginn et al., 2007a), and to determine why this lake, and no other study lake in Cape Breton Highlands National Park, recorded a decrease in diatom-inferred pH.

Material and methods

Study site and sediment core collection

Glasgow Lake (46°49.2′ N, 60°29.5′ W, elevation: 419 m above sea level) is located on the taiga plateau of Cape Breton Highlands National Park (Fig. 1; Table 1). Mean long-term precipitation and runoff are 1.44 and 1.06 m year^{-1}, respectively. While this park has a variety of ecosystems ranging from coastal forests and seashores, the taiga plateau has elevations 300–500 m above sea level and a climate more typical of subarctic regions with long winters, high winds and a sudden spring freshet in late April or May. Vegetation in this region consists of shrubby conifers, *Sphagnum* bogs and subarctic scrub (Davis & Browne, 1996).

The sediment core from Glasgow Lake was collected through 1.5 m of ice in March 2004 using a Glew gravity corer (Glew, 1989; Glew et al., 2001) equipped with a 7.6-cm internal diameter, 50-cm long Lexan® tube. The core was sectioned at 0.25 cm intervals using a Glew (1988) extruder with separate intervals placed in individual Whirl-Pak® bags, stored on ice and kept ~4 C for transport back to the lab and subsequent storage.

Radiometric dating

Sediment samples were dried using a Virtus® freeze dryer, and ~0.5 g of each core interval was placed in

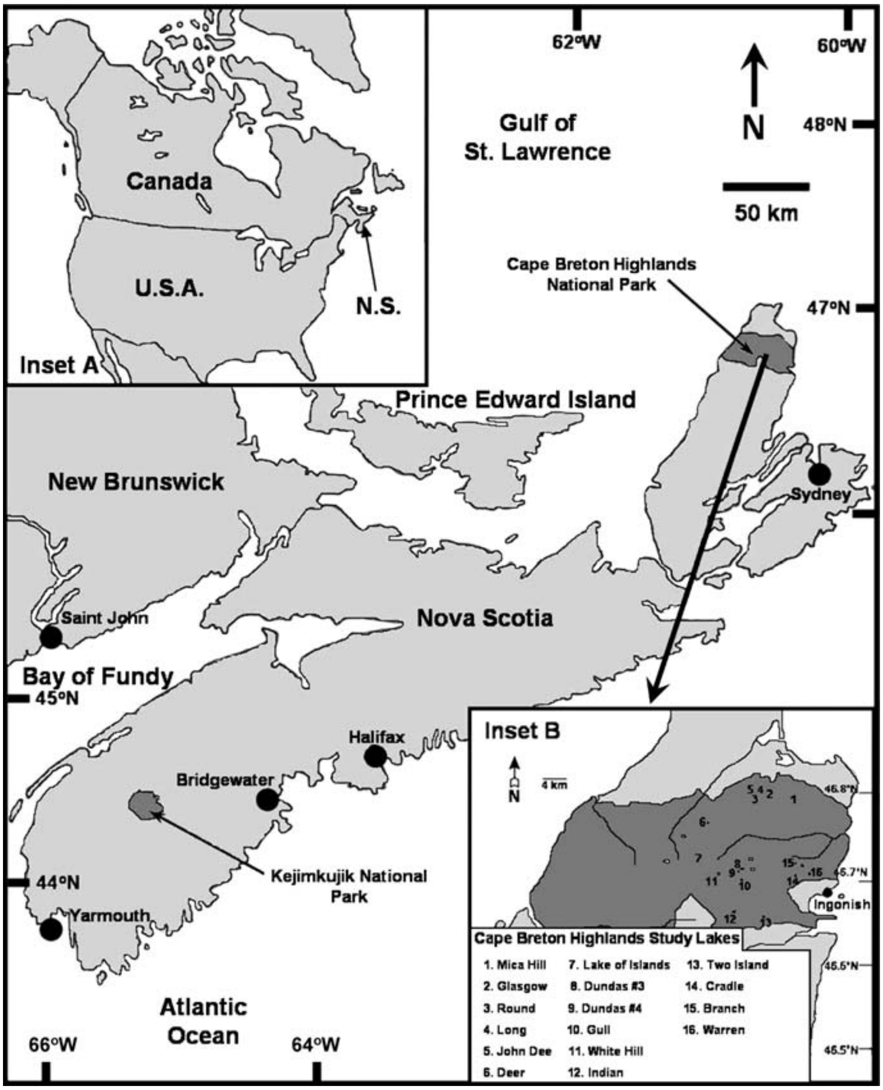

Fig. 1 Map showing the location of Cape Breton Highlands National Park and other study regions, in Nova Scotia, Canada. Inset A shows the location of Nova Scotia (NS) within the context of North America. Inset B shows the location of the 16 study lakes in Cape Breton Highlands National Park

plastic test tubes for ^{210}Pb gamma dating following procedures outlined by Schelske et al. (1994). Activities of ^{210}Pb, ^{226}Ra, ^{214}Bi and ^{137}Cs were calculated based on procedures outlined by Schelske et al. (1994) using an Ortec® germanium (Gr) crystal well detector for 80,000 s. Dates were calculated using the constant rate of supply (CRS) model with a computer program developed by Binford (1990, University of Florida).

Diatom preparation and analysis

Diatoms were isolated from the sediment using a 1:1 molar ratio of HNO_3 and H_2SO_4 as described by Battarbee et al. (2001) and mounted on slides using Naphrax®. A minimum of 300 diatom valves were enumerated per sample using a 100× oil immersion objective (NA = 1.3) on a Leica® DMRB microscope equipped with DIC optics. Diatoms were identified to the lowest taxonomic level possible using Patrick & Reimer (1966, 1975), Krammer & Lange-Bertalot (1991–2000), Round et al. (1990), Camburn & Charles (2000), Fallu et al. (2000), Wehr & Sheath (2002) and other references fully described in Ginn et al. (2007c).

Statistical analysis and inference of pH and Gran-alkalinity

Lakewater pH was identified in a canonical correspondence analysis (CCA) as the most important limnological variable influencing the distribution of diatom taxa in a dataset from northeastern North America, a dataset used to develop diatom-based pH (and other limnological variables) inference models based on a number of approaches (the NENA dataset; Ginn et al., 2007c). Here, we use the maximum likelihood model since it was the most robust model, although other techniques yielded similar results (Ginn, 2006; Ginn et al., 2007c). This pH model has strong predictive ability ($r^2_{\text{boot}} = 0.88$; RMSEP $= 0.45$) and was highly significant ($P < 0.001$). The Gran-alkalinity model was slightly less robust ($r^2_{\text{boot}} = 0.75$; RMSEP $= 0.38$) but still significant ($P < 0.05$). Relative frequency diagrams of the dominant diatom taxa (>5%) were constructed using the computer program C2 (version 1.4; S. Juggins, University of Newcastle), with diatoms arranged by principal components analysis (PCA) axis-1 species scores. PCA axis-1 site scores were used to track downcore variation. PCA of the 11 measured chemical and physical limnological characteristics was also used to assess if these characteristics differed between Glasgow Lake and the other 15 study lakes from Cape Breton Highlands National Park.

Biogeochemical modelling

Biogeochemical models were applied to a subset of six of the Cape Breton lakes investigated through paleolimnological analyses. Critical loads for sulphur (S) were calculated using the steady-state water chemistry model (SSWC: Henriksen & Posch, 2001), which is largely empirical, and bases estimates of the critical load of S on the current base cation flux from the catchment. Five-year (1998–2002) mean annual lake chemistry and long-term average runoff volume were used as model inputs. Full details are provided in Whitfield et al. (2006a). MAGIC was used to predict historical and future chemical conditions of the lakes and calibrated to a long-term time series of observed lake chemistry (1990–2002) and catchment soil base saturation (2004). See Whitfield et al. (2007) for a complete description of the modelling procedure. It is important to note that MAGIC estimates the acid neutralizing capacity, referred to here as the charge balance alkalinity (Alk_{CB}) and calculated as the difference between the sums of base cation charges and acid anion charges, while the paleolimnological assessment estimates Gran alkalinity (Alk). Alk and Alk_{CB} generally agree well except for low acid neutralizing capacity waters, as measurements of Alk do not include the influence of dissolved organic carbon or aluminium (Sullivan et al., 1989) and Alk may overestimate the buffering capacity of the water (Neal et al., 1999). Thus, these two measures are not directly comparable.

Table 1 Physical and limnological data from Glasgow Lake, Cape Breton Highlands National Park, Nova Scotia, Canada (water chemistry values are 3-year (2000–2002) annual averages)

Variable	
Mean annual precipitation	1.44 m year^{-1}
Long-term annual runoff	1.06 m year^{-1}
Mean depth	4.5 m
Surface area	23.9 ha
Watershed area	143 ha
Water residence time	1.43 year
Elevation (above sea level)	418 m
Total phosphorus (TP)	6.5 μg l^{-1}
pH	5.0
Dissolved organic carbon	6.5 mg l^{-1}
Specific conductivity	25.1 μS cm^{-1}
Gran alkalinity	−12 μmol$_c$ l^{-1}

Results

A total of 82 diatom taxa were recorded in the sediment core from Glasgow Lake, most of which were rare. Some modest changes in diatom assemblages occurred in the pre-industrial period (i.e. changes in dominance between *Aulacoseira distans* and *Tabellaria flocculosa* strain IIIp between ~1200 AD and ~1400 AD); however, these did not result in a large change in diatom inferred pH (Fig. 2). The more recent pre-industrial (~1800–1850) diatom assemblage was dominated by *A. distans* and *T. flocculosa* strain IIIp which started changing to an increased abundance in *Asterionella ralfsii* var. *americana* (>45 μm) at a depth of ~5 cm, corresponding to the early 1900s (Fig. 2). Further increases in the relative abundance of this taxon occurred in ~1960. Corresponding to this change in diatom assemblage, diatom-inferred lakewater pH decreased from a pre-industrial pH = 5.8 to a present-day pH = 5.3, which is close to the current (2000–2002) measured lakewater pH of 5.0. The PCA

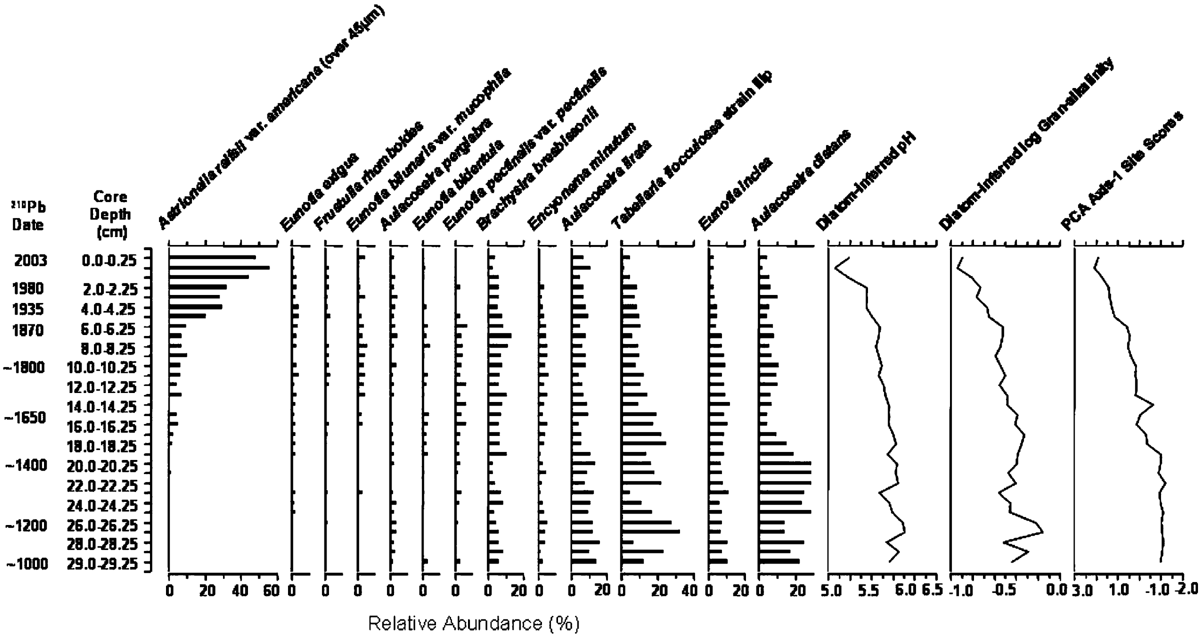

Fig. 2 Relative abundances of the dominant diatom taxa (>5%) in the sediment core from Glasgow Lake, Nova Scotia, Canada. Also included are diatom-inferred pH, diatom-inferred log Gran-alkalinity and PCA axis-1 site scores, which show the main direction of variation

axis-1 site scores summarize the main direction of variation in the downcore diatom assemblages and has a highly significant correlation ($r = 0.9, P < 0.001$) to the pH inferences (Fig. 2). Results of PCA analysis on the physicochemical variables of all 16 study lakes revealed Glasgow Lake separating from other lakes based on a small watershed area, large volume, low catchment area to lake area ratio and high retention time (or slow flushing rate) (Fig. 3).

When differences in Alk were examined between the 16 Cape Breton study lakes (Ginn, 2006), Glasgow Lake had the lowest pre-industrial diatom-inferred Alk as well as the lowest current diatom-inferred Alk (Table 2). Geochemical modelling supports these findings; pre-industrial $\mathrm{Alk_{CB}}$ was estimated to be lowest at Glasgow Lake for all the Cape Breton Highlands study lakes. Further, the estimated critical $\mathrm{SO_4^{2-}}$ load (SSWC) for Glasgow Lake was the lowest of all study lakes in Cape Breton Highlands National Park (Table 2). Using MAGIC, all Cape Breton lakes show a loss in $\mathrm{Alk_{CB}}$ due to acidic inputs, and five of six lakes show noticeable decline in pH (Whitfield et al., 2007). The model hindcast shows evidence of decreases in both $\mathrm{Alk_{CB}}$ and pH at Glasgow Lake through the mid-1970s (Fig. 4), coinciding with maximum sulphur emissions. At Glasgow Lake, MAGIC predicted a maximum pH depression of 0.5 units which is similar to the decrease inferred by paleolimnological techniques. Following the predicted bouts of acidification, MAGIC indicates subsequent increases in $\mathrm{Alk_{CB}}$ and pH, although both remain depressed in comparison to modelled historic levels.

Discussion

In contrast to the other 15 lakes we studied in Cape Breton Highlands National Park, Glasgow Lake has a very low pre-industrial buffering capacity and, consequently, was very susceptible to even small loads of acidic deposition. The inability of this lake to neutralize acid inputs resulted in a diatom-inferred pH decrease of 0.5 units starting in the early 1900s and accelerating in the 1960s, a time of increased $\mathrm{SO_4^{2-}}$ deposition. While the $\mathrm{SO_4^{2-}}$ deposition in this area did not result in changes in the diatom assemblages of most lakes, unchecked increases in sulphur emissions may have soon overwhelmed the ability of other lakes to neutralize acidic inputs and resulted in

Fig. 3 Principal components analysis (PCA) of 10 physical and chemical variables for the 16 study lakes from Cape Breton Highlands National Park

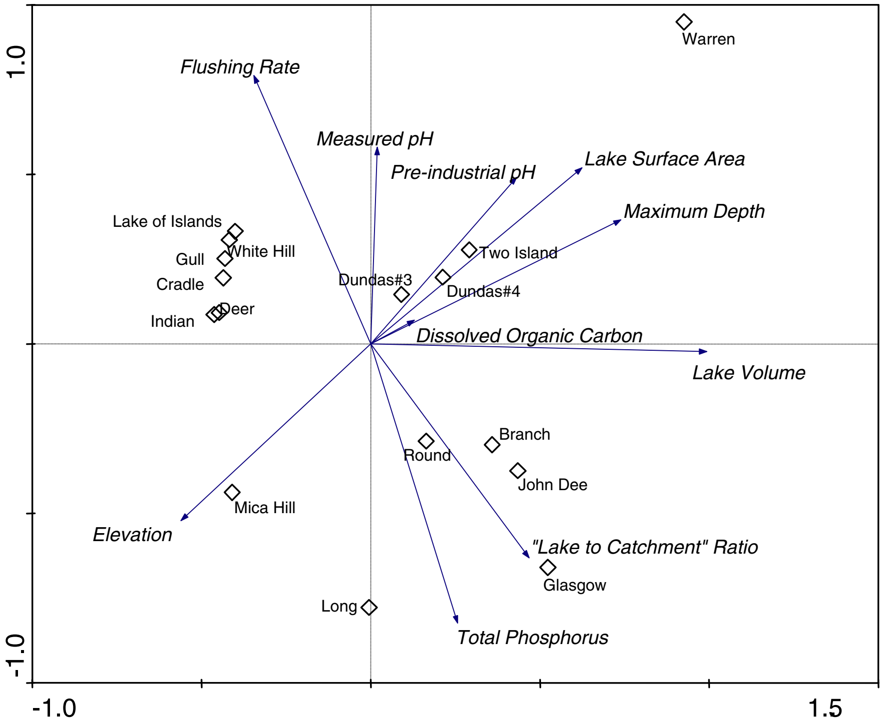

Table 2 Three years (2000–2002) observed, pre-1850 and current diatom-inferred Gran alkalinity (Alk) for the 16 study lakes from Cape Breton Highlands National Park (Nova Scotia, Canada: Ginn, unpublished data), MAGIC estimated charge balance alkalinity (Alk$_{CB}$) (from Whitfield et al., 2007) and SSWC model estimated critical loads (CL) (from Whitfield et al., 2006a) for six of the study lakes

Lake	Mean Alk (μmol$_c$ l^{-1})	Diatom inferred Alk		MAGIC estimated Alk$_{CB}$			SSWC CL (mmol$_c$ m^{-2} year^{-1})
		Pre-1850 (μmol$_c$ l^{-1})	Current (μmol$_c$ l^{-1})	1850 (μmol$_c$ l^{-1})	1975 (μmol$_c$ l^{-1})	2002 (μmol$_c$ l^{-1})	
Branch	−24.2	7.6	5.2	56	28	44	5.3
Cradle	5.4	9.8	5.8				
Deer	49.4	10.4	10.2				
Dundas #3	−2.6	9.0	7.0				
Dundas #4	−2.0	7.8	6.6				
Glasgow	−12.2	5.2	1.8	38	12	27	0.4
Gull	−4.2	5.4	4.0				
Indian	−0.6	5.8	6.2				
John Dee	20.0	7.2	6.2	72	41	59	36.6
Lake of Islands	−14.2	8.2	7.6				
Long	66.6	7.0	6.8	144	102	119	74.5
Mica Hill	28.8	7.0	8.0	79	46	64	41.3
Round	−2.8	6.4	6.8	67	38	54	13.1
Two Island	−14.2	9.2	5.8				
Warren	33.2	42.4	14.2				
White Hill	−12.0	9.2	7.0				

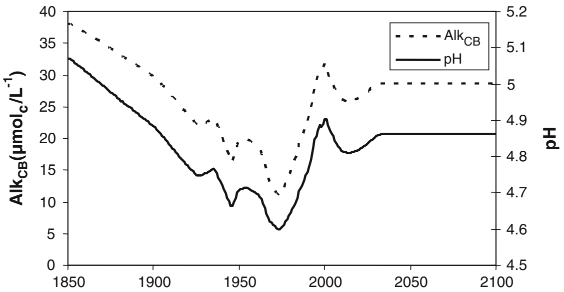

Fig. 4 MAGIC simulated charge balance alkalinity (Alk_{CB}) and pH for Glasgow Lake, Cape Breton Highlands National Park, for the period 1850–2100

a widespread acidification trend in Cape Breton Highlands National Park. The implementation of SO_4^{2-} emission restrictions in the 1980s and 1990s likely averted this trend for the other Cape Breton lakes. MAGIC modelling has estimated a loss of Alk_{CB} since pre-industrial times but has suggested an increase in Alk_{CB} since 1975 (Fig. 4). Lake water chemistry monitoring began in 1990 at Glasgow Lake; thus, this limited data set would not have captured these changes. Additionally, trends in water chemistry are sometimes confounded by the influence of major sea-salt events (Evans et al., 2001), which may obscure any recovery in Alk_{CB} during the 1990s at Glasgow Lake (Whitfield et al., 2006a). While no biological recovery has been observed to coincide with the predicted chemical recovery from acidification at Glasgow Lake, biological recovery is expected to be delayed (Keller et al., 1999) and it may be many years before detection. The increase in Alk is also estimated in most other lakes which did not record a significant change in lakewater pH. In addition, all lakes show a decrease, albeit very small, in diatom-inferred Alk since 1850 (Table 2).

In Glasgow Lake, the change in species composition from *Aulacoseira distans* to *Asterionella ralfsii* var. *americana* (>45 µm) corresponds with an acidification trend and mirrors patterns observed in other acidified Nova Scotia lakes, which have high concentrations of dissolved organic carbon (DOC) (e.g. Pebbleloggitch, Peskowesk and Kejimkujik lakes in Kejimkujik National Park; Ginn et al., 2007a, c). While these lakes in Kejimkujik Park are naturally acidic due to the presence of organic acids in DOC (pre-1850 diatom-inferred lakewater pH ~5.8), they have acidified further in response to SO_4^{2-} deposition. In fact, the minor increase in *Asterionella ralfsii* var. *americana* (>45 µm) beginning at the 17-cm depth (~1,500 AD) may indicate a long-term trend in natural acidification. In some lakes, changes in the diatom assemblage suggest that the lake underwent a degradation of DOC (humic, coloured water to clearwater) in response to acidification (e.g. Pockwock Lake in Halifax; Tropea et al., 2007).

The timing of acidification in Glasgow Lake is estimated to be in the early 1900s, which would be expected from a very acid-sensitive lake (Fig. 2), and corresponds with increasing SO_4^{2-} deposition in Cape Breton (e.g. Whitfield et al., 2007). While Cape Breton Island receives lower SO_4^{2-} deposition [~27 mmol$_c$ m^{-2} year^{-1} (13.0 kg ha^{-1} year^{-1})] than the southwestern parts of Nova Scotia, Glasgow Lake is more acid-sensitive than other lakes in Cape Breton Highlands National Park with both the lowest pre-1850 diatom-inferred Alk and MAGIC estimated Alk_{CB} (Table 2). Predictions from MAGIC also indicate a very low pre-industrial pH (~5.1). The other 15 lakes studied in Cape Breton (Ginn, 2006) did not record a pH trend, although the diatom-inferred alkalinities show a small decrease in Alk in many lakes compared to pre-1850 values (Table 2). In contrast, lakes in the southwestern Nova Scotia (especially in Kejimkujik National Park), an area of relatively higher SO_4^{2-} deposition, have recorded a widespread acidification trend starting ~1925–1940 (Ginn et al. 2007b). The low buffering capacity of Glasgow Lake is due in part to granitic bedrock and shallow, base-poor soils in its catchment. The combination of the above factors yields relatively small base cation pools in the catchment soil, as is common across Nova Scotia where weathering rates are often very low (Whitfield et al. 2006b). As a result, the contribution of base cations to runoff is limited and the estimated critical load for the catchment is only 0.4 mmol$_c$ m^{-2} year^{-1} (Table 2), among the lowest of the 20 catchments evaluated across the province. Thus, the physical characteristics of Glasgow Lake minimize the influence of the terrestrial drainage basin on water chemistry.

Glasgow Lake has one of the smallest catchment to lake ratios and the longest water residence time of the 16 study lakes (Fig. 3). The lake is much deeper than many of the other study lakes and, with its low flushing rate (0.70 year^{-1}), essentially acts as a bathtub, with much of the SO_4^{2-} deposited directly on the lake without being neutralized by interaction with the terrestrial catchment. While removal of SO_4^{2-} from lake water increases with increasing water residency time, the rate of removal through in-lake alkalinity generation is still quite short compared to the range used by Kelly et al. (1987). Thus, with a large proportion of SO_4^{2-} deposited directly onto the lake surface and little ability to generate alkalinity via in-lake processes reducing sulphur, SO_4^{2-} likely becomes more concentrated in the lake during times of heavy loading, promoting decreases in alkalinity and pH.

MAGIC infers some degree of recovery from acidification for lakes in Cape Breton Highlands National Park (Table 2), while results from the paleolimnological analyses have not indicated increases in Alk, although depression during the period of elevated acidic deposition has been small; likewise, no evidence of biological recovery at Glasgow Lake has been recorded. Potential recovery of lakes in this region will be limited, as base cation release from the soil has decreased in response to decreased SO_4^{2-} deposition (Clair et al., 2001), and generation of base cations from bedrock and soil is minimal (Whitfield et al., 2006b). Whitfield et al. (2007) reported that recovery patterns of the lakes beyond emission reductions scheduled through 2030 are predicted to be small, and in the case of Glasgow Lake, no recovery is expected past 2030 without additional emissions reductions.

The acidification of Glasgow Lake in Cape Breton Highlands National Park can potentially serve as a warning of a possible regional acidification, if SO_4^{2-} deposition occurs at higher than present levels since lakes in this region are so poorly buffered. Long-term monitoring of lake chemistry and acidic deposition in this area will prove valuable in determining critical loadings to prevent future acidification of these lakes.

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References

Battarbee, R. W., V. J. Jones, R. J. Flower, N. G. Cameron, H. Bennion, L. Carvalho & S. Juggins, 2001. Diatoms. In Smol, J. P., H. J. B. Birks & W. M. Last (eds), Tracking environmental change using lake sediments. Volume 3: Terrestrial, algal, and siliceous indicators. Kluwer Academic Press, Dordrecht.

Binford, M. W., 1990. Calculation and uncertainty analysis of 210Pb dates for PIRLA project lake sediment cores. Journal of Paleolimnology 3: 253–267.

Camburn, K. E. & D. F. Charles, 2000. Diatoms of low-alkalinity lakes in the northeastern United States. Academy of Natural Sciences of Philadelphia Special Publication 18.

Clair, T. A., T. Pollock, G. Brun, A. Ouellet & D. Lockerbie, 2001. Environment Canada's acid precipitation monitoring networks in Atlantic Canada. Occasional Report No. 16. Environment Canada.

Cosby, B. J., G. M. Hornberger, J. N. Galloway & R. F. Wright, 1985. Modeling the effects of acid deposition: Assessment of a lumped parameter model of soil water and streamwater chemistry. Water Resources Research 21: 51–63.

Cumming, B. F., J. P. Smol, J. C. Kingston, D. F. Charles, H. J. B. Birks, K. E. Camburn, S. S. Dixit, A. J. Uutala & A. R. Selle, 1992. How much acidification has occurred in Adirondack region lakes (New York, USA) since pre-industrial times? Canadian Journal of Fisheries and Aquatic Sciences 49: 128–141.

Davis, D. S. & S. Browne, 1996. The Natural History of Nova Scotia. Vol. 2: Theme Regions. Nimbus Publishing, Halifax.

Evans, C. D., D. T. Monteith & R. Harriman, 2001. Long-term variability in the deposition of marine ions at west coast sites in the UK Acid Waters Monitoring Network: Impacts on surface water chemistry and significance for trend determination. Science of the Total Environment 265: 115–129.

Fallu, M.-A., N. Allaire & R. Pienitz, 2000. Freshwater diatoms from northern Québec and Labrador (Canada). Bibliotheca Diatomologica 45: 1–200.

Ginn, B. K., 2006. Assessment of surface-water acidification using diatoms as paleoecological indicators in low alkalinity lakes in Nova Scotia (Canada) with a focus on lakes in Kejimkujik and Cape Breton Highlands National Parks. PhD dissertation, Department of Biology, Queen's University, Kingston.

Ginn, B. K., B. F. Cumming & J. P. Smol, 2007a. Assessing pH changes since pre-industrial times in 51 low-alkalinity lakes in Nova Scotia, Canada. Canadian Journal of Fisheries and Aquatic Sciences 64: 1043–1054.

Ginn, B. K., B. F. Cumming & J. P. Smol, 2007b. Long-term acidification trends in high- and low-sulphate deposition regions in Nova Scotia, Canada. Hydrobiologia 586: 261–275.

Ginn, B. K., B. F. Cumming & J. P. Smol, 2007c. Diatom-based environmental inferences and model comparisons from 494 northeastern North American lakes. Journal of Phycology 43: 647–661.

Ginn, B. K., L. C. Grace, B. F. Cumming & J. P. Smol, 2008. Tracking anthropogenic- and climatic-related environmental changes in the remaining habitat lakes of the endangered Atlantic Whitefish (*Coregonus huntsmani*) using paleolimnological techniques. Aquatic Conservation: Marine & Freshwater Systems. doi:10.1002/aqc.934.

Glew, J., 1988. A portable extruding device for close interval sectioning of unconsolidated core samples. Journal of Paleolimnology 1: 235–239.

Glew, J., 1989. A new trigger mechanism for sediment samplers. Journal of Paleolimnology 2: 241–243.

Glew, J. R., J. P. Smol & W. M. Last, 2001. Sediment core collection and extrusion. In Last, W. M. & J. P. Smol (eds), Tracking Environmental Change Using Lake Sediments Vol 1: Basin Analysis, Coring, and Chronological Techniques. Kluwer Academic Press, Dordrecht.

Gregory-Eaves, I., J. P. Smol, M. S. V. Douglas & B. P. Finney, 2003. Diatoms and sockeye salmon (*Oncorhynchus nerka*) population dynamics: Reconstructions of salmon-derived nutrients in two lakes from Kodiak Island, Alaska. Journal of Paleolimnology 30: 35–53.

Henriksen, A. & M. Posch, 2001. Steady-state models for calculating critical leads of acidity for surface waters. Water, Air and Soil Pollution: Focus 1: 375–398.

Keller, W. B., J. M. Gunn & N. D. Yan, 1999. Acid rain—Perspectives on lake recovery. Journal of Aquatic Ecosystem Health 6: 207–216.

Kelly, C. A., J. W. M. Rudd, R. H. Hesslein, D. W. Schindler, P. J. Dillon, C. T. Driscoll, S. A. Gherini & R. E. Hecky, 1987. Prediction of biological acid neutralization in acid-sensitive lakes. Biogeochemistry 3: 129–140.

Krammer, K. & H. Lange-Bertalot, 1991–2000. Bacillariophyceae 1–4. In Ettl, H., J. Gerloff, H. Heynig, & D. Mollenhauer (eds) Süßwasserflora von Mitteleuropa 2/1–4. Spektrum Akademischer Verlag, Berlin.

Krümmel, E., I. Gregory-Eaves, R. MacDonald, L. Kimpe, M. Demers, J. P. Smol, B. Finney & J. M. Blais, 2005. Concentrations and fluxes of salmon derived PCBs in lake sediments. Environmental Science & Technology 39: 7020–7026.

Laird, K. R., B. F. Cumming, S. Wunsam, J. Rusak, R. J. Oglesby, S. C. Fritz & P. R. Leavitt, 2003. Lake sediments record large-scale shifts in moisture regimes across the northern prairies of North America during the past two millennia. Proceedings of the National Academy of Sciences 100: 2483–2488.

Miettinen, J. O., H. Simola, E. Grönlund, J. Lahtinen & R. Niinioja, 2005. Limnological effects of growth and cessation of agricultural land use in Ladoga Karelia: Sedimentary pollen and diatom analyses. Journal of Paleolimnology 34: 228–243.

Moos, M. T., K. R. Laird & B. F. Cumming, 2005. Diatom assemblages and water depth in Lake 239 (Experimental Lakes Area, Ontario): Implications for paleoclimatic studies. Journal of Paleolimnology 34: 217–227.

Neal, C., B. Reynolds & A. J. Robson, 1999. Acid neutralisation capacity measurements within natural waters: towards a standardised approach. Science of the Total Environment 243/244: 233–241.

Patrick, R. & C. W. Reimer, 1966. The diatoms of the United States, exclusive of Alaska and Hawaii Vol. 1: Fragilariaceae, Eunotiaceae, Achnanthaceae, Naviculaceae. Monographs of the Academy of Natural Sciences of Philadelphia 13.

Patrick, R. & C. W. Reimer, 1975. The diatoms of the United States, exclusive of Alaska and Hawaii Vol. 2 Part 1: Entomoneidaceae, Cymbellaceae, Gomphonemaceae, Epithemiaceae. Monographs of the Academy of Natural Sciences of Philadelphia 13.

Round, F. E., R. M. Crawford, & D. G. Mann, 1990. The diatoms: Biology and morphology of the genera. Cambridge University Press, Cambridge: 747 pp

Salonen, V., N. Tuovinen & S. Valpola, 2006. History of mine drainage impact on Lake Orijäryi algal communities, SW Finland. Journal of Paleolimnology 35: 289–303.

Schelske, C. L., A. Peplow, M. Brenner & C. N. Spencer, 1994. Low-background gamma counting: applications for ^{210}Pb dating of sediments. Journal of Paleolimnology 10: 115–128.

Smol, J. P., 2008. Pollution of lakes and rivers: A paleoenvironmental perspective. Blackwell Publishing, Oxford.

Smol, J. P. & M. S. V. Douglas, 2007. Crossing the final threshold in high Arctic ponds. Proceedings of National Academy of Sciences 104: 12395–12397.

Sullivan, T. J., C. T. Driscoll, S. A. Gherini, R. K. Munson, R. B. Cook, D. F. Charles & C. P. Yatsko, 1989. Influences of aqueous aluminium and organic acids on measurement of acid neutralizing capacity in surface waters. Nature 338: 408–410.

Tropea, A. E., B. K. Ginn, B. F. Cumming & J. P. Smol, 2007. Tracking long-term acidification trends in Pockwock Lake (Halifax, Nova Scotia), the water supply for a major eastern Canadian city. Lake and Reservoir Management 23: 279–286.

Wehr, J. D. & R. G. Sheath, 2002. Freshwater algae of North America. Academic, New York.

Whitfield, C. J., J. Aherne, P. J. Dillon & S. A. Watmough, 2007. Modelling acidification, recovery, and target loads for headwater catchments in Nova Scotia, Canada. Hydrology and Earth System Sciences 11: 951–963.

Whitfield, C. J., J. Aherne, S. A. Watmough, P. J. Dillon & T. A. Clair, 2006a. Recovery from acidification in Nova Scotia: Temporal trends and critical loads for 20 headwater lakes. Canadian Journal of Fisheries and Aquatic Sciences 63: 1504–1514.

Whitfield, C. J., S. A. Watmough, J. Aherne & P. J. Dillon, 2006b. A comparison of weathering rates for acid-sensitive catchments in Nova Scotia, Canada and their impact on critical load calculations. Geoderma 136: 899–911.