

APPLIED ISSUES

# Marked recent increases of colonial scaled chrysophytes in boreal lakes: implications for the management of taste and odour events

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## SUMMARY

1. Lake managers suspect that taste and odour-causing algal blooms are increasing in frequency and intensity, although long-term monitoring records are scarce, and a number of critical scientific and management questions remain unanswered.
2. In nutrient-poor lakes and reservoirs, these events are caused primarily by sporadic outbreaks of some chrysophyte algae, which leave identifiable markers in lake sediments. We examine the siliceous remains of these organisms in more than fifty boreal lakes at broad temporal and spatial scales.
3. Colonial scaled chrysophytes, including the taste and odour-causing *Synura petersenii*, have increased markedly in more than 90% of the lakes examined since pre-industrial times.
4. Detailed stratigraphic analyses of two lakes show a rise in the abundance of colonial taxa in the 1930s to 1950s, with a sharp increase over the past two decades.
5. An examination of biogenic silica and biological ratios in Crosson Lake, Ontario, Canada, indicate that these changes represent true increases in the absolute abundance of colonial chrysophytes.
6. Rapid increases over the past two decades indicate that these trends are the result of one or more anthropogenic stressors that are operating at a broad, regional scale.

*Keywords:* boreal lakes, paleoecology, scaled chrysophytes, *Synura petersenii*, taste and odour

## Introduction

The frequency, intensity and geographic extent of algal blooms have increased sharply over the last few decades in marine and freshwater environments (Nicholls, 1995; Anderson & Garrison, 1997). Such events carry many negative repercussions including the production of taste and odour episodes (Hrudey,

McGuire & Whitfield, 1995). Until recently, much freshwater research has focused on taste and odour events caused by blue-green algae (i.e. cyanobacteria), which often bloom following nutrient enrichment from natural and anthropogenic sources (Chambers *et al.*, 2001). In low alkalinity, nutrient-poor lakes (e.g. boreal lakes in the Canadian Shield), however, taste and odour events caused by colonial chrysophytes are more commonly reported (Nicholls & Gerrath, 1985). Although lake managers maintain that the number of complaints has been increasing steadily in boreal lakes, few records have been kept. Moreover, by their nature, these reports are biased as they exclude

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remote lakes, and are often confined to the summer, recreational season. As a result, many taste and odour episodes likely remain unnoticed or unreported, and a number of critical scientific and management questions remain unanswered. For example, have abundances of taste and odour-causing algae increased in recent decades, or since pre-industrial times? If so, have human activities such as cultural acidification or eutrophication contributed to these changes?

Over the past two centuries, boreal lakes within the Canadian Shield have been impacted by an increasing number of environmental stressors. These disturbances may act at a lake or catchment scale, such as the input of nutrients from point sources (Chambers *et al.*, 2001), and at a regional scale, including the deposition of strong acids (Schindler *et al.*, 1991), climate change (Magnuson *et al.*, 1997) and the increasing exposure to harmful UV-B radiation (Schindler *et al.*, 1996b). Understanding the relative impacts of these disturbances on aquatic ecosystems is complicated because they may act synergistically and antagonistically in lakes (Folt *et al.*, 1999). However, some common trends have been observed in natural and experimental studies of individual stressors on phytoplankton communities (Nicholls, Nakamoto & Keller, 1992; Findlay *et al.*, 1999; Findlay *et al.*, 2001).

For example, in boreal lakes with moderate levels of acidification, increases in hypolimnetic flagellates are reported commonly, with a decline in the abundance of smaller, epilimnetic forms, such as planktonic diatoms and unicellular chrysophytes (Findlay *et al.*, 1999; Vinebrooke *et al.*, 2002). In part, this shift may be explained by species- or class-specific differences in algal tolerances to pH (Paterson *et al.*, 2001), or an indirect response to changes in grazing pressure (Klug *et al.*, 2000). Long-term changes in light quantity and quality at depth, however, may play a more important role. The reduction of dissolved organic carbon (DOC) with acidification, and associated increases in light transparency, are well documented in boreal lakes (Schindler *et al.*, 1996b). Furthermore, small declines in DOC can significantly increase the penetration of harmful UV-B radiation, particularly in lakes with historically lower DOC concentrations (Scully & Lean, 1994). Phytoflagellates that form sub-thermocline populations may thus have a selective advantage, avoiding harmful UV-R, experiencing reduced grazing intensity and being proximal to nutrient-rich

hypolimnetic waters (Leavitt *et al.*, 1999; Vinebrooke *et al.*, 2002).

Although specific bloom events cannot be elucidated from the sediment record, the causative agents of many taste and odour episodes (i.e. those caused by scaled chrysophytes) leave excellent records in lacustrine sediments (Smol, 1995), and thus paleoecological techniques can be used to track long-term trends in the abundance of problematic taxa. We used three approaches that differ in spatial and temporal scale to assess changes in scaled chrysophyte populations over the last two centuries. First, chrysophyte remains were examined in pre-1850 and post-1990 sediment samples of 48 low-alkalinity lakes in Ontario, Canada. This technique, referred to as the 'top-bottom approach', provides a snapshot of species changes since pre-industrial times in a suite of lakes, and has been used extensively to track regional changes in, for example, lake acidification (Cumming *et al.*, 1992; Dixit, Dixit & Smol, 1992b), eutrophication (Hall & Smol, 1996) and metal pollution (Blais *et al.*, 1999). Secondly, surface samples from 10 sediment cores taken in the early-1980s were also examined, thus providing an intermediate (i.e. early-1980s) sediment sample in 10 of the lakes. Finally, to identify the timing of the changes, we analysed continuous trends in chrysophyte assemblages from two lakes in the southern boreal shield. Scaled chrysophytes were identified and enumerated in contiguous samples of  $^{210}\text{Pb}$  dated sediment cores over the last 150–200 years.

## Methods

### *Study region*

The Muskoka-Haliburton region of south-central Ontario, Canada (44–45°N latitude, 78–79°W longitude) is underlain by Precambrian granitic bedrock of the Canadian Shield (Jeffries & Snyder, 1983). A marble intrusion, found in the eastern portion of the study area, underlies 12 of the study lakes. Soils are generally shallow and acidic, although thicker deposits of clay, sand or gravel occur locally (Chapman & Putnam, 1984). Much of this region is characterised by secondary mixed-deciduous and coniferous forests, following widespread deforestation in the mid- to late-1800s (Michalski, Johnson & Veal, 1973). Local climate is cool and moist with mean January and July

temperatures of  $-11$  and  $19$  °C, respectively, and precipitation in the range of 900–1200 mm annually (Hutchinson *et al.*, 1994). Because of the rough topography, thin soils and cool climate, agriculture is marginal in the region. Presently, human activity consists primarily of recreational activities associated with seasonal cottages, resorts and small municipalities.

#### Sample collection and analysis

In the autumn of 1992, 48 Muskoka-Haliburton lakes that vary widely in water chemistry characteristics, and degrees of human influences, were purposely chosen to represent the spectrum of lakes found in the Canadian Shield (Hall & Smol, 1996). Sediment cores were extracted from the deepest basin of each lake using a gravity corer fitted with a 6.35-cm internal diameter Lucite tube, and sectioned at the lakeshore into stratigraphic sections (Glew, 1988). Two sediment sections were examined for 'top-bottom' analysis: the top centimetre (present-day lake conditions), and a 1-cm interval taken at a minimum core depth of 20-cm (pre-industrial lake conditions). Although the precise date of the bottom sample of each core was not known, radiometric  $^{210}\text{Pb}$ -dating of other cores from the south-central Ontario region has shown that background conditions (i.e. >150 years) are typically reached at core depths of 15–20 cm (Hall & Smol, 1996). Furthermore, many of the cores exhibited a visible change in colouration corresponding to the time of forest clearance. The surface sediment from additional sediment cores, extracted in the early-1980s, provided an intermediate sample in ten of the lakes. Continuous sediment cores were also extracted from the deepest basin of two lakes, in 1984 (Clear Lake) and 1998 (Crosson Lake) (Table 1). These cores were sub-sampled on-site into 1-cm and 0.5-cm increments, respectively, and transferred to a cold-room ( $4$  °C) for storage.

Microscope slides were prepared following standard acid-digestion techniques (Hall & Smol, 1996). A minimum of 300 chrysophyte scales were enumerated along transects at  $1500\times$  ( $100\times$  objective,  $15\times$  ocular lens) using a Leica DMRB light microscope (Leica Microsystems, Bensheim, Germany) with differential-interference-contrast optics. Scales of a few taxa were grouped into broader taxonomic categories because of difficulty in identifying these scales to the species

**Table 1** Location and selected physical and water chemistry variables of Clear Lake and Crosson Lake, Ontario, Canada. Chemical variables are presented as mean values from samples collected during the ice-free seasons of 1990–92. Total phosphorus was calculated from samples collected during the spring overturn period of these years

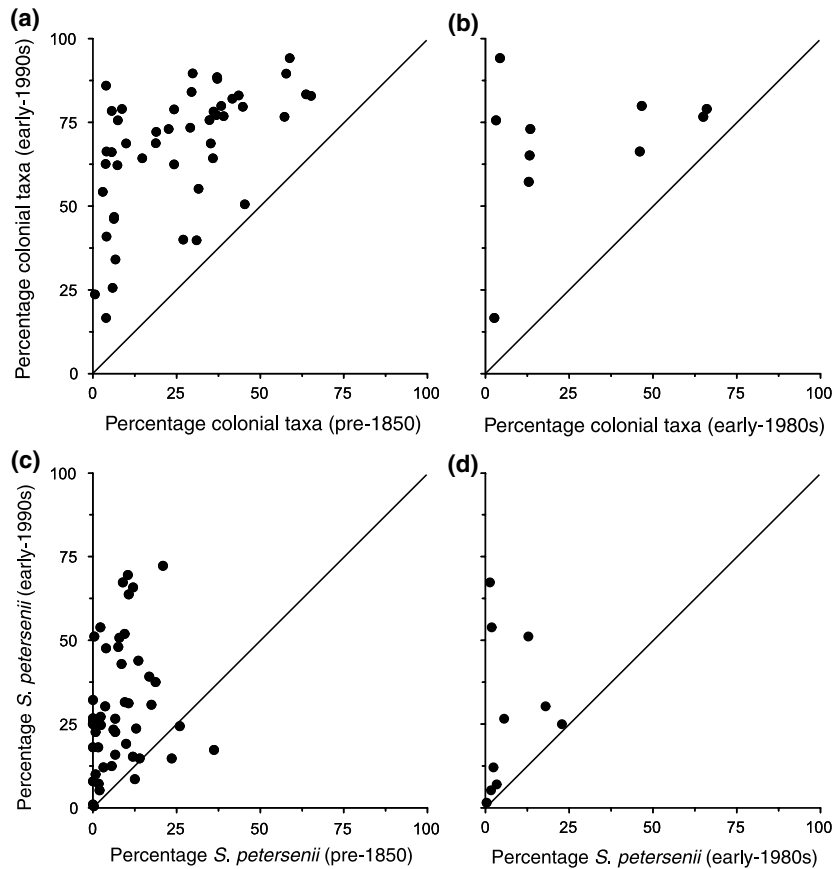
Variable	Clear Lake	Crosson Lake
Latitude (N)	45°11'	45°05'
Longitude (W)	78°43'	79°02'
Surface area (ha)	88.0	57.0
Maximum depth (m)	33.0	25.0
pH	5.8	5.6
Conductivity ( $\mu\text{S cm}^{-1}$ )	25.2	26.7
Total phosphorus (spring) ( $\mu\text{g L}^{-1}$ )	3.9	10.8
Dissolved organic carbon ( $\text{mg L}^{-1}$ )	1.7	4.5

level using a light microscope. For example, unidentifiable small and mid-sized scales were grouped into the categories *Mallomonas* 'small' and 'medium', respectively. These groups were relatively rare, with relative abundances of no more than 3 or 6% in any lake.

In addition to the relative abundance data mentioned above, the 'biogenic silica' technique was used to provide an estimate of the absolute abundance of siliceous microfossils in Crosson Lake through time (Conley & Schelske, 2001). Briefly, dried sediments were leached in a weak base (1%  $\text{Na}_2\text{CO}_3$ ) for 5 h at  $85^\circ$ , with aliquots removed periodically and measured for extracted soluble silica. Least-squares regression of concentration over time was calculated to distinguish amorphous and mineral silicate fractions (Krausse, Schelske & Davis, 1983). In addition, pairwise ratios of chrysophyte scales, chrysophyte cysts and diatom valves in the Crosson Lake core were compared to estimate the relative contribution of each indicator to the biogenic silica concentration.

#### Results

Based on scale morphology, 32 chrysophyte taxa were identified in the study lakes. *Synura petersenii*, a synurophyte linked to taste and odour problems in freshwater lakes and reservoirs (Nicholls, 1995; Watson *et al.*, 2001), was the most frequently encountered taxon in surface (c. 1990–92) sediment samples, reaching relative abundances of more than 30% in 20 of the lakes. *Synura petersenii* increased in abundance in 90% of the lakes, being far less prevalent in pre-industrial (bottom) samples (mean relative



**Fig. 1** Comparisons of the relative abundances of: (a) colonial chrysophytes in pre-1850 and modern (1990–92) sediment samples; (b) colonial chrysophytes in early-1980 and modern sediment samples; (c) *Synura petersenii* in pre-1850 and modern sediment samples and (d) *S. petersenii* in early-1980 and modern sediment samples, from a broad spectrum of boreal shield lakes in Ontario, Canada. Diagonal lines represent 1 : 1 lines.

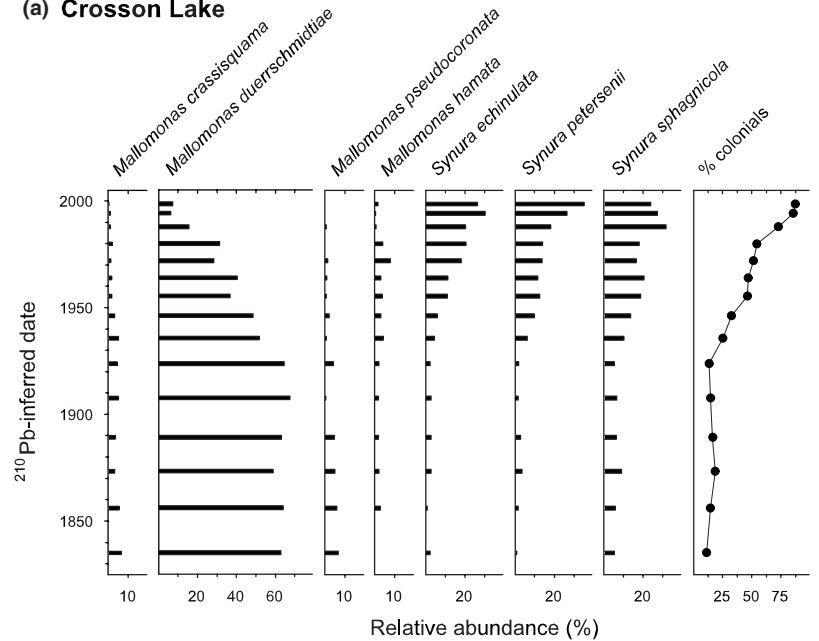
abundances: 8 and 28% in pre-industrial and modern samples, respectively) (Fig. 1c). Other colonial scaled taxa, including *S. sphagnicola* Korsh. and *S. echinulata* Korsh., were also more common in modern samples, reaching mean relative abundances of 14 and 8%, respectively (Fig. 1a). In general, unicellular taxa occurred at higher abundances in pre-industrial sediments. For example, *Mallomonas duerrschmidtiae* Siver, Hamer and Kling and *M. crassisquama* (Asmund) Fott, the dominant taxa in the pre-1850 samples (mean relative abundance of 26 and 15%), decreased in relative abundance to 7–9% in the modern samples. A comparison of modern species assemblages with those from the early-1980s showed similar patterns (Fig. 1b,d), indicating that colonial scaled chrysophytes linked to taste and odour events in boreal lakes (Nicholls & Gerrath, 1985; Nicholls, 1995) have increased in abundance over the last 15–20 years.

Colonial scaled chrysophytes increased through time in Crosson and Clear lakes, with relative abundances of 60–80% recorded in recent sediments

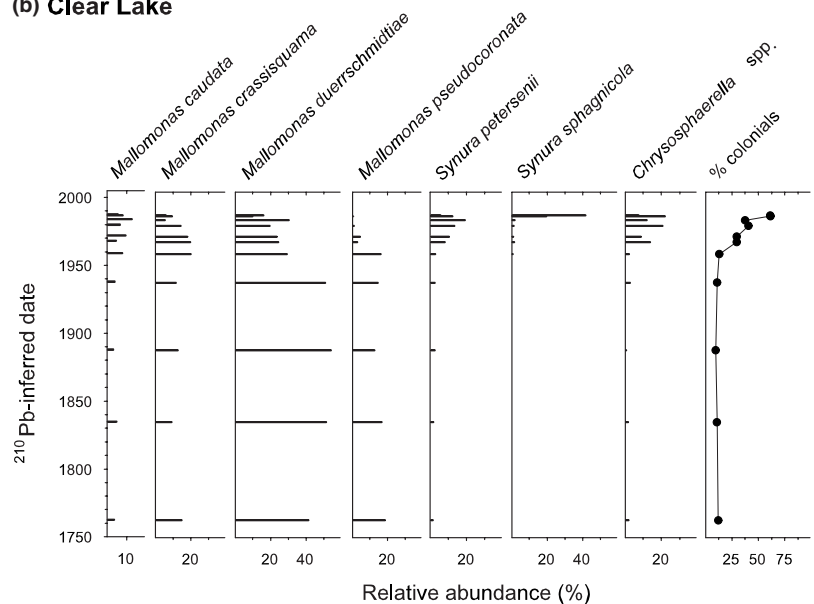
(Fig. 2a,b). The pre-industrial species assemblages of both lakes showed minimal variation through time and were dominated by unicellular *Mallomonas* taxa (Fig. 2a,b). Colonial species were also present and well preserved in pre-industrial samples, although occurring at relative abundances of <20%. The relative importance of colonial taxa increased in the 1930s and 1950s in Crosson and Clear lakes, respectively. This increase continued to the present in a unidirectional fashion, with a more marked rise in abundance over the past two decades (Fig. 2a,b). In other lakes, long-core data spanning millennia (Christie & Smol, 1986; Whitehead *et al.*, 1989) suggest that these changes are unprecedented.

The concentration of biogenic silica in Crosson Lake sediment samples was estimated as a measure of the absolute abundance of biological siliceous remains through time (Conley & Schelske, 2001). Although sample-to-sample variability was high, concentrations showed no directional trend through time (Fig. 3). There was, however, a change in the relative contribution of chrysophyte scales, chrysophyte cysts and

## (a) Crosson Lake



## (b) Clear Lake



**Fig. 2** Stratigraphic data of dominant scaled chrysophyte taxa, and the relative abundance of all colonial taxa from (a) Crosson Lake ( $45^{\circ}05'$ ,  $79^{\circ}02'$ ), and (b) Clear Lake ( $45^{\circ}11'$ ,  $78^{\circ}43'$ ), Ontario, Canada. Taxa with relative abundances of  $>5$  or  $10\%$  in at least one interval are shown for Crosson and Clear lakes, respectively. Core depths and  $^{210}\text{Pb}$  dates are also plotted. The catchments of these lakes were logged in the mid- to late-1800s, but are presently undisturbed.

diatom valves to the total biogenic silica supply. An examination of biological ratios revealed that the relative contribution of chrysophyte scales increased over the past several decades (Fig. 4). The ratio of scales to chrysophyte cysts and diatom valves increased initially in the late-1800s, with a more significant increase between 1940 and 1960, and a sharp rise over the past two decades. In contrast, there was no change in the ratio of chrysophyte cysts to diatom valves.

## Discussion

Colonial chrysophytes have exhibited large increases in abundance in low alkalinity lakes of the boreal shield over the past several decades (this study; Dixit, Dixit & Smol, 1992a; Cumming *et al.*, 1994; Vinebrooke *et al.*, 2002). Collectively, these results indicate that boreal shield lakes have experienced a dramatic, widespread shift in chrysophyte composition over the last century, with accelerated changes over the past

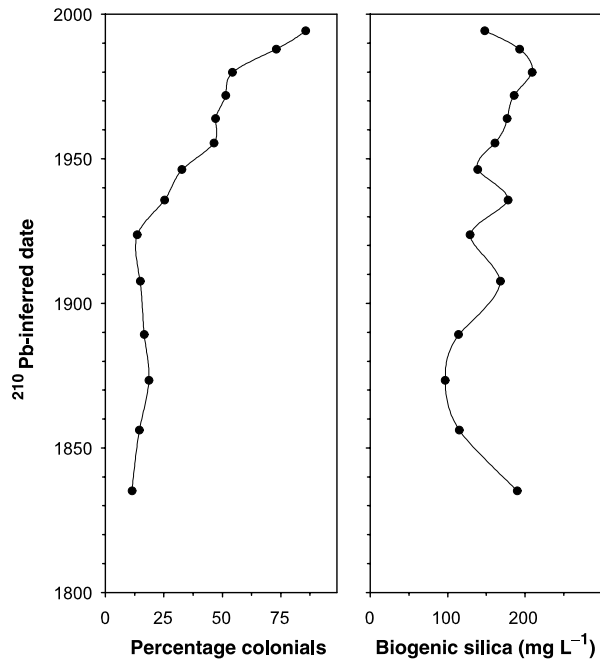


Fig. 3 Plots of the relative abundance of colonial taxa (left) and biogenic silica concentrations (right) through time in sediment samples from Crosson Lake, Ontario, Canada. Data are plotted against  $^{210}\text{Pb}$ -inferred dates.

two decades. Furthermore, an examination of biogenic silica and biological ratios indicate that these changes may represent an increase in the absolute abundance of colonial scaled taxa through time. *Synura petersenii*, a taxon clearly linked to taste and odour events in

freshwater lakes and reservoirs (Nicholls, 1995; Watson *et al.*, 2001), has increased markedly since pre-industrial times in many lakes.

The mechanisms responsible for these dramatic floristic shifts are not fully understood; however, many potential factors can be ruled out. For example, several lines of evidence indicate that these changes are real, and not related to artefacts of preservation. Well-preserved scales of colonial taxa were present in pre-industrial sediment samples, although found at much lower abundances. Furthermore, the siliceous remains of other organisms, including the thinly silicified spines of chrysophyte cysts, showed no evidence of dissolution in the pre-1850 samples.

Our results also show that the direct effects of acidic precipitation on lakewater pH could not explain the observed patterns. Colonial taxa increased in all of the study lakes, regardless of the direction or degree of change in inferred lake water pH (diatom-inferred pH change versus percentage change in colonial chrysophytes:  $r = 0.00$ ,  $P > 0.05$ ,  $n = 48$ ). In general, the greatest percentage increase of colonial taxa was found in lakes with the least change in inferred pH since pre-industrial times. Moreover, species changes showed no relation to the degree of catchment disturbance, occurring in basins with and without shoreline development. Long-term changes in total phosphorus (TP), inferred independently from diatom assemblages, were not related to the increase in colonial chrysophytes (diatom-inferred TP change

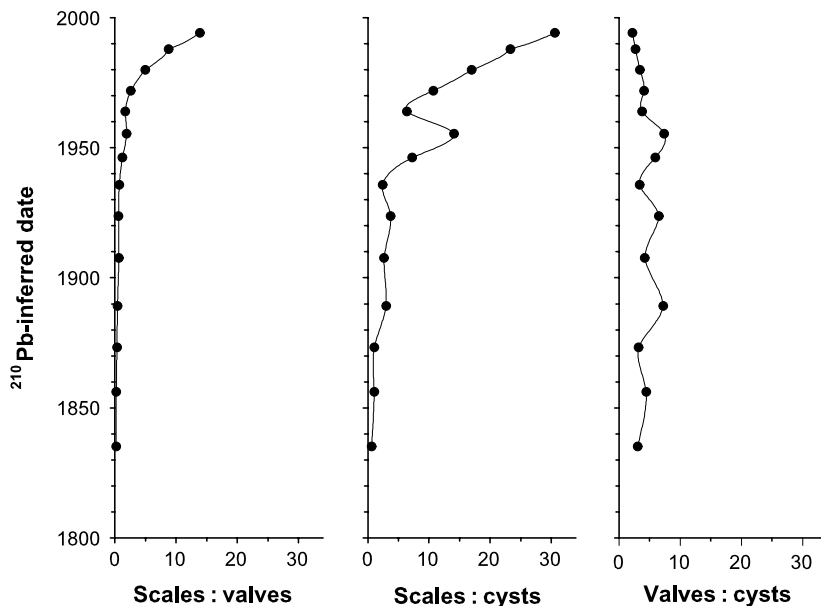


Fig. 4 Ratio plots comparing numbers of chrysophyte scales and diatom valves (left), chrysophyte scales and chrysophyte cysts (middle), and diatom valves and chrysophyte cysts (right) through time in sediment samples from Crosson Lake, Ontario, Canada. Data are plotted against  $^{210}\text{Pb}$ -inferred dates.

versus percentage change in colonial chrysophytes:  $r = 0.02$ ,  $P > 0.05$ ,  $n = 48$ ).

The shift from unicellular to colony-forming species may represent a change in the vertical structure of scaled chrysophytes in the water column. Larger, colonial chrysophytes (e.g. including scaled chrysophytes of the genera *Synura* and *Chrysosphaerella*) are commonly found below the thermocline in stratified lakes, forming short-lived, monospecific blooms (Fee, Shearer & DeClercq, 1977; Nakamoto, Heintsch & Nicholls, 1983; Sandgren, 1988). In contrast, smaller, unicellular forms are generally concentrated in the epilimnia of lakes, and are rarely associated with metalimnetic or hypolimnetic peaks (Fee *et al.*, 1977). The observation that floristic changes have occurred in a broad spectrum of lakes, coupled with the relatively recent timing of these shifts, suggests that a regional stressor, or combination of stressors, may have been involved. Climatic change, and the synergistic influences of climatic change and lake acidification, can lead to long-term increases in water transparency in boreal shield lakes (Schindler *et al.*, 1996b; Leavitt *et al.*, 1999). Ultimately, through decreases in dissolved organic carbon concentrations, these stressors may cause an increase in the zone of sub-thermocline production (Schindler *et al.*, 1996a), favouring deep-water chrysophytes over epilimnetic forms, and indirectly providing a refuge from harmful UV-B radiation (Vinebrooke *et al.*, 2002). Similar hypotheses, although reported at broader taxonomic levels, have been observed in other boreal lakes (Schindler *et al.*, 1991; Leavitt *et al.*, 1999; Xenopoulos, Prairie & Bird, 2000; Findlay *et al.*, 2001).

Our results show that colonial scaled chrysophytes have increased in low alkalinity, oligotrophic to mesotrophic lakes of the boreal shield. Consequently, there has been a marked rise in the abundance of *S. petersenii*, a taxon proven to cause taste and odour events in freshwater lakes and reservoirs. Although individual bloom episodes cannot be inferred from the sediment record, a rise in importance of a problem taxon suggests that these events are more common today than in the past. Given the timing of the changes, the observed species trends are likely the result of one or more regional, human-induced disturbances on lake environments. Recent limnological studies have recognised that boreal lakes have become increasingly threatened by multiple

anthropogenic stressors over recent decades, including acidic precipitation, climatic warming and stratospheric ozone depletion, among many others (Schindler, 1998). We present new evidence that these disturbances have produced major, unprecedented changes in phytoplankton assemblages, which have serious negative implications for water quality.

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