Insights for lake management gained when paleolimnological and water column monitoring studies are combined: A case study from Baptiste Lake

Katrina E. Adams [a], Zofia E. Taranu [a], Ron Zurawell [b], Brian F. Cumming [c] & Irene Gregory-Eaves [a]

[a] Department of Biology, McGill University, Stewart Biology Building, 1205 Docteur Penfield, Montreal, QC, H3A 1B1, Canada

[b] Water Policy Branch, Alberta Environment and Sustainable Resource Development, Edmonton, AB, Canada

[c] Department of Biology, Queen's University, Kingston, ON, K7L 3N6, Canada
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Insights for lake management gained when paleolimnological and water column monitoring studies are combined: A case study from Baptiste Lake

Katrina E. Adams,[1] Zofia E. Taranu,[1] Ron Zurawell,[2] Brian F. Cumming,[3] and Irene Gregory-Eaves[1,*]

[1]Department of Biology, McGill University, Stewart Biology Building, 1205 Docteur Penfield, Montreal, QC H3A 1B1, Canada
[2]Water Policy Branch, Alberta Environment and Sustainable Resource Development, Edmonton, AB, Canada
[3]Department of Biology, Queen's University, Kingston, ON, K7L 3N6, Canada

Abstract

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Many lakes within the Boreal Plain and Grassland regions of Canada are currently eutrophic to hypereutrophic. Limited paleolimnological work has been conducted to define water quality trajectories of lakes within this region. A 25-year intermittent monitoring and a ~150-year paleolimnological time series from Baptiste Lake, Alberta, were analyzed using a combination of trend, correlation, and multivariate analyses. The temporal overlap between the monitoring and paleolimnological time series provides an opportunity to assess coherence between the data sources. Diatom assemblages in the sediment core show that eutrophic conditions were present for at least 150 years. Monitored water chemistry data since the early 1980s show that total Kjeldahl nitrogen (TKN) has increased by approximately 50% since the early 1990s, whereas concentrations of total phosphorus (TP) have remained stable. Further, measured TKN is significantly correlated to measurements of chlorophyll *a* over the monitoring period and to diatom-inferred TKN values, suggesting nitrogen limitation in Baptiste Lake. In contrast, measured TP was not correlated to chlorophyll *a* or diatom-inferred TP. Changes in land use over the past 100 years is the most parsimonious explanation for the nutrient changes. No statistical support for climatic change as a linear predictor of nutrient dynamics was found. Our contemporary and paleolimnological analysis provides an important perspective on the timing and magnitude of nutrient dynamics over ~150 years. Future government and community decisions on Baptiste Lake management would benefit from testing nutrient limitation and detailed modeling of nutrient runoff from the watershed.

Key words: Baptiste Lake, diatoms, eutrophication, lake management, paleolimnology, total Kjeldahl nitrogen, total phosphorus, water quality

Nutrient enrichment of lakes from anthropogenic activities is one of the most widespread forms of pollution worldwide (Smith and Schindler 2009). International lake surveys have shown that eutrophic lakes are a common part of the landscape in Europe and North America, where >45% of the sampled lakes have total phosphorus (TP) concentrations near 30 μg/L (Moe et al. 2008, USEPA 2009). Based on the analysis of a large spatial dataset of temperate lakes, Orihel et al. (2012) showed that eutrophic lakes are particularly susceptible to microcystin concentrations above the recommended guidelines of the World Health Organization; however, these lake surveys often have little to no temporal dimension; thus it is unclear how many of these lakes were naturally eutrophic.

Baptiste Lake (Fig. 1), our study site, is one of the more-studied lakes within the Boreal Parkland region of Alberta. This site is part of a long-term water quality program and thus has 25 years of intermittently collected limnological data. Although these data are useful in understanding the dynamics of the system, pairing these time series with

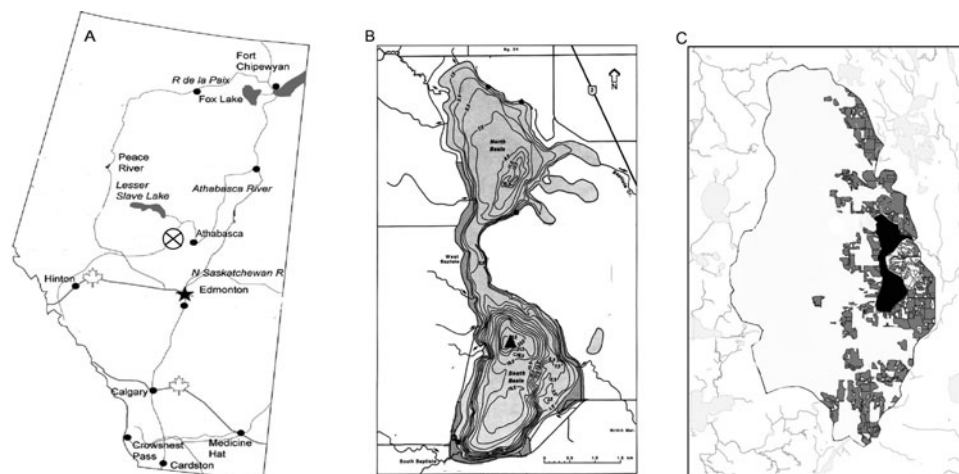*Corresponding author:. E-mail: irene.gregory-eaves@mcgill.ca

Figure 1.-(A) Location of Baptiste Lake (shown by the symbol where an x is contained within a circle) in relation to large cities in Alberta, Canada. (B) The bathymetry of Baptiste Lake's 2 basins, where isobaths represent distance in meters. The black triangle in the south basin marks where the core was taken. Map (B) modified from Mitchell and Prepas 1990. Plot (C) shows the extent of agricultural land cover (pasture and croplands), modified from Carlson (2008).

quantitative paleolimnological records can potentially provide a longer-term perspective on nutrient dynamics within this lake.

Diatom assemblages preserved in lake sediments are particularly useful because they can track past water quality dynamics. With their rapid turnover and specific ecological preferences, diatoms are ideal bioindicators because they respond quickly to changes in their environment (Smol and Stoermer 2010). In particular, diatoms respond strongly to changes in nutrient concentrations, especially phosphorus (P) and nitrogen (N), within lakes (Hall et al. 1997, Dixit et al. 1999, Bennion and Simpson 2011). Based on these underlying principles, numerous paleolimnological transfer functions have been developed over the past few decades to estimate past changes in nutrients concentrations from subfossil diatom assemblages (reviewed in Hall and Smol 2010). Likewise, paleolimnological studies of sediment cores collected from widely spaced sampling sites within a lake have provided evidence that developing a basin reconstruction from a single core is a reasonable approach (e.g., Charles et al. 1991, Brenner et al. 1999).

Whereas the paleolimnological approach of tracking past changes in nutrients with subfossil assemblages has been widely applied and tested (Hall et al. 1997, Rippey et al. 1997, Bennion and Simpson 2011, Hobaek et al. 2012), several key criticisms have been raised recently and merit closer investigation. For example, Juggins et al. (2013) recently emphasized that P might not always be the nutrient driving diatom assemblages in freshwater systems. Consistent with this idea, many limnologists in general are rethinking the "phosphorus paradigm," and evidence is growing that

in certain circumstances lake-water N concentrations are equally or more important than P concentrations in driving phytoplankton production (e.g., Elser et al. 2007, Lewis et al. 2008, Donald et al. 2011). This topic is still actively debated, however, and counter-arguments have been presented (Schindler 2012). For this reason, we have applied both P and N transfer functions to the subfossil assemblage from Baptiste Lake. By comparing the diatom-inferred nutrient concentrations with the contemporaneous water column data, we identify which nutrient variable, TP or total Kjeldahl nitrogen (TKN), more closely tracks the monitoring record.

The primary aim of this study was to provide a long-term history (at least ∼150 years) of trophic state dynamics from Baptiste Lake, a eutrophic lake in Alberta, Canada. By expanding the monitoring window through a paleolimnological approach, we are able to assess the coherency between long-term water quality and changes in climate as well as make scientifically grounded recommendations for future management to Alberta Environment and Sustainable Resource Development (ESRD).

Study site

Baptiste Lake is currently eutrophic and experiences frequent cyanobacteria blooms during the summer (Fig. 1 and 2). We focused our analyses on the southern basin of Baptiste Lake, which is one of two basins connected by a narrow channel. Although both basins are eutrophic, the southern basin is more strongly stratified and, as such, nutrient concentrations peak in spring and fall (Mitchell and Prepas
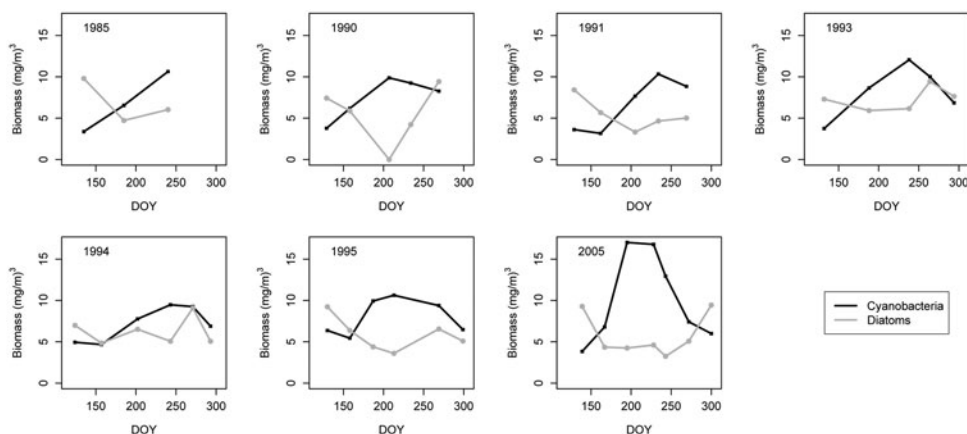
Figure 2.-Double root transformed cyanobacterial and diatom biomass plotted as a function of day of the year (DOY) for the 6 years of available phyological data.

1990). The southern basin is also slightly less nutrient-rich than the shallower, northern basin. Both basins have anoxic bottom waters in summer and winter (Mitchell and Prepas 1990).

Over the past century, the catchment of Baptiste Lake has been developed for agriculture, forestry, oil and gas exploration, as well as residential settlements. Agriculture in the catchment started in 1904 and has grown over much of the last century. Today, about 20% of the catchment area is being used for agriculture, 11.4% for pasture, 5% for cropland, and the remaining percentage is forested area. The majority of the farms in the watershed consist of beef (including feedlots) and hay farms, along with horse, oilseed, and other grain farms (Cooke and Prepas 1998, Statistics Canada 2011). The industrial footprint (e.g., roads, seismic lines, and pipelines) of the Baptiste watershed makes up an additional 4% of the watershed. Human settlements are also an important land use in the watershed (∼1%). The immediate shoreline of Baptiste Lake consists almost entirely of residential private settlements (Carlson 2008), and the total area of settlements in the watershed has increased by ∼32% since 1991 (Carlson 2008).

Materials and methods

Water column and sediment core collection and analyses

The ESRD staff has collected a detailed suite of water column measurements (i.e., water temperature, pH, and dissolved oxygen at 1.0 m depth intervals) as well as euphotic-zone integrated water samples for chemical and phytoplankton analyses (Table 1). Measurements taken from the water column included TP and TKN, which is the sum of

organic N, ammonia (NH_3), and ammonium (NH_4^+), but did not include nitrate or nitrite, although these were analysed separately. Measurements were taken annually from 1983 to 2007, with a sampling hiatus between 1996 and 2003. The lake was sampled 4–6 times during each open-water season (May–Oct), and temperature profiles were taken from the deepest point of the south basin (details of sampling methodology are provided in Taranu et al. 2012). Based on the temperature profiles and a freshwater density–temperature conversion table (Kalff 2002), we calculated water column stability using the Schmidt Stability Index equation (SSI in g/cm; Soranno 1996).

A sediment core (46 cm in length) was retrieved from the deepest part of the south basin of Baptiste Lake (54°44′N, 113°33′W; coring depth = 25 m) using a modified Kajak-Brinkhurst gravity corer (Glew 1989) in June 2010. The

Table 1.-Lake and catchment characteristics (compiled from Mitchell and Prepas 1990) of the south basin of Baptiste Lake. We have also reported key water quality values that represent averages from the monitoring record (Casey 2011).

Variable	Measurement
Mean depth (m)	12
Maximum depth (m)	28
Surface area (km^2)	5
Catchment area: surface area	57
Water residence time (years)	6
pH (mean)	8.5
Chlorophyll *a* (ug/L, mean)	32.4
Total NH_3+NH_4 (μg/L, mean, as N)	45
NO_3-NO_2 (μg/L, mean, as N)	37
Transparency (Secchi depth, m, mean)	1.8
Mixing regime	Strongly Stratified

core was sectioned in the field at 0.25 cm intervals, and the samples were stored in the dark and frozen until processed further in the lab. The core chronology was established by applying the constant-rate-of-supply model to the ^{210}Pb activity (Binford 1990). All radiometric isotopic measurements were made using a Canberra gamma-ray Spectrometer with a well configuration based on a subset of 21 freeze-dried samples spanning the length of the core. The age of the nondated sections (located between dated intervals) was estimated by linear interpolation.

From the core, we prepared and plated 51 samples for diatom analysis using standard techniques described in Battarbee et al. (2001). A minimum of 400 diatom valves were counted for each slide using a Leica DM4500 B microscope at $1000\times$ magnification with oil immersion. Diatoms were identified to the lowest possible taxonomic level using several references (Krammer and Lange-Bertalot 1986, 1988, 1991a, 1991b).

Data analysis

To reconstruct past changes in TP and TKN from the diatom assemblages (referred to here as DI-TP and DI-TKN, respectively), we applied a calibration set from western North American freshwater lakes (salinity <1 g/L; n = 271; Moos et al. 2009). This represents an expansion of the freshwater lakes in a dataset originally published by Cumming and Smol (1993), where details regarding surface sediment and water chemistry sampling are described fully. Within the 271-lake calibration set, the lakes spanned a strong TP and TKN gradient (i.e., mean $\pm$ 1 standard error $= 46 \pm 14 \, \mu g/L$ TP and mean $= 744 \pm 51 \, \mu g/L$ TKN). We chose to perform a reconstruction for both TP and TKN, but these variables are significantly correlated (r = 0.60, p < 0.001, n = 271).

Using the C2 Data Analysis package v1.6.7, we applied a weighted-averaging (WA) model based on square-root transformed species abundances, boot-strapping with classical de-shrinking for TP and TKN (Juggins 2007). Because the nutrient data were highly skewed, we applied a log(x) transformation. We also removed several sites in the development of the TKN model because they were either below the detection limit, or one site was an extreme outlier in terms of the composition of the diatom assemblages. Because we made minor adjustments to the calibration set to standardize the taxonomy of the core and removed an outlier, we ran each WA model twice. Consistently, the r^2_{boot} between predicted and observed TP was modest ($r^2_{boot} = 0.45$ and 47, n = 271) and the root mean squared error of prediction (RMSEP) was 0.47 log TP units. The TKN data produced a stronger inference model ($r^2_{boot} = 0.64$ and 0.69, n = 266 or 267) and lower RMSEP (0.28 or 0.31 log TKN units).

The strength of these inference models are comparable to those previously reported for diatom-based inference models for nutrients (e.g., Dixit and Smol 1994, Reavie and Smol 2001).

To evaluate the appropriateness of using the calibration set on the diatom assemblages in the core from Baptiste Lake, we first conducted a correspondence analysis (CA) and passively plotted the subfossil assemblages. As part of a different analysis we ran a principal component analysis (PCA) to summarize the main direction of variation (i.e., PCA axis-1 scores) in the diatom assemblages from the Baptiste Lake sediment core. We then ran linear correlations between the PCA axis-1 scores and DI-TP and DI-TKN to assess whether the reconstructed nutrient variables were significantly related to the main direction of variation found in the diatom record. Ordination analyses were run using CANOCO for Windows, and correlations were run in the R v.2.11.1 statistical program (R Core Team 2012).

We used a correlation approach to evaluate if diatom-inferred nutrients tracked the changes observed in water chemistry from the water column. We also evaluated the strength of the correlations between seasonal and yearly values of nutrients. Our definition of the seasons was based on the thermal structure and the seasonality of phytoplankton blooms in the south basin of Baptise Lake. Specifically, in all but one year, the water column from the south basin of Baptiste Lake was mixed (i.e., less than a one degree temperature change across 1 m of water) before 15 May (Julian day 135) and after 20 October (Julian day 293). Diatoms and cyanobacterial dynamics also largely followed this pattern (Fig. 2). As such, we separated the seasons as spring: 1 May to 1 June (Julian day 121–152); summer: 2 June to 1 October (Julian day 153–274); and fall: 2 October to 1 November (Julian day 275–305).

Finally, we applied a nonparametric Mann-Kendall trend test (using the Kendall package in R; McLeod 2011, Hipel and McLeod 2005) to the spring, summer, fall, and average growing season TP and TKN data of Baptiste Lake to test for the presence and direction of monotonic temporal trends (Yue et al. 2002, R Core Team 2012). To compare the variability between the time series of the seasonal monitoring TP and TKN data, the coefficient of variation was calculated for each series.

To test whether changes in climate could explain some of the observed variation in nutrient concentrations, we applied correlations between the nutrient time series and climate data taken from the nearby Athabasca and Meanook weather stations. The climate factors considered were annual and growing season air temperature and precipitation data, as well as annual records of changes in lake level. For all correlations, data transformations (either a log or

square-root transformation) were used when assumptions of normality were violated.

Results

Sediment core analyses

Analysis of the ^{210}Pb activity in the core reveals that the 46 cm core spans at least 150 years. Across the entire record, diatoms were well preserved and abundant, and the assemblage was largely dominated by planktonic taxa. Overall, the *Stephanodiscus minutulus/parvus* complex indicative of nutrient-rich conditions (Hobaek et al. 2012) was most dominant, but also highly variable in terms of its abundance (Fig. 3). Specifically, the *S. minutulus/parvus* complex displayed a recurring pattern, decreasing between 4 and 14 cm, and again between 26 and 30 cm, as well as around 40 cm. Decreases in *S. minutulus/parvus* to <15% were synchronous with increases in the relative abundances of *Aulacoseira granulata* and/or *Aulacoseira ambigua*, taxa known to be competitive in both nutrient-rich and turbulent waters (Bradbury et al. 2004; Fig. 3). In the top 10 cm of the sediment core (~1980 to present), a distinct increase in *Stephanodiscus hantzschii* was observed (Fig. 3), although abundances of ~5% were also present in the 1800s. Consistent with the diatom flora changes, inferred nutrient concentrations showed several substantial fluctuations over the ~150 years represented (Fig. 3). In particular, DI-TKN and DI-TP notably increased in the last decade.

Evaluation of DI-TP and DI-TKN and a comparison with monitoring data

Similar to the diatom-inferred nutrient trends, both TKN and TP measurements based on water column samples were highest in the last decade. With the summer, fall, and growing season TKN data, we detected significant increasing trends through time (Mann-Kendall Tau coefficients ≥0.4, p ≤ 0.03). The spring TKN data showed a marginally increasing trend (Tau = 0.4, p = 0.08). In contrast, we detected no pattern in the seasonal TP data (Tau ≤ 0.1; p-values > 0.5). The TP data were more variable than the TKN time series, in which the coefficient of variation (CV) values for each of the seasonal TP series were more than double than those calculated from the TKN seasonal trends (Table 2). As a standardized measurement of dispersion, high CV values reveal high variability in the data, which could explain the lack of trends in the TP datasets.

To evaluate whether the DI-TP and DI-TKN reconstructions represent a robust reflection of the trophic history of Baptiste Lake, we conducted several different analyses. We first considered the overlap in the composition of the di-

Table 2.-Coefficient of variation values for the seasonal TP and TKN trends from monitoring data taken from Baptiste Lake.

Variable	n	Coefficient of variation	Mean (μg/L)
Growing season TP	18	18.7	62.6
Growing season TKN	18	15.2	1209.8
Spring TP	14	40.4	99.1
Spring TKN	14	22.3	1125.7
Summer TP	18	17.2	52.9
Summer TKN	18	15.9	1234.1
Fall TP	13	23.9	86.1
Fall TKN	12	15.9	1097.9

atom assemblage between the calibration set and subfossil assemblages. Our correspondence analysis clearly showed that the Baptiste core samples fell within the envelope of the calibration set (data not shown), suggesting the presence of appropriate analogs. Strong and significant correlations were also detected between the PCA axis-1 scores and DI-TKN (r = −0.76, p < 0.0001) or DI-TP (r = −0.74, p < 0.0001), clearly indicating the main direction of variation in the diatom record is consistent with a trophic signal (Fig. 4). Finally, we compared the diatom-inferred nutrient estimates with the contemporaneous water column data from the early 1980s to 2010 (Fig. 5 and 6). We found that the strongest correlations were with the TKN time series (Fig. 6), but no significant correlation was detected among any of the TP time series (Supplemental Fig. 1).

Comparing nutrient concentration data with environmental and climatic factors

To test whether both or a single nutrient variable were significant predictors of phytoplankton abundance, we ran correlations between chlorophyll *a* (Chl-*a*) and TP or TKN as measured in the water column. This analysis clearly showed a strong relationship between TKN and Chl-*a* (r = 0.81, p = 0.03), but no significant relationship was detected between TP and Chl-*a* (r = 0.25, p = 0.59).

To explore whether changes in nutrient dynamics recorded in Baptiste Lake were primarily driven by climate variability, we ran correlations between the nutrient time series and climate data taken from the nearby Athabasca and Meanook weather stations (data from Canadian Daily Climate Database and the Water Level and Streamflow Statistics Database; Environment Canada 2006, 2012; see Supplemental Fig. 2 and 3). First, we considered the nutrient concentration measurements (averaged over the growing season) but detected no significant relationships (p > 0.15) between TKN or TP and air temperature, water levels, or precipitation, even when annual or seasonal climatic
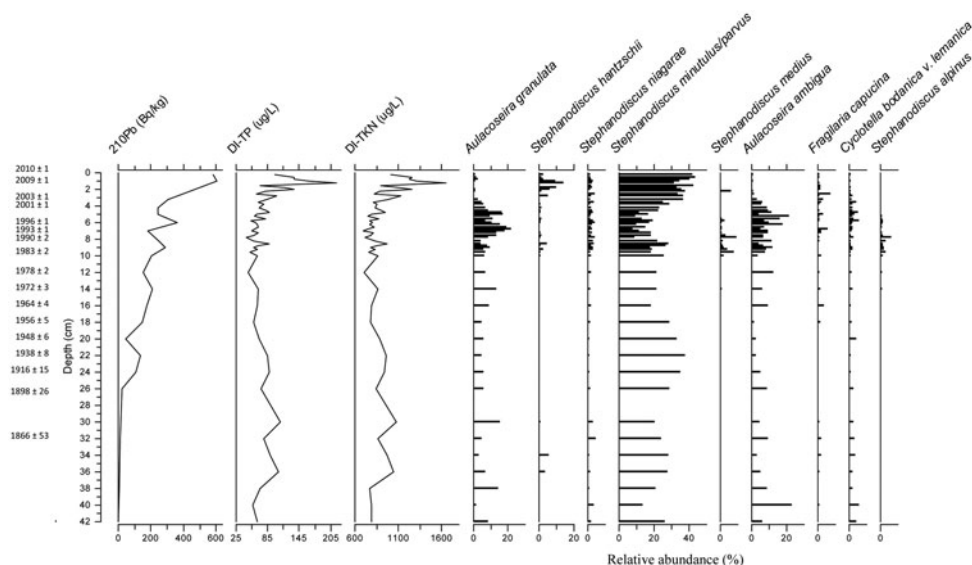
Figure 3.-The unsupported ^{210}Pb profile and diatom-inferred TP (DI-TP) and DI-TKN estimates are plotted alongside the dominant diatom taxa (>5% abundance) in Baptiste Lake over at least the past 150 years. The age estimates (shown on the extreme left) refers to the estimated age of the sediments based on the application of the constant rate of supply model to the ^{210}Pb data.

estimates were used. Recognizing that only 13 years of water column TKN and TP data were available to evaluate these relationships, we also adopted a similar framework with the DI-TKN and DI-TP data (with 51 data points); however, none of these analyses were significant ($p > 0.5$).

Discussion

Based on our paleolimnological analyses, we conclude that Baptiste Lake has been eutrophic for at least the last 150 years; however, both the sediment core and monitoring

data show a general increase in TKN over the last decade. Our comparison of the water column monitoring data with the diatom-inferred nutrient records since the early 1980s from Baptiste Lake show that DI-TKN tracks the modern trends in measured TKN and consequently may allow the reconstruction of this nutrient over time. The DI-TP trends, however, were not correlated to the monitoring records and thus should be viewed with caution.

Over the last 150 years the diatom assemblages in the core from Baptiste Lake are dominated by taxa reflective of
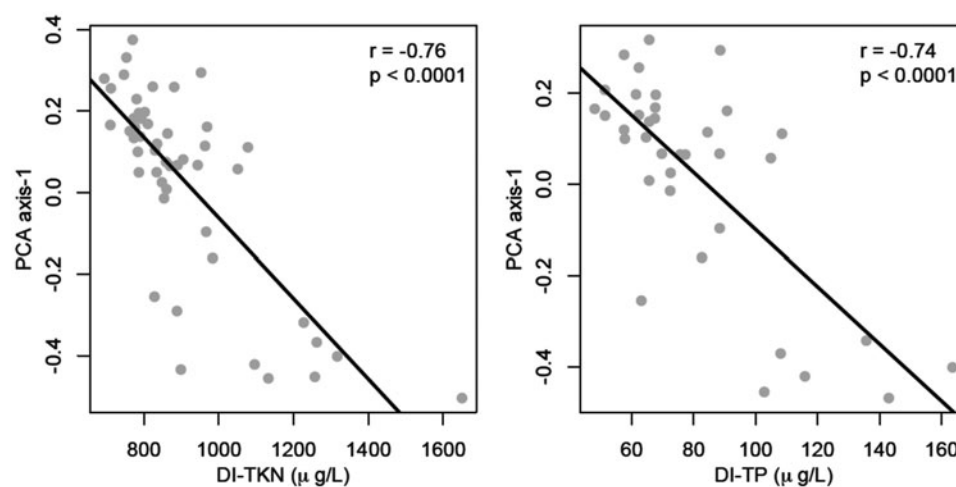

Figure 4.-The relationship between the DI-TKN and DI-TP estimates and the corresponding PCA axis-1 sample scores based on the subfossil diatom assemblages.
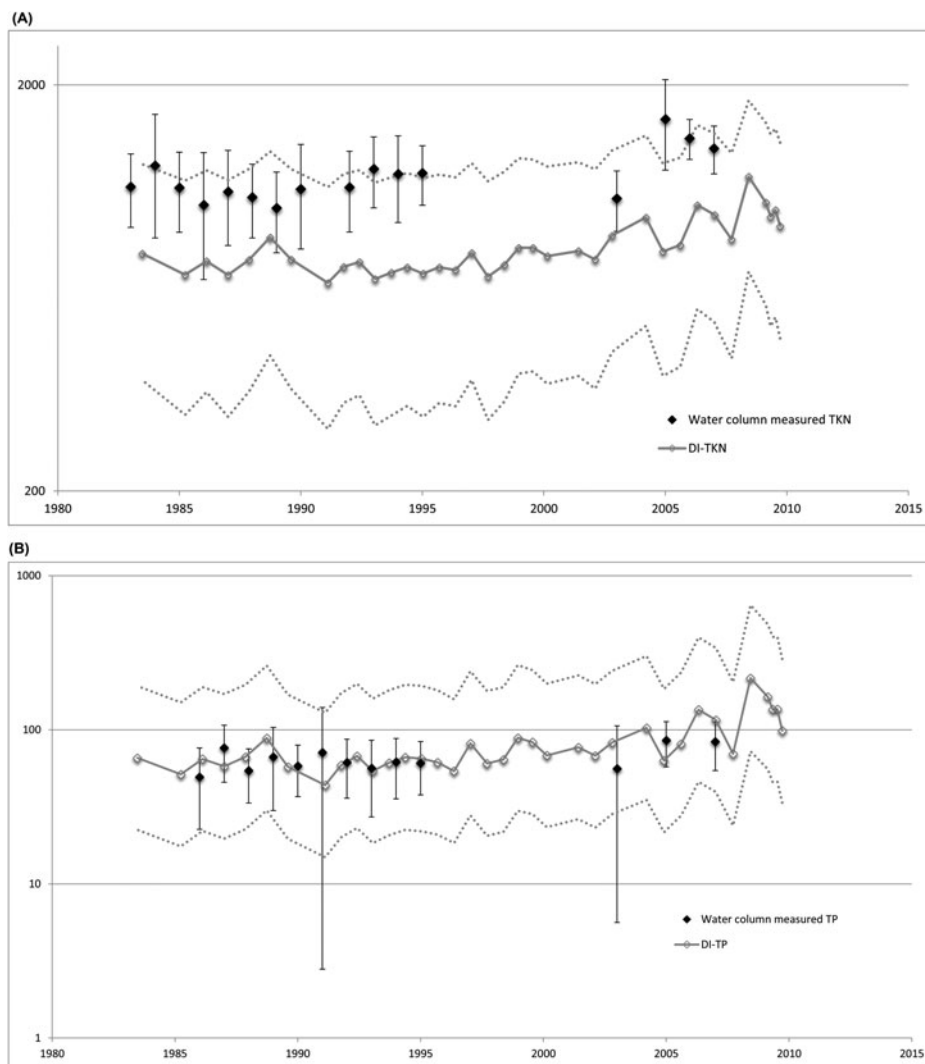
Figure 5.-(A) Average total Kjeldahl nitrogen (TKN; shown as filled diamonds) and diatom-inferred TKN (DI-TKN; shown as open diamonds) concentrations since 1985. (B) Total phosphorus (TP; shown as filled diamonds) and diatom-inferred TP (DI-TP; shown as open diamonds) concentrations since 1985. The error bars for the water column data show the full range of measurements made during the growing season and the dotted series indicate ± 1 root mean squared error values for the diatom-inferred nutrient data (which has been back-transformed). Note that there was a substantial interruption in the water column sampling of Baptiste Lake from 1996 to 2003.

eutrophic conditions. This result echoes the more qualitative and longer-term study (spanning the past ~4000 years) by Hickman et al. (1990), who analyzed diatom assemblages preserved in a core collected in the south basin of Baptiste Lake. Based on their analysis, they inferred that changes in lake stratification were revealed in the sediment record. In particular, small *Stephanodiscus* taxa were most abundant in laminated sequences (which they suggested were reflective of meromictic conditions) and *Aulacoseira granulata* was most abundant during the unlaminated sequence (reflective of dimictic or polymictic waters). In accordance with this logic and other studies of *Aulacoseira* (Rühland et al. 2008, Selbie et al. 2011) that have reported an association between this taxonomic group and turbulent water

column conditions, we tested whether changes in the relative abundance of *Aulacoseira* taxa were negatively correlated to Schmidt stability measures. Based on our analyses of the water column monitoring record, however, no significant relationship was detected between the relative abundances of *A. ambigua* and *A. granulata* and water column stability, possibly due to insufficient statistical power (n = 19) or because *Aulacoseira* spp. are sensitive to mixing under particular conditions (and thus the relationship is nonlinear).

Although the DI-nutrient values were consistently reflective of eutrophic conditions before the 20th century, the values recorded in the early 21st century are unprecedented
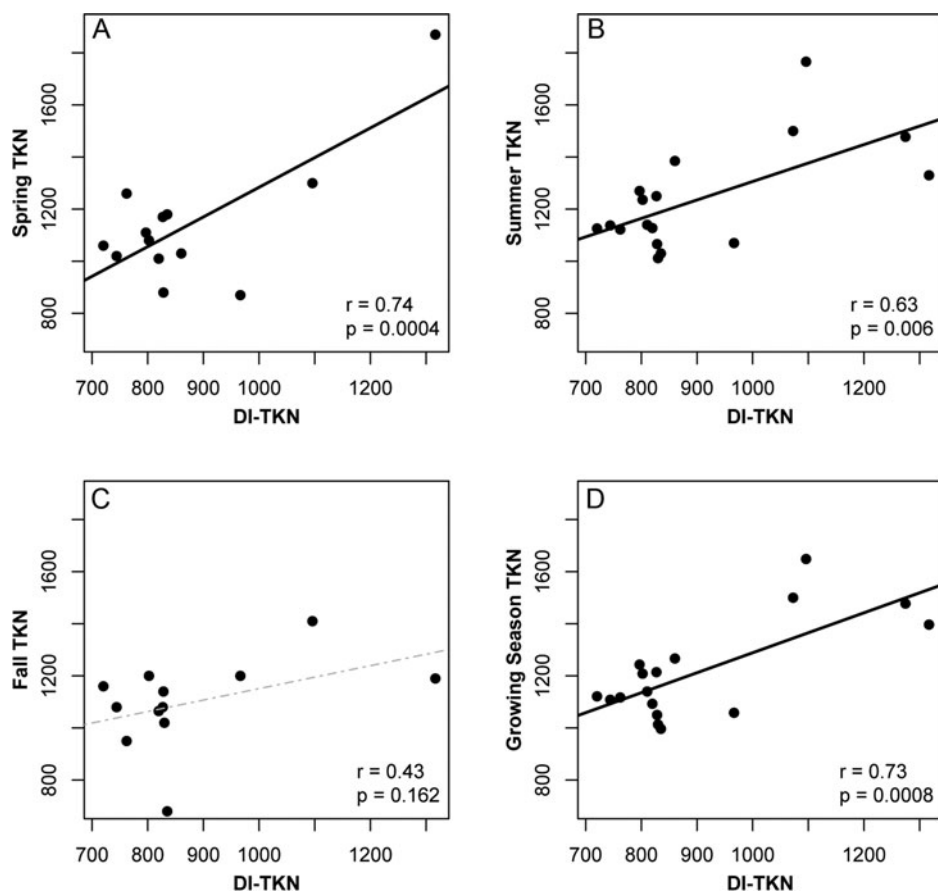
Figure 6.-Correlation plots between DI-TKN and (A) spring, (B) summer, (C) fall, and (D) growing season TKN concentrations from the water column of Baptiste Lake (south basin). The DI-TKN data from the core have been averaged by year in order to compare it with the monitoring data.

compared to the previous 150 years. The high DI-TKN and DI-TP values around 2003 are associated with the high abundance of *S. hantzschii* (Fig. 3), a species known to proliferate with increasing nutrient inputs (Stoermer et al. 1978, Eriksson and Forsberg 1992, Bradbury et al. 2004). In the Hickman et al. (1990) Baptiste Lake record, *S. hantzschii* was abundant (typically >20% relative abundance) in the past 4000 years, and *S. minutulus* (a eutrophic, but less nutrient-rich indicator than *S. hantzschii*) was only present in trace abundances (<1% relative abundances). However, these investigators likely combined *S. parvus* with *S. hantzschii* because the taxonomy of *S. parvus* was not well developed until after the publication of the Hickman et al. study (see Stoermer and Håkansson 1984, Håkansson and Stoermer 1988), and they did not report any presence of *S. parvus*. As such, direct comparisons between our core and the core assessed by Hickman et al. (1990) is difficult.

In many freshwater lakes, P has been considered the most important limiting nutrient to primary production (Schindler 1977). More recently, however, limnologists and lake man-

agers increasingly recognize the role of other nutrients, such as N (Lewis and Wurtsbaugh 2008), as a limiting nutrient in primary production. In support of this change in paradigm, we found that TKN was a significant predictor of Chl-*a* in Baptiste Lake, where Chl-*a* was independent of TP. Likewise, we found that the DI-TKN data tracked the contemporaneous TKN dynamics measured in the water column; however, TP dynamics, which were relatively stable during the monitoring window, were not correlated to the DI-TP results. We also found that the dissolved inorganic N (DIN):TP ratios for 82% of all open-water sampling dates (n = 110) were indicative of N limitation (using the >75% probability of N limitation criterion developed by Bergström 2010). Finally, experimental work by Donald et al. (2011, 2013) in eutrophic waters has shown that both total phytoplankton and diatom standing crop can be significantly enhanced by the addition of organic N (i.e., urea) to eutrophic waters.

Consistent with our DI-TKN record, the 25-year intermittent monitoring record from ESRD showed that growing

season average TKN concentrations had increased by ~50% (997 μg/L in 1989 to 1649 μg/L in 2005) before decreasing slightly in the most recent years. Additionally, our comparison of the water column data with the paleolimnological time series show that recent nutrient increases are outside the range of variation observed over the last 2 centuries. Given these results, the intensification of agricultural and urban activities (Mitchell and Prepas 1990, Carlson 2008) as well as climate change must be considered as possible explanations.

Runoff from agricultural fields in the watershed has been shown to contribute to the elevated levels of nutrients into Baptiste Lake (Trew et al. 1987, Cooke and Prepas 1998). Cooke and Prepas (1998) showed the export of different fractions of P and N in streams were often at least 2 times higher in those draining cropland and cow–calf operations in the Baptiste Lake drainage area compared to those draining natural forests. Furthermore, epilimnetic TP concentrations were found to be significantly related to the proportion of agricultural land cover in a regional study of dimictic lakes (Taranu et al. 2010). Ideally, we would quantify the relationship between land-use changes and diatom-inferred nutrient concentrations over the last century, but the large agricultural census regions preclude a meaningful analysis at the local watershed scale. As a result, we can only provide supporting literature and weigh the evidence for alternative hypotheses.

Increased nutrient levels could arise when higher summer air temperatures lead to drought conditions (i.e., lower water levels), whereby dissolved and particulate substances in the water would become more concentrated (Carlson 2008). To address this hypothesis, we ran correlations between average growing season TKN and TP and average growing season air temperature. Similarly, we ran correlations between annual water levels and growing season TKN and TP to test the possible effect of drought conditions on nutrient levels. With both the monitoring record as well as the DI-TKN and DI-TP data, we detected no significant relationship between trophic state variables and average growing season air temperature as well with annual water levels.

Precipitation may also affect the concentration of nutrients because high precipitation could increase runoff of nutrients from the watershed into the lake; however, no correlation between annual precipitation data from the Baptiste Watershed (Environment Canada 2012) and growing season TKN and TP was found. Overall, based on the absence of any significant relationships between the nutrient data and the suite of climatic factors considered, we conclude that a direct effect of climate change on the nutrient fluctuations in Baptiste Lake is unlikely. Rather, the role of localized anthropogenic activities (e.g., agriculture, residential development, land clearance) in the Baptiste catchment area seem to be more important drivers of TKN and TP concentrations. Future studies are needed to explore whether climate change could be interacting with land-use and if any nonlinear relationships exist between climate change and water quality, which were not examined here but could also be a factor in driving nutrients.

Atmospheric deposition of N seems an unlikely factor to explain the observed DI-TKN dynamics in Baptiste Lake. First, stable isotope modeling work in the region suggests that the sphere of influence of N deposition arising from the Oil Sands operation is limited to a 30 km radius (Proemse et al. 2013), whereas Baptiste Lake is a few hundred kilometers away from Fort McKay and Edmonton. A larger paleolimnological study on remote lakes has detected an N deposition signal beyond a 30 km radius, but the lakes considered had much lower epilimnetic concentrations of N (Holtgrieve et al. 2011). Furthermore, we also conducted a paleolimnological analysis of a regional lake, Ethel Lake, which is similar in morphometry to Baptiste Lake (e.g., differ in Z_{max} by 2.5 m) but has a smaller coverage of agricultural lands in its watershed (11%) and limited shoreline development (Mitchell and Prepas 1990, Taranu et al. 2010). The DI-TKN and DI-TP profiles from Ethel Lake clearly show no directional change over at least the last 150 years (Supplemental Fig. 4), a finding that differs from the paleolimnological results for Baptiste Lake.

Given that Baptiste Lake has been a eutrophic lake over the past ~150 years, expecting any mitigative strategy to change the lake to an oligotrophic state is unreasonable; however, proper management and prevention strategies could reduce excessive inputs of nutrients from the watershed, which could mitigate the frequency and density of cyanobacterial blooms (Taranu et al. 2012). With reports of animal mortality near the lake attributed to toxic cyanobacteria (Mitchell and Prepas 1990), prevention of nutrients entering the lake is not only an issue of maintaining the lake's health, but also that of the Baptiste Lake community. Management efforts currently implemented in Baptiste Lake and its watershed include the (near complete) elimination of grey-water pits and toilet pits (Carlson 2008), as well as a halt in shoreline development in 1977 (Mitchell and Prepas 1990). Preventing nonpoint source runoff from croplands and pastures is more difficult, but a multitude of methods are available to prevent a substantial amount of nutrients from entering the lake. Techniques such as rotational grazing, proper fertilizer applications, and the use of alternate watering sources would be beneficial in reducing nutrient loading to the lake (Carlson 2008). One particularly effective and fairly simple strategy is the conservation and maintenance of riparian zones, which could play a crucial role in the prevention

of nutrient-rich waters entering Baptiste Lake (Anbumozhi et al. 2005).

Collectively, our analyses provide insights into the trophic state dynamics of Baptiste Lake that extend the modern monitoring record by at least 150 years. Knowing the timing of nutrient fluctuations allows a clearer understanding of lake dynamics and helps identify the factors that play paramount roles in influencing the chemical and biological characteristics of the lake, resulting in improved management recommendations. We also provide support for lake-water N as a limiting nutrient of primary production and, more specifically, as a driver of diatom assemblages of Baptiste Lake. With these results, future research of Baptiste Lake should test experimentally where and when N limits algal growth. With this information, appropriate management guidelines could be developed to control N and P sources in the watershed. Ultimately, we believe that coupling paleolimnology with long-term monitoring data provides insights that can contribute to the development of future management strategies (e.g., Battarbee et al. 2012).

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References

Anbumozhi V, Radhakrishnan J, Yamaji E. 2005. Impact of riparian buffer zones on water quality and associated management considerations. Ecol Eng. 24(5):517–523.

Battarbee RW, Anderson NJ, Bennion H, Simpson G. 2012. Combining limnological and palaeolimnological data to disentangle the effects of nutrient pollution and climate change on lake ecosystems: problems and potential. Freshwater Biol. 57(10):2091–2106.

Battarbee RW, Jones VJ, Flower RJ, Cameron NG, Bennion H. 2001. Diatoms. In: Smol JP, Birks HJB, Last WM, editors. *Tracking environmental change using lake sediments: Terrestrial, algal, and siliceous indicators*. Dordrecht (Netherlands): Kluwer Academic Publishers. p. 155–202.

Bennion H, Simpson G. 2011. The use of diatom records to establish reference conditions for UK lakes subject to eutrophication. J Paleolimnol. 45(4):469–488.

Bergström A-K. 2010. The use of TN:TP and DIN:TP ratios as indicators for phytoplankton nutrient limitation in oligotrophic lakes affected by N deposition. Aquat Sci. 72(3):277–281.

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

Bradbury J, Colman SM, Reynolds RL. 2004. The history of recent limnological changes and human impact on Upper Klamath Lake, Oregon. J Paleolimnol. 1(2):151–165.

Brenner M, Whitmore TJ, Lasi MA, Cable JE, Cable PH. 1999. A multiproxy trophic state reconstruction for shallow Orange Lake, Florida, USA: possible influence of macrophytes on limnetic nutrient concentrations. J Paleolimnol. 21:215–233.

Carlson M. 2008. State of the Baptiste Lake Watershed. Report prepared for the Baptiste Lake Watershed Stewardship Group; [cited May 2012]. Available from: http://www.southbaptiste.com/download_files/State%20of%20Baptiste%20Lake%20Watershed%20report.pdf

Casey R. 2011. *Water quality conditions and long-term trends in Alberta Lakes*. Edmonton (AB): Alberta Environment and Water. 419 pp + Appendix (6p).

Charles CF, Dixit SS, Cumming BF, Smol JP. 1991. Variability in diatom and chrysophyte assemblages and inferred pH: Paleolimnological studies of Big Moose Lake, New York, USA. J Paleolimnol. 5(3):267–284.

Cooke SE, Prepas EE. 1998. Stream phosphorus and nitrogen export from agricultural and forested watersheds on the Boreal Plain. Can J Fish Aquat Sci. 55(10):2292–2299.

Cumming BF, Smol JP. 1993. Development of diatom-based salinity models for paleoclimatic research from lakes in British Columbia (Canada). Hydrobiologia. 269/270:179–196.

Dixit SS, Smol JP. 1994. Diatoms as indicators in the Environmental Monitoring and Assessment Program-Surface Waters (EMAP-SW). Environ Monit Assess. 31(3):275–306.

Dixit SS, Smol JP, Charles DF, Hughes RM, Paulsen SG, Collins GB. 1999. Assessing water quality changes in the lakes of the northeastern United States using sediment diatoms. Can J Fish Aquat Sci. 56(1):131.

Donald D, Bogard M, Finlay K, Leavitt P. 2011. Comparative effects of urea, ammonium, and nitrate on phytoplankton abundance, community composition, and toxicity in hypereutrophic freshwaters. Limnol Oceanogr. 55(6):2161–2175.

Donald D, Bogard M, Finlay K, Bunting L, Leavitt P. 2013. Phytoplankton-specific response to enrichment of phosphorus-rich waters with ammonium, nitrate, and urea. PLoSONE. 8(1):e53277.

Elser JJ, Bracken MES, Cleland EE, Gruner DS, Harpole WS, Hillebrand H, Ngai JT, Seabloom EW, Shurin JB, Smith JE. 2007. Global analysis of nitrogen and phosphorus limitation of primary producers in freshwater, marine and terrestrial ecosystems. Ecol Lett. 10(12):1135–1142.

Eriksson E, Forsberg C. 1992. Nutrient interactions and phytoplankton growth during the spring bloom period in Lake Erken, Sweden. Int Rev Ges Hydrobiol. 77(3):517–551.

Environment Canada. 2006. Water level and streamflow statistics; [cited Sep 2012]. Available from: http://www.wsc.ec.gc.ca/staflo/index_e.cfm

Environment Canada. 2012. Canadian daily climate database; [cited Apr 2012]. Available from: http://climate.weather office.gc.ca/climateData/canada_e.html

Glew JR. 1989. A new trigger mechanism for sediment samplers. J Paleolimnol 4(2):241–243.

Håkansson H, Stoermer EF. 1988. A note on the centric diatom Stephanodiscus parvus. Diatom Res. 3(2):267.

Hall R, Leavitt P, Smol JP, Zirnhelts N. 1997. Comparison of diatoms, fossil pigments and historical records as measures of lake eutrophication. Freshwater Biol. 38(2):401–417.

Hall R, Smol JP. 2010. Diatoms as indicators of lake eutrophication. In: Smol JP, Stoermer EF, editors. *The diatoms: Applications for the environmental and earth sciences*. New York (NY): Cambridge University Press. p. 122–152.

Hickman M, Schweger C, Klarer DM. 1990. Baptiste Lake, Alberta - A late Holocene history of changes in a lake and its catchment in the southern Boreal forest. J. Paleoli. 4:253–267.

Hipel KW, McLeod AI. 2005. Time series modelling of water resources and environmental systems. Electronic reprint of book orginally published in 1994; [cited Sep 2012]. Available from: http://www.stats.uwo.ca/faculty/aim/1994Book/

Hobaek A, Løvik JE, Rohrlack T, Moe SJ, Grung M, Bennion H, Clarke G, Piliposyan GT. 2012. Eutrophication, recovery and temperature in Lake Mjøsa: Detecting trends with monitoring data and sediment records. Freshwater Biol. 57(10):1998–2014.

Holtgrieve GW, Schindler DE, Hobbs WO, Leavitt PR, Ward EJ, Bunting L, Chen G, Finney BP, Gregory-Eaves I, Holmgren S, et al. 2011. A coherent signature of anthropogenic nitrogen deposition to remote watersheds of the Northern Hemisphere. Science. 334(6062):1545–1548.

Juggins S. 2007. *C2 Version 1.5 User guide. Software for ecological and palaeoecological data analysis and visualisation*. Newcastle upon Tyne (UK): Newcastle University. 73 p.

Juggins S, Anderson NJ, Hobbs JMR, Heathcote AJ. 2013. Reconstructing epilimnetic total phosphorus using diatoms: statistical and ecological constraints. J Paleolimnol. doi: 10.1007/s10933-013-9678-x

Kalff J. 2002. *Limnology: Inland water ecosystems*. Upper Saddle River (NJ): Prentice Hall.

Krammer K, Lange-Bertalot H. 1986. Bacillariophyceae 1. Teil: Naviculaceae. In: Ettl H, Gerloff J, Heynig H, Mollenhauer D, editors. *Die Susswasserflora Mitteleuropa 2/1*. Stuttgart (Germany): G. Fischer. 876 p.

Krammer K, Lange-Bertalot H. 1988. Bacillariophyceae 2. Teil: Bacillariaceae, Fragilariaceae, Eunotiaceae. In: Ettl H, Gerloff J, Heynig H, Mollenhauer D, editors. *Die Susswasserflora Mitteleuropa 2/3*. Stuttgart (Germany): G. Fischer. 576 p.

Krammer K, Lange-Bertalot H. 1991a. Bacillariophyceae 3. Teil: Centrales,Epithemiaceae, Surirellaceae. In: Ettl H, Gerloff J, Heynig H, Mollenhauer D, editors. *Die Susswasserflora Mitteleuropa 2/2*. Stuttgart (Germany): G. Fischer. 596 p.

Krammer K, Lange-Bertalot H. 1991b. Bacillariophyceae 4. Teil: Achnanthaceae, Kritische Erganzungen zu Navicula (Lineolatae), und Gomphonema. In: Ettl H, Gerloff J, Heynig H, Mollenhauer D, editors. *Die Susswasserflora Mitteleuropa 2/4*. Stuttgart (Germany): G. Fischer. 596 p.

Lewis WM, Saunders JF, McCutchan JH Jr. 2008. Application of a nutrient-saturation concept to the control of algal growth in lakes. Lake Reserv Manage. 24(1):41–46.

Lewis WM, Wurtsbaugh WA. 2008. Control of lacustrine phytoplankton by nutrients: Erosion of the phosphorus paradigm. Int Rev Hydrobiol. 93(4–5):446–465.

McLeod AI. 2011. Kendall: Kendall rank correlation and Mann-Kendall trend test. R Package version 2.2. Available from: http://CRAN.R-project.org/package=Kendall

Mitchell PA, Prepas EE. 1990. *Atlas of Alberta Lakes*. Edmonton (AB): University of Alberta Press.

Moe SJ, Dudley B, Ptacnik R. 2008. REBECCA databases: experiences from compilation and analyses of monitoring data from 5,000 lakes in 20 European countries. Aquat Ecol. 42(2):183–201.

Moos MT, Laird KR, Cumming BF. 2009. Climate-related eutrophication of a small boreal lake in northwestern Ontario: A paleolimnological perspective. Holocene. 19(3): 359–367.

Orihel DM, Bird DF, Brylinsky M, Chen H, Donald DB, Huang DY, Giani A, Kinniburg D, Kling H, Kotak BG, et al. 2012. High microcystin concentrations occur only at low nitrogen-to-phosphorus ratios in nutrient-rich Canadian lakes. Can J Fish Aquat Sci. 69(9):1–6.

Proemse BC, Mayer B, Fenn ME, Ross CS. 2013. A multi-isotope approach for estimating industrial contributions to atmospheric nitrogen deposition in the Athabasca oil sands region in Alberta, Canada. Environ Pollut. 182:80–91.

R Core Team. 2012. *R: A language and environment for statistical computing*. Vienna (Austria): R Foundation for Statistical Computing.

Reavie ED, Smol JP. 2001. Diatom-environmental relationships ion 64 alkaline southeastern Ontario (Canada) lakes: A diatom-based model for water quality reconstructions. J Paleolimnol. 25(1):25–42.

Rippey B, Anderson NJ, Foy RH. 1997. Accuracy of diatom-inferred total phosphorus concentrations and the accelerated eutrophication of a lake due to reduced flushing and increased internal loading. Can J Fish Aquat Sci. 54(11):2637.

Rühland K, Paterson A, Smol JP. 2008. Hemispheric-scale patterns of climate-related shifts in planktonic diatoms from North American and European lakes. Global Change Biol. 14(11):2740–2754.

Selbie DT, Sweetman JN, Etherton P, Hyatt KD, Rankin DP, Finney BP, Smol JP. 2011. Climate change modulates structural and functional lake ecosystem responses to introduced anadromous salmon. Can J Fish Aquat Sci. 68(4):675–692.

Schindler DW. 1977. Evolution of phosphorus limitation in lakes. Science. 195:260–262.

Schindler DW. 2012. The dilemma of controlling cultural eutrophication of lakes. P Roy Soc B-Biol Sci. 279:4322–4333.

Smith VH, Schindler DW. 2009. Eutrophication science: where do we go from here? Trends Ecol Evol. 24(4):201–207.

Smol JP, Stoermer EF. 2010. *The diatoms: Applications for the environmental and earth sciences*. New York (NY): Cambridge University Press.

Soranno PA. 1996. Factors affecting the timing of surface scums and epilimnetic blooms of blue-green algae in a eutrophic lake. Can J Fish Aquat Sci. 54(9):1965–1975.

Statistics Canada. 2011. Census of agriculture, farm and farm operator data; catalogue no. 95–640-XWE; [cited Oct 2013]. Available from: http://www29.statcan.gc.ca/ceag-web/eng/community-agriculture-profile-profil-agricole.action?

Stoermer EF, Håkansson H. 1984. *Stephanodiscus parvus*: Validation of an enigmatic and widely misconstrued taxon. Nova Hedwigia. 39(3–4):497–511.

Stoermer EF, Ladewski BG, Schelske CL. 1978. Population responses of Lake Michigan phytoplankton to nitrogen and phosphorus enrichment. Hydrobiologia. 57(3):249–265.

Trew DO, Beliveau DJ, Yonge UEI. 1978. *The Baptiste Lake study summary report*. Edmonton (AB): Alberta Environment, Pollution Control Division, Water Quality Control Board.

Taranu Z, Köster D, Hall RI, Charette T, Forrest F, Cwynar L, Gregory-Eaves I. 2010. Contrasting responses of dimictic and polymictic lakes to environmental change: A spatial and temporal study. Aquat Sci. 72(1):97–115.

Taranu Z, Zurawell RW, Pick F, Gregory-Eaves I. 2012. Predicting cyanobacterial dynamics in the face of global change: The importance of scale and environmental context. Global Change Biol. doi: 10.1111/gcb.12015

[USEPA] US Environmental Protection Agency. 2009. *National lakes assessment: A collaborative survey of the nation's lakes*. Washington (DC): USEPA, Office of Water and Office of Research and Development. EPA 841-R-09-001.

Yue S, Pilon P, Cavadias G. 2002. Power of the Mann–Kendall and Spearman's rho tests for detecting monotonic trends in hydrological series. J Hydrol. 259(1–4):254–271.