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Paleolimnological reconstruction of forest fire induced changes in lake biogeochemistry

by

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SUMMARY

This study was designed to assess the impact of a natural catchment perturbations (forest fires) on the chemistry of the lakes into which they drain. To this end, a survey of the chemistry of 42 lakes was undertaken to establish quantitative relationships between the specific composition of diatom assemblages and the present chemistry of these lakes. Using multivariate statistical techniques, we were able to construct reliable and precise predictive functions for lake pH, total phosphorus (an important nutrient) and Dissolved Organic Carbon concentrations.

Once developed, these relationships can be used to infer past values from the diatom assemblages found in sediment cores dating back several hundreds or thousands of years. We focused on 4 major fire events that occurred within the watershed of Lac Francis over the past 2000 years. Diatom-inferred values for pH and DOC did not show any significant changes in relation to fires. However, diatom-inferred total phosphorus significantly increased, on average, by a factor of 50% relative to pre-fire conditions. This enriching effect however, was relatively short-lived, lasting only about 10-15 years and quite variable between fires.

Over the past 2000 years, however, Lac Francis became progressively richer and the magnitude of the effect of fires on phosphorus enrichment appeared to have diminished. This suggests that oligotrophic lakes are the most sensitive lakes to natural perturbation.

We suggest that sustainable forest management require the development of practices that maintain similarly low or ephemeral effects on the generation and transport of solutes from watersheds to lakes.

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INTRODUCTION

Sustainable forestry management cannot be achieved or indeed conceived of independently of the natural state of the ecosystem in which the forest grows. Baseline characteristics as well as the natural variability in both space and time are key attributes of the template from which forest harvest practices must be decided. However, measures of baseline characteristics and natural variability are very difficult to obtain in relatively short-term studies (a few years).

In the boreal forest, much of this natural variability stems from the periodic occurrence of large perturbations, the most important of which is believed to be forest fires (Bergeron, 1991). Because of its ecological importance, forest fire is one of the most documented natural disturbance factor in the boreal forest (Wright and Heinselman, 1973; Chandler *et al*, 1983; Dansereau and Bergeron, 1993; Liski, 1998). Forest fires affect radically the structure and the dynamics of the boreal forest and acts as a reset mechanism for the successional sequence.

There is growing consensus that harvest practices modeled on the characteristics of natural perturbations are most likely to be sustainable. Although one can reasonably develop forest harvest practices that mimic the frequency and extent of forest fires, proper sustainable forest management implies also that the properties of the land (hydrology and geochemistry) are maintained, i.e. that chemical losses to the surface waters draining that land are not significantly greater than losses occurring during natural perturbations such as fires. While several authors (Bayley *et al*., 1992; Wright, 1976; McColl and Grigal, 1975) reported increased nutrient and base cation export from burned catchments, others (e.g. Lewis, 1974; Richter and Rolston, 1982) argue that no important changes take place in the litter and in the fluxes of nutrients, sulfur and base cations from burned areas. These results, clearly contradictory at times, reflect the complexity of the processes induced by forest fires on the watershed area and the modulating influence of regional conditions. It is therefore difficult *a priori* to predict what effect fires will have on lakes draining these catchments.

<u>The main objective of this research project was to assess several aspects of the impact of natural perturbations (forest fires) on the biogeochemistry of lakes. Here, we use lakes as the ultimate integrators of the chemical changes occurring in the catchments following perturbations.</u> Using a long-term database, afforded by the use of paleolimnological tools, we examined a) whether fires affected the chemical losses from catchments (and hence chemical status of the lakes), b) the magnitude and duration of these altered losses, c) the natural variability of the impacts of successive fires within a catchment on lake chemistry.

To answer these questions, one needs a long-term record of both fire occurrence and of lake chemistry. Although direct measurements are not possible in this case, paleolimnological tools can be used to infer past value of the lake chemical variable over several millennia and micro-charcoal analysis permits the identification of past fires as well.

Briefly, paleolimnological reconstructions proceed in two main steps. In the first, we establish the quantitative relationships between modern fossil indicators (here, diatoms) and present day lake chemistry from a data set of several lakes. In the second, the relationships developed in the first step are applied to fossil diatom assemblages within a sediment core spanning several millennia of sediment accumulation. The main results of these two components are presented below separately under calibration and reconstruction.

In addition to these specific objectives, we used our lake database to examine the natural factors controlling lake chemistry in this particular region. Because the area has a unique geological (Holocene) history (see study sites section), we needed to confirm that the factors known to influence lake chemistry in other regions also applied to lakes located on the Clay Belt.

Study sites

The relationships between diatoms assemblages and lake chemical variables were developed from a so-called calibration set of 42 lakes located in the Abitibi region of Quebec and covered more than 16500 km^2 in area (Fig. 1). The lakes were chosen according to the following criteria: a) only headwater lakes so as to minimize the influence of within-lake retention of nutrients, b) no significant perturbation (natural or man-made) within its recent past (15-20 years). This region is unique within the Canadian Shield and the boreal forest in that it is part of the Clay Belt, an area rich in clay derived from the sedimentation process of the large proglacial freshwater L. Ojibway which covered the area for about 2000 years (from 10000 to 8000 yrs BP).

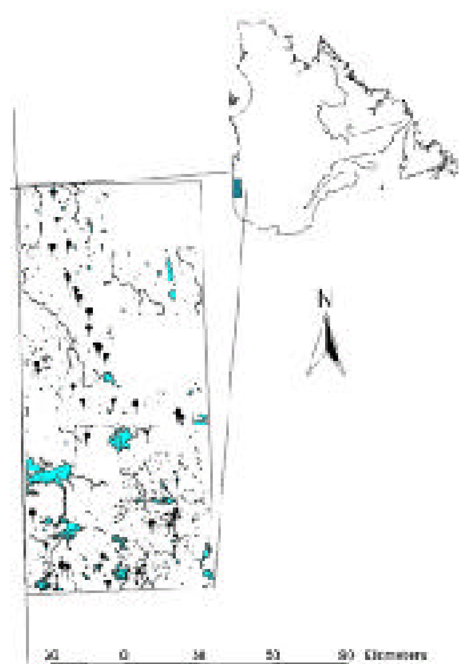


Figure 1. Location of the 42 lakes used in the diatom-lake chemistry calibration

The geology, morphology, vegetation and soils of the study area are heterogeneous. Geologically, the study area belongs to the Abitibi Subprovince of the Canadian Shield. It is a large folded geosynclinal area from Timmins to Chibougamau which is made up of volcanic and sedimentary rocks (GSC, 1990). Geological substratum of the watersheds surrounding our lakes show a high petrographical variability: from granitic or granodioritic substratum (lakes KI, Altura, Deux Montagnes, Petit Aldas), intermediate (KJ, Ducharme), to basaltic (Brunet, Pas de Fond, Landry, Francis) or sedimentary substratum (Arsenault, Long, Morillon, Vert). Some lakes (Fabie, Poison) have many types of rocks in their substratum (personal observations and geological charts). The surficial geology is very heterogeneous but contains eskers, organic material, and glaciolacustrine deposits from proglacial lake Ojibway.

Vegetation is primarily represented by coniferous boreal forest. In the south part of the study area (below 49˚N) balsam fir (*Abies balsamea*), white birch (*Betula papyrifera*) and white spruce (*Picea glauca*) are dominant on mesic sites whereas black spruce (*Picea mariana*), eastern cedar (*Thuja occidentalis),* larch (*Larix laricina)* associated to ash (*Fraxinus nigra)* and elm (*Ulmus americana)* are dominant on bogs and hydric sites. Species of poplar (*Populus tremuloides, P. balsamifera),* birch (*Betula papyfera*) are dominant on sites that were affected by forest fires (Bergeron and Dubuc, 1989). The northern part is dominated by species of spruce (*Picea glauca*, *Picea mariana*) and pine (*Pinus banksiana*). Many lakes are surrounded by *Sphagnum* peats (e.g. Ducharme, Francis).

Once the calibration between diatoms and lake biogeochemical variables is established, we applied the resulting transfer functions to quantitatively reconstruct past values of these variables in a lake for which we also established the fire chronology. The lake chosen was Lac Francis, a small kettle lake rich in nutrients and colored organic acids (see table 1 for general characteristics of L. Francis). The sediments (nearly 3 m of sediments, covering the entire Holocene) are discontinuously laminated and thus provide us with a reliable chronology (see Carcaillet et al., submitted) for a detailed account of the lake's sedimentation chronology.

Table 1. Principal characteristics of Lac Francis

Area L (km^2)	0,01	NT(µg l^{-1} N)	565,5
Area D (km^2)	0,21	NTD (µg l^{-1} N)	381,75
ALT (m)	305	NO_3 (µg l^{-1} N)	1
Slope (deg)	1,3522	NH_4 (µg l^{-1} N)	12
Z max (m)	6,1	PT (µg l^{-1} P)	27,5
pH	5,54	PTD (µg l^{-1} P)	8
Alka(µeql^{-1})	70,5	Chla (µg l^{-1})	32,95
Secchi (m)	0,8	DOC (mg l^{-1})	14,55

METHODS

Sampling

The 42 lakes were sampled twice during June-August 1996 (n=20) and 1997 (n=22). Surface sediment samples were collected in the deepest area using a Kajak-Brinkhurst gravity corer (Glew, 1991). The uppermost cm of sediment was carefully extruded in the field, kept in cool storage and returned to the laboratory for subsequent analyses. These samples were considered to provide an integrated sample (in space and time) of the diatom taxa that accumulated over the previous few years. Measurements of Secchi transparency, temperature and dissolved oxygen profiles, alkalinity and pH were carried out in the field. Integrated surface water samples of the epilimnion were collected in clean polyethylene bottles and immediately transferred in acid-washed and rinsed glass tubes (triplicates) for nutrient analyses. Chemical analyses were performed on an autoanalyser using standard methods. Further details on the sampling methods used can be found in Enache and Prairie, submitted).

Diatom analysis

Diatoms are a group of microscopic algae characterized by a siliceous shell called frustule which can remain intact after their death for thousands of years. The shape and ornamentation of the frustule is sufficiently characteristic and well preserved to identify each cell to the species or variety level (Fig. 2). Preparation of diatom samples followed standard methods (Battarbee, 1973, 1986) used for sediment samples without $CaCO_3$. For each sample, a minimum of 500 diatom valves was identified and counted with a Leica DMR microscope under oil immersion objectives at 1000X-1600X magnification along random transects. Diatom taxonomy followed standard floras (see Enache 1999 for details) and many other references. Because a high taxonomic precision is very important in quantitative paleoenvironmental studies (Birks, 1994), diatom taxa were carefully identified to the lowest taxonomic level (i.e. variety and *formae*). Sediment samples, microscope slides and cleaned diatom slurries are stored at the Department of Biological Sciences, UQAM, Quebec, Canada.

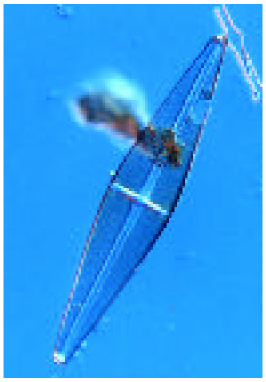


Figure 2 Example of a diatom frustule showing specific ornamentation (*Stauroneis sp.*)

Statistical analyses

Ordination in reduced space allows the derivation of quantitative information on the relationship among descriptors (species, environmental variables) as objects (sites) (Legendre and Legendre, 1998). All paleoecological reconstruction require the use of a heavy arsenal of multivariate statistical techniques. The details of the approach used in this study are given in Enache and Prairie (submitted) and will be omitted here. The basic idea is that a quantitative relationship is built between the diatom assemblages (i.e. the relative abundances of each diatom species) and the chemical variables.

RESULTS

Relationships between diatom assemblages and lake chemistry

Suitably for the calibration portion of this project, the lakes displayed a wide range in limnological characteristics covering many spectra: from oligotrophic to eutrophic, acid to basic, and clear to dystrophic. The general characteristics of the lakes are given in Table 2.

Such wide spectra are rare within a restricted geographical region and likely reflect the complex and heterogeneous nature of the terrain, a legacy of the glaciers and the large proglacial L. Ojibway. In each of these lakes, surface sediments representing the last few years of sedimentation were collected along with several geochemical variables of the lake water itself (total phosphorus, total dissolved phosphorus, total nitrogen, total dissolved nitrogen, nitrates, ammonia, DOC, pH, alkalinity, major cations, conductivity, temperature and oxygen profiles,...) In all, over 250 diatoms species were identified and counted. After processing the data with multivariate statistical techniques, final transfer function models (the actual mathematical relationships between diatoms and lake chemistry) were constructed using WA-PLS algorithms developed in our laboratory. These yielded highly significant predictive models to describe and predict pH, total phosphorus (TP, the most important nutrient in lakes) and dissolved organic carbon (DOC) as a function of diatom assemblages. These variables are particularly important to the biology of lakes. In this region, as in many others in Canada, phosphorus is the primary nutrient limiting algal growth, DOC the main determinant of lake transparency and pH is a key variable controlling the speciation of many elements and compounds. The predictive power of these models is illustrated in Fig. 3 as plots of observed against predicted values. Our results showed that pH could be very accurately predicted (r^2=0.89), followed by phosphorus (r^2=0.77) and lastly DOC (r^2=0.65) . Greater details on the methodology used to construct these models can be found in Enache and Prairie (a, submitted) and Enache (1999). In terms of predictive power, these models are as good or better than similar models developed in other regions of the world.

Table 2. General chemical characteristics of the 42 lakes. All nutrient and chlorophyll concentrations in µg l^{-1}. Alkalinity in µeq l^{-1} and DOC in mg l^{-1}.

	min	average	max
NT	79,0	333,1	1489,5
NTD	39,0	243,6	1172,5
NO3	0,0	4,6	35,0
NH4	3,5	31,5	657,0
PT	2,8	12,9	52,0
PTD	0,5	5,0	15,5
pH	4,2	6,2	8,0
Chla	1,5	10,7	245,5
DOC	1,8	9,9	18,5
Secchi	0,3	2,1	6,6
Alka	5,0	331,3	2495,0

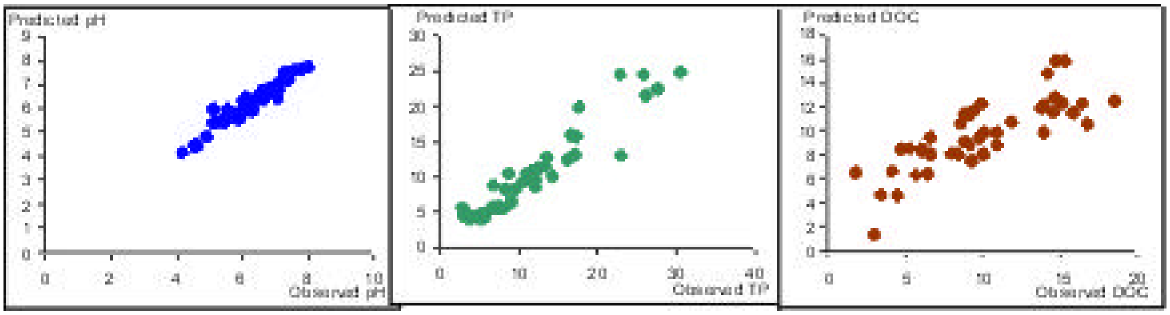


Figure 3 Observed against predicted values from WA-PLS models for pH, total phosphorus and DOC.

Reconstruction

Using the models developed as described above, we reconstructed the lake chemistry history of L. Francis in relation to the historical fire events that occurred on its watershed. The fire levels were identified using micro-charcoal analysis (Carcaillet et al.,b submitted). Sediments slices above, within and below the charcoal horizons were processed for diatom analysis. In all we examined diatom samples surrounding 4 fire events that have occurred during the last 2000 years.

Fluctuations in diatom abundance and species composition generally reflect changes in environmental factors. Diatom-inferred total phosphorus values revealed important chemical changes in the fire or post-fire levels. As with the total diatom abundance, the most important changes were detected in the oldest fires studied . **Diatom-inferred total phosphorus revealed important increase of TP concentrations within these fire disturbance levels.** Relative to pre-fire concentrations, TP values increased by about 4 ugl-1 and 13 ug l-1, respectively. In the most recent fire events, diatom-inferred values showed some increase in TP concentrations but less important as in preceding cases. To compare the relative impact of forest fires on TP concentrations among the 4 studied fires, we calculated the ratio between fire (and post-fire values) and the mean of the pre-fire values.

The results, illustrated in Fig. 4, show that there is a highly significant difference between pre-fire and fire values ($p<0.01$) and between fire and post-fire values ($p<0.01$) but that the difference between pre and post-fire values is not statistically significant ($p>.05$). The two oldest fire perturbances studied here had a very important impact on lake water TP concentrations with increase of 55% and 150% relative to pre-fire concentrations, respectively. In contrast, the more recent fires had much lower or no detectable impact on the TP concentrations with maximum increases of only 20% and 1%, respectively. Thus, while fires have an overall effect on lake TP concentrations (on average an increase of 51%), the magnitude of the effect varies considerably from fire to fire. Given that the lake's nutrient status has become progressively enriched over the past 2000 years (Fig. 5), it suggests that fire may exert a relatively smaller impact on already eutrophic systems.

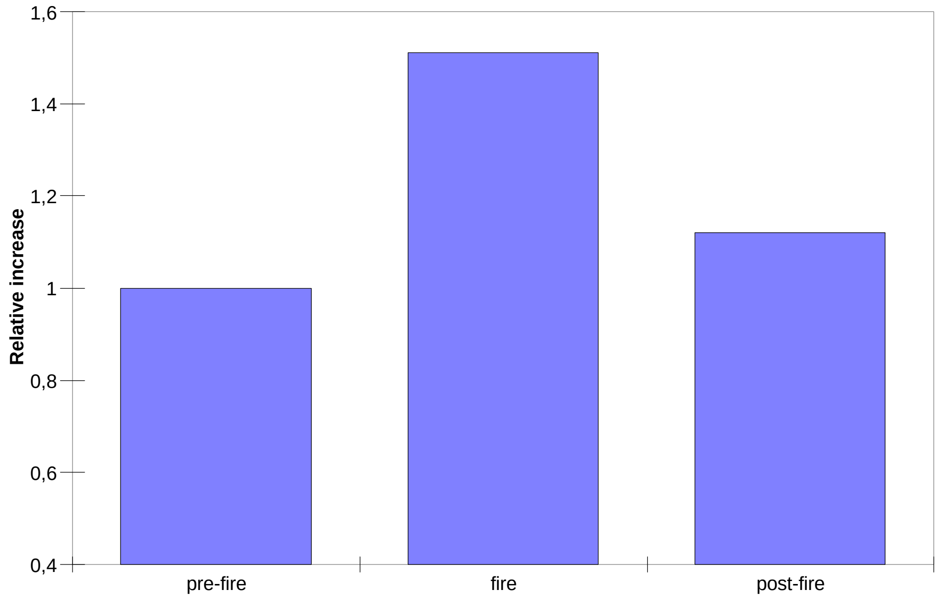
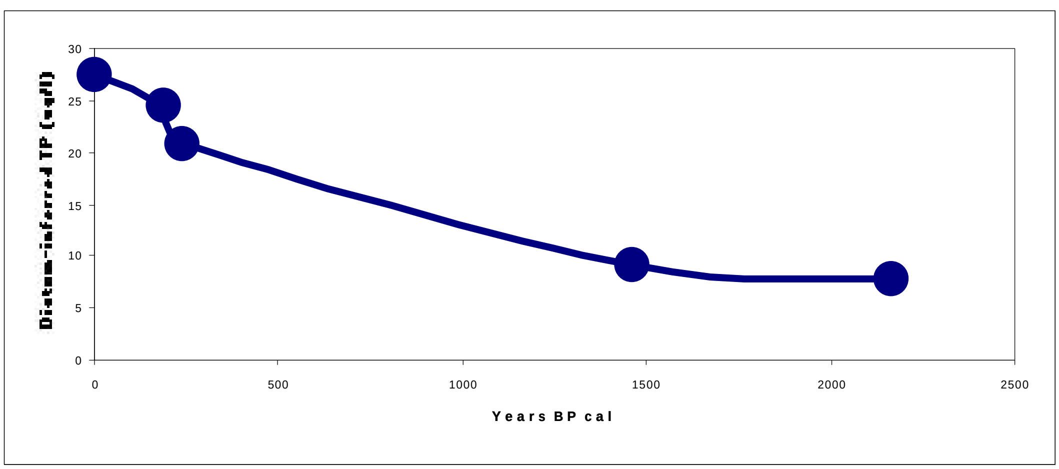


Figure 4. Relative increase in phosphorus concentration in pre-fire, fire, and post-fire sediment



horizons, as inferred by diatoms

Figure 5. Diatom-inferred TP concentrations over the past 2000 years

pH and DOC

While fires can affect the nutrient status of the lakes, diatom-based paleo-reconstruction of pH and DOC in L. Francis showed little effects of fires on lake DOC and inconsistent effects on pH . In the oldest fire studied, there was a trend for the pH to be more acid after the fire while in the subsequent fire studied the tendency was reversed with an apparent increase of about 0.5 pH unit. Overall however, we did not find any significant difference between pre-fire, fire and post-fires values (p>.05) for either DOC or pH. Similar results were obtained by Carignan et al., (1998) and Lamontagne et al., (accepted) in their comparison of lakes within recently burnt catchments with unperturbed systems from the Haute-Mauricie region of Quebec (about 200 kms east of L. Francis). These results contrast with those of Rhodes and Davis (1995) and Korhola et al. (1996) who inferred higher pH resulting from fires, presumably due to the input of alkaline ashes. We suggest that a possible higher alkaline inputs may have been counter-balanced by the much higher input of the acid nitrate anions following fires (Lamontagne et al., accepted). It is also possible that the magnitude of the fire-impact on pH and DOC concentration exists, but that it is much more short-lived than for phosphorus and therefore less readily detectable from sediment slices pooling several years.

IMPLICATIONS FOR MANAGEMENT

Our results have several implications in forest management practices. First, it sets a baseline against which the impact of anthropogenic perturbations can be compared. As far as we could determine, forest fires have little impact on both the pH and DOC concentrations in lake water of this region. If forest harvesting practices are to maintain these same characteristics, they will have to be performed so as to minimize solute transport from the watersheds. In practice, this means avoiding areas of the land saturated with water. Indeed, these saturated zones are typically the main site of exchange and transport of nutrients and DOC from the catchments to the receiving bodies of water. In this respect, our results on the natural factors affecting lake chemistry suggests that the impact of forest harvest will be largest in areas of very low relief (low slope gradient). However, this was not the case for the important lake nutrient phosphorus. Average increases of 50% over pre-perturbation concentrations were detected in L. Francis albeit with considerable variability among fires.

Second, our results indicate that although forest fires do have a measurable impact on the nutrient (phosphorus) status of the lakes within, that impact is relatively short-lived (around a decade). Again, to be sustainable, forest management practices should therefore maintain this characteristic as well. Our work on the natural factors influencing lake chemistry suggests that the impact of forest harvest is largest in areas of low relief (low slope gradient).

Third, our results also indicate that a key variable in determining the sensitivity and response of a particular lake to natural disturbances (in our case, the effect of forest fires on lake phosphorus levels) is its initial chemical balance. Nutrient-rich lakes did not appear as sensitive to fire impacts. It this is indeed the case, it is likely to be reflected in the lakes'response to *other* types of perturbations as well, such as forest harvesting.

Finally, our work shows that paleolimnological tools have the power to address questions and provide answers relevant to the forest managers on a time scale not amenable to experimental manipulations. Given that the long and arduous work of calibration is now completed, these diatom-lake chemistry relationships can then be transported and applied to lakes with other catchment characteristics and therefore assess the generality of our claims.

All these considerations should be taken into account in forest management decisions.

CONCLUSIONS

In conclusion, we have shown that it is possible to establish quantitative relationships between diatom assemblages and lake chemical characteristics. Once established, these relationships can be used to infer past changes in the chemistry of lakes from changes in the specific composition of the diatom assemblages through time. Using this approach, we were able to show that although forest fires had little impact on the pH and DOC concentration, fires did produce a marked increase in the important lake nutrient phosphorus. On average, P increased by 50% relative to pre-fire levels and remained elevated for about a decade. In addition, the relative impact of fires on lake nutrient concentration seems to be greatest when the lake is oligotrophic and lessens as the lake progressively becomes richer. Effective forest management should be practiced so as to maintain similar catchment-lake interactions.

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