Evaluation of Limnological Responses to Recent Environmental Change and Caribou Activity in the Rivière George Region, Northern Québec, Canada

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Abstract

The influence of natural terrestrial disturbances on the limnology of northern lakes is little known, yet important for understanding the ecology of these remote ecosystems. The Rivière George Caribou Herd (RGCH) in northern Québec has undergone a large population increase since the 1950s, which has been accompanied by pronounced impacts (i.e., degradation of vegetation cover, soil erosion) on terrestrial environments of the Rivière George region. The goal of our study was to evaluate if the increased caribou activity and resulting terrestrial impacts have been accompanied by impacts on adjacent aquatic ecosystems. We studied the recent diatom assemblages (i.e., about the last two centuries) preserved in six sediment cores taken from lakes located in the most heavily impacted region, and in one core from a lake showing little evidence of recent caribou activity in the catchment basin. Core chronologies based on $^{210}Pb$ dating techniques indicated that average mass sedimentation rates in this subarctic region were very low (0.0039 to 0.012 g cm$^{-2}$ yr$^{-1}$). Perhaps surprisingly, diatom assemblages from all seven cores showed very little change, indicating remarkably stable limnological conditions throughout the past ~200 yr. The lack of a signal from caribou activity is most likely due to (1) short-term impacts being too transitory to be registered in the sediment record, and (2) long-term impacts not representing a significant perturbation outside the natural variability of these aquatic ecosystems. In contrast to other arctic regions, the limnological stability of our study sites suggests that recent climatic change impacts have been negligible in this region of northern Québec, which seems to confirm climate model predictions that northern Québec and Labrador will remain climatically stable under global warming scenarios.

Introduction

Much paleolimnological research has focused on the influence of human activities on aquatic ecosystems, such as acid rain (e.g., Battarbee et al., 1999) or cultural eutrophication (e.g., Hall and Smol, 1999). However, comparatively little is known about the role of natural factors in influencing limnological conditions, with the exception of vegetation and climatic changes (e.g., Rouse et al., 1997; Engstrom et al., 2000; Smol and Cumming, 2000). This is especially true for northern aquatic systems, where anthropogenic impacts are generally small compared to the south. Animal populations in northern regions, such as caribou, are characterized by large fluctuations in population size and can have potentially significant impacts on the terrestrial environment. However, the potential role of these disturbances in the ecology of adjacent aquatic systems is largely unstudied. Furthermore, in light of the significant temperature changes predicted for these sensitive northern regions under global warming scenarios (e.g., Kattenberg et al., 1996), an understanding of the natural variability and ecology of these systems is crucial.

The Rivière George Caribou Herd (RGCH) in northern Québec and Labrador has undergone large fluctuations in population size over the past century, which have been accompanied by pronounced effects on the terrestrial environment of the Rivière George region. For example, air survey estimates placed the number of animals in the herd at approximately 5000 individuals in 1955; by 1990, the population had grown to between 600,000 and 800,000 individuals (Messier, 1995), and it was identified as the largest caribou herd in the world (Couturier et al., 1996). Recent research suggests that the herd is in decline, most likely as a result of habitat degradation and nutrition deficiency (Crête and Huot, 1993; Messier, 1995; Manseau et al., 1996). The population expansion of the RGCH coincided with widespread degradation of terrestrial vegetation communities, characterized by the disappearance of lichen mats which are preferentially eaten by the caribou (Manseau et al., 1996; Morneau, 1999; Morneau and Payette, 1998). In addition, repeated trampling results in the compaction and erosion of the soil upper organic layer (Evans, 1996; Pelletier, 2001; Dubuc, 2001); large areas of denuded mineral soil are evident throughout the Rivière George study region (Morneau, 1999).

Given the widespread impacts of the increase in caribou activity on terrestrial environments in the Rivière George region, the aim of our study was to investigate if these changes were accompanied by impacts on aquatic ecosystems. Caribou activity and overgrazing have the potential to affect aquatic limnology in several ways. For example, shifts in vegetation communities and soil conditions have been shown to influence the chemistry of catchment runoff entering the lake, in turn altering the composition of aquatic communities (e.g., Laing et al., 1999; Pienitz et al., 1999; Seppä and Weckström, 1999; Engstrom et al., 2000). In addition, the input of nutrients from caribou feces, as well as
the erosion of the organic-rich surficial soil layer, can significantly alter the trophic status of northern lakes (e.g., Leshko and Kuzmina, 2002). Such animal-induced changes in trophic status and sediment geochemistry have been successfully used to track past changes in the abundance of other organisms, such as salmon (Finney et al., 2000) and penguins (Sun et al., 2000). Because of their well-known sensitivity to lakewater chemistry and trophic status changes (e.g., Hall and Smol, 1999), we chose to use diatoms as an indicator to evaluate past limnological changes in the study lakes.

A similar approach was used by Engstrom et al. (1991) to evaluate impacts of increased ungulate activity on lakes in Yellowstone National Park, U.S.A., in which they did not find conclusive evidence of a significant change in limnological conditions related to the rise in elk populations. However, their study was complicated by the influence of human activities during the same period, as well as the relative insensitivity of the naturally eutrophic study lakes to further nutrient additions. Our study differs in that (1) lakes in the study region are naturally oligotrophic to ultraoligotrophic and thus potentially sensitive to additions of nutrients; (2) human activities in this region are negligible; and (3) impacts of caribou on the surrounding terrestrial environment have been pronounced and widespread. Our research forms part of a multidisciplinary project investigating the effects of caribou activity on terrestrial and aquatic environments in the Rivière George region, and the results of our work will eventually be integrated with those from other indicators, such as dendroecology and modern vegetation ecology, sedimentology, geochemistry, and remote-sensing. The results of this project should provide valuable information on the role of caribou in influencing the terrestrial and aquatic ecology of northern ecosystems, as well as quantifying past changes in caribou activity for the Rivière George region.

**Methods**

**STUDY REGION AND GEOGRAPHICAL SETTING**

The seven study lakes are all located in the Rivière George region of northern Québec, to the southeast of the Ungava Bay (Fig. 1). The sites are positioned at the transition between the Whale River Plateau, which is covered by thick glacial and glaciofluvial sediment deposits, and the George Plateau, which has large areas free of glacial deposits with erratics deposited on
rocky outcrops (Gouvernement du Québec, 1984). The topography is undulating to hilly, and inclines from the Tonnat Mountains in the east to the Ungava Bay in the northwest, with an elevation range between approximately 0 and 900 m. Geologically, the sites are located in the Churchill Province on the Canadian Shield, and are underlain by granitic bedrock of Precambrian age (Vincent, 1989). The region was deglaciated between 9000 and 6000 yr BP (Dyke and Prest, 1987), and most lakes are of glacial origin (Gouvernement du Québec, 1984).

The Rivière Géorgie study region is dominated by tundra vegetation, with scattered conifer stands (forest and krummholz) of black spruce (Picea mariana [Mill] BSP) or larch (Larix laricina [Du Roi] K. Koch) in the most protected sites. Well-drained sites on the tundra are characterized by lichen heath (e.g., Ericaceae) and shrub communities (e.g., dwarf birch; Betula glandulosa Michx; Morneau, 1999), while moist sites are dominated by Poaceae and Cyperaceae. Our study sites were located in the area most severely affected by caribou grazing and trampling, as evaluated by analyses of vegetation community structure in 1992–93 (Morneau, 1999) and 1999–2000 (Boudreau, unpublished data). Vegetation communities in this area were characterized by the absence of Cladina stellaris (Opiz) Brodo lichen mats, as well as the frequent occurrence of plaques of denuded soil. Few trees were found within the catchment basin of the study lakes, with the exception of site PC2, which had significant numbers of spruce (Picea mariana) and larch (Larix laricina) trees surrounding the lake.

Mean annual temperatures in the study region vary from approximately −5°C in the south to −7.5°C in the northeast (Wilson, 1971). Annual precipitation varies from 400 to 600 mm, of which 35 to 45% falls as snow (Environment Canada, 1981). The growth season is between 80 and 100 d, with the length of the frost-free season between 40 and 60 d (1931–1966; Gouvernement du Québec, 1984). Snow melt occurs between the beginning and middle of June for the majority of the sites, with snow cover reappearing in October (Morneau, 1999). The ice-free season for the lakes is approximately 5 mo (mid-June to early November; Gouvernement du Québec, 1984). Analysis from seven meteorological stations surrounding the summer range of the Rivière Géorgie caribou herd indicated that no significant change in average summer temperatures occurred for the period between 1950 and 1991 (Jacobs et al., 1996), although winter temperatures show a slight decrease over this period.

The study sites are all located within the calving ground of the Rivière Géorgie Caribou Herd (RGCH; Fig. 1), with the exception of site PC5 positioned close to the village of Kangiqsualujjuaq. Although the calving ground has increased in size over the last 30 yr concurrent with the population increase of the herd (Couturier et al., 1990), topographic constraints limit the calving ground to a relatively small (≈34 000 km²) portion of the annual range (Crête and Huot, 1993). Adult females of the RGCH show strong fidelity to the calving ground and return to the same general area on an annual basis (Crête and Huot, 1993). Telemetric data indicate that the herd is generally within the Rivière Géorgie region from April–May until September–October each year, with the highest population densities in June and July (Québec Government, unpublished data). Calving occurs in the first three weeks of June, and the females and calves mostly stay within the calving ground until the end of July. The herd leaves the Rivière Géorgie region in September/October, and passes the winter season to the southwest and southeast of the Rivière Géorgie area. Dendroecological analysis of trampling scars on conifer roots from a series of sites located throughout the region indicates consistent patterns in reconstructed caribou activity within the Rivière Géorgie area. These data suggest that caribou activity was low during the 1950s and 1960s, but started to increase in the early 1970s, with a peak in caribou activity occurring in the mid- to late 1980s (Morneau and Payette, 1998, 2000). The 1990s have been marked by a sharp decline in caribou activity (Morneau and Payette, 1998; Boudreau, unpublished data).

The seven study lakes (Fig. 1) were selected on the following basis in order to maximize the potential for the preservation of a caribou “signal” in the lake sediments. Each study lake selected was relatively small (surface area between 3.9 and 29.1 ha; Table 1) and shallow (maximum depth between 4.0 and 15.5 m; Table 1), had clearly marked caribou trails and degraded vegetation cover around the lake, and exhibited gently sloping topography in the catchment basin, which would facilitate sediment transport to the lake. In addition, one lake (PC5) with little evidence of recent caribou activity in the catchment (as indicated by overgrown caribou trails and the presence of lichen mats) was selected as a control lake for comparison with the other sites. The near-shore littoral areas were characteristically rocky, with little evidence of macrophyte growth. No water chemistry data are available for the study sites. However, they are most likely typical of other forest-tundra and tundra lakes in northern Québec, which are generally dilute, slightly acidic to circumneutral, oligotrophic to ultraoligotrophic, and low in dissolved organic carbon (DOC; Fallu and Pienitz, 1999; Fallu et al., 2002).

**SAMPLING AND LABORATORY METHODS**

Coring of the study lakes took place in August 1999 (sites LM and LR) and July 2000 (sites PC1, PC2, PC3, PC4, and PC5). A series of transects were made with a depth recorder in order to establish the bathymetry of each lake. The cores were then taken from the deepest part of the lake using a modified gravity corer, such as a mini-Glew corer (Glew 1991, internal diameter = 4 cm, sites LM and LR) or an HTH-Teknik corer (internal diameter = 8.2 cm, sites PC1 to PC5), which allow for undisturbed recovery of the surface sediment layer. The cores were subsectioned in the field at fine intervals (i.e., 0.4 cm for cores LM and LR, and 0.25–0.5 cm for cores PC1 to PC5) using an extruding device, placed into Whirlpak® sampling bags, and refrigerated until further analyses in the laboratory.

**DIATOM ANALYSES**

Diatom sample preparation followed techniques outlined in Pienitz and Smol (1993). A subsample of wet sediment (approximately 0.2 g) was boiled in a 50:50 mixture of HNO₃:H₂SO₄ in order to digest the organic material. The sample was then boiled for 24 h, then mixed with acid mixture was siphoned off and replaced with distilled water; this rinsing step was repeated nine times. An aliquot of the remaining siliceous slurry was resuspended in distilled water, evaporated onto coverslips, and mounted onto slides using Naphrax® mounting medium (R.I. = 1.74). At least 500 diatom valves were identified for each sample, following standard counting procedures (Kingston, 1986). Diatom identification was mainly followed Fallu et al. (2000) and Kramer and Lange-Bertalot (1986–1991), although a variety of other taxonomic references were also consulted.

**LEAD-210 DATING**

Lead-210 dating analyses were performed for each lake on the same sediment core that was used for the diatom analyses.
TABLE 1
Geographic coordinates and selected morphometric characteristics of study lakes from the Rivière George region, northern Québec

<table>
<thead>
<tr>
<th>Study site</th>
<th>Latitude</th>
<th>Longitude</th>
<th>Surface area (ha)</th>
<th>Coring depth (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LM</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Core 1 (LM-1)</td>
<td>58°17'N</td>
<td>65°40'W</td>
<td>3.94</td>
<td>6.0</td>
</tr>
<tr>
<td>Core 2 (LM-2)</td>
<td>58°17'N</td>
<td>65°40'W</td>
<td>3.94</td>
<td>6.6</td>
</tr>
<tr>
<td>Core 3 (LM-3)</td>
<td>58°17'N</td>
<td>65°40'W</td>
<td>3.94</td>
<td>6.5</td>
</tr>
<tr>
<td>LR</td>
<td>58°19'N</td>
<td>65°38'W</td>
<td>12.63</td>
<td>6.0</td>
</tr>
<tr>
<td>PC1</td>
<td>57°34'N</td>
<td>65°31'W</td>
<td>18.13</td>
<td>8.0</td>
</tr>
<tr>
<td>PC2</td>
<td>57°28'N</td>
<td>65°21'W</td>
<td>29.06</td>
<td>13.5</td>
</tr>
<tr>
<td>PC3</td>
<td>57°36'N</td>
<td>65°24'W</td>
<td>11.00</td>
<td>4.0</td>
</tr>
<tr>
<td>PC4</td>
<td>58°30'N</td>
<td>65°45'W</td>
<td>12.94</td>
<td>15.5</td>
</tr>
<tr>
<td>PC5</td>
<td>58°43'N</td>
<td>65°57'W</td>
<td>6.19</td>
<td>7.3</td>
</tr>
</tbody>
</table>

In addition, two replicate cores from site LM were also analyzed for 210Pb to evaluate how consistent sediment deposition patterns were amongst different cores from the same lake. Between 15 and 16 depth intervals from each core were analyzed for 210Pb in order to estimate age and mean sediment accumulation rates for the past 100 to 150 yr. A minimum of 0.5 g of dry sediment was used for each sample, with several consecutive depth intervals combined if insufficient material was contained in a single interval. Lead-210 concentrations were determined by measuring the radioactive granddaughter decay product 210Pb using alpha spectrometry. The core chronology and sedimentation rates were obtained using the constant rate of supply (CRS) model (Appleby and Oldfield, 1978), with confidence intervals calculated by first-order error analysis of counting uncertainty (Binford, 1990). Dates plotted on the diatom stratigraphy represent the midpoint of two dates calculated for the top and bottom of an analyzed interval.

Results and Discussion
LEAD-210 DATING AND MASS SEDIMENTATION RATES

Mean mass sedimentation rates and 210Pb parameters for the Rivière George region study sites are summarized in Table 2. Calculated mean 210Pb fluxes for our study sites are mostly within the range estimated for atmospheric deposition (0.2 to 1.0 pCi cm⁻² yr⁻¹; Krishnaswamy and Lal, 1978), with an average value of 0.277 pCi cm⁻² yr⁻¹ (excluding PC4 with 0.591 pCi cm⁻² yr⁻¹). In comparison with mean 210Pb fluxes reported from temperate regions (e.g., Engstrom et al., 1991; Blais et al., 1998), the 210Pb fluxes in our study are slightly lower. These lower average 210Pb fluxes are typical for arctic regions and reflect the influence of permafrost in suppressing the release of radon gas (the parent of 210Pb) from the soil, as well as the extended periods of ice cover which prevent atmospheric 210Pb from reaching the lake sediments (Hermanson, 1990).

Cumulative unsupported 210Pb activities range between 4.82 and 18.98 pCi cm⁻², indicating a fair amount of variation in sedimentary conditions within the study region. It is possible that this variation reflects redistribution of sediment within the study lakes through processes such as ice-rafting, slumping events, erosion, or sediment-focusing. There is some evidence that such redistribution of sediment has occurred at a couple of our study sites. For example, site PC4 exhibits anomalously high surface level unsupported 210Pb activities and cumulative unsupported 210Pb (Table 2), discrepancies in the cumulative dry mass vs. unsupported 210Pb profile (Fig. 2), and a brief period in the core where mass sedimentation rates apparently doubled. This lake was situated in a small, relatively deep, steep-sided basin (Table 1) and it is possible that these discrepancies are indicative of slumping events, suggesting that 210Pb dates calculated for this site are approximate and should be viewed with caution. Furthermore, one of the replicate cores from site LM (core LM-2) showed evidence of a mixed layer in the upper 3 cm of the sediment core. However, in contrast with other studies where clear evidence of within-lake sediment redistribution was shown (e.g., Oldfield and Appleby, 1984; Hermanson, 1990), the differences in cumulative unsupported 210Pb activities amongst our sites are not large. For example, the three replicate cores taken from site LM showed relatively consistent unsupported 210Pb activities and average mass sedimentation rates, especially between the two cores that were taken from the same basin of the lake (cores LM-2 and LM-3; Table 2). Overall, the average cumula-

TABLE 2
Lead-210 parameters and sediment-accumulation rates for lake sediment cores from the Rivière George region, northern Québec

<table>
<thead>
<tr>
<th>Study site</th>
<th>Cumulative unsupp. 210Pb (pCi cm⁻²)</th>
<th>Unsupp. 210Pb at surface (pCi g⁻¹)</th>
<th>Supported 210Pb (pCi g⁻¹)</th>
<th>Number of supported samples</th>
<th>Mean sed. rate (g cm⁻² yr⁻¹)</th>
<th>Mean 210Pb flux (pCi cm⁻² yr⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LM</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Core 1 (LM-1)</td>
<td>4.82</td>
<td>28.75</td>
<td>2.21</td>
<td>8</td>
<td>0.0039</td>
<td>0.150</td>
</tr>
<tr>
<td>Core 2 (LM-2)</td>
<td>7.11</td>
<td>17.82</td>
<td>2.53</td>
<td>2</td>
<td>0.0060</td>
<td>0.221</td>
</tr>
<tr>
<td>Core 3 (LM-3)</td>
<td>8.11</td>
<td>19.67</td>
<td>1.45</td>
<td>7</td>
<td>0.0070</td>
<td>0.253</td>
</tr>
<tr>
<td>LR</td>
<td>6.08</td>
<td>19.54</td>
<td>4.88</td>
<td>7</td>
<td>0.0049</td>
<td>0.189</td>
</tr>
<tr>
<td>PC1</td>
<td>16.00</td>
<td>38.02</td>
<td>2.32</td>
<td>3</td>
<td>0.012</td>
<td>0.498</td>
</tr>
<tr>
<td>PC2</td>
<td>10.97</td>
<td>45.82</td>
<td>6.79</td>
<td>10</td>
<td>0.0050</td>
<td>0.342</td>
</tr>
<tr>
<td>PC3</td>
<td>7.63</td>
<td>13.50</td>
<td>1.45</td>
<td>3</td>
<td>0.010</td>
<td>0.238</td>
</tr>
<tr>
<td>PC4</td>
<td>18.98</td>
<td>82.53</td>
<td>8.32</td>
<td>7</td>
<td>0.0063</td>
<td>0.591</td>
</tr>
<tr>
<td>PC5</td>
<td>10.48</td>
<td>35.18</td>
<td>1.26</td>
<td>3</td>
<td>0.0083</td>
<td>0.326</td>
</tr>
</tbody>
</table>
tive unsupported $^{210}\text{Pb}$ for our study (excluding site PC4) was 8.9 pCi cm$^{-2}$, which is similar to other values reported from lakes in this northern region (e.g., Hermanson, 1990; Courcelles, 1998).

Plots of unsupported $^{210}\text{Pb}$ concentration versus cumulative dry mass (Fig. 2) indicate that most show slight deviations from an exponential relationship and several show slight nonmonotonic variations. These deviations indicate changes in sediment accumulation rates which are best accounted for by the CRS dating model (Oldfield and Appleby, 1984); therefore we chose this model to calculate chronologies for the cores based on the $^{210}\text{Pb}$ profiles. Cumulative dry masses versus calculated ages are shown in Figure 3, with the corresponding dates plotted on the diatom stratigraphies (Fig. 4a–g). The error bars, which were calculated by first-order analysis (Binford, 1990), represent minimum errors associated with the calculation of ages at each depth. In general, error bars become progressively large for ages greater than 110 yr, and are noticeably large for lower sediment intervals in cores PC2, PC3, LM-1, and LM-3. Error bars were particularly large for site LR as a result of the high standard deviation calculated for the mean supported $^{210}\text{Pb}$ value due to discrepancies in the lower portion of the $^{210}\text{Pb}$ profile, possibly reflecting a buried mixing event in the core. The lower $^{210}\text{Pb}$ fluxes characteristic of arctic regions, coupled with very low mass accumulation rates, limit the length of the core chronology which can be resolved due to difficulties in detecting unsupported $^{210}\text{Pb}$ compared with supported $^{210}\text{Pb}$ at the bottom of the $^{210}\text{Pb}$ profile. Dates were calculated in our cores only to the depth where the error associated with the age-calculation eclipsed the preceding date. Using these criteria, the minimum chronology length calculated was 40 yr (site LR), while the maximum chronology length was 140 yr (site PC1).

Average mass sedimentation rates calculated for our sites were low, ranging from 0.0039 to 0.012 g cm$^{-2}$ yr$^{-1}$ (average = 0.0071 g cm$^{-2}$ yr$^{-1}$, excluding site PC4). These rates are comparable to those reported from other lakes on the Canadian Shield (Crustius and Anderson, 1995; Blais et al., 1998) or in subarctic regions (e.g., Hermanson, 1990; Courcelles, 1998; Korkola et al., in press), reflecting the rocky catchments and low primary production typical of northern lakes. The low sedimentation...
tation rates characteristic of subarctic and arctic regions represent a particular challenge for paleolimnological studies interested in fine resolution chronologies. The region of unsupported $^{210}\text{Pb}$ activity in most of our cores represented only the top 5 to 10 cm of the sediments, severely reducing the resolution of events that could be resolved in the sediment record. For example, at site PC2, 1 cm of sediment represents approximately 30 yr of accumulation; therefore our samples taken at 0.25-cm intervals for this lake represent integrations of approximately 7 to 8 yr. Events which occur on shorter timescales than this period, such as short-term catchment disturbances, may therefore not be detectable in the sediment record.

Several recommendations can be made for attaining higher resolution for sediment cores from arctic and subarctic regions. First, study site selection should be made carefully in order to maximize the potential for long sediment records; i.e., relatively small, moderately shallow basins with gently sloping topography in the catchment basin. Secondly, since $^{210}\text{Pb}$ analyses generally require a minimum of 0.5 g of dry sediment, using a coring device with a relatively large diameter enables this amount of sediment to be contained in a finer depth interval than with a smaller coring device and improves the resolution achievable with $^{210}\text{Pb}$ dating. Thirdly, cores may be sectioned in the field at finer depth intervals (e.g., every 0.25 cm), which enable greater temporal resolution than coarser sediment intervals (e.g., 1 cm). Using these criteria, we were able to achieve generally higher resolution of the $^{210}\text{Pb}$ dating chronologies for the second set of cores in comparison with those taken in the first year of the study (sites LR and LM). Our cores may therefore represent close to the maximum resolution achievable for small lakes in subarctic regions using a gravity coring device.

**FLORISTIC CHANGES**

Overall, the floristic composition of the seven study cores was very similar (Fig. 4). The most abundant taxa amongst the study sites are as follows: *Achnanthes marginulata* Groen in Cleve & Groen, *Achnanthes minutissima* Kützing, *Aulacoseira distans* (Ehrenberg) Simonsen, *Aulacoseira distans* var. *nivalis* (W. Smith) Haworth, *Aulacoseira periglabra* (O. E. Strup) Haworth, *Aulacoseira periglabra* var. *floriniae* (C. Camburn) Haworth, *Brauchysira brebissonii* Ross in Hartley, *Cyclotella stelligera* (Cleve & Groen) Van Heurck, *Cymbella gaeumannii* Meister, *Fragilaria virescens* var. *exigua* Groen in Van Heurck, *Fragilaria rhomboidea* auct. non (Ehrenberg) De Toni, *Nitzschia perminuta* (Groen) Peragallo, *Pinnularia interrupta* W. Smith, and *Tabellaria flocculosa* (Roth) Kützing Strain IV sensu Koppen. These taxa are all typical of slightly acidic to circumneutral, oligotrophic, electrolyte-poor lakes, and many are cosmopolitan species that are commonly found in Nordic and alpine regions (Krammer and Lange-Bertalot, 1986–1991; Fallu et al., 2000). *Fragilaria virescens* var. *exigua* (synonymous with *Fragilaria virescens* sensu Krammer and Lange-Bertalot) was particularly abundant at several sites (PC3, LM-1, LR); this taxon was also very abundant at other sites in northern Québec (e.g., Saulnier-Talbot and Pienitz, 2001; Ponader et al., 2002); however, the specific autecology remains largely unknown. The total percentage of planktonic taxa was generally higher at the two deepest
study lakes (PC2 and PC4), most likely reflecting the greater proportion of planktonic habitat available as lake depth increased (Wolin and Duthie, 1999).

Surprisingly, all of our seven study cores showed very little change in the diatom assemblages throughout the last roughly 200 yr. The timing of minor changes in diatom species composition for the study cores varied from site to site and showed no consistent correspondence with the period of increased caribou activity within the region. In addition, changes occurring in cores sampled from heavily impacted lakes (as evidenced by the lack of lichen and the presence of many caribou trails in the catchment) were not more pronounced than the changes in a lake where the catchment had little evidence of recent caribou activity (PC5). Our data suggest that, overall, limnological conditions

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**FIGURE 4.** Stratigraphy of the most abundant diatom taxa in seven sediment cores from the Rivière George region, northern Quebec. (a) PC1; (b) PC2; (c) PC3; (d) PC4; (e) PC5; (f) LM-1; (g) LR.
have remained remarkably stable for the study sites within the last 200 yr.

Several potential hypotheses may explain the lack of a signal for increased caribou activity in these lake sediment cores. One possibility is that our study sites were not heavily frequented or impacted by caribou. However, this seems highly unlikely due to the fact that the study lakes were chosen specifically because of the evidence of caribou activity in the catchment. In addition, other analyses performed at or near the study sites indicated widespread pronounced impacts of caribou on the terrestrial environment. For example, analyses of vegetation composition indicated that the lichen mat was completely degraded throughout the study area (Manseau et al., 1996; Morneau, 1999; Boudreau, unpublished data). Dendroecological analyses from a grid of sampling sites throughout the region indicate a consistently large increase in trampling scars from caribou activity in the 1980s, indicating that the terrestrial impacts of caribou activity were widespread (Morneau and Payette, 1998, 2000).
addition, the organic soil horizon was heavily compacted and eroded in areas criss-crossed by caribou trails (Dubuc, 2001; Pelletier, 2001), and there was evidence of a slight erosional signal from the catchment in the littoral zone of one of the study lakes (Dubuc, 2001). Given the widespread and long-term impacts of the increase in caribou activity on the terrestrial environments of the Rivière George region, the lack of a signal in the paleolimnological record is especially interesting.

An alternative possibility is that the limnological changes caused by caribou activity are within the limits of natural variability for the ecosystem. Lakes are buffered against small water chemistry changes due to the dilution effects of the large quantity of water contained within them. An external disturbance must therefore represent a significant and prolonged shift in chemical runoff composition in order to impact limnological conditions. Other paleolimnological studies have demonstrated significant changes in the trophic status of lakes resulting from the input of nutrients from abundant salmon (Finney et al., 2000) and penguin populations (Sun et al., 2000). However, these studies represent a large transfer of nutrients from the marine to the freshwater environment which would not occur in the absence of these animal vectors. The input of nutrients from caribou activity and soil erosion in our study may represent mostly a redistribution of nutrients always present within the catchment basin, rather than addition from an external source. Furthermore, these slight changes in nutrient transport may be insignificant in the context of the natural variability in catchment runoff chemical composition, which is ultimately controlled by the combined influence of climate, basin hydrology, and catchment lithology.

In addition, the time period where a specific lake is directly affected by caribou activity may be too short to be detected in the sediment record, especially given the limited resolution due to the low sedimentation rates within the study lakes. Migratory caribou are well known to show high fidelity to calving areas during the summer period (e.g., Gunn and Miller, 1986; Schaef er et al., 2000). However, this fidelity is scale-dependent (Schaef er et al., 2000), and within the summer range, the herd is highly mobile. The limnological changes resulting from the passage of caribou may be too transitory to be recorded in the sediment record. Our study corroborates research from Yellowstone National Park (Engstrom et al., 1991), which also did not find conclusive evidence that increased migratory ungulate activity had significantly impacted the limnology of the study lakes. However, a study from Russia where a herd of reindeer was corralled next to the study lake for a month every summer indicated that the lake had become eutrophic as a result of runoff from the reindeer enclosures (Leshko and Kuzmina, in press). Our results suggest that in order for a perturbation to be recorded in the sediment record, it must be sustained and significantly outside baseline conditions for the lake.

The limnological stability of our study sites is noteworthy from a climatic-change perspective. There is widespread and accumulating evidence for dramatic changes in terrestrial and aquatic communities across northern circumpolar regions within the last two centuries (e.g., Overpeck et al., 1997), which has been attributed to post-Little Ice Age and anthropogenically induced climatic warming. For example, such results have been reported from subarctic Fennoscandia (Sorvari and Korthola, 1998; Korthola et al., 2000), the Canadian Arctic (Douglas et al., 1994; Joynt and Wolfe, 2001; Wolfe and Perren, 2001), and lakes located in the western subarctic zone of the Canadian Northwest Territories (Rühland, 2001). However, this study and others from the Québec-Labrador region (Betta-Piper, 2001; Saulnier-Talbot and Pienitz, 2001; Ponader et al., 2002) have not shown evidence of these recent changes in aquatic ecosystems, suggesting that recent climatic warming has not been negligible in this region. The available instrumental data records appear to corroborate these findings (Jacobs et al., 1996; Serreze et al., 2000), as do studies indicating recent permafrost aggradation in the region (e.g., Allard et al., 1992). Furthermore, this climate scenario is in agreement with current climate models, which predict that the Québec-Labrador region will remain climatically stable or undergo a slight cooling under doubled CO₂ scenarios (Kattenberg et al., 1996; Serreze et al., 2000). Our data indicate a close correspondence between the paleoecological record and current model predictions for this region, which are in contrast to the general warming trend detected across the rest of the circumpolar Arctic.

Conclusions

Our study of the diatom assemblages from seven lake sediment cores in the Rivière George region, northern Québec, has indicated that limnological conditions have been remarkably stable over the last roughly 200 yr. The consistent lack of response at all our study sites, despite a large increase in caribou activity and associated terrestrial impacts, suggests that migratory caribou populations have little significant impact on the limnology of northern lakes. Short-lived catchment disturbances caused by the passage of caribou are likely too transitory to be registered in the sediment record, especially given the low mass sedimentation rates characteristic of arctic and subarctic regions. Longer-term effects arising from caribou activity, such as soil erosion and changes in terrestrial vegetation, do not appear to perturb the limnology of the system outside the ranges of natural variability. In human terms, this suggests that large caribou populations will not significantly alter the water quality of lakes unless large numbers of animals are kept in continuous proximity to a single site. Periodic measures of lake water chemistry throughout the summer migration period would be useful in confirming our study results, as well as identifying the magnitude and duration of limnological changes associated with caribou activity on a seasonal basis.

The results of our study confirm that, in order to be registered in the diatom paleolimnological record, a perturbation must be sustained and significantly outside baseline natural variability for a lake. While this is often evident for anthropogenic impacts on water quality, evaluating the relative importance of natural factors as influences on limnological conditions is more complicated. The water chemistry of a lake is influenced by a suite of variables (e.g., catchment lithology, hydrology, catchment disturbances such as fire or caribou activity, climate, biotic interactions), which may work in synergistic or antagonistic ways to determine water chemistry and aquatic ecology at any one time. Nonetheless, evidence suggests that factors such as climate, catchment lithology, and basin hydrology are the overriding controls which ultimately determine the limnology of a lake in the absence of human impacts. In the face of such dominant controlling factors, a catchment disturbance must represent a pronounced shift in chemical runoff in order to perturb the system outside the limits of natural variability.

The limnological stability of our study sites is particularly interesting in the context of recent global climatic change. These results are in contrast with accumulating evidence from sites around the circumpolar Arctic of recent shifts in aquatic communities, which have been attributed to climatic warming. The weak response in our study corresponds with the instrumental data record from this area, and confirms model predictions that northern Québec and Labrador will remain climatically stable or
undergo a slight cooling under global warming scenarios. Such results highlight the spatial complexity of climatic change, and indicate the need for widespread regional coverage of paleoecological data in order to better understand the regional dynamics of future global change.

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