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Lake Water Salinity and Periphytic Diatom Succession in Three Subarctic Lakes, Yukon Territory, Canada

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ABSTRACT. Seasonal changes in water chemistry and periphytic diatom assemblages were monitored for a saline, a subsaline, and a freshwater lake in the central Yukon Territory. Athalassic saline lakes, such as these, are believed to be extremely rare in arctic regions. All three study lakes exhibited a gradual shoreline retreat over the season (28 May to 22 August 1992) due to evaporative water loss. As the season progressed, the saline lake exhibited a marked increase in conductivity and salinity, similar to changes observed for inland salt lakes in more southern regions. The seasonal changes in water chemistry were less pronounced in the subsaline and freshwater lakes. The periphytic diatom populations of the saline lake closely tracked changes in the lake's salinity, exhibiting a successional shift from taxa with low salt tolerances (e.g., *Nitzschia* cf. *commutata* and *N*. cf. *palea*) to those with high salt tolerances (e.g., *Amphora acutiuscula*) over the study period. Periphytic diatoms in the subsaline and freshwater lakes also exhibited marked successional changes, shifting to almost complete dominance by a single species (*Cocconeis placentula* and *Achnanthes minutissima* respectively), but these shifts were not related to lake water salinity alone.

Key words: lakes, diatoms, seasonal succession, saline, subarctic, Yukon

RÉSUMÉ. On a observé les variations saisonnières dans la composition chimique de l'eau et les assemblages de diatomées périphytoniques, dans un lac salin, un lac subsalin et un lac d'eau douce dans le centre du Territoire du Yukon. On croit que de tels lacs salins n'ayant jamais eu de contact avec la mer, sont très rares dans la région arctique. Les trois lacs étudiés ont tous montré un retrait du rivage dû à la perte d'eau par évaporation au cours de la saison (du 28 mai au 22 août 1992). Au fur et à mesure que la saison avançait, le lac salin montrait une augmentation marquée de conductivité et de salinité semblable à celle observée dans les lacs intérieurs salins de régions plus méridionales. Les changements saisonniers dans la composition chimique de l'eau étaient moins prononcés pour les lacs subsalin et d'eau douce. Les populations de diatomées périphytoniques du lac salin variaient directement en fonction des changements de salinité du lac, montrant des changements de succession allant de taxa à faible tolérance au sel (p. ex., *Nitzschia* cf. *commutata* et *N*. cf. *palea*) à des taxa à forte tolérance au sel (p. ex., *Amphora acutiuscula*) pendant la période d'étude. Les diatomées périphytoniques dans les lacs subsalin et d'eau douce ont aussi montré des changements de succession marqués, allant jusqu'à la domination presque complète d'une seule espèce (*Cocconeis placentula* et *Achnanthes minutissima* respectivement); ces changements n'étaient cependant pas reliés uniquement à la variation de salinité de l'eau des lacs.

Mots clés: lacs, diatomées, succession saisonnière, salin, subarctique, Yukon

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INTRODUCTION

There is presently considerable interest in inland saline (athalassic) lakes, as they are very different from saline lakes in coastal areas, which are influenced by marine systems (Pagé et al., 1987). Athalassic saline lakes are intimately associated with climate and may respond quickly and significantly to even small climatic changes (Williams, 1981; Hammer et al., 1983; Hammer, 1986; Fritz et al., 1993). In such systems, any climatic perturbation that alters the balance between evaporation and precipitation may have a dramatic effect on the lake's depth and water chemistry. For example, Hammer (1990) and Cumming and Smol (1993) demonstrated that inland saline lakes in temperate regions of Canada exhibit seasonal changes in salinity. As the summer progresses and evaporation exceeds precipitation, a net water loss occurs and the concentration of dissolved salts in the lakewater increases (Hammer, 1990). Conversely, during cooler and/or wetter periods, the opposite pattern was observed, with lakes becoming more dilute. Furthermore, Renaut and Long (1987) demonstrated that during winter, a freeze-out of salt may occur from ice-covered inland saline lakes. Hammer (1990) also demonstrated that athalassic saline lakes exhibit long-term (decadal) changes in salinity correlated with fluctuations in climate.

Because athalassic saline lakes may be sensitive to changes in climate, these lakes may serve as valuable paleoclimatic

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reference sites for long-term monitoring of climate change. Diatoms (class Bacillariophyceae) are the most widely used bioindicators in paleolimnological studies. Many studies have shown that diatoms are strongly influenced by lake water salinity and brine composition (Hammer, 1986; Cumming and Smol, 1993; Fritz et al., 1993). Therefore, the diatom assemblages of these systems may be used as biomonitors of past climatic change. Paleolimnological studies of athalassic saline lakes have begun to make important contributions to deciphering past climate trends (Hickman et al., 1984; Last and Slezak, 1988; Fritz et al., 1991). Until recently, these studies had been limited to lakes in temperate and equatorial regions. However, a recent study by Pienitz et al. (1992) was conducted on a subarctic saline lake in the central Yukon Territory. Such systems are very uncommon in arctic environments, and this site is believed to represent the most northerly inland salt lake recorded thus far (Pienitz et al., 1992).

The purpose of this study was to determine whether this high-latitude inland saline lake exhibited seasonal changes in water chemistry similar to those observed in more southern regions, and to determine whether periphytic diatom assemblages of this lake appeared to track these changes. In addition, seasonal changes in water chemistry and periphytic diatom populations of a subsaline and freshwater lake from the same area were assessed for comparative purposes.

STUDY AREA

The three study lakes are located near Pelly Crossing (62˚48′N, 136˚35′W), in the central Yukon Territory (Fig. 1), an area characterized by a subarctic continental climate with a mean annual daily temperature of -4 to -5˚C (Wahl et al., 1987). This region falls in the rain-shadow of the St. Cyr Range of the Pelly Mountains, and therefore has low relative humidity and precipitation levels (generally less than 300 mm/year) (Wahl et al., 1987). Permafrost is discontinuous, and local vegetation is dominated by boreal forest, particularly white spruce (*Picea glauca*), black spruce (*P. mariana*), poplar (*Populus tremuloides*), and willow (*Salix*).

All three study lakes are fairly small and shallow and exhibit polymictic circulation. However, despite similar basin morphologies and climatic influences, these lakes exhibit fundamental differences with respect to salinity. L1 (62˚45′N, 136˚ 38′W) is a closed-basin saline lake (> 3.0 g l^{-1} salinity) with a surface area of 0.095 km^2. Maximum depth observed on two separate occasions during the summer of 1990 and 1993 was 1.1 and 1.6 m, respectively (Pienitz et al., 1992). The area closest to the lake's shoreline is dominated by *Potamogeton pectinatus* and foxtails (*Hordeum jubatum*), followed by willows and boreal forest with increasing distance from the basin.

L2 (62˚46′N, 136˚38′W) is a closed-basin, subsaline lake (0.5 to 3.0 g l^{-1} salinity) slightly larger than L1 (0.12 km^2), with a maximum depth of approximately 1.7 m. It is located in a marshy area, and its surrounding vegetation is dominated by grasses and boreal forest. By 13 June 1992, the lake's entire littoral zone was covered by a dense algal bloom dominated by

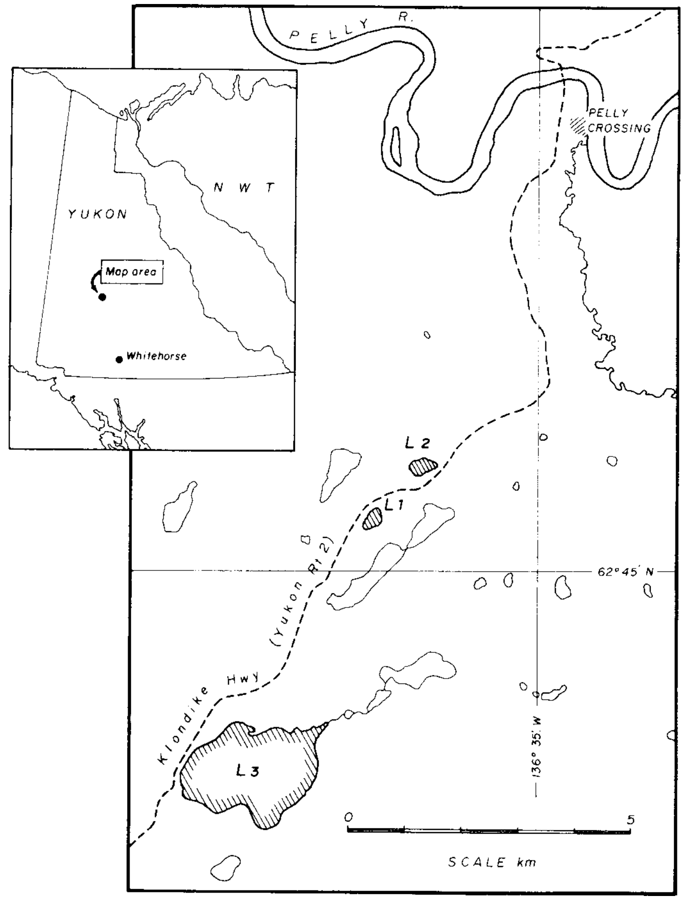

FIG. 1. Location of the three study sites in the central Yukon Territory.

green (*Oocystis* spp. and *Crucigenia* spp.) and blue-green (*Oscillatoria formosa* and *O. agardhi*) algae, which persisted for the remainder of the study period.

L3 (62˚43′N, 136˚41′W), also known as Rock Island Lake, is a freshwater lake (< 0.5 g l^{-1} salinity) that has a small outlet and two intermittent stream inlets during periods of snowmelt. It has a surface area of 3.2 km^2 and a maximum depth of 3.7 m (Lindsey et al., 1981). Tall macrophytes are abundant in the lake's littoral zone, and the bottom sediment is generally rocky. L3 supports some recreational activity (e.g., fishing, swimming), and signs of human disturbance such as campfire sites are apparent in the lake's catchment.

MATERIALS AND METHODS

Limnological variables were monitored at two- to three-week intervals from early spring (28 May) to late summer (22 August) of 1992. All limnological measurements were made from a designated area of the littoral zone of each lake about 3 m from the shoreline. Surface measurements of water temperature, conductivity, and salinity were conducted using a YSI Model 33 SCT meter corrected to the standard reference temperature of 25˚C. Surface pH was measured using a portable Fisher Scientific pH meter. Measurements of pH were made only up to 17 July 1992 because of an equipment failure.

The extent that the margin of each lake retreated over the summer was used as a relative index of evaporative water loss from the study lakes. Shoreline retreat was measured as the distance between the existing shoreline and a marginal marker stationed at the edge of the original shoreline (on 28 May 1992).

An artificial substrate apparatus (ASA) was placed in a protected region of the littoral zone of each lake on 28 May 1992. The ASA consisted of glass slides held vertically in an open Plexiglas rack and supported by aluminum posts, approximately 20 cm high. The substrates were completely submerged (water depth approximately 0.5 m) at least 1 m from the shoreline of each lake. Each ASA consisted of a set of six slides, and sampling of one slide from each ASA occurred at two-to three-week intervals until 22 August 1992. Slides were sampled without replacement so that colonization was cumulative over the study period. Once sampled, slides were stored in distilled water in Whirlpak® bags and kept cool and in the dark until analysis at Queen's University (Kingston, Ontario).

Samples were prepared for examination of diatoms by placing slides in 30% H_2O_2, and boiling for 1.5 hours to digest the organic material. Digested samples were washed with distilled water and left undisturbed for 96 hours to allow diatoms to settle. Excess acid was then siphoned off, and samples were centrifuged for 10 minutes at 6000 rpm. A 50 μl volume of the prepared samples was pipetted onto coverslips and left to dry for 36 hours in a covered drying tray. Once dry, coverslips were mounted onto glass microscope slides in Hyrax® mounting medium.

A minimum of 300 diatom valves were identified and enumerated for each sample at 1000 × magnification using a Nikon Optiphot microscope. Identifications were done with reference to taxonomic works of Germain (1981), Krammer and Lange-Bertalot (1986–1991), Pienitz et al. (1992), and Cumming et al. (in press).

RESULTS

Limnological Variables

All three study lakes exhibited a pattern of increasing shoreline retreat as the season progressed (Fig. 2a). The maximum retreat for L1, L2, and L3 was 2.16, 2.21, and 2.39 m, respectively. Although the rate of shoreline retreat varied over the study period, all three lakes followed a similar pattern. Lake water temperature exhibited considerable fluctuations in all three study lakes, but they followed relatively similar patterns of change (Fig. 2b).

L2 and L3 exhibited little change in conductivity over the summer (Fig. 3a), but L1 showed a marked increase as the season progressed. The conductivity of L3 was relatively stable, ranging only from 221 µS to 297 µS over the entire study period. L2 exhibited a gradual, more substantial increase in conductivity over the summer, ranging from 1500 µS in early spring (28 May 1992) to 1940 µS by late summer (22 August 1992). L1, whose minimum conductivity (2500 µS) was greater than the maximum conductivities of both L2 and L3, exhibited the greatest increase, reaching 11 900 µS by late summer. Similarly, the respective salinities of L2 and L3 were relatively stable over the study period (Fig. 3b), but L1 became increasingly more saline over the course of the season, ranging from 1.6 g l^{-1} in early spring to 8.9 g l^{-1} by late summer.

Throughout the period during which pH was measured, all three lakes were alkaline, ranging from pH 7.3 to 9.0 (Fig. 3c).

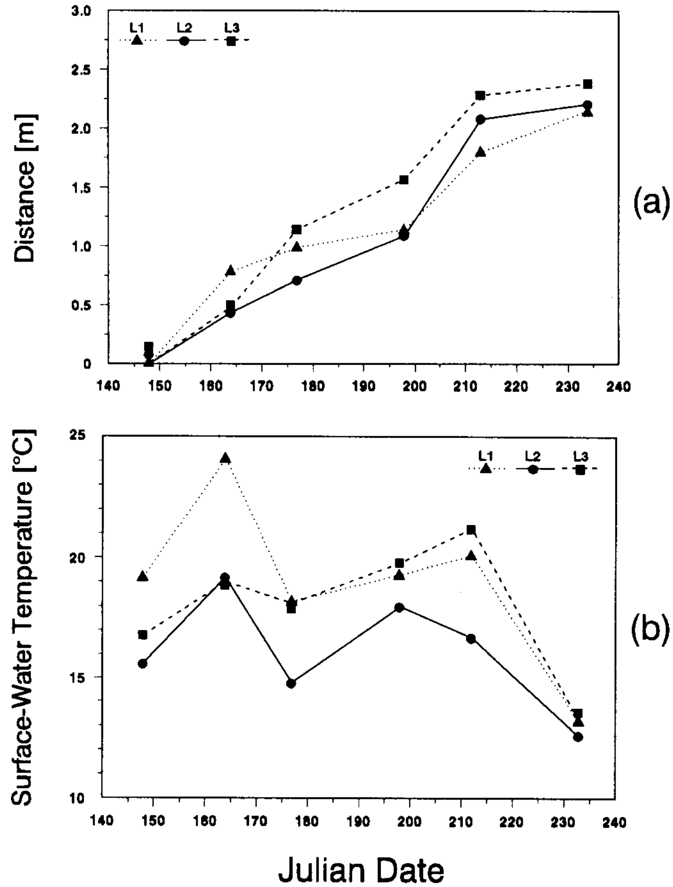

FIG. 2. Seasonal shoreline retreat (a) and surface water temperature (b) of the study lakes (summer 1992). Julian date 140 = May 28; 234 = August 22.

Diatoms

In total, 36 periphytic diatom taxa were identified from the three study lakes. The number of taxa found in a single lake ranged from 13 to 22, but species richness decreased as the season progressed (Figs. 4 to 6). The largest decrease occurred in L2 (Fig. 5), which was dominated by ten taxa (> 1% abundance) during early spring (13 June), but by only one species (*Cocconeis placentula* Ehrenberg) by late summer (22 August).

A substantial shift in dominance was observed for the periphytic diatom assemblage of L1 over the study period (Fig. 4). The gradual increase in relative abundance observed for *Amphora acutiuscula* Kützing and *Navicula veneta* Kützing was accompanied by a decrease in *Nitzschia* cf. *commutata* Grunow and *Nitzschia* cf. *palea* (Kützing) W. Smith as the season progressed. *Cymbella pusilla* Grunow and *Craticula halophila* (Grunow) D.G. Mann persisted at relatively constant

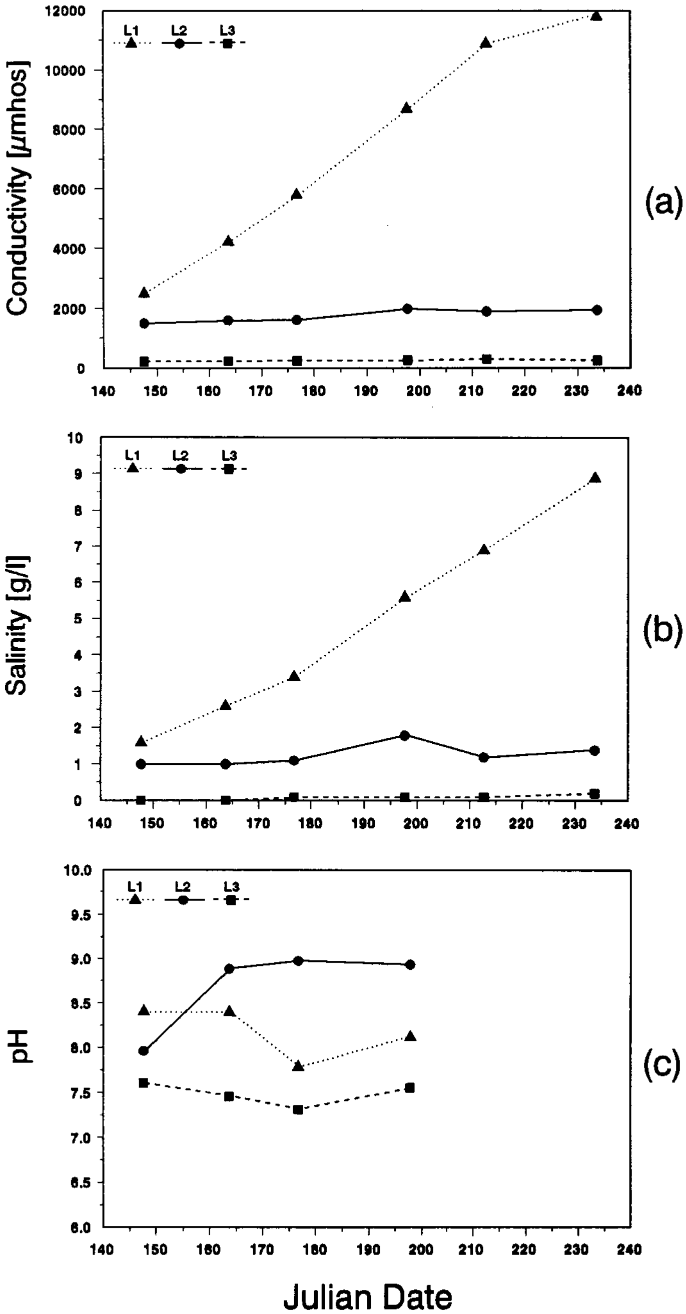

FIG. 3. Seasonal variation of conductivity (a), salinity (b), and pH (c) in the study lakes (summer 1992). Julian date 140 = May 28; 234 = August 22.

levels throughout the summer. With the exception of a sharp increase in the relative abundance of *Fragilaria construens* (Ehrenberg) Grunow during the final three weeks, all the other taxa (*Anomoeoneis sphaerophora* (Ehrenberg) Pfitzer, *Cocconeis placentula*, *Navicula* cf. *seminulum* Grunow, *Nitzschia frustulum* (Kützing) Grunow, *Nitzschia* cf. *liebetruthii* Rabenhorst, *Nitzschia* sp.3 PISCES, and *Nitzschia* sp.4 PISCES) were present only at brief intervals during the season and only at relatively low levels (< 6%).

The periphytic diatom assemblage in L2 exhibited a marked shift in dominance over the summer, as *Cocconeis placentula* increased in relative abundance from 4.5% in early spring to 98.7% by late summer (Fig. 5). Collectively, *Epithemia adnata* (Kützing) Brébisson, *E. turgida* (Ehrenberg) Kützing, *Fragilaria capucina* var. *mesolepta* (Rabenhorst) Rabenhorst, *F. tenera* (W.Smith) Lange-Bertalot, and *Nitzschia* cf. *incognita* Krasske comprised the majority of individuals during early to mid-spring (13 June to 26 June 1992), but decreased to negligible levels because of the large increase in *Cocconeis placentula*. Other taxa were present only at trace levels (< 6%) and at sporadic intervals over the study period.

In L3, the dominant diatom, *Achnanthes minutissima* Kützing, exhibited a progressive increase in relative abundance over the study period such that it represented 77.3% of the periphytic diatom community by late summer (Fig. 6). The rest of the community in L3 was dominated by species of the genera *Fragilaria* and *Gomphonema*, which were present in relatively constant abundances throughout the study period. Other taxa (*Asterionella formosa* Hassall, *Cymbella pusilla*, *Navicula veneta*, *Nitzschia* cf. *palea*, and *Rhopalodia gibba* (Ehrenberg) O. Müller) appeared only sporadically during the season at relative abundances < 6%.

DISCUSSION

All three study lakes exhibited relatively similar fluctuations in surface water temperature (Fig. 2b) and an approximately equivalent extent of shoreline retreat (Fig. 2a) over the study period. This is not surprising, as these lakes are in close proximity to each other and are exposed to essentially identical climatic conditions. Changes in surface-water temperature tended to mirror seasonal fluctuations in ambient air temperature.

The gradual shoreline retreat can be explained as part of an evaporative "drawdown effect" that occurs as the balance between evaporation and precipitation shifts in favour of evaporation during the summer months, resulting in a net water loss from the lakes. This loss had varying degrees of impact on the conductivity (Fig. 3a) and salinity (Fig. 3b). The shallowest, most saline lake (L1) exhibited by far the greatest increase in conductivity and salinity over the study period (Figs. 3a and 3b). Conversely, the deepest, most freshwater lake (L3) exhibited almost negligible increases over the season (Figs. 3a and 3b). The response of the shallow, subsaline L2 was intermediate between sites L1 and L3. Therefore, these subarctic lakes appear to undergo patterns of seasonal change relatively similar to those of lakes in more southern regions, such as the southern interior of British Columbia (Cumming and Smol, 1993) and the Canadian Prairies (Hammer, 1990; Hammer et al., 1990).

The periphytic diatom assemblages of all three study lakes underwent marked successional changes in relative abundance over the study period (Figs. 4 to 6). However, based on the limnological changes recorded during this time, the factors driving the successional shifts are thought to be very different among the three lakes.

The successional pattern of periphytic diatoms in L1 appears to be consistent with seasonal changes in the lake's conductivity and salinity. Based on diatom salinity tolerances

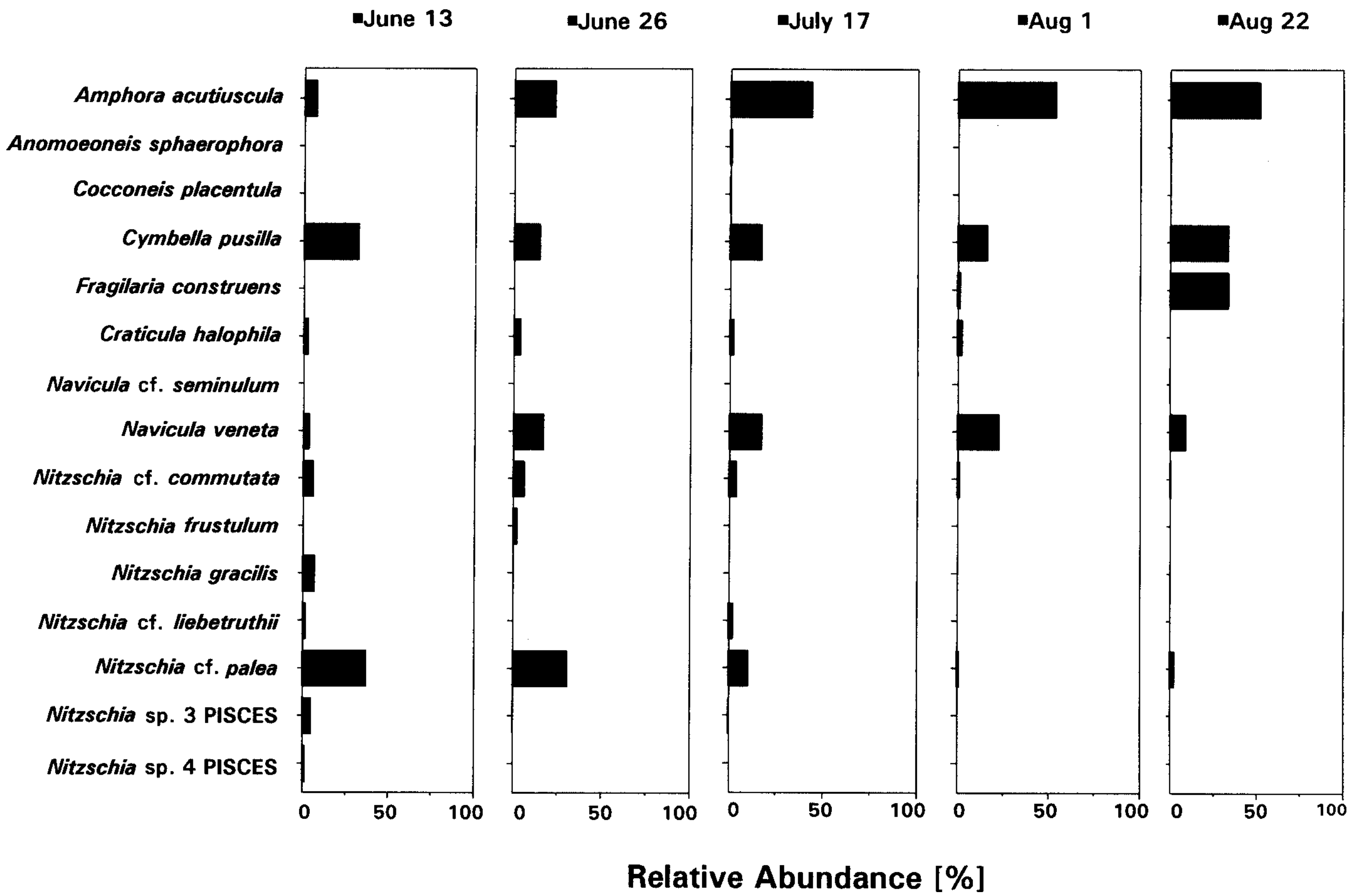

FIG. 4. Relative abundance of diatoms in L1 (summer 1992).

estimated by Cumming and Smol (1993) for lakes in British Columbia, the periphytic diatom assemblage of L1 shifted in dominance from taxa of relatively low salt tolerance (*Nitzschia commutata* and *Nitzschia* cf. *palea*) in early spring to taxa of high salt tolerance (*Amphora acutiuscula*) by late summer (Fig. 4). The appearance of *Fragilaria construens* in relatively large abundance in late summer was somewhat surprising, as its maximum salt tolerance was estimated at approximately 0.13 $g\,l^{-1}$ in British Columbia (Cumming and Smol, 1993). However, this taxon has been previously recorded in lakes receiving marine influents, and so clearly it can tolerate higher salt levels (Florin, 1977; Stabell, 1985; Pienitz et al., 1991). Species persisting at relatively constant levels throughout the season (i.e., *Cymbella pusilla* and *Navicula veneta*) are "salt generalists" and have broad tolerance ranges.

The periphytic diatom assemblages of both L2 and L3 exhibited successional patterns characterized by some fluctuation in early spring, accompanied by a shift toward dominance by a single species as the season progressed (Figs. 5 and 6). These 'opportunistic' species were *Cocconeis placentula* and *Achnanthes minutissima* in L2 and L3, respectively. Both diatoms are considered "generalists" because of their broad tolerance ranges to a number of environmental variables (Hammer et al., 1983; Shortreed et al., 1984). Since none of the limnological variables monitored during this study (surface-water temperature, pH, conductivity, and salinity) exhibited a substantial, unidirectional change over the study period for lakes L2 and L3, the development of such skewed dominance structures in these lakes may be attributed to other abiotic or biotic factors.

It is possible that the above shifts in dominance were the result of biotic interactions. Since species diversity tends to be inversely correlated with salinity (Castenholz, 1960; Hammer et al., 1983; Hammer, 1986; Hammer et al., 1990), we would expect complex trophic interactions in lakes of lower salinity, which may result in greater 'top-down' control on the periphytic diatom populations and other primary producers in these lakes. Thus, the success of *C. placentula* and *A. minutissima* in L2 and L3 may be the result of some competitive advantage (e.g., an anti-herbivory strategy) that acts to minimize predatory control on these species.

Another possibility is that the shifts in dominance were the result of changes in limnological variables not monitored in this investigation (e.g., nutrient status, water transparency and circulation) for which *A. minutissima* and *C. placentula* may have some competitive advantage or affinity. For example, these taxa may exhibit strong substrate affinities and, therefore, have a competitive advantage over other periphytic diatoms when available substrates become limiting. Such may have been the case for L2 and L3 during the summer months when evaporative water loss from the lakes caused the shoreline to retreat (Fig. 2a), thereby reducing the number of natural

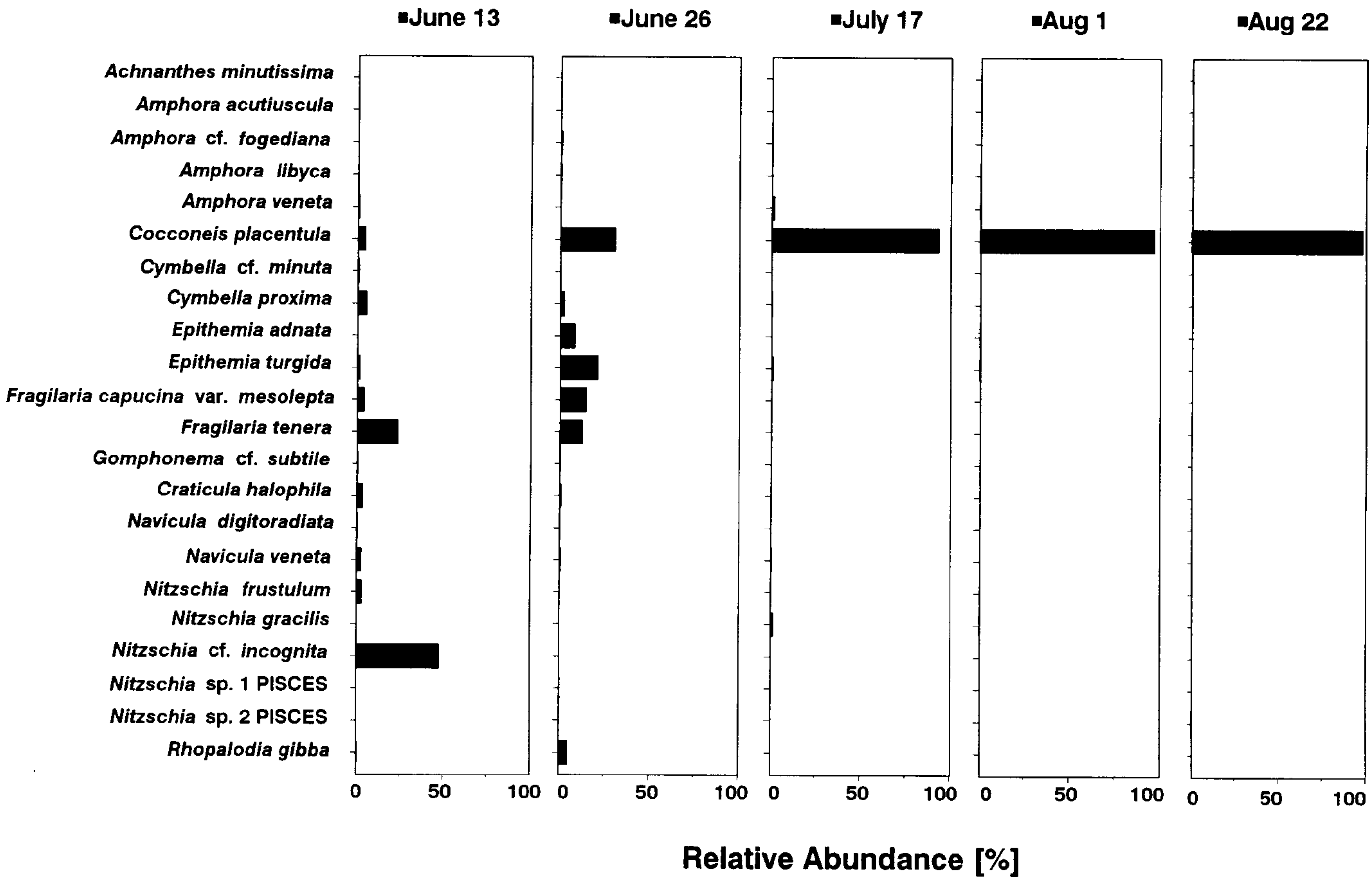

FIG. 5. Relative abundance of diatoms in L2 (summer 1992).

substrates (e.g., macrophytes, rocks) in the lakes' littoral zones. Also, though widely used in periphyton research, artificial substrates somewhat simplify the complexity of natural conditions by reducing the substrate heterogeneity. It is therefore possible that diatom taxa that grow prostrate to substrates, such as *A. minutissima* and *C. placentula*, may have been favoured by the use of glass slides.

CONCLUSIONS

High-latitude, subarctic, athalassic saline lakes appear to exhibit very similar limnological patterns to inland saline lakes in more southern regions. The subsaline (L2) and freshwater (L3) lakes we examined did not exhibit such striking seasonal changes in water chemistry as did the saline lake in the same area. Little overlap in species composition was observed for the periphytic diatom assemblages of the three study lakes, but each supported taxa similar to those of comparable lakes in more southern regions. The periphytic diatom assemblage in the northern saline lake (L1) appeared to track closely seasonal changes in lake water salinity. A successional shift from species with low salt tolerances (*Nitzschia commutata* and *N.* cf. *palea*) to species with high salt tolerances (*Amphora acutiuscula*) occurred as the season progressed. The periphytic diatom assemblages of the subsaline (L2) and freshwater (L3) lakes also showed marked successional changes, but these changes were most likely the result of abiotic or biotic factors other than lake water salinity.

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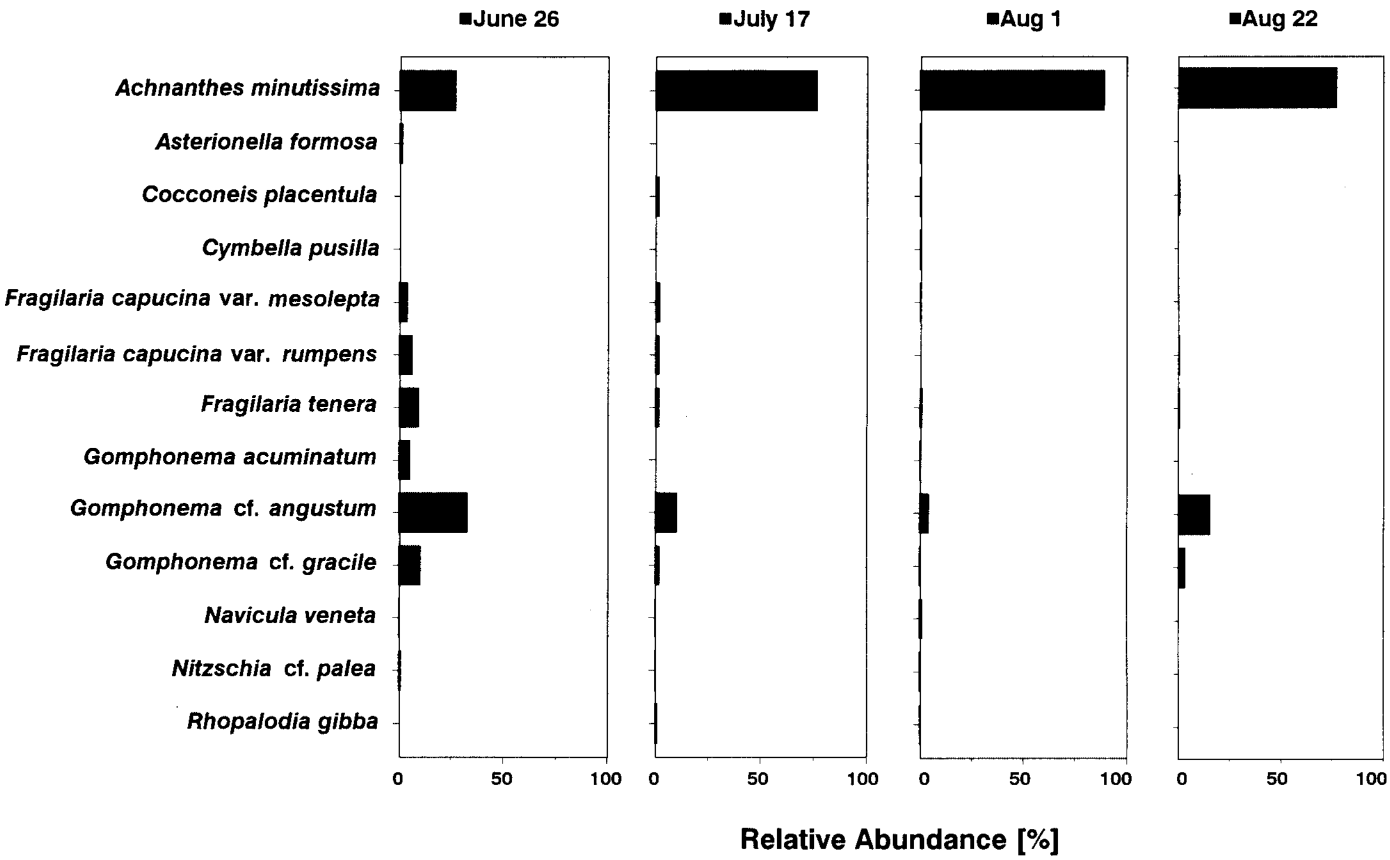

FIG. 6. Relative abundance of diatoms in L3 (summer 1992). No measurements were taken on 13 June 1992.

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