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Article abstract

Long-term monitoring data are required to make effective environmental decisions. Unfortunately, such direct measurements are rarely available. Long-term data are especially sparse in arctic tundra regions, where logistic concerns often preclude the implementation of standard monitoring programs. However, paleolimnological techniques, such as the use of diatom assemblages preserved in dated lake and pond sediment profiles, can provide proxy data of past environmental changes.This paper summarizes some of the ways biological-based paleolimnological techniques can be used in arctic tundra environmentsto monitor environmental changes. Specific examples include studies of climatic change, airborne contaminants, and local disturbances.

Long-term Environmental Monitoring in Arctic Lakes and Ponds Using Diatoms and Other Biological Indicators

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SUMMARY

Long-term monitoring data are required to make effective environmental decisions. Unfortunately, such direct measurements are rarely available. Long-term data are especially sparse in arctic tundra regions, where logistic concerns often preclude the implementation of standard monitoring programs. However, paleolimnological techniques, such as the use of diatom assemblages preserved in dated lake and pond sediment profiles, can provide proxy data of past environmental changes. This paper summarizes some of the ways biological-based paleolimnological techniques can be used in arctic tundra environments to monitor environmental changes. Specific examples include studies of climatic change, airborne contaminants, and local disturbances.

RÉSUMÉ

Pour être en mesure de prendre de bonnes décisions en matière d'environnement, il faut disposer de données d'observation environnementales de long terme. Malheureusement, de telles banques de mesures en direct sont rares et, pour les régions arctiques, elles sont encore plus rares étant donné les difficultés logistiques existantes qui empêchent l'utilisation de programmes normaux de prise de mesures. Cela dit, le recours à des techniques paléolimnologiques telle l'étude d'assemblages de diatomées de certaines séquences de sédiments de lacs ou d'étangs d'âge connu, peut constituer une source de données indirectes pouvant témoigner de changements environnementaux passés. Le présent article explique brièvement comment des techniques biopaléolimnologiques peuvent être utilisées dans l'étude de changements environnementaux en milieu de toundra arctique. Les changements climatiques, la pollution atmosphérique et des perturbations locales du milieu sont parmi les exemples étudiés.

INTRODUCTION

Freshwater ecosystems in the Arctic are subjected to a variety of environmental changes, many of which may have been accelerated or caused by anthropogenic activities. For example, it is now widely recognized that stressors such as increased UV-B penetration (Vincent and Pienitz, 1996), deposition of atmospherically borne contaminants (Wadleigh, 1996), and pollution from more local sources, such as human sewage, are affecting the lakes, ponds and rivers of the Arctic. In addition, it is possible that climate is changing more rapidly now, as a consequence of increased concentrations of greenhouse gases in the atmosphere. High-latitude regions are considered to be especially vulnerable to these changes, and hence there is a need to monitor these ecosystems (Rouse *et al.*, in press).

As many of the above potentially negative environmental changes may only be gradually affecting aquatic systems, long-term monitoring data are required to determine how, if at all, ecosystems are responding to these changing stressors. Unfortunately, direct observations of limnological and other environmental variables, which are collected in a standard manner over long time periods, are often lacking for almost all aquatic systems (Smol, 1995). This is especially true for arctic regions, where logistic concerns and large geographic distances do not allow for frequent monitoring. Nonetheless, long-term environmental data are required for effective ecosystem management (Smol, 1992, 1995), so that background conditions can be determined (*i.e.*, realistic targets or reference conditions: "What was the environment like before human impact?"); natural variability can be assessed ("What proportion of the changes that we are presently recording are due to natural changes, and how much is due to human influences?"), and what future conditions can be inferred ("What might future conditions be like, and how will organisms respond to these changes?").

Although long-term observational data are rarely available, lake and pond sediments preserve a large number of biological indicators that can be used to reconstruct past environmental and climatic trends, using paleolimnological techniques. Paleolimnology, the multidisciplinary science that uses physical, chemical and biological information preserved in lake and pond sedimentary profiles to reconstruct past environmental conditions in aquatic systems, has seen many advances over the last 15 years (Smol and Glew, 1992). These techniques are powerful, reproducible, and can now be applied to a large number of emerging environmental issues (*e.g.*, see reviews by Smol, 1992, 1995).

Paleolimnological techniques are based on the observation that lakes are continuously depositing sediments, which incorporate the remains (as fossils) of the organisms that lived in the lake (Smol and Glew, 1992). If the sediments are not disturbed, the sedimentary sequences can be dated (*e.g.*, using ^{14}C or ^{210}Pb geochronology), and the information preserved in the sedimentary profiles represents "archives" of the lake's history. The job of the paleolimnologist is to study these sediments, to reconstruct past environmental conditions in a defensible manner, and then to interpret this information in a way that is meaningful to other scientists, environmental managers, and the public at large.

This summary focusses on applications of aquatic biological remains, and especially diatoms, in arctic tundra sediments. Other papers in this issue deal with different types of proxy indicators (*e.g.*, pollen; Mode, 1996), and other environmental problems, as they relate to tundra ecosystems in the Canadian Arctic.

INDICATORS OF PAST LAKE BIOTA

Warner (1990) collated a series of review articles summarizing most of the major proxy indicators used by paleolimnologists. This paper focusses on the use of diatoms (class Bacillariophyceae, Fig. 1), a very opportunistic group of algae (Round *et al.*, 1990), whose high species diversity, large numbers, and siliceous (glass) cell walls make them ideal paleoenvironmental indicators (Smol, 1987; Dixit *et al.*, 1992a; Moser *et al.*, 1996). Furthermore, because many species have well-defined environmental optima and tolerances, these species can be used to quantitatively reconstruct past environmental conditions in dated sediment cores. Diatoms are often a dominant algal group in arctic tundra lakes, ponds, and rivers, especially in the benthic habitats (*e.g.*, Douglas and Smol, 1993, 1995; Hamilton *et al.*, in press; Pienitz *et al.*, 1995; Wolfe, 1996a).

Because of space limitations, we will restrict our discussions primarily to diatoms. However, other indicator groups, such as chrysophyte cysts (Duff and Smol, 1988, 1989; Duff *et al.*, 1992, 1995), chironomid head capsules (Walker, 1987), fossil algal and bacterial pigments (Leavitt, 1993), and so forth (see Gray, 1988; Warner, 1990), are also powerful paleolimnological markers, and should be included in paleoenvironmental assessments of tundra ecosystems. A considerable archive of information is also contained in the physical and chemical sedimentary record (*e.g.*, Wolfe and Härtling, 1996), often providing information on the coupling of catchment and aquatic processes. Such combined studies provide independent verifications on interpretations, and result in more holistic overviews of lake and pond development.

Considerable progress has been and is being made on quantitatively estimating the environmental optima and tolerances of many paleoindicators (especially diatoms), and constructing transfer functions, which allow paleolimnologists to quantitatively infer past limnological conditions. Surface sediment calibration sets (reviewed in Charles and Smol, 1994) are the most effective approaches to construct these transfer functions, using direct gradient analysis statistical techniques (reviewed in Birks, 1995). Although only a few surface sediment calibration sets are yet available for arctic regions (*e.g.*, Douglas and Smol, 1993, 1995; Pienitz and Smol, 1993; Pienitz *et al.*, 1995; Rühland, 1996; Ng, 1996), many more are currently being completed.

APPLICATIONS

Below we discuss some of the major environmental issues facing the Canadian Arctic, and explore how biological-based paleolimnological techniques may be used to assist in the studies of environmental change in tundra environments.

Climatic Change

Paleolimnological approaches can be used to study global environmental problems, such as those dealing with climatic change (Smol *et al.*, 1991, 1995). It is generally recognized that high-latitude regions are especially susceptible to climatic changes. As with most environmental problems, long-term climatic instrumental data of sufficient length, quality and spatial coverage are not available to assess many climate-related problems (Hardy and Bradley, 1996). For example, without long-term data, it is not possible to answer questions such as: "Are recent climatic changes any greater or more significant than climate's long-term natural range of variability?", "Have extreme climatic events become more frequent over the recent past (*i.e.*, the period of potential anthropogenic impacts)?". Paleolimnological and other paleoenvironmental studies can provide the critical "missing" data required for a more effective understanding of climatic change, which can then be used to as-

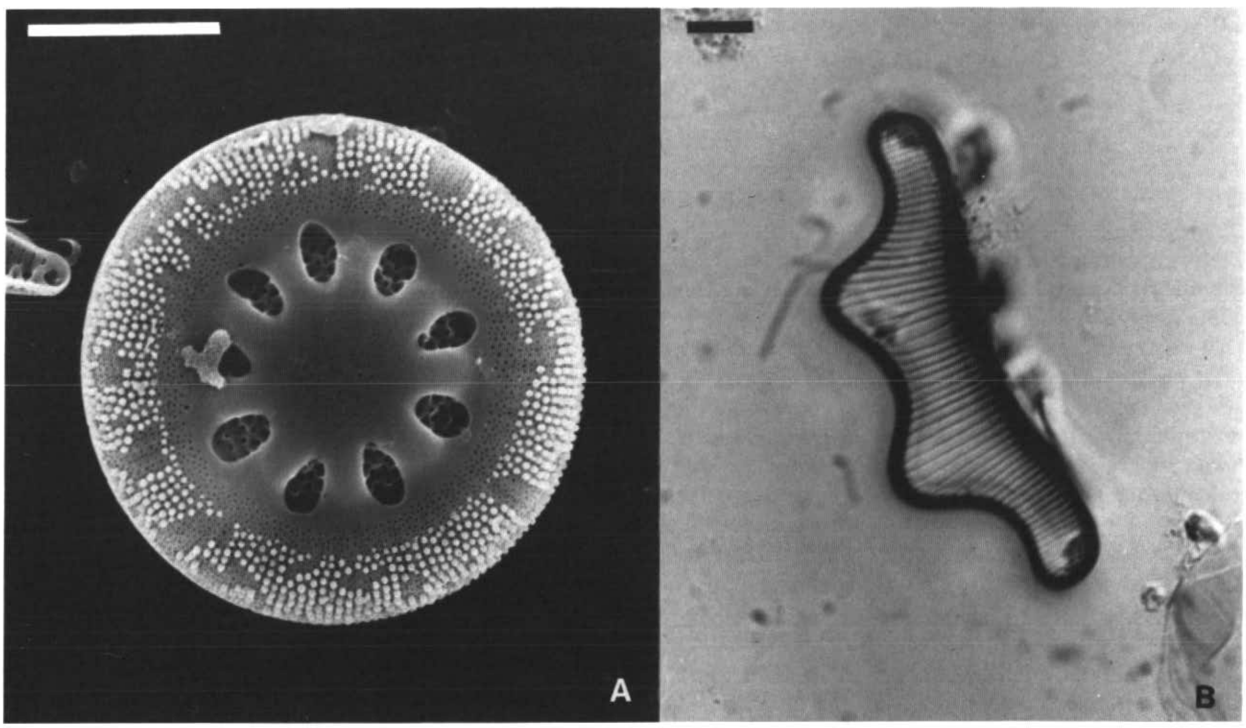

Figure 1 *Examples of freshwater diatoms from the Arctic. Scale bars = 5μm.* **(A)** *Scanning electron micrograph of the centric diatom* Cyclotella antiqua *W. Smith, a taxon characteristic of arctic environments.* **(B)** *Light micrograph of a* Eunotia *diatom, a pennate taxon associated with acidic waters.*

sist in the development of realistic policy and management decisions.

We have recently reviewed some of the ways that biological-based paleolimnological techniques could be used to infer past climatic changes in Canada (Smol *et al.*, 1995). Thus, only the major points are summarized here, with some updates of recent studies that deal specifically with tundra ecosystems. Many of these paleolimnological approaches, especially as they relate to tundra ecosystems, are still exploratory, but preliminary data are promising.

Paleolimnological data on past climatic changes in arctic regions may be especially important, as many of the more traditional, terrestrial-based paleoenvironmental techniques (*e.g.*, palynology, see Mode, 1996) are especially challenging in tundra regions (*e.g.*, Ritchie, 1995; Gajewski *et al.*, 1995). For example, low pollen production, problems with dispersal, reworking of old pollen grains, and so forth may limit, to some degree, the full application and interpretation of pollen data in arctic environments (Ritchie, 1995). It is therefore important to employ complementary paleoenvironmental techniques that can augment paleoclimatic interpretations.

The biological response of lake or pond assemblages (such as diatoms, chrysophytes and invertebrates) to climatic change will depend on the system under study and the organisms being used as response variables. For example, shallow ponds, which characterize much of the Arctic, are especially sensitive to even small climatic changes, as water temperatures closely track ambient air temperatures (Douglas and Smol, 1994). Although one might assume that the sediments of shallow ponds would be greatly disturbed by cryoturbation and other mixing processes, it appears that many pond sediment profiles faithfully archive sensitive records of past environmental change (discussed in Douglas *et al.*, in press). For example, Douglas *et al.* (1994) recorded striking successional changes in fossil diatom communities from a series of high arctic ponds on Cape Herschel, east-central Ellesmere Island. These changes occurred over the last two centuries, and may be related to climatic changes.

Working on a slightly deeper site from the Fosheim Peninsula on west-central Ellesmere Island, Wolfe (in press) similarly recorded striking diatom changes in the upper 3 cm of his sediment core, reminiscent of the Douglas *et al.* (1994) changes noted above.

In contrast, deep lakes, with their relatively higher thermal capacities and larger ice covers, show far smaller changes in lakewater temperature. Nonetheless, biotic communities may indirectly track even modest climatic changes in these larger lake systems. Many of the limnetic effects on diatoms and other aquatic assemblages will be indirectly related to climate. For example, as summarized in Smol (1988) and Smol *et al.* (1991, 1995), the extent and depth of ice and snow cover on a lake affect many aspects of the physical, chemical and biological characteristics of a lake system (*e.g.*, light penetration for photosynthesis, habitat availability, turbulence, water chemistry, *etc.*). These environmental changes can greatly affect biotic communities, many of which leave good fossil records, such as diatoms. Much of this is discussed in Smol (1988), and is not dealt with further here.

Recently, Ludlam *et al.* (1996) developed a habitat index (called a Lotic Index) for benthic diatoms present in Lake C2 (northern Ellesmere Island) and its watershed. They found that certain diatom species [*e.g.*, *Hannaea arcus* (Ehrenb.) Patr., *Meridion circulare* (Grev.) Ag.] were characteristic of the inflowing streams, while other taxa (*e.g.*, *Achnanthes* spp., *Cymbella* spp.) were littoral lake taxa. By examining changes in a varved lake sediment core, spanning the last 191 years, they found changes in the contribution of lotic (river) and lake littoral taxa, which they ascribed to past changes in runoff, a factor that is largely climatically driven. When the Lotic Index was calculated for diatom assemblages preserved in a Lake C2 sediment core, it showed a clear positive relationship to sedimentation rate, as recorded in the varves, while profiles in littoral taxa showed an opposite trend.

A common problem noted in several paleolimnological studies from the Arctic is low sedimentation rates, and hence only a generally low temporal resolution may be available from arctic lake and pond sediment cores. This problem is not universal, however, as high-resolution sediment cores do exist in arctic environments (*e.g.*, Hughen *et al.*, 1996). In fact, the extended ice covers that characterize deeper lakes may foster the preservation of annually laminated (varved) sediments. For example, Bradley (1996) has compiled a series of 10 papers summarizing the paleoenvironmental history (including diatoms: Douglas *et al.*, 1996; Ludlam *et al.*, 1996) of annually laminated lake sediment cores from meromictic Lake C2, from Taconite Inlet on northern Ellesmere Island. Similarly, Gajewski *et al.* (in press) established the annual nature of laminae in their sediment core taken from a non-meromictic lake on Devon Island. Diatom concentrations increased by two orders of magnitude during this century, with major increases in the 1920s and 1950s. These changes, along with increases in varve thickness, coincide with an increase in summer snow melt percentage in the Devon ice core (Koerner, 1977).

Although varved sediments are ideal for many types of analyses, relatively high-resolution studies are still possible in non-laminated systems using appropriate coring and sectioning techniques, such as those developed for addressing lake management issues (*e.g.*, Charles *et al.*, 1994). In the absence of varves, careful geochronological control using ^{210}Pb and ^{14}C dating is critical.

Many other diatom-based paleolimnological studies are now underway in tundra regions, throughout Canada, Alaska, Greenland, Lapland and Siberia.

Airborne Contaminants

Tracking past changes in airborne contaminants, using chemical-based paleolimnological techniques, has resulted in many important insights (*e.g.*, Muir *et al.*, 1995). However, biological-based techniques potentially may also be used to track airborne pollutants that are not directly preserved in lake sediment by a chemical signature.

For example, one well-tested paleolimnological application, which has not been fully explored in arctic systems, is the use of biological indicators to study the possible environmental effects of acidic deposition. A dominant limnological variable often determining the distributions of diatoms and other biological paleoindicators, such as chrysophytes, is lakewater pH and related limnological variables (reviewed in Charles *et al.*, 1989). Powerful transfer functions, based on surface lake sediment calibration sets (*e.g.*, Charles and Smol, 1994), which quantitatively relate the distributions of diatoms and chrysophytes to lakewater pH, have been constructed for many temperate lake regions (*e.g.*, Charles *et al.*, 1989). These transfer functions, which are statistically robust and ecologically sound, can then be used to quantitatively infer past lakewater pH from the species composition of fossil algal assemblages preserved in sediment cores. These approaches were widely used in the 1980s and early 1990s to assist policy decisions on, for example, the amount of acidic deposition that can fall on regions in the northeastern United States (*e.g.*, Cumming *et al.*, 1992, 1994), as well as the effects of acidic and metal deposition on Sudbury area lakes (*e.g.*, Dixit *et al.*, 1991, 1992a, b, 1995), and other regions (Battarbee and Renberg, 1990).

Although large parts of the Canadian Arctic are well buffered against the effects of acid rain, certain regions — such as parts of Baffin Island (Wolfe, 1996a), Ellesmere Island (Smol, 1983), Ellef Ringnes Island and other regions (Douglas and Smol, unpubl. data) — have very low buffering capacities. Moreover, precipitation in some of these regions can be very acidic (Wolfe, 1996a; Smol and Douglas, unpubl. data). If this acidic deposition is not natural, and it is the consequence of long-range atmospheric transport of acids, then some arctic lake ecosystems are almost certainly being affected detrimentally. Diatom-based paleolimnological techniques should be applied to potentially acid-sensitive arctic lakes, to determine if in fact they are being affected by these pollutants, and if so to what extent. Some preliminary work in this general area has been done by Wolfe (1996a, b), who has used the known ecological preferences of diatom taxa to qualitatively infer past, long-term, natural acidity changes in a small lake on Baffin Island.

Diatoms may also be used potentially as biomonitors of past changes in other stressors, such as inorganic (Genter, 1996) and organic (Hoagland *et al.*, 1996) contaminants. Such paleolimnological approaches, however, have yet to be initiated.

Local Disturbances

As the human population of arctic communities continues to increase, it is likely that water quality in nearby lakes and ponds will decrease. For example, local disturbances in a lake's drainage basin, such as road building, garbage dumps, and other types of construction, will affect water quality. A major goal of environmental research is to be able to determine what these effects might be, and how to mitigate environmental degradation. Since most environmental assessments are done after the fact, the crucial pre-disturbance data on what the system was like prior to the disturbance, and how it changed as a result of the activities, have not been gathered. Paleolimnological techniques, however, could be used to reconstruct these missing data sets.

Diatom-based paleolimnological approaches have been used very effectively in temperate regions to study the effects of local disturbances on lake systems, such as the limnological repercussions of development in drainage basins (*e.g.*, Hall and Smol, 1996). These approaches could easily be applied to arctic regions. For example, increased lake eutrophication, as a result of human activities, is becoming a major problem in some far northern areas, especially in the more populated regions of Siberia (Vekhov, 1987). With continued expansion of human populations in the Canadian Arctic, these problems likely will be exacerbated further. Paleolimnological techniques could be used to help study these environmental problems. For example, Douglas and Smol (in preparation) used diatoms preserved in a ^{210}Pb-dated lake sediment core from Meretta Lake (Resolute Bay, Cornwallis Island) to study the ecological effects of sewage inputs into this high arctic ecosystem. Wolfe (1991) completed a paleolimnological study of a water supply lake for Pond Inlet (Baffin Island). He found that diatom assemblages were relatively stable over *ca.* 7000 years, but then recorded marked species changes in the lake's more recent sediments. He attributed these diatom changes to local anthropogenic activities.

Similarly, as mining activities continue to expand into arctic regions, paleolimnological techniques could be used to study affected lake basins, using similar procedures that were used successfully in more southern regions, such as Sudbury (Dixit *et al.*, 1991, 1992a, b, 1995). Many other types of studies could be initiated.

Biological Monitoring Using Diatoms

Water chemistry is the mainstay of most long-term monitoring programs of aquatic systems, but it is now widely recognized that biological indicators are also important components to these programs (Loeb and Spacie, 1994). A major reason to include biological data is that most studies are based on a "snapshot" approach, whereby detection of changes in ecosystems are based on only a few samplings per year, and in some cases only one sampling every four years or so. Organisms monitor environmental conditions continually, reacting not only to subtle changes in individual physical, chemical and biological variables, but also to synergistic interactions. Given the many advantages diatoms have as monitors of environmental change (*e.g.*, Dixit *et al.*, 1992a; Lowe and Pan, 1996), it is not surprising that several large-scale monitoring programs in the United States, such as the Environmental Protection Agency's Environmental Monitoring and Assessment Program (EMAP) (Whittier and Paulsen, 1992), and the United States Geological Survey's (USGS) National Water-Quality Assessment (NAWQA) Program (Gilliom *et al.*, 1995) have adopted diatoms as one of their primary bioindicators of environmental change. For example, as part of the EMAP program, diatoms are being analysed from the surface sediments of a large suite of lakes that should be resampled every four years (Dixit and Smol, 1994). Changes in diatom communities will be used to interpret if the environmental conditions in the study lakes have deteriorated, improved, or have not changed. The USGS program focuses on river systems and aquifers, studying changes in diatom assemblages and other organisms over time (Porter *et al.*, 1993).

Given the logistic problems of sampling sites frequently in arctic regions, biomonitoring tundra lakes, ponds and rivers using organisms such as diatoms would be a very cost-effective way of assessing environmental change. Many of the diatom protocols (*e.g.*, Porter *et al.*, 1993) developed for programs such as EMAP or NAWQA could be readily adapted to arctic environments. Moreover, many of these approaches can be melded with ongoing paleolimnological programs (see Charles *et al.*, 1994).

CONCLUSIONS

Diatom and other paleolimnological approaches have much to offer studies of environmental change in tundra regions. In addition to resolving some of the questions posed by environmental managers and the community at large, these research programs also contribute directly to more basic research endeavors, such as descriptions of new taxa and methods, and provide new insights to aquatic and landscape ecology. Many of the studies summarized in this paper are still preliminary and exploratory, but a large co-ordinated research effort is now underway to explore these research avenues more fully. Given the successes of these early studies, we are confident that numerous new insights into patterns of environmental change will be forthcoming.

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