Postsettlement eutrophication histories of six British Columbia (Canada) lakes

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Abstract: Eutrophication is a serious problem in many British Columbia lakes. However, long-term nutrient data are rare or unavailable for most lake systems, so the natural, predisturbance characteristics of lakes are unknown, as are the trajectories of past environmental change. We used paleolimnological analyses of diatoms to quantitatively assess eutrophication trends for approximately the last 150 years in six British Columbia lakes. A transfer function was used to infer past lake-water total phosphorus concentrations from the sedimentary diatom assemblages in ^{210}Pb-dated sediment cores: all of the lakes had relatively high total phosphorus levels (>13 μg/L) prior to European settlement. Three of the lakes showed significant eutrophication since that time, whereas the others were only mildly affected. Total phosphorus inferences using the transfer function satisfactorily estimated the modern total phosphorus concentrations of our six study lakes. Minor quantitative problems arose when some fossil assemblages provided poor analogues to the calibration function, but eutrophication trends were still clearly apparent. Our results confirm that some British Columbia lakes have suffered considerable eutrophication as a result of anthropogenically related nutrient inputs, while others, although situated within human-influenced regions, have been relatively unaffected. These results can now be used to help set realistic goals for restoration projects.

Résumé : L'eutrophisation pose un grave problème dans de nombreux lacs de Colombie-Britannique. Toutefois, pour la plupart des systèmes lacustres, on ne dispose dans les meilleurs des cas que de rares données à long terme sur les matières nutritives, de sorte qu'on ne connaît pas les caractéristiques naturelles des lacs avant perturbation, pas plus que l'histoire des modifications antérieures de l'environnement. Nous avons eu recours à des analyses paléolimnologiques des diatomées pour évaluer de façon quantitative les tendances de l'eutrophisation, pendant les 150 dernières années environ, dans six lacs de la province. Une fonction de transfert a servi à reconstituer les concentrations passées de phosphore total dans l'eau des lacs à partir des assemblages de diatomées sédimentaires dans des carottes de sédiments datées au ^{210}Pb : tous les lacs présentaient des niveaux relativement élevés de phosphore total (>13 μg/L) avant la colonisation européenne. Trois des lacs ont connu par la suite une eutrophisation notable, tandis que les autres n'ont été que légèrement touchés. Le calcul des concentrations de phosphore total à l'aide de la fonction de transfert a permis d'estimer de façon satisfaisante les concentrations actuelles de phosphore total dans les six lacs de l'étude. Des problèmes quantitatifs mineurs se sont posés quand certains assemblages fossiles n'ont fourni que des analogues médiocres à la fonction d'étalonnage, mais les tendances à l'eutrophisation restaient nettement apparentes. Nos résultats confirment que certains lacs de Colombie-Britannique ont subi une eutrophisation considérable à la suite d'apports anthropiques de matières nutritives, tandis que d'autres, quoique situés dans des régions soumises à l'influence humaine, ont été relativement peu atteints. Ces résultats peuvent maintenant servir à fixer des objectifs réalistes pour les projets de rétablissement.

[Traduit par la Rédaction]

Received February 3, 1995. Accepted May 29, 1995.
J12755

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Introduction

British Columbia (B.C.) contains many lakes that are believed to have become eutrophic as a result of human activities since European settlement, circa 1850 (Northcote and Larkin 1963; Stockner and Northcote 1974). Possible nutrient sources have included direct inputs (such as sewage disposal) and indirect sources (such as runoff from pastures, and more recently, agricultural fertilizers). Deterioration of water quality, together with increased agricultural and industrial water demands, have jeopardized aspects of the B.C. economy that are based on tourism and recreational activities. Lake restoration measures are therefore desirable, but it is first necessary to determine the causes and timing of lake-water quality deterioration. Unfortunately, as is typically the case with water quality assessments (Smol 1992, 1995), most lake monitoring programs in B.C. did not begin until a problem had been identified. Using paleolimnology, we can identify trophic changes that occurred before conventional monitoring programs were initiated (Charles et al. 1994).

Paleolimnology is the synthetic science that is used to describe the physical, chemical, and biological histories of aquatic systems. This is achieved by analyzing materials archived in the sedimentary record. Attempts at reconstructing past nutrient concentrations by simply analyzing the phosphorus content of sediments are unreliable, as sedimentary phosphorus concentrations are affected by many factors, such as redox conditions and concentrations of coprecipitates (Engstrom and Wright 1984). Instead, proxy methods, such as those using past diatom species composition, must be used (Anderson and Rippey 1994).

Paleolimnological analyses aimed at reconstructing past eutrophication trends have been conducted in many regions (Anderson et al. 1993; Fritz et al. 1993; Salonen et al. 1993; Brugam 1988; Stoermer et al. 1985), including a few in B.C. (e.g., Stockner and Northcote 1974). Sedimented diatoms are sensitive indicators of nutrient concentrations and can be used to infer past water quality. The remains of diatoms have been considered the most useful paleoindicators for several reasons: their siliceous cell walls make them resistant to dissolution and breakage, they occur in most environments where water is present, they are very diverse and often identifiable to the level of species or subspecies, and their taxonomy is generally well described (Dixit et al. 1992). Stockner and Northcote (1974) used diatoms in a pioneering study to reconstruct the trophic histories of four B.C. lakes, but their methods were based on the qualitative environmental preferences of a few common diatom genera. Paleolimnologists can now use more advanced inference methods to infer past lake-water quality.

It is possible to estimate quantitatively the relationship of a taxon to a given environmental variable, and to use such relationships to infer that variable from fossil diatom assemblages (Charles and Smol 1994). These relationships are obtained by assessing the diatom assemblages from the surficial sediments of several lakes and relating the species distributions to modern limnological conditions. Several diatom-based transfer functions have been developed to infer environmental characteristics from diatom assemblage data. For example, pH (Birks et al. 1990), salinity (Cumming and Smol 1993), and nutrient (e.g., Agbeti 1992; Anderson et al. 1993; Hall and Smol 1992) inference functions have been constructed using weighted-averaging regression and calibration approaches. This method assumes that diatom species respond in a unimodal fashion to environmental variables, and thus an environmental optimum can be determined for each taxon. A quantitative estimate for a fossil sample is then determined from the average of the optima of all taxa in that sample, weighted by their relative abundances.

The main objective of this paper was to infer past trends in total phosphorus concentration ([TP]) for one presently mesotrophic and five eutrophic B.C. lakes. To gain a historical perspective on eutrophication in B.C., past changes in [TP] were inferred from diatom valves in lake sediment cores from the region. We used a [TP] inference model that was originally designed by Hall and Smol (1992) and has been recently updated (Reavie et al. 1995) to increase the range of [TP] optima represented by the diatom species. We also evaluate the reconstructive ability of this new model.

Site descriptions

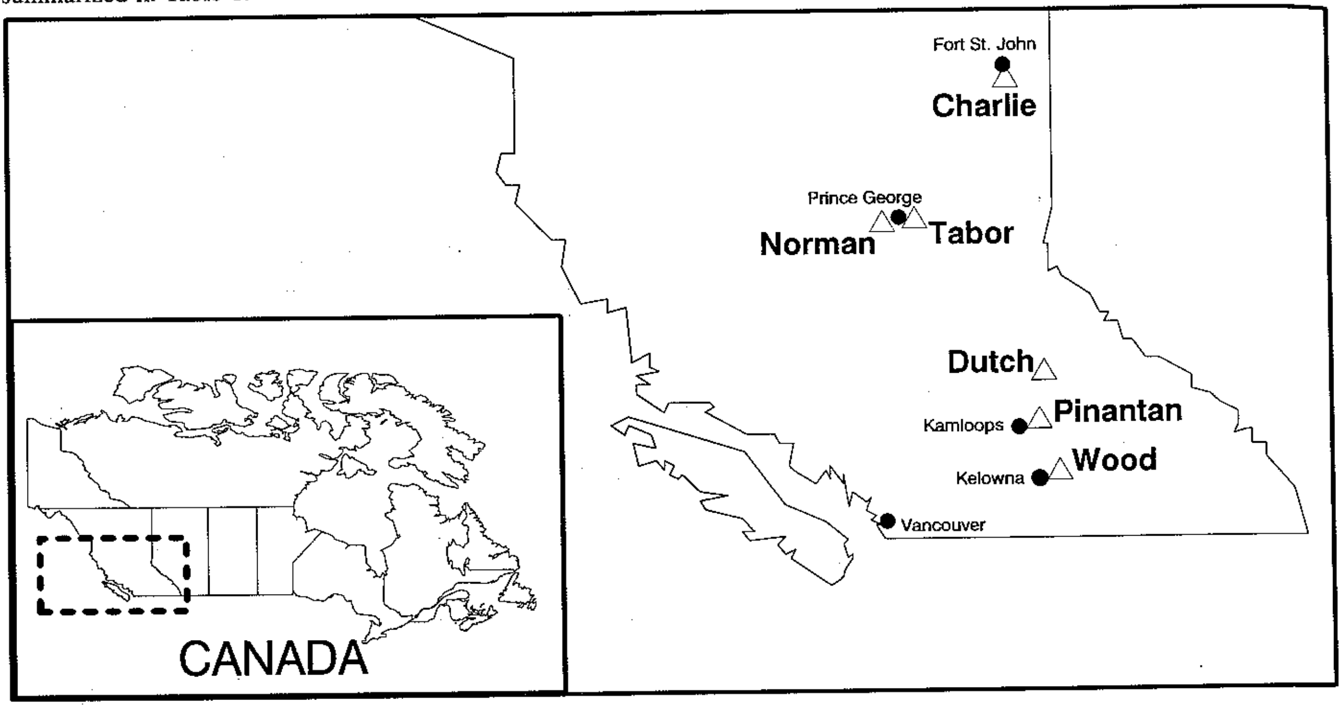
The lakes selected for this study are scattered over a wide area of inland B.C. (Fig. 1, Table 1), and most were suspected of becoming mesotrophic or eutrophic as a result of anthropogenic activities (B.C. Environment, unpublished data). Three of the lakes were of interest to B.C. Environment (Lands and Parks) because they have highly developed watersheds (Charlie), they have productive macrophytic and cyanobacterial communities (Charlie and Tabor), or they may be subject to increased land use and related impacts following the introduction of electrical power (Norman). Wood Lake, in the Okanagan basin, has been notably affected by human influence over the last few decades and has been the subject of much research (Walker et al. 1994; Stockner and Northcote 1974). Pinantan and Dutch lakes are presently eutrophic, and they were arbitrarily selected for study from a list of problem lakes (B.C. Environment, unpublished data). All of the lakes would be considered mesotrophic to eutrophic by general North American standards (Wetzel 1983). However, as explained below, they differ greatly in many respects.

Okanagan Valley

The Okanagan basin is a U-shaped valley where over 100 headwater lakes support a valuable sports fishing industry. The lowest lands, which contain the largest lakes, support considerable cottage and tourist industries as well as several dairy farms. The middle benchlands contain fertile soil with fruit orchards. The uppermost open forest lands are predominantly used for cattle grazing.

Wood Lake is somewhat unusual for this region because the history of European settlement in the watershed is well known for the past century. The catchment has been highly disrupted. Natural vegetation has been replaced by orchards and pasture land, and the southern shore is now surrounded by summer homes. The retention time of the lake may have been reduced by the installation of a pumping station in 1971 (Gray and Jasper 1982). Wood Lake receives

Fig. 1. Locations of the six study lakes (open triangles) in British Columbia, Canada. Limnological characteristics are summarized in Table 1.



nutrients primarily from leaking septic tanks and Vernon Creek, which drains agricultural lands (Walker et al. 1994). Stein and Coulthard (1971) speculated that Wood Lake was naturally eutrophic, but this has not been firmly established because long-term limnological measurements are not available. One recent study shows that specific eutrophication events in Wood Lake's catchment are closely associated with trends in the sedimentary diatom and chironomid fossil remains (Walker et al. 1994). We present the diatom data again here because quantitative [TP] reconstructions have not yet been performed for Wood Lake.

Kamloops area

Dutch Lake is located north of Clearwater in a popular tourist region. Information on the trophic status of Dutch Lake was first collected in the early 1970s when Lovell and Sackey (1973) attributed the poor flavour of fish to the excessive growth of blue-green algae. Shortly thereafter the Thompson–Nicola Regional District and the Clearwater Improvement District requested that the lake's water quality be evaluated (Nordin 1982). The filling time of the lake was estimated at 20 years; since closure of the only outflow by road construction, most of the lake's water loss is by evaporation, hence the term filling time. Because virtually no nutrient material can be lost from the lake basin, the lake is very susceptible to nutrient inputs. Hypolimnetic oxygen deficits, high nutrient concentrations, and dense algal blooms have been noted. Numerous septic tanks appear to be the most probable source of nutrients (Nordin 1982). In the last decade, considerable development has occurred north of the lake. No long-term limnological data, however, are available for this period, except for some very recent measurements.

Less information is available concerning Pinantan Lake, except that it is presently a eutrophic system (R. Nordin, B.C. Environment, Victoria, B.C., personal communication). Impacts from development and tourism are similar to those affecting Dutch Lake. However, Pinantan has a relatively small drainage basin and presumably has been less affected by anthropogenic nutrient inputs.

Prince George region

The economic activity surrounding Prince George consists largely of forest-related industries. Beef and other livestock industries are also active (Collins 1985). Two lakes near Prince George were chosen for detailed paleolimnological analyses.

Norman Lake is mesotrophic (Table 1) and receives a higher than permissible annual phosphorus load of 1213 kg/year (Carmichael 1992; Dillon and Rigler 1975). The north shore is developed with about 140 seasonal-use cabins, most with outhouses. Carmichael (1992), after assessing the general limnology of Norman Lake, recommended land-use strategies to decrease anthropogenic nutrient inputs. He also suspected, however, that much of the phosphorus load to the lake came from natural land sources and precipitation. Unfortunately, no monitoring of trophic variables (e.g., [TP], chlorophyll *a* concentration, Secchi depth) was performed before 1988.

Tabor Lake, located approximately 11 km east of Prince George along the Yellowhead Highway, has a spring [TP] (Table 1) similar to that in Norman Lake; however, Tabor Lake has higher mean summer chlorophyll *a* level and lower water clarity. Therefore, Tabor Lake is considered eutrophic (N.B. Carmichael, unpublished data). Tabor Lake has experienced severe midsummer algal blooms. Also, the dramatic spread of the macrophyte *Elodea canadensis* over recent years is believed to be responsible for a major fish kill in 1993. This worsening condition is believed to be recent, but long-term data are not available. Nutrient inputs are suspected to originate from up to 166 domestic residences, from sawmill burners that operated until the 1960s, and from general aerial loading associated with the development of Prince George. Also, in 1961, a significant fire occurred in the lake's watershed, and in the early 1970s, the diversion of an inflow stream resulted in a longer water replacement time (N.B. Carmichael, unpublished data).

Fort St. John area

Charlie Lake is one of the most eutrophic freshwater lakes in British Columbia. It is one of seven aquatic systems in the Peace River area that has been selected for water quality assessment and development of rehabilitation objectives (Nordin and Pommen 1985), primarily because the lake provides the city of Fort St. John (population 20 000) with fisheries, recreation, industrial, and domestic water resources. There is concern that agricultural inputs and the disposal of sewage directly into groundwater from domestic residences have been providing the lake with nutrient-rich effluent. Water quality assessments of Charlie Lake have shown that trophic variables are at highly undesirable levels (Table 1), and dense blue-green algal (*Aphanizomenon flos-aquae*) blooms have occurred over at least the last two decades (N.B. Carmichael, unpublished data). Unfortunately, historical records on the lake's trophic status date back only to the mid-1970s.

Materials and methods

Coring procedures

Charlie, Norman, and Tabor lakes were cored in the late summer of 1991 by B.C. Environment personnel. Wood Lake was sampled in the summer of 1992 (Walker et al. 1994). Pinantan and Dutch lakes were cored in the spring of 1993.

The sediment cores, ranging from 27 to 45 cm in length, were collected using a modified Kajak–Brinkhurst (KB) gravity corer equipped with a 6.35 cm inside diameter core tube (Glew 1989). Sites were located in or near the deepest part of each lake. Cores were immediately sectioned on shore using a close-interval extruder (Glew 1988) and 1-cm slices were stored in Whirlpak® bags prior to subsampling. In the laboratory, subsamples of sediment were taken for ^{210}Pb dating and diatom preparation.

^{210}Pb dating

Sediment subsamples (approx. 30 g) of selected intervals were weighed, oven dried (24 h at 110°C), and ground to a fine dust. Samples were reweighed to determine dry weight and submitted to Atomic Energy of Canada Limited (Chalk River, Ont.) for ^{210}Pb analysis.

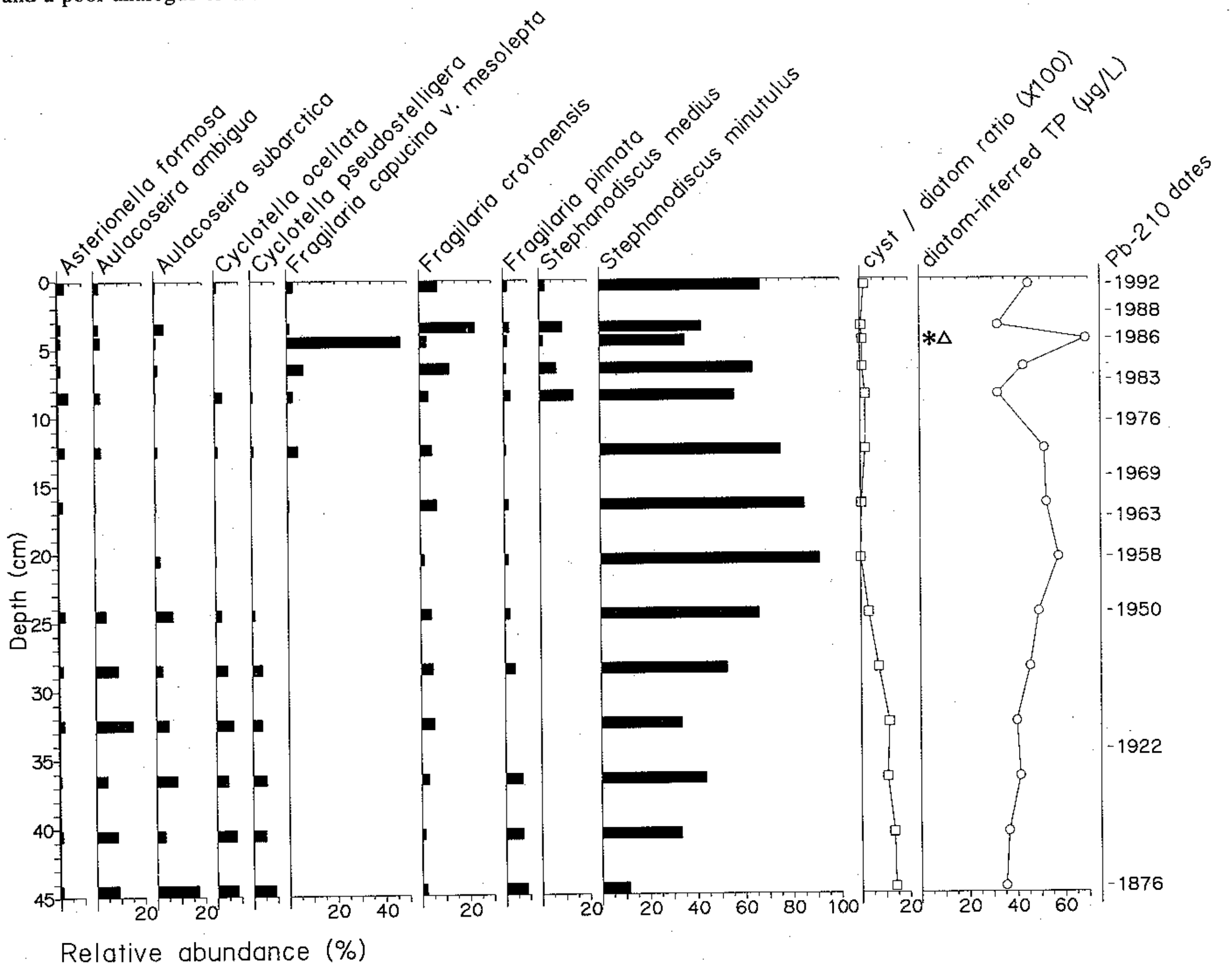
^{210}Pb dating is calculated from determinations of ^{210}Po, a decay product of ^{210}Pb. Quantitative measurements were made using alpha spectroscopy (Cornett et al. 1984). Unsupported ^{210}Pb was calculated by subtracting supported ^{210}Pb (the baseline ^{210}Pb activity naturally present in the sediments)

Table 1. Environmental characteristics of the study lakes.

		Physical					Chemical				
Lake	Location	Surface area (ha)	Max. depth (m)	Mean depth (m)	Watershed area (km^2)	Altitude (m)	Chlorophyll *a* (μg/L)	pH	Conductivity (μS/cm)	[TP] (μg/L)	Diatom-inferred [TP] (μg/L)
Wood	50°10′N, 119°38′W	930	34	21.5	190	390	4.1	8.3	325	45.4	46
Pinantan	50°75′N, 120°00′W	73	19	10	10	853	—	7.8	420	54	22
Dutch	51°65′N, 120°02′W	65.5	39	14.4	3.9	765	3.0	8.1	235	46	18
Charlie	56°40′N, 121°00′W	3120	12	5	298	691	47.3	8.1	169	55	62
Tabor	53°55′N, 122°33′W	417	9	5.4	44	702	7.6	7.8	145	25	47
Norman	53°47′N, 123°22′W	510	24	12	129.4	876	4.5	7.8	137	25	18

Note: The most important variables, according to Reavie et al. (1995), are presented. Chlorophyll *a* data were unavailable for Pinantan Lake. Values for actual [TP] are averages of available spring data, whereas values for all other variables are derived from all available data. Included are the inferred [TP] values from the uppermost sediment intervals of the study lakes.

Fig. 2. Diatom, stomatocyst/diatom ratio and inferred [TP] stratigraphies for Wood Lake. *△, the interval with poor fit to TP and a poor analogue to the calibration set.



from total activity at each level. Dates were then determined from unsupported isotopes using the constant rate of supply model (Appleby and Oldfield 1978); a computer program designed by Binford (1990) was used to perform these calculations. ^{210}Pb dating is limited to approximately 150 years before present, so extrapolations beyond this period were made on the basis of calculated sediment accumulation rates for the lowest intervals of the core. Varves were counted to determine the chronology of Pinantan Lake and charcoal particles were used to confirm the recent chronology of Tabor Lake.

Diatom preparation

Twelve evenly spaced intervals were selected from each core for diatom analysis. Extra intervals were added later for some cores, for which better stratigraphic resolution was desired. Subsamples of wet sediment (0.3–1.0 g) were heated for 1 h in a mixture of potassium dichromate and sulphuric acid to digest organic matter. Samples were then repeatedly washed in distilled water and centrifuged until they were clear and free of residual acid. The siliceous remains were settled onto cover slips, and the cover slips were mounted on glass slides using Hyrax®. For each slide, at least 500 diatom valves were identified and counted along transects under oil immersion at 1000× magnification. Diatom taxonomy was based primarily on Krammer and Lange-Bertalot (1986, 1988, 1991*a*, 1991*b*), Camburn et al. (1984–1986), and Patrick and Reimer (1966). Chrysophyte cysts were also enumerated and expressed relative to the diatom sum (Smol 1985).

Inferring total lake-water phosphorus

The transfer function we used was constructed by determining the relationship between water chemistry variables and diatom distributions in the surface sediments of 59 B.C. lakes (Reavie et al. 1995). Canonical correspondence analysis (CCA) was used to identify environmental variables with strong correlations to modern diatom assemblages (Ter Braak 1990*a*, 1990*b*). Lake-water [TP] had a significant influence on the diatom communities in our lakes, so weighted averaging calibration (Line et al. 1994) was used to estimate the [TP] optima for common diatom taxa. The final regression equations were based on the [TP] optima of the 150 most common diatom taxa found in the 59 calibration lakes (Reavie et al. 1995).

Quantitative [TP] inferences were performed using the computer program WACALIB version 3.3 (Line et al. 1994). The distribution of [TP] measurements for the calibration set was skewed toward the oligotrophic extreme of the spectrum, so calculations were performed using transformed (ln(TP + 1)) data (see Birks et al. 1990 for details). The inferred [TP] values furnished by WACALIB were subsequently back transformed.

Fit to [TP] and modern analogue measures

A CCA constrained to [TP] was used to evaluate our [TP] reconstructions (Reavie et al. 1995). The residual distance of diatom assemblages to the TP axis provided a measure to assess lack of fit to TP. First, CCA determined what were extreme residual distances from the TP axis on the basis of modern samples with environmental data (Reavie et al. 1995). Core samples were then run passively in CCA and positioned, by means of transition formulae (Ter Braak 1990*a*), with respect to the TP axis. Fossil samples with residual distances greater than the 90 and 95% confidence limits of the calibration set were considered to have poor and very poor fits to TP, respectively.

Fossil samples with close modern analogues are more likely to provide reliable inferred [TP] values (Birks et al. 1990). Using the computer program ANALOG (J. Line and H.J.B. Birks, unpublished program), we performed analogue matching to identify fossil diatom assemblages with poor analogues to modern assemblages in the training set. Details of this method are described by Hall and Smol (1993).

Results and discussion

Okanagan Valley

The pre-20th century sediments of the Wood Lake core were dominated by a complex of planktonic diatoms, primarily *Aulacoseira ambigua*, *Aulacoseira subarctica*, *Cyclotella ocellata*, *Cyclotella pseudostelligera* (Krammer and Lange-Bertalot 1991*a*), and *Stephanodiscus minutulus* (Fig. 2). Total phosphorus inferred from this assemblage indicated that the lake already had relatively high spring nutrient levels ([TP] = 35 μg/L) before cultural impacts occurred in the drainage basin. *Stephanodiscus minutulus*, a eutrophic taxon (Håkansson 1976), increased considerably from the late 19th century until about 1958, when it constituted 93% of the diatom assemblage. Chrysophyte stomatocysts gradually decreased relative to the diatoms; cyst to diatom ratios declined from 0.14 in the older sediments (~1876) to trace amounts by about 1958. During this same period, inferred [TP] increased from 35 to 58 μg/L.

The eutrophication indicated by these trends is corroborated by other studies. In 1974, a study of the Okanagan basin suggested that Wood Lake had begun to rapidly deteriorate during the early 1900s because of agricultural development and diversion of inflow streams for irrigation (British Columbia Water Resources Service 1974). Profundal chironomids also disappeared from our sediment core around 1940 (Walker et al. 1994). Such an occurrence is characteristic of hypolimnetic anoxia resulting from eutrophication.

Diatom-inferred [TP] and the relative abundance of *Stephanodiscus minutulus* decreased after 1958, indicating that water quality improved. The opening of a Hiram Walker distillery in about 1970 is considered to be the most important event to have affected Wood Lake in recent years. Since 1971, the distillery has been pumping large volumes of water from nearby Okanagan Lake (average [TP] in the 1980s ≤21 μg/L) for cooling, and releasing it into Vernon Creek, upstream from Wood Lake (British Columbia Water Resources Service 1974). This pumping resulted in a reduction of the theoretical water replacement time from 30 to 14 years. Although this estimate varies because of precipitation (Gray and Jasper 1982), it is believed that the distillery's release of Okanagan Lake water is largely responsible for the water quality improvement (Walker et al. 1994).

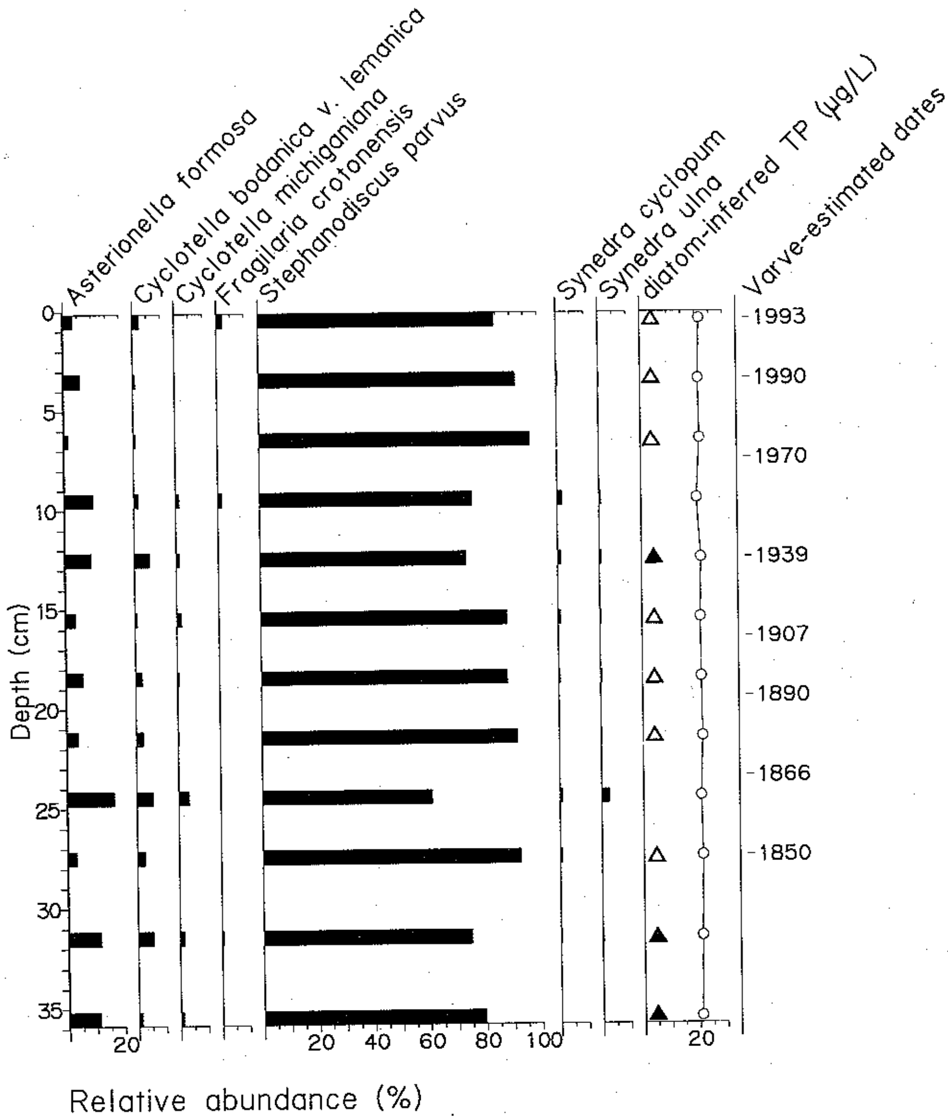
Little Round Lake, in southeastern Ontario, experienced similar changes in its recent history (Smol et al. 1983; Christie and Smol 1993). As anthropogenic nutrient enrichment occurred in Little Round Lake, the relative abundance of small *Stephanodiscus* spp. increased. Subsequently, most of the disturbance in the drainage basin ceased, and seepage from road salt enhanced meromixis, thus preventing the resuspension of hypolimnetic nutrients. Surface water quality improved and eutrophic taxa decreased in relative abundance. Water quality recoveries as dramatic as those in Wood and Little Round lakes have rarely been observed.

The lower diatom-inferred [TP] values during the past 25 years in Wood Lake were interrupted at the 4- to 5-cm interval with a sudden increase to 70 μg/L, in conjunction with a sudden increase in *Fragilaria capucina* var. *mesolepta*. The brief (2 or 3 year) bloom of *F. capucina* var. *mesolepta* may have been caused by an irregularly high nutrient load in Wood Lake at that time. However, a misleading [TP] inference may have occurred at this interval because of poor assemblage fit to [TP] (i.e., a poor analogue). This taxon is considered periphytic, so it is possible that it is responding to other changes in the ecosystem (e.g., macrophyte growth). Unfortunately, no historical information is available to explain this incident. Overall, we conclude that Wood Lake was fairly productive before the commencement of human impacts, European development caused a degradation in water quality, and recent unintentional mitigation (water pumping) has resulted in a reduction of TP concentrations.

Kamloops area

The Pinantan Lake core was varved, and on the basis of the sediment laminations, the core dates to well before 1850 (Fig. 3). *Stephanodiscus parvus*, a well-known eutrophic indicator (Anderson et al. 1990; Christie and Smol 1993), occurred in relative abundances of 60–96% throughout the core, suggesting that Pinantan is naturally eutrophic and that this has changed little since European settlement. In general, the assemblages did not shift markedly, except for a minor peak of *Asterionella formosa* during the 1850s. Similarly, the inferred [TP] values were almost uniform (at about 21 μg/L) throughout the core. However, few

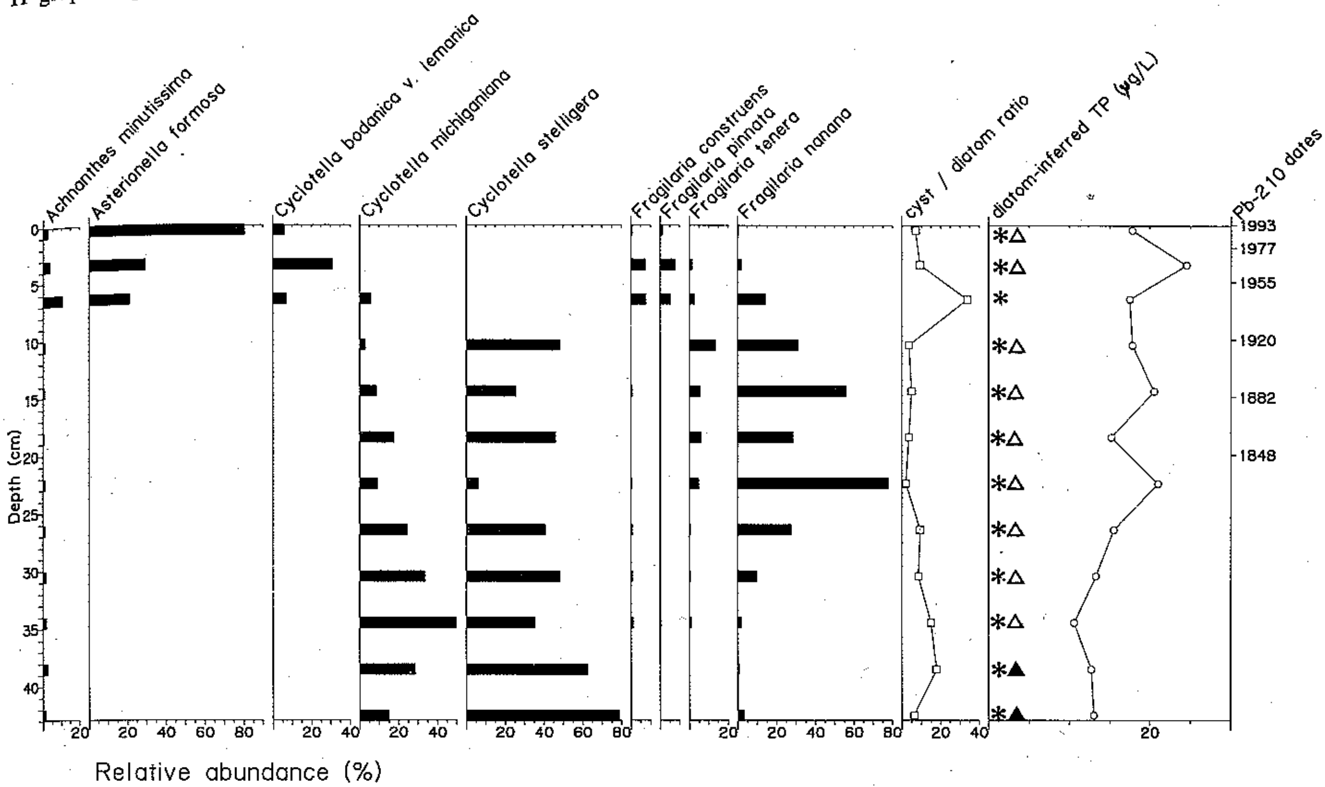
Fig. 3. Diatom and inferred [TP] stratigraphy for Pinantan Lake. Assemblages are designated on the inferred TP graph as poorly fitted to TP (▲), very poorly fitted to TP (△), and poor analogue to the calibration set (*).



analogous assemblages (with such a high relative abundance of *Stephanodiscus parvus*) occurred in our calibration set, and therefore many of the intervals showed poor fit to [TP]. Because of this, we suspect that our inference model underestimated TP concentrations. In summary, the diatom data indicate that there has been little anthropogenic impact on [TP] in Pinantan Lake.

The Dutch Lake core recorded five major diatom community shifts (Fig. 4). *Cyclotella stelligera* occurred in high relative abundance at the bottom of the core. *Cyclotella michiganiana* gradually increased in abundance until the 34-cm depth, after which it gradually tapered off to trace amounts. *Fragilaria nanana* sharply increased from 10 to 78% between the 30- and 22-cm (~1850–1920) intervals. Little is known about the ecology of *F. nanana*, but Reavie et al. (1995) described this taxon as having a relatively high [TP] optimum, indicating that eutrophication may have occurred between 1850 and 1920. From 22 to 10 cm, *F. nanana* and *C. stelligera* were dominant, but above 10 cm both species declined in the sediments. *Asterionella formosa* and *Cyclotella bodanica* var. *lemanica* increased in the uppermost 38 years of sediments, with *Asterionella formosa* dominating the 0- to 1-cm assemblage (80% relative abundance). The cyst to diatom ratio gradually decreased from 0.17 (at the 38- to 39-cm interval) to about 0.04 (between 23 and 10 cm), but at the 6- to 7-cm interval, the ratio increased sharply to 0.34, then decreased again to low levels. Dutch Lake's microfossil history closely mirrors that of other culturally affected lakes (O'Sullivan 1992; Brugam and Vallarino 1989; Brugam 1988; Stoermer et al. 1985). For example, Brugam and Vallarino (1989) documented similar diatom shifts for Meridian Lake, Washington: a presettlement *Cyclotella* community, followed by *Synedra* spp. (during deforestation), and a later increase in *Asterionella formosa*. Their observations confirmed a strong relationship between the onset of human

Fig. 4. Stratigraphies of siliceous microfossils and inferred [TP] for Dutch Lake. Assemblages are designated on the inferred TP graph as poorly fitted to TP (▲), very poorly fitted to TP (△), and poor analogue to the calibration set (*).



disturbance and an increase in *Asterionella formosa*. They also recorded a poor relationship between lake-water TP concentration and patterns in the diatom assemblages. Conversely, Stoermer et al. (1985) observed that substantial phosphorus loading to Lake Ontario resulted in community shifts similar to those in Dutch Lake (such as an increasing abundance of *Asterionella formosa*), so this matter is still disputable.

Inferred [TP] from the Dutch Lake core fluctuated with the diatom species changes, but an approximate increase from 13 to 20 µg/L was apparent. Even though a variety of assemblages are represented in the Dutch Lake core, many of the assemblages are poorly fit to our [TP] transfer function, and analogues to the calibration set were poor. Dutch Lake has probably been highly affected by human influence, but perhaps other limnological variables (e.g., dissolved organic carbon, total nitrogen) are also controlling diatom communities. Therefore, the diatom-inferred [TP] measurements may be somewhat insensitive to changes in the algal communities. However, as discussed in the previous paragraph, the species changes we observed in Dutch Lake probably indicate eutrophication.

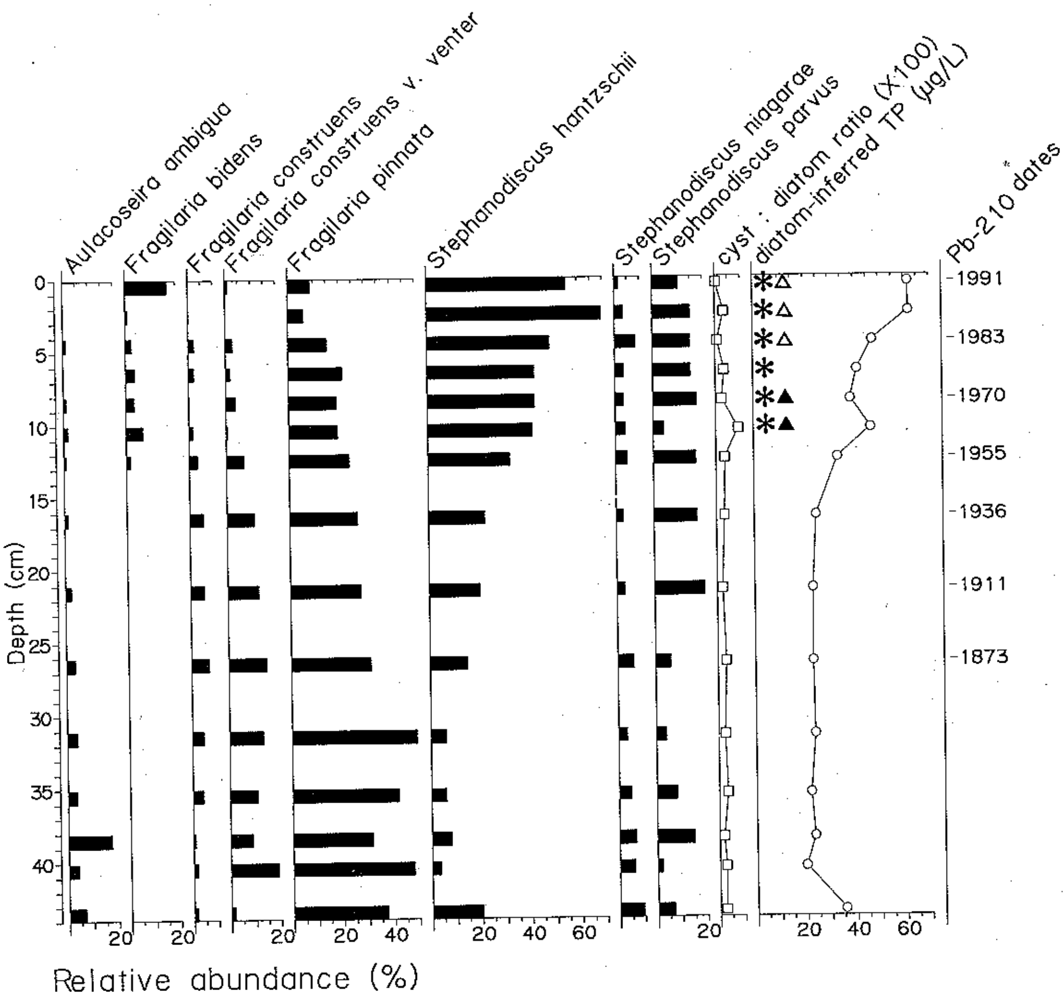
Dutch Lake is particularly interesting because it appears that increases in phosphorus loading occurred before European settlement (i.e., before 1850). By extrapolating the ^{210}Pb dates, we estimate that species shifts began ca. 1750. It is possible that the earliest recorded shift in the diatom community was due to natural causes or, more likely, that water quality changes occurred as a result of inputs from Indian settlements. Although it is known that the Shuswap tribe occupied this area well before 1800 (Balf 1969), approximate locations and populations of settlements are unknown. Therefore, the causes of this early limnological change are uncertain.

Prince George region

Diatom assemblages from the lakes in the vicinity of Prince George indicate naturally productive conditions, but the changes that have occurred since settlement differ between the two lakes (Figs. 5 and 6).

The common taxa in Norman Lake, *Aulacoseira italica* var. *subarctica*, *Fragilaria pinnata*, and *Stephanodiscus minutulus*, maintain relatively constant distributions throughout most of the core (Fig. 5). Drastic community changes have not occurred in the approximately 175 years represented by the core, and the inferred [TP] values indicate that Norman Lake is naturally mesotrophic (~24 µg/L predisturbance conditions) and has changed little since European settlement. This is not surprising because before 1970, settlement in the lake's drainage basin was limited (Carmichael 1992). *Stephanodiscus minutulus* slightly displaced other taxa after approximately 1976, suggesting a minor increase in nutrient inputs. Carmichael (1992) reported that the sewage disposal facilities (outhouses) around the lake are no more than 25 years old, so nutrient inputs from these sources are a possible cause of this slight eutrophication, as are general land disturbances associated with road and cabin construction. Our [TP] inference model appears to have been insensitive to the modest community shifts occurring within the last 15 years, and we in

Fig. 5. Stratigraphies of siliceous microfossils and inferred [TP] for Charlie Lake. Assemblages are designated on the inferred TP graph as poorly fitted to TP (▲), very poorly fitted to TP (△), and poor analogue to the calibration set (*).



fact infer slight water quality improvement. Although this contradicts our qualitative interpretation of the diatom stratigraphy, the shift is relatively minor.

In the Tabor Lake core (Fig. 6), *F. pinnata* is the most common taxon in all intervals, varying between 65% at the bottom of the core and 33% at the 1- to 2-cm interval. Many other *Fragilaria* taxa are also present, but no obvious shifts are noted. Since the mid-1970s, the eutrophic indicator *Stephanodiscus hantzschii* increased in abundance to peak in about 1985. This profile shows a trend in diatom shifts similar to that of Norman Lake, with a modest increase in small *Stephanodiscus* species to as high as 30% within the last two decades, indicating minor eutrophication. The consistent dominance of the littoral, generally ubiquitous diatom *F. pinnata* (Patrick and Reimer 1966) makes this profile difficult to interpret. *Fragilaria pinnata* is difficult to classify ecologically because it occurs in both high- and low-nutrient environments (Christie and Smol 1993; E.D. Reavie, personal observations). Tabor Lake's relative shallowness (Table 1) allows for a largely benthic assemblage to dominate.

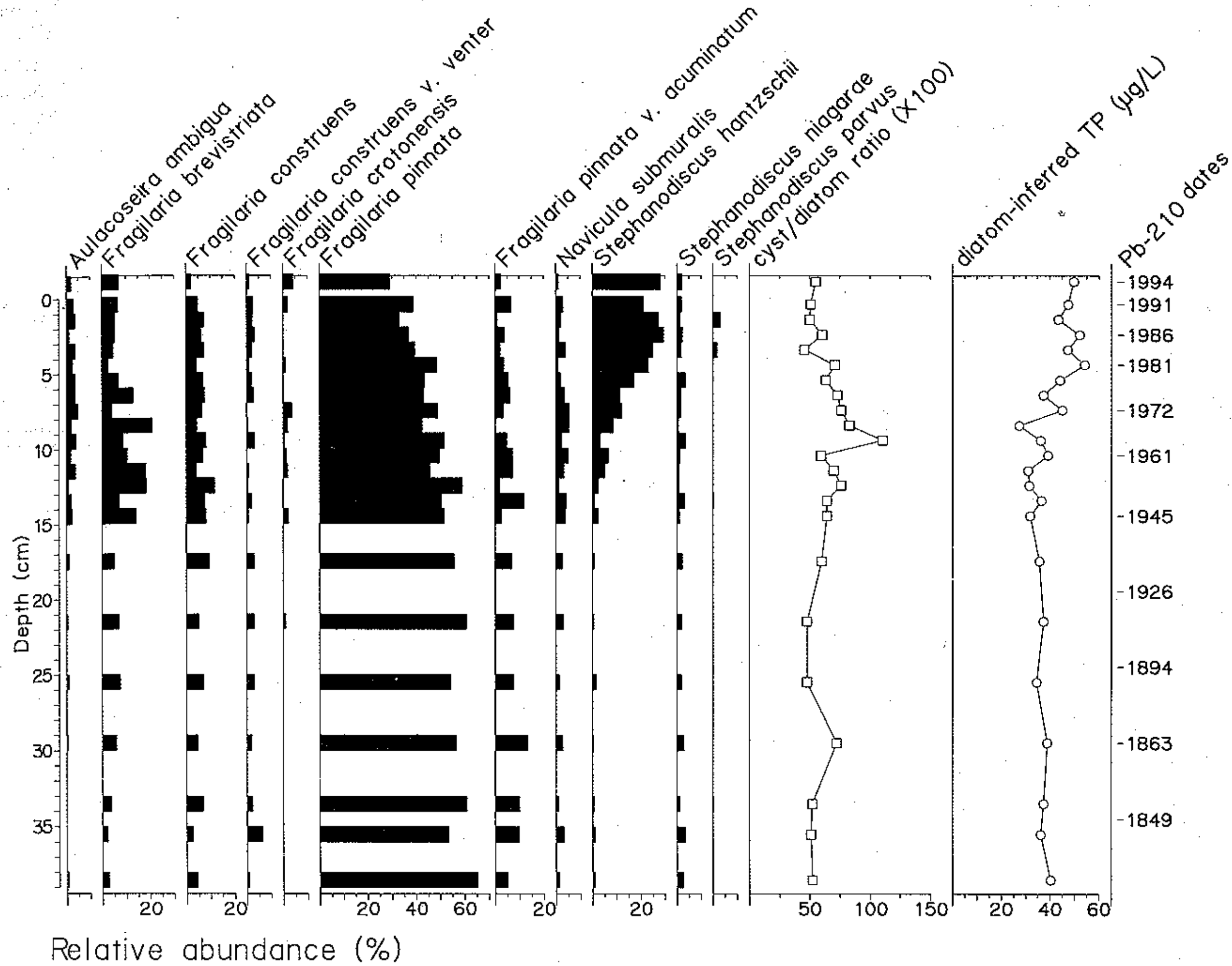
The inferred phosphorus history of Tabor Lake indicates relatively stable TP concentrations (~35 μg/L) until the 1970s, after which some modest eutrophication occurred. Another interesting trend is the apparent nutrient decrease in the uppermost two intervals, indicating that phosphorus loading may have been declining. However, a recent analysis of surface sediment (sampled in 1994; Fig. 6) shows that the relative abundance of *Stephanodiscus hantzschii* and inferred [TP] levels are similar to 1985 levels, and so water quality has probably not improved recently.

A subsequent analysis of raw sediment from the Tabor Lake core revealed numerous charcoal particles in the 11- to 9-cm depths, probably coinciding with the severe watershed fire in 1961. Nutrient inputs to the lake may have increased following the fire-induced vegetation clearance.

Fort St. John area

Aulacoseira ambigua, *F. pinnata*, and three *Stephanodiscus* species are the most common taxa in the pre-1900 sediments of Charlie Lake (Fig. 7), indicating that it was a naturally eutrophic system. The eutrophic indicator

Fig. 6. Diatom and inferred [TP] stratigraphies for Tabor Lake.



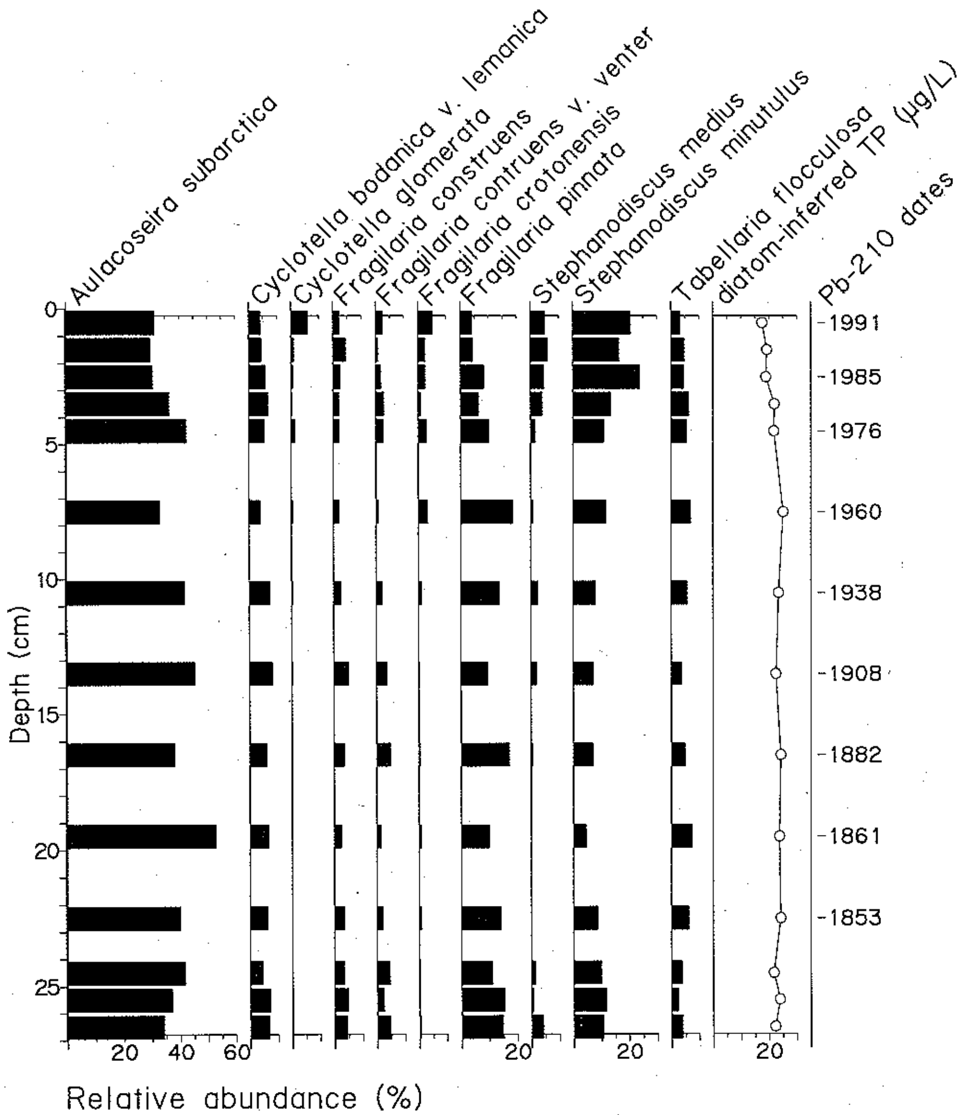
S. hantzschii increased strikingly between 1873 and 1991. *Stephanodiscus parvus* also increased slightly during this time, whereas *F. pinnata* decreased from a relative abundance of 48 to 7%. The impact of settlement was apparently severe; several papers document such dramatic increases in *Stephanodiscus* spp. with eutrophication (e.g., Osborne and Moss 1977; Anderson et al. 1990). *Fragilaria bidens* (Krammer and Lange-Bertalot 1991*a*) is not in our calibration set (Reavie et al. 1995), although it appears in the surficial sediments of Charlie Lake. Its autecology is unknown, and because it does not occur in our [TP] transfer function, our inferred [TP] was not influenced by this taxon. As expected, the most recent intervals provided poor analogues to the calibration set and contained assemblages with poor fit to [TP], probably resulting from the absence of *F. bidens* in the calibration set, and the very high relative abundances of *Stephanodiscus* spp. in the top 11 cm of the Charlie Lake core. The naturally high productivity of Charlie Lake probably prevented chrysophytes from occurring in high abundances (Sandgren 1988), as stomatocysts were found only at trace levels throughout the core.

Inferred [TP] measurements indicated an approximate 40 μg/L increase in [TP] (from 22 to 62 μg/L) since the end of the 19th century. Aquatic productivity in Charlie Lake appears to have increased during the period of deforestation, agricultural development, and sewage disposal in the region.

Evaluation of the weighted-averaging [TP] inference model

Because this is the first application of our new [TP] inference model (Reavie et al. 1995) for hindcasting long-term changes in lake-water TP concentration, it is important to assess the reliability and performance of the model. In some cases, TP concentrations inferred from surface sediment diatom assemblages closely matched available water chemistry measurements (Table 1) (Wood, Charlie, and Norman lakes), indicating that our model may be capable of providing accurate quantitative estimates of lake-water TP concentration. However, the most recent [TP] inferences from Pinantan and Dutch lakes underestimated measured values. It was inevitable that the accuracy of our [TP] inferences would be affected by the influence of other variables. The absence of analogues and lack of fit to [TP] of many fossil diatom assemblages is attributable to the effect of other factors, such as conductivity (Cumming

Fig. 7. Diatom and inferred [TP] stratigraphies for Norman Lake.



et al. 1995), which exert control over the diatom communities. This may explain the underestimated [TP] reconstructions for Pinantan and Dutch lakes. The overestimation of modern [TP] in Tabor Lake was probably caused by the high relative abundance of *F. pinnata*, a taxon with a high [TP] optimum in the calibration set. Inaccurate quantitative reconstructions are not a fatal problem, however. The addition of eutrophic lakes to the original calibration set (Hall and Smol 1992) allowed us, by providing more analogues, to more realistically infer [TP] in Wood Lake (Reavie et al. 1995). Presumably the addition of more lakes will further improve our transfer function.

General discussion and conclusions

The trends in relative abundance of siliceous microfossils provide several insights concerning the influence of cultural activities on lakes in B.C. For example, the predominant relationship between small *Stephanodiscus* taxa and high nutrient levels has been known for some time (Hustedt 1930; Håkansson 1976), and a considerable increase in *Stephanodiscus* spp. with a concomitant decline in benthic taxa has been recorded in several eutrophied lakes (Osborne and Moss 1977; Engstrom et al. 1985). Our results confirm that such a trend appears to coincide with cultural eutrophication in B.C. lakes. The diatom stratigraphy that occurred in Dutch Lake (i.e., the replacement of *Cyclotella* spp. by *Synedra* spp. and *Asterionella formosa*) is also a common indicator of anthropogenic nutrient loading (e.g., Brugam and Vallarino 1989).

The nature of some of the events in the six study lakes is not entirely clear. This may be because diatom community composition is controlled by multiple variables, making the diatom data for all of the lakes inherently "noisy." For instance, it is clear that a major episode occurred around 1986 in Wood Lake, though we have no direct knowledge of a specific historical event to explain the *F. capucina* var. *mesolepta* peak. *Fragilaria pinnata* played a major role in the [TP] inference for Tabor Lake; however, it is probable that this taxon thrives not only because it is tolerant of high [TP] (Reavie et al. 1995), but also because its growth is optimal in shallow lakes with suitable microhabitats.

Many interesting eutrophication trends were observed in the six B.C. lakes. As expected, recent increases in phosphorus levels were inferred in some of the lakes. Others seem to have maintained their natural trophic state since pre-European settlement of inland B.C. In all cases it appears that the lakes were quite productive prior to human settlement.

The underlying hypothesis of this study was that nutrient inputs increased as human populations grew in the watersheds of every study lake. The response to this loading varied among the six lakes included in this study. The lakes with the largest catchment areas (Wood and Charlie lakes; Table 1) appear to have been the most severely affected. Hall and Smol (1993), whose studies involved a paleolimnological analysis of eutrophication following the Ontario hemlock decline (~4800 years BP), also noticed that the degree of eutrophication was related to catchment size. Apparently, forest decimation by natural causes (e.g., pathogens) has a limnological effect similar to that of human exploitation (e.g., deforestation) of the landscape.

Other variables besides catchment size obviously affected the pattern in eutrophication trends that we observed. For instance, Dutch Lake has the smallest watershed area (3.9 km^2), yet it showed more eutrophication than Norman Lake (watershed area 129.4 km^2). The relatively unaffected lakes (e.g., Norman Lake) were subjected to fewer cultural impacts than the highly perturbed systems (e.g., Dutch Lake).

Interestingly, a lake such as Pinantan that has had some development in its drainage basin (e.g., cottages, roads) showed little concomitant evidence of increased eutrophication. Similarly, Norman Lake is also naturally productive and receives nutrients mainly from natural sources (as was suggested by Carmichael (1992)). From our data, arguments could be made that possible restoration measures for these systems should be postponed until better evidence for anthropogenic eutrophication is produced. The amelioration of present human inputs to such lakes may prevent future water quality problems; however, a significant reduction in TP concentrations is probably an unrealistic goal. Conversely, Charlie Lake is an example of a severely culturally affected lake system, where remediation may improve water quality.

Acknowledgements

We are most grateful to the B.C. Environment (Environmental Protection Branch) for facilitating many aspects of this project. We also thank Ian Walker at Okanagan University College for providing sediments and ^{210}Pb dates for Wood Lake. Brian Cumming and John Glew of the Paleoecological Environmental Assessment and Research Laboratory (PEARL) retrieved the Dutch and Pinantan Lake cores. Rick Nordin and Colin McKean at the B.C. Environment supplied environmental lake data. Additional ^{210}Pb dating was performed by B. Risto and R.J. Cornett at Atomic Energy of Canada Limited. Colleagues at PEARL provided many useful comments on this paper. Thanks are extended to Professor H.J.B. Birks (University of Bergen) for the use of his unpublished computer program (ANALOG) and to Roland Hall for performing the analogue matching.

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