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A record of hypolimnetic oxygen conditions in a temperate multi-depression lake from chemical evidence and chironomid remains

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Abstract

A multiproxy paleolimnological study of Douglas Lake, Michigan, was undertaken to elucidate the history of productivity and oxygen depletion in three basins of this multi-depression lake. Indicators investigated in three dated cores included chlorophyll *a*, Fe and Mn stratigraphy, and fossil chironomid assemblages. The coring sites were chosen to correspond to modern studies of oxygen depletion rates, and to determine if conclusions reached in these studies were supported by paleolimnological evidence. Stratigraphies of chlorophyll *a*, Fe and Mn indicate that two of the basins, South Fishtail Bay and Fairy Island, have been eutrophic and anoxic for a long period of time, predating European settlement. The third basin, Grapevine Point, has been consistently less productive, and had less severe oxygen depletion. Results of the chironomid analysis agree with these conclusions, including a change from mesotrophic to eutrophic indicator taxa in the Grapevine Point basin. All three cores show evidence of increasing trophic state in the most recent sediments, supporting some of the conclusions reached in the modern studies. It is also demonstrated that deforestation of the watershed had profound effects on littoral chironomid assemblages. Paleolimnological investigations also demonstrated the individual nature of the separate basins in Douglas Lake.

Introduction

A paleolimnological study of Douglas Lake, Michigan, was undertaken to elucidate past oxygen regimes and productivity changes in the lake. Several factors led to the selection of this lake and the questions posed. First, I wanted to investigate the use of fossil Chironomidae (Diptera) as qualitative paleoindicators of hypolimnetic oxygen levels in this lake. Although chironomids have long been used as bioindicators of organic enrichment and dissolved oxygen, only a few studies have examined fossil chironomids as paleo-oxygen indicators, such as Walker et al. (1993) in Wood Lake, British Columbia and Brodin (1982) in Lake Växjöjön, Sweden. Quinlan et al. (1998) have since developed a quantitative inference model for chironomids and oxygen levels in Ontario lakes.

Second, Douglas Lake has been the site of the University of Michigan Biological Station since 1909, and thus many limnological investigations have been carried out there during this century. There has been some use of the available long-term data, including studies of oxygen depletion rates (described below) (Bazin & Saunders, 1971; Lind, 1978, 1987; Lind & Dávalos-Lind, 1993). One of the goals of this work was to compare paleolimnological interpretations based on chironomids and chemical signals, with those made from historical data sets and modern studies.

Two other factors make Douglas Lake an interesting case study. It has multiple basins with separate hypolimnia, and this complex morphometry (Figure 1A) has intrigued limnologists working there since the inception of the Biological Station. Differences in the biota and chemical/physical parameters among the basins have been documented many times (Welch, 1927, 1944; Eggleton, 1931; Welch & Eggleton, 1932; Campbell, 1941). Welch (1927) even hypothesized that each basin behaves almost as an independent lake. Another goal of the study was to determine if this 'depression individuality', the term used by Welch (1927), was reflected in the stratigraphic record. Lastly, the lake underwent severe disturbance in the form of massive timber cutting in the watershed starting about 1880, a disturbance that can potentially result in profound changes in lake characteristics and biota.

Multiple lines of evidence are always important in any paleolimnological study, and thus in addition to using fossil chironomid fauna as paleo-oxygen indicators, chemical signals of oxygen depletion were also investigated. The stratigraphy of the redox-sensitive metals Fe and Mn, and the degree of preservation

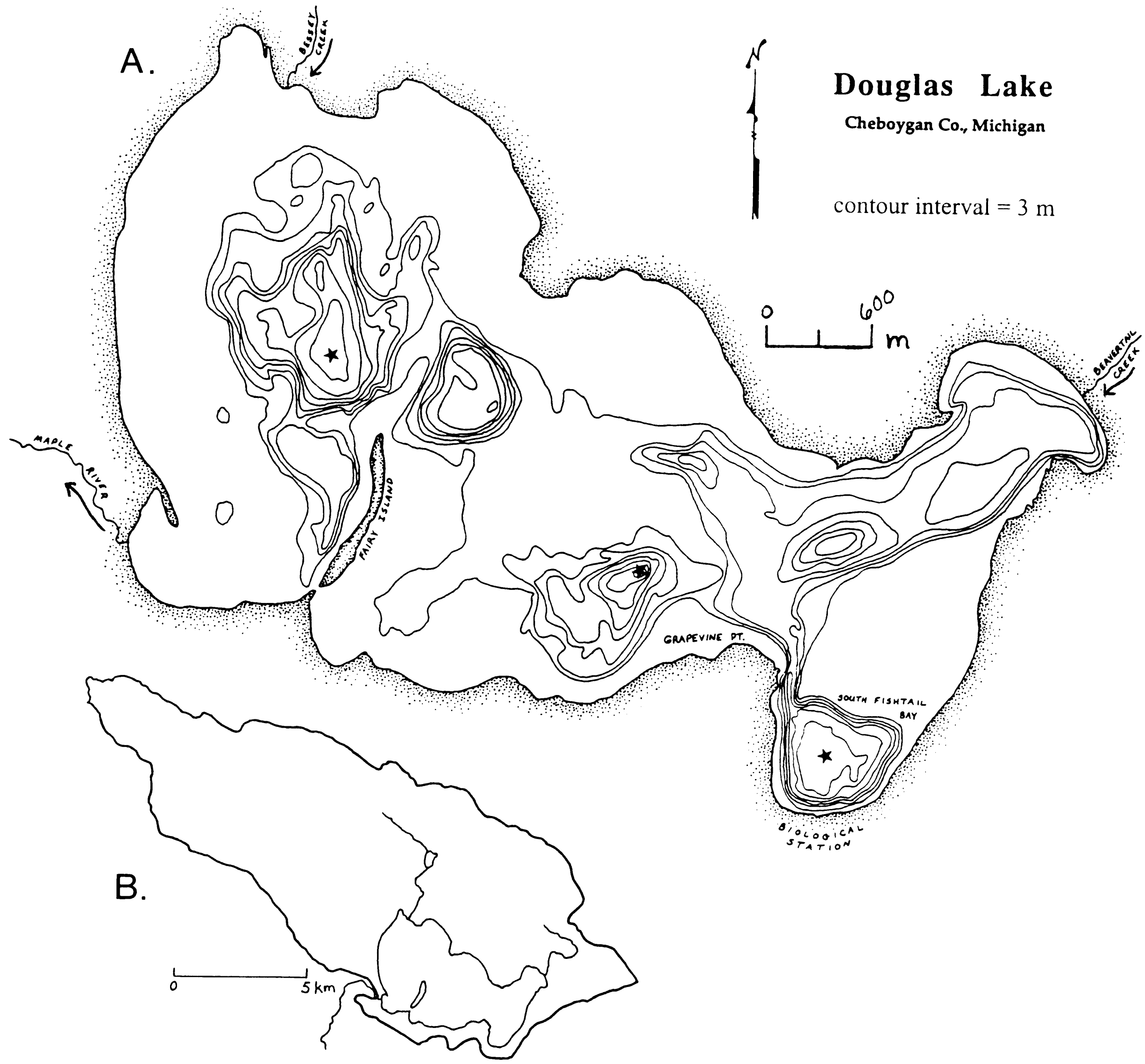

Figure 1. (A) Bathymetric map of Douglas Lake, Cheboygan County, Michigan, USA. Stars indicate coring sites. The three basins are named, left to right, Fairy Island basin, Grapevine Point basin, and South Fishtail Bay basin; (B) The watershed area of Douglas Lake.

of chlorophyll *a*, were examined in dated cores from three of the depressions in Douglas Lake.

The questions addressed by the research include: (1) Does the sedimentary record reflect changes in dissolved oxygen and therefore productivity as discerned by Bazin & Saunders (1971), Lind (1978, 1987) and Lind & Dávalos-Lind (1993)?; (2) How well do profundal chironomid fossil assemblages perform as paleoindicators of hypolimnetic oxygen conditions in this lake?; (3) Does the sedimentary record reflect inter-depression differences as noted by Welch and other early limnologists at Douglas Lake?; and (4) What was the effect of catchment deforestation on chironomid communities in this lake?

Studies of oxygen depletion rates in Douglas Lake

Bazin & Saunders (1971) made use of the long-term data from the biological station to investigate hypolimnetic oxygen deficits as an indication of eutrophication. They calculated the rate of change of total oxygen below the thermocline in South Fishtail Bay by regressing total oxygen against time during the stratified season for the years 1911 to 1964 and detected a trend of increase in the rate of oxygen depletion over these years. They felt this reflected increasing productivity due to human activity. Other work on oxygen depletion rates was done by Lind (1978, 1987) and Lind & Dávalos-Lind (1993), looking at three of the Douglas Lake depressions: South Fishtail Bay, the Grapevine Point depression, and the Fairy Island depression (Figure 1A). Using data collected during the summers of 1971, 1982, and 1991, they noted differences in oxygen depletion rates among the basins (with Grapevine Point having the lowest rates, and Fairy Island the highest), and trends of increasing oxygen depletion rates over the time interval studied, which were interpreted as indicating increasing productivity, particularly in the Fairy Island basin. They felt that productivity increases were greatest in the Fairy Island basin because of summer houses built there following World War II. None of these studies made use of independent measures of lake productivity such as measurement of chlorophyll *a* or total phosphorus.

Site description and history

Douglas Lake (45° 35′ N, 84° 41′ W) is a multi-depression lake of glacial origin in the northern lower peninsula of Michigan, USA, formed by ice blocks following retreat of the Valders ice sheet about 9000 yrs B.P. (Spurr & Zumberge, 1956). The total area of Douglas Lake is 1509 ha, maximum depth is 27 m, and mean depth is 5.5 m. There are seven basins in the present day lake (Figure 1A); three of these were cored for this study.

Although French fur traders were in the area in the 18th century, the first permanent settlers in Cheboygan County arrived in 1845 and population peaked in 1910 (Kilburn, 1957). A few farms were established, but the greatest draw to the area were the stands of red and white pine (*Pinus*), hemlock (*Tsuga*), and hardwoods such as maple (*Acer*), beech (*Fagus*), and oak (*Quercus*) forests. The first sawmill was established in 1846, and lumber production reached a peak in 1896. Kilburn (1957) interviewed long-time residents of Cheboygan County and learned that the area just south of Douglas Lake was logged during the winter of 1879–1880, mostly for white pine. By 1900, pines were mostly gone and the hemlock-hardwood forests were then logged, until about 1920 (Kilburn, 1957).

Fire was also a major disturbance in the watershed. Kilburn (1957) found evidence of at least nine major fires in the 43-yr period of peak timber cutting, 1880–1923. Occurrence of frequent fires is corroborated by the testimony of the local residents, early workers at the Biological Station, and fire scars on red pine stumps (Kilburn, 1957). The timing of pine and hardwood logging, along with fires, was also documented by botanists working at the biological station (Gates, 1912; Gleason & McFarland, 1914). Gates (1912) states 'Without exception the pine land was cut clear and if, perchance, any part escaped cutting the fire took it'. Vegetation that replaced the pines included aspens (*Populus* spp.), birch (*Betula*), and fire cherry (*Prunus pennsylvanica*), with abundant bracken fern (*Pteridium aquilinum*) and bush honeysuckle (*Diervilla lonicera*) on the forest floor (Gates, 1912). Fires ceased after the 1920s with the establishment of fire control measures.

The University of Michigan Biological Station was established in 1909 on the shore of South Fishtail Bay. It is used mostly in the summer months, and sewage is piped away from the lake watershed. Other development in the watershed consists of summer cottages built since World War II along the western shore, adjacent to the Fairy Island basin.

Methods

Sediment cores were collected through ice cover from three basins of Douglas Lake in March, 1989 using a

Benthos Corp. gravity corer with a 6.7-cm diameter Lexan core tube, modified by the addition of a rubber piston. Water depth at the South Fishtail Bay site was 21.5 m; at the Grapevine Point site was 23.1 m; and at the Fairy Island site was 25.0 m. The three basins were selected to correspond to those studied by Bazin & Saunders (1971), Lind (1978, 1987), and Lind & Dávalos-Lind (1993). Cores were extruded immediately and sectioned at 1-cm intervals and stored at 4 °C. Samples were later split into two portions; one portion was freeze-dried for chemical analyses, the other stored at 4 °C for pollen, chironomid, and pigment analyses.

The cores were dated using ^{210}Pb and pollen chronologies. Activity of ^{210}Pb in sediment samples was determined by the alpha activity of its daughter product ^{210}Po, using methods modified from Robbins et al. (1990). Samples were spiked with the man-made isotope ^{208}Po as an internal yield tracer, and extracted in hot 10% HCl and 30% H_2O_2. Isotopes were self-plated onto copper planchets, and activities were counted on an EG&G Ortec alpha spectrometer. Ages and sedimentation rates were calculated using a CRS point transformation model similar to that proposed by Binford (1990), including first-order error analysis. Estimates of supported ^{210}Pb were made using the method of Binford (1990).

Pollen analysis was done on one ml of wet sediment from fourteen levels of the South Fishtail Bay core only. Methods for sample preparation followed those of Fægri & Iversen (1975). The percentage of organic matter was estimated by loss on ignition at 550 °C, and carbonates on the same sample by combustion at 1000 °C (Dean, 1974). Sediment extracts for metal analysis were prepared as described above for ^{210}Pb dating. Fe and Mn concentrations were measured using flame atomic absorption spectrophotometry. Concentrations were calculated from standard curves using atomic absorption reference standards.

Chlorophyll *a* and phaeopigments were determined on wet sediment samples. One-gram aliquots were placed in plastic scintillation vials, and freeze-dried overnight. The samples were then extracted for 24 h at 10 °C in a mixture of acetone:methanol:distilled water in proportions of 85:15:5. Extracts were filtered through 0.2 μm polytetrafluoroethylene (PTFE) filters and brought to 10 ml with solvent. Fluorescence of the filtrate was read immediately on a Turner Designs fluorometer, both before and after acidification with 50% HCl. This method for sample preparation is modified from Leavitt et al. (1989). Calculations of chlorophyll *a* and phaeopigment concentrations followed Strickland & Parsons (1968).

Techniques for chironomid analysis followed those of Walker (1987). Two to five ml of wet sediment were analyzed, with the amount dependent on the density of head capsules present. At least 50 head capsules per sample were recovered. Samples were treated with 10% HCl at room temperature over night, and warm 5% KOH for 15 min, and rinsed through a 100 μm 'Nitex' nylon bolting cloth sieve. Samples were sorted under a stereomicroscope at 50X using a Bogorov counting chamber (Gannon, 1971). All chironomid head capsules were removed from the sample and permanently mounted in Euparal. Chironomid remains were identified to the generic level with reference to Oliver & Roussel (1983), Wiederholm (1983), Coffman & Ferrington (1984), Kowalyk (1985), and Epler (1992).

Plotting and numerical zonation of chemistry, pollen, and chironomid data were accomplished using the program psimpoll version 2.30 (Bennett, 1997). Zones were determined by optimal splitting based on information content, and the number of statistically meaningful zones determined by a Broken Stick model in the psimpoll program. Minimum value for inclusion of taxa in the zonation was 3% of the total Chironomidae.

Results and discussion

Dating, sedimentation rates, and inter basin differences

Pollen analysis of the South Fishtail Bay core shows a gradual increase in *Ambrosia* pollen beginning at 100 cm (Figure 2). This *Ambrosia* rise corresponds to about 1845 and the first European settlement. *Ambrosia* pollen increases again at 80 cm, along with bracken fern (*Pteridium*). This corresponds to the logging of white and red pine in the area at approximately 1880. The second period of high percentages of bracken fern at 65 cm corresponds to the peak in hemlock (*Tsuga*) and hardwood logging, about 1910. There is also a distinct decline in hemlock pollen at this level. Aspen (*Populus*) pollen also increases in abundance between these two dates, which corresponds to reports that aspen dominated in the clear-cut and burned areas (Gates, 1912; Gleason & McFarland, 1914). Dates generated using the CRS model show good agreement with the pollen date estimates. Age-depth curves for the three cores are depicted in Figure 3.

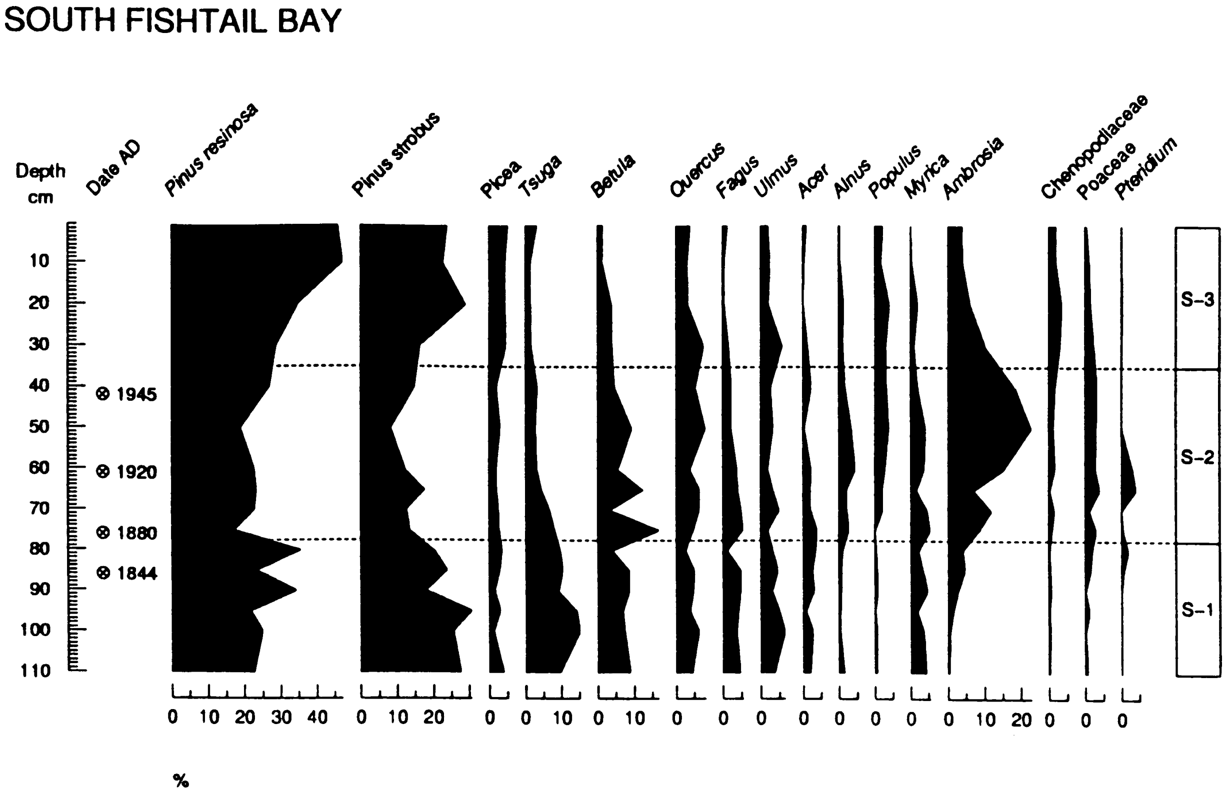

Figure 2. Pollen diagram from the South Fishtail Bay sediment core, expressed as percentages of the total pollen sum. Dates are based on ^{210}Pb and historical records from the area. Analyst: Xueming Xu.

The three cores varied considerably in ^{210}Pb characteristics (Table 1). The South Fishtail Bay core had the greatest surface activity, total inventory, and flux rate of ^{210}Pb to the sediments. The Grapevine Point core had the lowest inventory and flux, but not the lowest surface activity. The flux of ^{210}Pb to South Fishtail Bay and Fairy Island is high compared to many lakes reported in the literature. Oldfield & Appleby (1984) found a mean flux of 0.55 pCi cm^{-2} yr^{-1} for all lakes in their data set, which is close to the mean deposition

Table 1. ^{210}Pb characteristics of cores from three basins of Douglas Lake, Michigan

	South Fishtail Bay	Grapevine Point	Fairy Island
Supported ^{210}Pb (pCi g^{-1})	1.29 ± 0.17	0.69 ± 0.13	1.26 ± 0.20
Unsupported ^{210}Pb at surface (pCi g^{-1})	29.14	20.36	18.35
Total inventory of unsupported ^{210}Pb (pCi cm^{-2})	66.19	15.94	44.78
Flux of ^{210}Pb (pCi cm^{-2} yr^{-1})	2.06	0.50	1.44
Sediment mass (g cm^{-1})	9.13	3.71	10.01

Flux = total inventory of unsupported ^{210}Pb multiplied by the ^{210}Pb decay constant (0.03114 yr^{-1}). Sediment mass is the cumulative dry weight of sediments in the zone of the core in which unsupported ^{210}Pb activity occurs. Sediment mass is the total cumulative over the zone of unsupported ^{210}Pb.

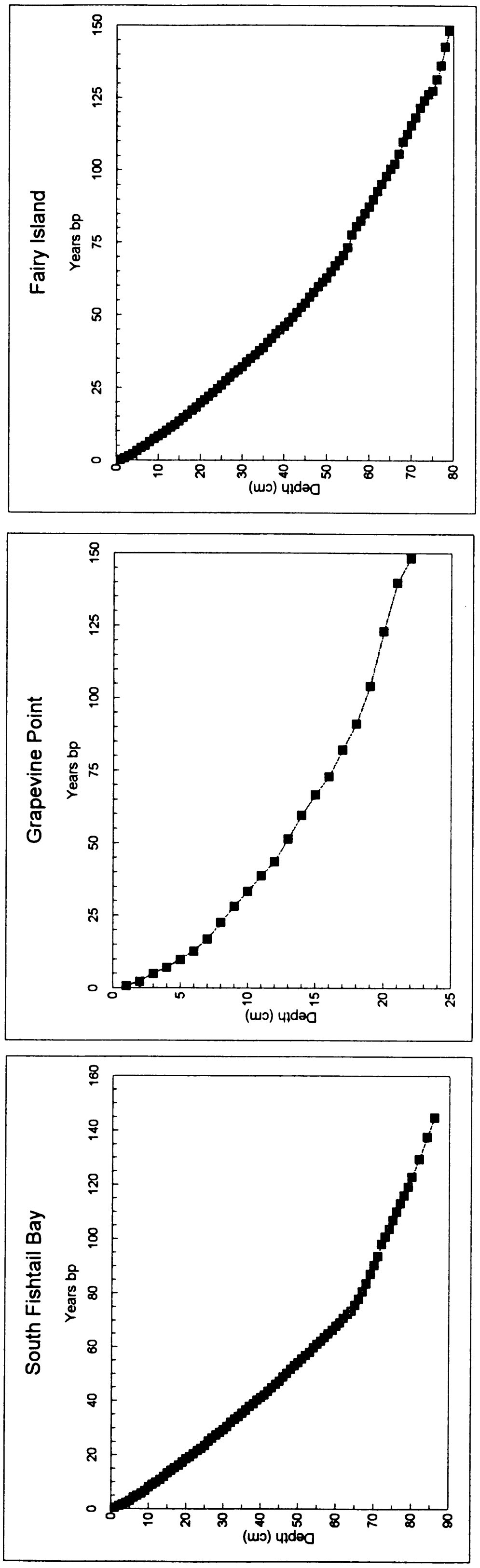

Figure 3. Age-depth profiles for the three basins based on ^{210}Pb dating, CRS model.

rate from the atmosphere. When the flux is averaged for the three basins, the mean is 1.34 pCi cm^{-2} yr^{-1}. This rate is higher than all but one lake of 32 in the PIRLA project (Binford et al., 1993). Hustler Lake, in the Northern Great Lakes region, had a flux of 1.51 pCi cm^{-2} yr^{-1}. It also had high surface activity and total inventory.

Binford et al. (1993) concluded that many factors, including sediment focusing, can result in different inventories from cores in a single lake. The use of ^{210}Pb as a means of deriving a 'focussing factor' for anthropogenic pollutants has been suggested (Kada & Heit, 1993). Murchie (1985) also found different ^{210}Pb inventories in cores from Crystal Bay, Lake Minnetonka, and determined that focusing was the main factor involved. The morphometry of Crystal Bay, however, is simple, and sediment focusing to the deepest part of the lake, with change in focusing patterns over time, is expected (Davis & Ford, 1982). The Douglas Lake cores were from three deep basins (Figure 1A). It is surprising that so little focusing of sediments has occurred in the Grapevine Point basin as compared to the other two.

Sedimentation rates calculated using the CRS algorithm show a marked increase at the point corresponding to settlement, logging, and fires in all three cores (Figure 4). Increased sedimentation following deforestation has also been documented in paleolimnological studies by Davis (1976), Engstrom et al. (1985), Gaillard et al. (1991), and Fritz et al. (1993). In a study of four lakes in the northern lower peninsula of Michigan approximately 100 km from the Douglas Lake region, Fritz et al. (1993) found that sediment accumulation rates increased about 3-fold after logging and settlement in the area.

Sedimentation rates in Douglas Lake decreased only slightly in recent years (Figure 4), even though the catchment is presently reforested. This pattern was somewhat unexpected when compared to other clearcut areas such as Hubbard Brook (Likens et al., 1970), however, the same phenomenon was observed in the four Michigan lakes studied by Fritz et al. (1993). Some possible reasons for the sedimentation rate remaining high include higher productivity rates in the lake, changes in the drainage to the lake, and a change from mostly conifers to mostly broadleaf trees in the catchment. In a study of the hemlock decline of 4800 BP and replacement by hardwoods in a small lake in western Massachusetts, Whitehead et al. (1973) suggested a higher lake productivity may have resulted from erosion as well as the input of deciduous litter to the lake. Increased productivity following the hemlock decline was also noted at some sites by Boucherle et al. (1986) and Hall & Smol (1993). Broadleaf trees potentially contribute more allochthonous input to the lake than do conifers. Coniferous forests also intercept more water and result in lower water yields than hardwood forests (Swank et al., 1988). The watershed of Douglas Lake extends to the lowlands far to the west of the lake (Figure 1B), and drainage in this region may have been altered by logging, road building, or both. There is ample evidence of increased runoff from watersheds deforested by both cutting and natural disturbance (Patric, 1974; Bosch & Hewlett, 1982; Swank et al., 1988). A combination of the above factors may have been instrumental in keeping the sedimentation rate high during the 20th century.

The results of the ^{210}Pb analyses support the idea that the basins of Douglas Lake function rather like individual lakes. The mechanisms that result in the observed deposition patterns cannot be determined without more intensive sampling of all the basins, but some possible ideas can be discussed. The prevailing winds are westerly (Gannon & Brubaker, 1969) parallel to the long axis of Douglas Lake. Currents produced by prevailing winds might bring material into South Fishtail Bay, particularly light organic particles, and thus contribute to the high sedimentation rate observed there. ^{210}Pb is more likely to adsorb to organic rather than mineral particulates (Robbins, 1978; Wang & Cornett, 1993), which may in part explain the high levels of ^{210}Pb in the South Fishtail and Fairy Island cores. High sedimentation rate in the Fairy Island basin may be a consequence of large volume for algal productivity and large area for resuspension of sediments. The very low sedimentation rates in the Grapevine Point basin may result in part from the small proportion of the total watershed that drains directly to this basin.

History of productivity and anoxia based on sediment chemistry

Profiles of organic matter content are similar in the South Fishtail Bay and Fairy Island cores (Figure 4). Both show a decrease in organic matter, at about 80 cm in South Fishtail Bay, and 69 cm in Fairy Island, corresponding to the ~ 1880 date. The decline in organic matter probably represents dilution by the increased runoff of mineral sediment accompanying deforestation and fires. Percent organic matter increases again near the top of both cores. Presettlement levels of organic matter were slightly higher in Fairy Island, averaging 35–40%, as opposed to nearly 30% in South Fishtail Bay. The carbonate content mirrors the organic matter. Higher carbonate levels would be expected with increased terrestrial inputs, but could also be the result of increased biogenic precipitation associated with greater productivity. In the Grapevine Point core, organic matter averaged less than the other two cores at all points (Figure 4B). Organic material was very low and carbonates high at the bottom of the Grapevine Point core (below 100 cm). Organic material in Grapevine Point also increases near the top of the core, as seen in the other basins. This increase in organic matter in the most recent sediments may be an indication of increasing productivity, but may also reflect less dilution as mineral sedimentation decreased with revegetation.

Concentrations of total pigments (chlorophyll *a* plus phaeopigments) expressed as μg pigment g^{-1} organic matter, are shown in Figure 4. Concentrations in the Fairy Island core are stable except for a slight increase post-1945, followed by a decline at the very top (Figure 4C). If pigment concentration is taken as an index of productivity, this profile suggests support for Lind's (1978, 1987) and Lind and Dávalos-Lind's (1993) conclusion that the Fairy Island basin is becoming more eutrophic. However, even larger increases can be seen in the other two cores. South Fishtail Bay has the most dramatic increase in pigment concentration during the post-settlement period. The Grapevine Point core had the lowest levels of pigments overall, which is consistent with other indicators of productivity such as percent organic matter (Figure 4B). Lind (1978) reported the lowest levels of total organic carbon from this basin. Based on organic matter and pigment concentrations, the Grapevine Point basin has consistently had lower productivity levels than the other two basins.

The amount of pigment preservation in sediments has been employed as a paleoindicator of oxygen levels because preservation is enhanced in reducing conditions (Engstrom et al., 1985; Swain, 1985; Leavitt, 1993). If the amount of undegraded chlorophyll *a* (percent of the sum of chlorophyll *a* plus its degradation products) is accepted as an indication of better preservation due to anoxic conditions, then trends shown in profiles from Grapevine Point and Fairy Island (Figure 4) support the hypothesis of increasing hypolimnetic anoxia in those basins in recent decades. In Fairy Island, the amount of preserved chlorophyll *a* changes little until the upper 15–20 cm. In South Fishtail Bay there are three zones of chlorophyll *a* preservation. The first

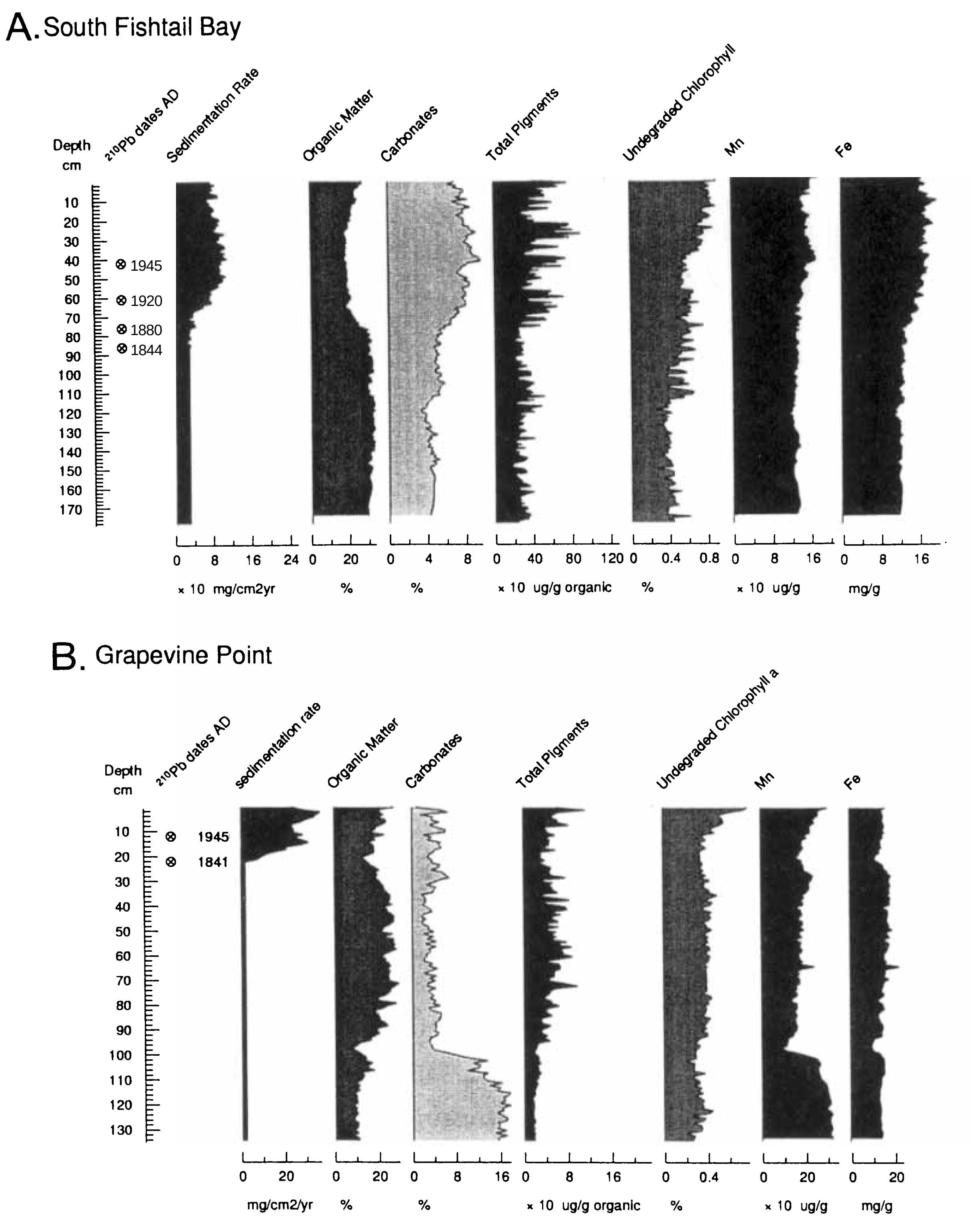

Figure 4. Summary diagram for chemical signals analyzed in three cores from Douglas Lake. Total pigments = the sum of chlorophyll *a* and its degradation products (phaeopigments), as μg g^{-1} of organic matter. Undegraded chlorophyll is the percentage of total pigments that existed as undegraded chlorophyll *a* molecules. Dates are based on ^{210}Pb and pollen chronologies.

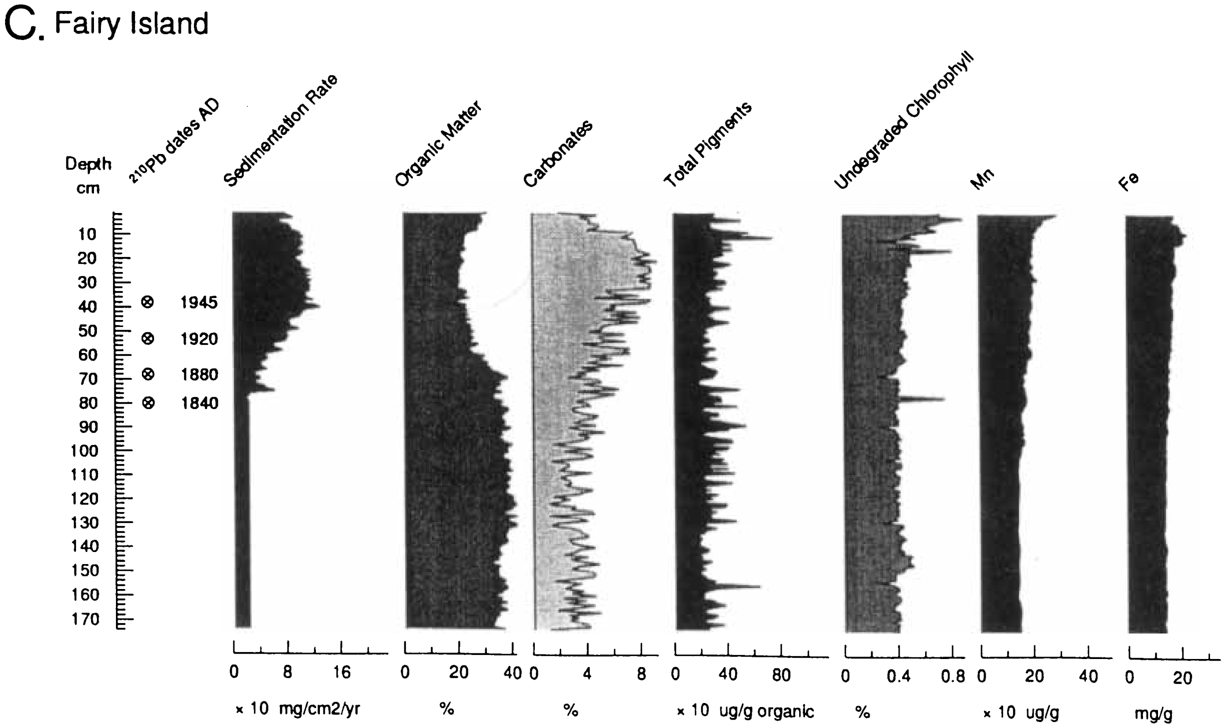

Figure 4. Continued.

increase in undegraded chlorophyll *a* at 110 cm suggests an early phase of eutrophication, even before European settlement. The second increase at 45 cm may indeed reflect increasing productivity during the 20th century. The least amount of preservation of chlorophyll *a* is at the base of the Grapevine Point core (Figure 4B), which is the oldest sediment in the study, and may represent oxygenated conditions. There may also be some degradation due to loss of double bonds which occurs over a time span of centuries (Leavitt, 1993).

Fe and Mn, the solubilities of which are governed by redox conditions, have also been used as paleo-indicators of hypolimnetic oxygen conditions (Engstrom & Wright, 1984; Engstrom et al., 1985). In oxygenated water, Fe and Mn form insoluble precipitates which have a low density and fine texture, and are winnowed from coarse materials and transported to deeper protected areas (Engstrom & Wright, 1984). When reducing conditions prevail, these elements can be redissolved and mobilized from sediments. The original model proposed for Fe and Mn as paleo-indicators by Mackereth (1966) predicts that concentrations of these metals will be lowered under reducing conditions, assuming that the dissolved forms are flushed from the lake before they can precipitate again. Engstrom et al. (1985), however, found that the opposite effect occurred in Harvey's Lake, Vermont. During periods of anoxia, Fe and Mn accumulation increased, and they proposed that, because of the deep, steep-sided basin, the Fe and Mn precipitates formed during fall overturn would be focused in the deepest part of the lake, and not flushed out. Reducing conditions during summer stratification enhanced release of Fe and Mn which then precipitated at overturn. The basins of Douglas Lake are also deep and steep-sided, particularly South Fishtail Bay, and Fe and Mn precipitates are probably behaving in a manner similar to Harvey's Lake.

Fe concentration increases during the settlement period in the South Fishtail Bay core (Figure 4A). This could be due to increased erosion from the watershed, but this is not reflected in the other two cores. Fe increases only slightly in the Fairy Island core, and not at all in the Grapevine Point core. Also, the Fe concentrations remain constant throughout the post-settlement period in South Fishtail Bay, which argues against an increased supply of Fe from soils during the period of intense logging and fires. Mn concentrations have a similar pattern in the Fairy Island and South Fishtail Bay cores. The greatest increase is seen in South Fishtail Bay, less in Fairy Island. In Grapevine Point, Mn concentrations increase distinctly during the settlement period. Higher levels of Fe and Mn in recent sediments again support the idea that the lake is becoming more anoxic, but also again, the change is more pronounced in South Fishtail Bay than in the other two basins.

The very high levels of Mn at the base of the Grapevine Point core (Figure 4B) are probably not an indication of anoxia caused by high productivity because organic material in that section of the core is very low. This section of the core is much older than the other two cores, and the high Mn is possibly due to inputs of different sediment types. There is also a high percentage of carbonates in this section and it was a gray clayey material, as opposed to the dark brown gyttja in the rest of the core.

The surface maxima of Mn seen in all three cores may be due to mobilization from recently buried sediments below the oxidized zone (usually a few centimeters), and upward diffusion. This maximum is often observed in lake and ocean sediments (Engstrom & Wright, 1984). Because of this phenomenon, caution must be used in interpreting trends at the very top of cores.

Based on the evidence in the recent sediments, this study supports the conclusions of Bazin & Saunders (1971), Lind (1978, 1987), and Lind & Dávalos-Lind (1993) that the intensity of hypolimnetic oxygen deficits has been increasing during the 20th century. Although the South Fishtail Bay and Fairy Island basins may have experienced anoxia throughout the post-glacial period (Stoermer, 1977), these data suggest an increase in intensity, or longer periods of anoxia during stratification. However, the contention of Lind (1978, 1987), and Lind & Dávalos-Lind (1993), that productivity levels and oxygen deficits have shown the most change in the Fairy Island basin due to shoreline housing development, is not necessarily supported. The degree of increase in chlorophyll *a* preservation is as intense in the Grapevine Point core as in the Fairy Island core, and levels are similar to those in South Fishtail Bay. If organic matter and pigment concentration are considered as indices of productivity, all three cores show increasing levels towards the surface. Surface levels of organic matter are only slightly higher in Fairy Island than in South Fishtail Bay. It would appear that all three basins have become more productive in the recent past, with greatest changes having occurred in the South Fishtail Bay and Grapevine Point depressions.

Chironomidae as indicators of anoxic conditions

The total number of chironomid taxa recovered from the three cores was 40. In some cases, it is impossible to distinguish between two genera based on characters present in fossil material, and these are designated as such (e.g. *Corynoneura/Thienemanniella*) (Figure 5). Members of the subfamily Chironominae, which include the tribes Chironomini and Tanytarsini, are by far the most common in all cores. This is typical of temperate, meso- to eutrophic lakes (Sæther, 1979). Relative abundance (as percentages) of the most common chironomid taxa are shown in Figure 5. Most of the genera recovered are usually associated with littoral habitats, which indicates that material from the littoral zones is being deposited in the deepest parts of the basins and give a representative sample for the whole basin. Only four genera are commonly found in profundal zones, including *Chironomus*, *Stictochironomus*, *Procladius*, and *Sergentia*. *Chironomus*, *Procladius*, and *Stictochironomus* are present throughout the length of the three cores, but *Sergentia* occurs only in the lower portion of the Grapevine Point core.

Numerical zonation of chironomid data from South Fishtail Bay yields three significant zones (Figure 5A). Zone S-2, beginning with the period of deforestation, shows a decline in the relative abundance of several taxa such as *Dicrotendipes* and *Glyptotendipes*, while other taxa are enhanced, such as *Corynoneura/Thienemanniella* and *Polypedilum*. These taxa are from littoral habitats. The profundal taxa *Procladius*, and *Stictochironomus* change little throughout the core. After 1945, several taxa indicative of eutrophic conditions increase, particularly *Dicrotendipes* and *Glyptotendipes*.

In contrast, the Fairy Island core data yielded no significant zones (Figure 5C). There are some trends similar to the South Fishtail Bay core, but not as pronounced. There is a decline in *Dicrotendipes* corresponding to the period of deforestation, and also a decline in other taxa such as *Labrundinia*. *Polypedilum* responds positively during that period. In the post-1945 sediments, there is also an increase in the same eutrophic indicators, *Dicrotendipes* and *Glyptotendipes*. *Pagastiella* decreases in abundance during this recent period.

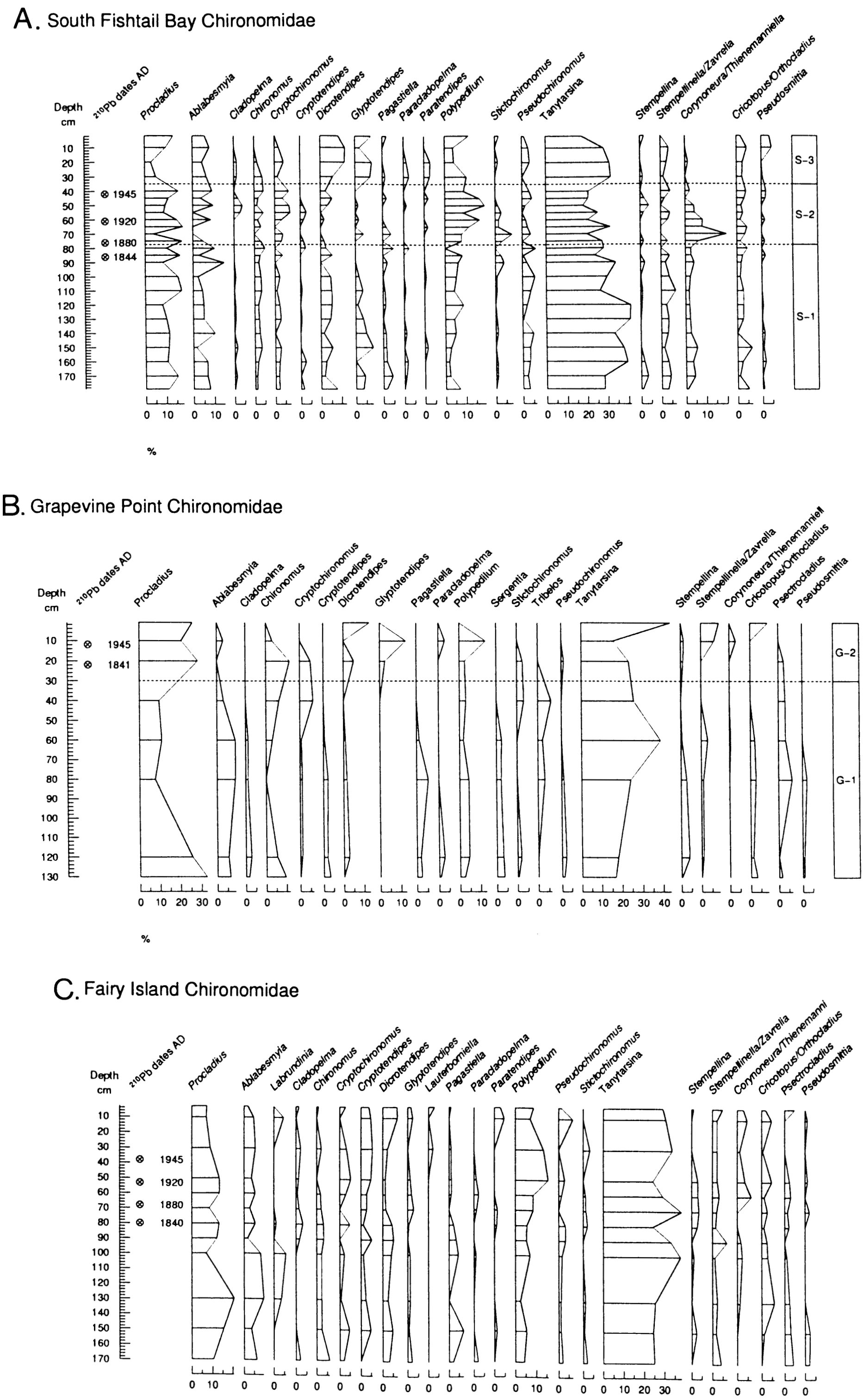

Figure 5. Summary diagrams of the most common chironomid taxa recovered from the three cores. Numbers are relative abundance (per cent). Zones shown are objectively calculated, (see text for details) and only statistically significant zones are indicated. Dates are based on ^{210}Pb and pollen chronologies.

Two significant zones resulted from zonation of the Grapevine Point core chironomids (Figure 5B). Zone G-2 starts just prior to the European settlement period and is marked by increasing abundance of the eutrophic indicators *Chironomus*, *Dicrotendipes*, *Glyptotendipes*, *Polypedilum*. Taxa that are absent in this zone include *Pagastiella* and *Sergentia*. *Sergentia* was not present at all in the other two cores. *Sergentia* is a profundal species of mesotrophic lakes. The presence of this taxon, and its disappearance at the top of the core, suggests that the Grapevine Point basin did not experience severe anoxia in pre-settlement times, and that eutrophication of this basin has occurred since then. Stahl (1959) also found a decline in *Sergentia* remains in sediments from Myers Lake, Indiana, as the oxygen deficit increased due to decreased hypolimnetic volume as the lake filled in. Decreasing hypolimnetic volume is probably not a factor in Douglas Lake over the time span being considered. In a study of Green Lake, Michigan sediments, Lawrenz (1975) also found that numbers of *Sergentia* (= *Phaenopsectra*) were greatly reduced when the lake went from mesotrophic to eutrophic conditions. Also, Welch (1927) reported that the Grapevine Point basin did not go anoxic as frequently as the other two in the early part of the 20th century.

The other three profundal taxa are present at all levels in all three cores (Figure 5). *Chironomus* spp. typically are indicators of eutrophic conditions and tolerant of low oxygen levels. In their surface training set, Quinlan et al. (1998) found that *Chironomus* and *Procladius* were correlated with low oxygen conditions, while *Sergentia* was associated with mesotrophic lakes with moderate oxygen deficiencies.

Many paleolimnological investigations have focused on the profundal midges, partly because of the lake-typology legacy (Stahl, 1959; Kansanen, 1985; Meriläinen & Hamina, 1993), but also because less work has been done with littoral communities and they are much more diverse than the profundal community (Kansanen et al., 1984). However, littoral taxa have also been shown to be useful in interpretations of trophic history (Brodin, 1982) The fact that littoral taxa show distinct changes during the period of heavy logging and fires, especially in South Fishtail Bay, is also interesting. It suggests that logging may have had a profound impact on littoral communities, possibly from siltation, nutrient enrichment, and/or changes in macrophyte communities. Clear-cutting of a forested ecosystem usually results in increased export of sediment and nutrients to surface waters (Likens et al., 1970), and increasing productivity levels can be expected. Andresen (1976) documented an increase in diatom taxa indicative of eutrophic conditions that corresponds to the clearcutting in South Fishtail Bay. If nutrient enrichment led to increased phytoplankton biomass, shading of macrophytes and their decline could have occurred. Change in macrophyte communities could alter the chironomid fauna that inhabits the macrophyte zone. Also, increased siltation could affect the chironomid fauna directly, by decreasing food availability or affecting respiration. Disruption in littoral habitats of Douglas Lake was also documented by changes in the bryozoan communities that utilize macrophytes as a substrate (Francis, 1997). Changes in assemblages of littoral taxa were also noted in Wood Lake, British Columbia, when agriculture and industrialization in the area led to eutrophic conditions in the lake (Walker et al., 1993).

Results of the chironomid analysis indicate a possible trend toward increasing eutrophication in the recent sediments, based on the increase of taxa such as *Polypedilum*, *Dicrotendipes*, and *Glyptotendipes*. *Dicrotendipes* and *Glyptotendipes* are large tube-building larvae that depend on a rain of plankton and detritus as food, and tend to be associated with eutrophic conditions. This lends support to the conclusions of Bazin & Saunders (1971), Lind (1978, 1987), and Lind & Dávalos-Lind (1993) that eutrophication in Douglas Lake has been on the increase. However, the chironomid evidence suggests that Grapevine Point, rather than the Fairy Island basin, is experiencing the greatest changes in trophic state, as was indicated by Lind (1978, 1987), and Lind & Dávalos-Lind (1993).

Conclusions

Paul S. Welch (1927), who studied Douglas Lake for many summers starting in the 1920s at the University of Michigan Biological Station, made the comment that each of the seven basins acted rather like separate lakes. This study of the sediments of only three of those basins lends a good deal of support to that statement. The sediment history of the three basins, while similar and correlated, could easily have been derived from three different lakes in the same region. The most distinctive basin is the Grapevine Point depression, in which sedimentation rates and productivity levels have been much lower than the other two depressions. This basin also appears to be undergoing the greatest change in eutrophication and oxygen depletion rates in recent times.

Remains of chironomid larvae were investigated as potential indicators of the oxygen levels of the past in Douglas Lake. As with the sediment chemistry, the most significant changes in chironomid assemblages occur at the time of deforestation, mostly reflecting changes in the littoral fauna in South Fishtail Bay and Fairy Island. Profundal taxa in these two cores show little change. In the Grapevine Point basin, changes in littoral fauna were also accompanied by the disappearance of *Sergentia* near the deforestation horizon. *Sergentia* indicates that this basin was mesotrophic and only mildly anoxic before settlement and deforestation. The stable character of the profundal fauna in South Fishtail Bay and Fairy Island indicate that these two basins have probably experienced anoxia for a long period of time, even before European settlement. The same conclusion was reached by Stoermer (1977) based on diatom assemblages from a much longer core from South Fishtail Bay. Despite differences among the basins, and with the exception of *Sergentia*, the changes in chironomid assemblages were similar in the three cores. Many paleolimnological studies have focused on the profundal fauna of lakes, but this study indicates that changes in littoral faunas can also be used in making interpretations. It is also evident that disturbance in the catchment in the form of logging and fires changed assemblages of littoral chironomids, particularly in South Fishtail Bay.

Stratigraphy of redox-sensitive Fe and Mn, preservation of chlorophyll *a*, and chironomid assemblages all suggest a slight trend of increasing productivity and hypolimnetic anoxia conditions in all three basins studied. These data support the contentions of Bazin & Saunders (1971), Lind (1978, 1987) and Lind & Dávalos-Lind (1993), that the rate of hypolimnetic oxygen depletion has been increasing during the 20th century, and also that productivity has increased. However, the most intense changes have occurred in the Grapevine Point basin, which is counter to the conclusions of Lind (1978, 1987) that the oxygen depletion rates and therefore productivity are increasing at the fastest rate in the Fairy Island basin.

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