Total Mercury and Methylmercury Contents of Insects from Boreal Lakes: Ecological, Spatial and Temporal Patterns

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Mercury (Hg) and methylmercury (MeHg) concentrations in insects from 19 lakes in Quebec (Canada) and Sweden ranged from <25 to >550 ng Hg g⁻¹ dry weight (dw). The mean proportion of MeHg to total Hg concentrations depended on the feeding behaviour of the animals, increasing from 35-50% in detritivore-grazers (dipterans, ephemeropterans, trichopterans) to 70-95% in predators (heteropterans, coleopterans, odonates). These differences were attributed to the biomagnification of MeHg in the food web since the MeHg/total Hg ratio in the organisms was not related to their body size. A large part of the overall variability of total Hg (r²=0.57, p=0.0001) and MeHg (r²=0.79, p=0.0001) concentrations in insects was explained by taxonomic differences, probably related to feeding behaviour, and the differences between lakes. MeHg concentrations in chironomids and in odonates were significantly correlated with sediment MeHg contents (r=0.78, p=0.005; r=0.62, p=0.001, respectively). However, our results suggest that animal feeding behaviour and the quality of ingested food are more important in determining MeHg accumulation in insects than either MeHg contents of sediment or atmospheric Hg deposition rates. Our data indicate that the bioavailability of Hg to the lower trophic levels of the food web is determined by abiotic factors and controls contamination of predators at the top of the food chain. Total Hg concentrations in insects increased from spring to fall, from 60-80 ng Hg g⁻¹ dw to 125-175 ng Hg g⁻¹ dw in the detritivore-grazer taxa, and from 88-120 ng Hg g⁻¹ dw to 180-200 ng Hg g⁻¹ dw in the predator taxa. MeHg/total Hg ratios showed little variability from spring to fall and the increase of Hg and MeHg concentrations in insects seemed to be related to enhanced methylation resulting from the rise of water temperature and to the variations in the nature of the food ingested.

Key words: mercury, methylmercury, benthic invertebrates, insects, lakes

Les concentrations en mercure (Hg) et en méthylmercure (MeHg) d’insectes provenant de 19 lacs du Québec (Canada) et de la Suède varient entre <25 et >550 ng Hg g⁻¹ poids sec (dw). La proportion moyenne de MeHg:Hg total dépend du mode alimentaire des organismes et augmente de 35-50% pour les détritivores-brouteurs (diptères, éphéméroptères, trichoptères) à 70-95% chez les prédateurs (hétéroptères, coléoptères, odonates). Cette différence peut être
attribuée à la bioamplification du MeHg dans la chaîne trophique, puisque la proportion de MeHg:Hg dans les organismes n’est pas reliée à leur taille. Une grande proportion de la variabilité totale des concentrations en Hg total ($r^2=0.57$, $p=0.0001$) et en MeHg ($r^2=0.79$, $p=0.0001$) des insectes, peut être attribuée aux différences taxonomiques, qui sont reliées à leur mode d’alimentation et aux différences entre les lacs. Des corrélations ont été obtenue entre les concentrations de MeHg dans les sédiments et celles des chironomidés ($r=0.78$, $p=0.005$) et des odonates ($r=0.62$, $p=0.001$). Cependant, nos résultats suggèrent que le mode d’alimentation des organismes ainsi que la qualité des aliments ingérés sont plus importants dans l’accumulation du Hg par les insectes que la concentration de Hg dans les sédiments ou des apports atmosphériques. Nos résultats indiquent que la biodisponibilité du Hg pour les organismes au bas de la chaîne trophique est déterminée par les facteurs abiotiques et contrôle la contamination des prédateurs au haut de la chaîne trophique. Les concentrations de Hg total dans les insectes augmentent du printemps à l’automne, de 60–80 ng Hg·g$^{-1}$ poids sec à 125–175 ng Hg·g$^{-1}$ chez les taxons de détritivores-brouteurs et de 88–120 ng Hg·g$^{-1}$ à 180–200 ng Hg·g$^{-1}$ chez les taxons prédateurs. La proportion de MeHg:Hg total demeure sensiblement la même tout au long de la saison et l’augmentation des teneurs en Hg total et en MeHg au cours de la saison semble être reliée à la hausse de la méthylation provoquée par l’augmentation de la température et par la qualité de la nourriture ingérée.

Introduction

Sediments are an important reservoir of anthropogenic metals in lakes. In remote lakes, metal fluxes to sediments result from wet and dry atmospheric deposition either directly on the water body or indirectly via runoff from the watershed. The upward increase of metal concentrations towards the sediment-water interface in sediment profiles is interpreted as reflecting an increase in atmospheric deposition over time (Evans 1986; Swain et al. 1992; Lucotte et al. 1995a). The sediment-water interface has an important ecotoxicological potential because it is the habitat of an abundant and diverse community that may include epipelic microalgae, rooted aquatic plants and bacteria, as well as detritivorous, filter-feeding and predatory invertebrates (Campbell and Tessier 1991; Jackson 1992). As a consequence of their close association with surface sediments, benthic invertebrates tend to accumulate large quantities of metals (Bissonnette 1975; Young and Harvey 1991; Parkman and Meili 1993).

Uptake from food is the predominant pathway for mercury (Hg) accumulation in many animals and, in combination with slow elimination from their tissues, leads to the biomagnification of Hg up the food chain, resulting in high concentrations in predators at the top of the chain (Jackson 1991; Meili 1991; Cabana et al. 1994). This is a serious problem for northern countries such as Sweden, Canada and the United States, where thousands of lakes are believed to contain predatory fish with Hg concentrations greater than 1 mg·kg$^{-1}$ wet weight (ww) for a body weight of 1 kg (Håkanson et al. 1990; McMurtry et al. 1989; Meili 1991a; Lathrop et al. 1991). Although there are many reports of Hg enrichment along aquatic
food chains (Philips and Gregory 1979; Allard and Stokes 1989; Meili 1991a; Jackson 1991; Cabana et al. 1994; Tremblay et al. 1996), relatively little information is available on Hg concentrations in animals at low trophic levels in pristine aquatic systems. Invertebrates such as insects and zooplankton play a key role in the biomagnification process because they constitute a major food source for many fish species (Scott and Crossman 1974; Dumont and Fortin 1978; Doyon et al. 1996).

Total Hg contents ranging from <60 ng Hg g⁻¹ dw to >1,000 ng Hg g⁻¹ dw have been reported for various insect taxa in Swedish forest lakes (Parkman and Meili 1993), in a small polyhumic Finnish lake (Rask et al. 1994) and in an oligotrophic lake in Quebec (Canada) (Tremblay et al. 1996). Furthermore, a few studies have also reported high Hg concentrations in mixed zoobenthos samples (Huckabee et al. 1979; Surma-Aho et al. 1986; Jackson 1988). While MeHg concentrations have been reported for both crayfish and zooplankton in natural ecosystems (Wright et al. 1991; Watras and Bloom 1992; Back et al. 1995; Plourde et al. 1996), to our knowledge the literature provides very few MeHg data for aquatic insects (Surma-Aho et al. 1986; Tremblay et al. 1996).

To fill this gap, we determined the total Hg and MeHg concentrations in insects from 19 lakes remote from direct Hg pollution. To our knowledge, this constitutes the first data set on MeHg contents of insects from natural ecosystems. To assess the relative importance of biotic and abiotic factors on the accumulation of Hg and MeHg in the insect food web, we collected insects from lakes at different latitudes and longitudes in Quebec and in two regions of Sweden differing with respect to their atmospheric Hg deposition rates. In addition, seasonal variations in certain lakes were studied over several years. The spatial and temporal variations of Hg and MeHg concentrations in insects were compared with concentrations in sediment as well as with chemical and ecological variables.

Materials and Methods

Study Areas

Eleven lakes located at different latitudes and longitudes in northern Quebec were sampled during the summers of 1992, 1993 and 1994. Six lakes (Duncan, Detcheverry, Des Voeux, Jobert, Lake 136 and Lake 150) were visited in different seasons (spring, summer and fall) during that period, while the five others (Evans, Laporte, Matagami, Opinaca and Koury) were sampled only once in the summer of 1994.

Eight Swedish lakes were sampled during the summers of 1985 and 1986. Four of the lakes are located in southern Sweden where the atmospheric Hg deposition rate is relatively high, while the others are in central Sweden, where the rate is lower (Meili 1991c) (Fig. 1). The catchments of all lakes, both in Quebec and in Sweden, are dominated by coniferous forest, shallow podzolic and peat soils, and igneous bedrock. Morphological, water and sediment characteristics of the lakes are presented in Table 1.
Sampling

Insects from the Quebec lakes were collected from littoral zones (<2 m deep) using a 250 μm-mesh hand-held net. In the Swedish lakes, insects from the littoral zone were collected using a colander while those from profundal zones were sampled by dragging a framed nylon bag. Details on insect sampling in the Swedish lakes can be found in Parkman and Meili (1993).

From the surface sediments collected with the net, all insects visible to the naked eye were picked using tweezers with stainless steel tips, sorted to genus or species and counted. They were then placed in separate small plastic jars and frozen. All these manipulations were carried out within 8 hours of sampling. In order to avoid Hg contamination, all material used to sort the organisms (tweezers, small containers, glass trays, etc.) were thoroughly rinsed with tap and nanopure water after processing each sample. In this study, whole insects were analyzed and no attempt was made to exclude ingested sediments or metals adhering to outer surfaces since Parkman and Meili (1993) and Hare et al. (1989) shown that these processes were not important in pristine lakes. Total Hg and MeHg concentrations in insect samples were assumed to represent those potentially available for food chain transfer (see below). According to the general feeding habits described by Merritt and Cummins (1985), we regrouped...
Table 1. Lake characteristics, water and sediment chemistry, and total mercury and methylmercury concentrations in littoral zone sediments of 11 Quebec lakes sampled in 1992-94 and in profundal zone sediments of 8 Swedish lakes sampled in 1985-86

<table>
<thead>
<tr>
<th>Lake</th>
<th>Trophic status</th>
<th>Area (km²)</th>
<th>Watershed area (km²)</th>
<th>pH</th>
<th>Colour (Pt mg L⁻¹)</th>
<th>Conduct. (mS m⁻¹)</th>
<th>C (%) dw</th>
<th>C/N</th>
<th>Total Hg (ng g⁻¹ dw)</th>
<th>MeHg (ng Hg g⁻¹ dw)</th>
<th>Lake group</th>
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<tbody>
<tr>
<td>Laporte</td>
<td>Oligotrophic</td>
<td>0.6</td>
<td>2.3</td>
<td>6.3-6.6</td>
<td>54</td>
<td>30</td>
<td>17-18</td>
<td>20-22</td>
<td>294-351</td>
<td>0.63-1.44</td>
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<td>Matagami</td>
<td>Oligotrophic</td>
<td>228.8</td>
<td>1086.8</td>
<td>17-18</td>
<td>8-10²</td>
<td>14-15²</td>
<td>73-83²</td>
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<tr>
<td>Evans area</td>
<td>Oligotrophic</td>
<td>0.03</td>
<td>0.3</td>
<td>6.8-7.4</td>
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<td>Detcheverry</td>
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<td>8.3</td>
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<td>6.8-7.3</td>
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<td>37</td>
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<td>Duncan</td>
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<td>281.5</td>
<td>6.8-7.1</td>
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<td>Koury</td>
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<td>6.4-6.8</td>
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<td>32</td>
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<tr>
<td>Des Voeux</td>
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<td>29.3</td>
<td>90.0</td>
<td>6.9-7.1</td>
<td>18</td>
<td>12</td>
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<td>Jobert</td>
<td>Oligotrophic</td>
<td>15.1</td>
<td>58.8</td>
<td>6.8-7.1</td>
<td>46</td>
<td>14</td>
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<td>0.2</td>
<td>6.9-6.3</td>
<td>42</td>
<td>15</td>
<td>2</td>
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<td>Lake 150</td>
<td>Oligotrophic</td>
<td>4.7</td>
<td>13.2</td>
<td>7.0-7.3</td>
<td>37</td>
<td>13</td>
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<tr>
<th>Lake</th>
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<th>Total Hg (ng g⁻¹ dw)</th>
<th>MeHg (ng Hg g⁻¹ dw)</th>
<th>Lake group</th>
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<td>4.2</td>
<td>5.0-6.4</td>
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<td>24</td>
<td>13-16</td>
<td>12-15</td>
<td>130-245</td>
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<td>Acidic dystrophic</td>
<td>0.36</td>
<td>6.0</td>
<td>5.2-6.1</td>
<td>80-190</td>
<td>60</td>
<td>19-21</td>
<td>13-14</td>
<td>210-300</td>
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<td>Blackåstjärn</td>
<td>Neutral dystrophic</td>
<td>0.12</td>
<td>2.2</td>
<td>6.0-7.1</td>
<td>75-130</td>
<td>31</td>
<td>12-16</td>
<td>11-13</td>
<td>120-220</td>
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<td>Löjesjön</td>
<td>Neutral dystrophic</td>
<td>0.31</td>
<td>2.1</td>
<td>6.1-6.6</td>
<td>75-125</td>
<td>72</td>
<td>23-25</td>
<td>13-14</td>
<td>180-250</td>
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<td>Loppesjön</td>
<td>Mesotrophic</td>
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<td>6.3-7.6</td>
<td>45-80</td>
<td>51</td>
<td>7-10</td>
<td>10-11</td>
<td>90-140</td>
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<td>Gårdsjön</td>
<td>Mesotrophic</td>
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<td>0.9</td>
<td>6.1-7.3</td>
<td>20-60</td>
<td>71</td>
<td>26-29</td>
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<td>19</td>
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<td>6.0</td>
<td>6.3-7.3</td>
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<td>85</td>
<td>14-19</td>
<td>10-12</td>
<td>210-300</td>
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</table>

²Water was collected from the productive surface layer (1-2 m) for pH, colour and conductivity measurements. The classification of the Quebec lakes (Groups 1, 2 and 3) is based on their sediments Hg, MeHg and organic C concentrations. 
²Obtained from a neighbouring lake.
the insects by feeding guilds: detritivores (dipterans, ephemeropterans), detritivores-grazers (trichopterans), grazers-predators (heteropterans, coleopterans), and predators (odonates).

Sublittoral sediment cores from the Quebec lakes were collected by SCUBA divers using 15 cm-diameter PVC tubes, whereas cores were taken from the Swedish lakes by means of a 6.5 cm-diameter gravity corer at various profundal zone sites. The cores were sectioned at 1 cm intervals, and the sections were kept frozen until analyses. The values of total Hg and MeHg in sediment represent the integrated values of the mixed layer (first 4 centimeters) of one core, where most of the benthic insects were growing (Wetzel, 1983). The difference between the top and the bottom of the mixed layer was about 20% (Lucotte et al. 1995a). For determination of water physicochemical characteristics (pH, DOC, colour, etc.), three 250 mL Nalgene bottles were rinsed twice with lake water before being filled to overflowing in order to eliminate air bubbles, and then stored in a refrigerator until analyses. Surface areas of the lakes and their catchments were determined from maps.

Analyses

Pooled insect samples consisting of at least 10 individuals were placed in plastic vials, freeze-dried for 3 days and then homogenized. Samples were ground to powder using a glass rod, directly in the vial in order to reduce manipulation and the risks of Hg contamination. The use of homogenized pool samples was decided upon since this procedure allows all analyses (Hg, MeHg, C/N) to be conducted on the same sample.

All labware was acid washed in 10% HNO₃, triple-rinsed with nanopure water and then heated to 300°C for 8 hours. Total Hg concentration was determined by atomic fluorescence spectrophotometry (AFS). The analytical method was modified from Bloom (1989) and is described in detail by Louchouarn et al. (1993) and Montgomery et al. (1995). Briefly, 1 to 10 mg (dw) insect aliquots and 0.5 to 1 g (dw) sediment aliquots were transferred to glass tubes and digested, respectively, in 1 and 10 mL of a 10 HNO₃:1 HC1 mixture for 6 hours at 120°C. Hg was then reduced to elemental Hg (Hg⁰) vapour by a tin chloride (SnCl₂) solution in a reaction vessel and the Hg⁰ analyzed by AFS. The reaction vessel, a 30-mL Teflon centrifugation tube, was continuously bubbled with Hg-free stream of argon (AR) gas. Following a 200 µL injection, Hg⁰ was stripped out of the reactor and carried in an Ar gas stream at an optimal flow of 200 µL min⁻¹ to a fluorescence cell, where it was excited by a 4-W germicidal Hg vapour fluorescent tube. The upper part of the reduction chamber and the fluorescent cell were kept at a temperature of 50–70°C to avoid condensation. The analog amplifier output was converted (1 conversion/s) to digital data with a resolution of at least 15 bits. The converted data were recorded and analyzed on an Amiga computer using software developed in our laboratory. Total Hg concentration was calculated from the area of the fluorescence peak. The detection limit was 9.9 picograms Hg, which corresponds to 1.9 ppb for a typical 5 mg sample. This value corresponds to
three times the standard deviation of the procedural blanks. The accuracy of the method was tested by analyzing a National Research Council of Canada standard (DORM-1) during several sample analysis runs. These measurements yielded a mean value of 798 ± 36 ppb, as compared with the certified value of 798 ± 74 ppb.

MeHg in the sediments was released with a CuSO₄-KBr-H₂SO₄ mixture and then extracted with toluene (Westoo 1967). The methylmercury bromide content of the toluene extract was separated by gas-chromatography on a 10% FFAP. The MeHg concentration was measured as Hg by atomic fluorescence following thermal decomposition on silica (400°C) (Bloom 1989). Accuracy was checked by standard addition measurements which gave a 90 ± 15% recovery rate (Bégin and Lucotte 1996). The detection limit (3 standard deviations) for a 1 mg (dw) sample was 5 ng Hg·g⁻¹ and the coefficient of variation (<3%) was verified regularly using the DORM-1 standard.

Because various organic substances extracted with the organic solvent were decomposing in the chromatograph injector and catalyzing the decomposition of MeHgBr, thus leading to low analytical results, and because of the large samples required (300–500 mg dw) for these analyses, a distillation process was used to measure MeHg contents of insect samples. This analytical procedure, modified from that of Horvat et al. (1993), allows as little as 1 mg dw of material to be analyzed. A mixture of 0.7 mL water, 0.2 mL 2M H₂SO₄ and 0.1 mL 4M KBr was added to a 1–2 mg sample of insects. Distillation was carried under a 100 mL/min nitrogen gas flow, at a constant temperature of 90°C and lasted 90 minutes. This procedure released MeHg as volatile CH₃HgBr which was then recovered in a quartz tube filled with 1 mL of nanopure water and kept on ice. The tube was then sealed with Parafilm and stirred. To check for the presence of inorganic Hg which may have co-distilled and contaminated the solution, a 100 µL subsample was taken and analyzed for the total Hg determination in AFS as described above. If inorganic Hg contamination was greater than 15% of the MeHg concentration of the sample, the sample was reanalyzed. To each tube, 50 µL of a 50 gL⁻¹ potassium persulfate solution were added as an oxidizing agent. The tubes were resealed with Parafilm and stirred before subjecting the solution to ultra-violet oxidation for 20 min to reduce CH₃HgBr to Hg. The resulting Hg was then analyzed by AFS as described above.

Total Hg concentrations determined in the distillates were multiplied by a factor of 1.25 to obtain MeHg values. The MeHg recovery rate of the distillation procedure determined on standard insect samples was 99 ± 11%. The reproducibility of the method was verified by analyzing a National Research Council of Canada standard (DORM-1): this yielded a mean value of 793 ± 47, as compared with the certified value of 731 ± 60 ppb.

The total Hg and MeHg concentrations in the insects are expressed on a dry weight basis and represent the content of whole animals. To evaluate the homogeneity of pooled insect samples, every tenth sample was
analyzed in triplicate. The coefficient of variation between replicate analyses was always less then 10% for both total Hg and MeHg. Carbon concentrations of insect and sediment samples were determined using a Carlo-Erba autoanalyzer, with a reproducibility of about 1% (coefficient of variation). The water colour was determined by spectrophotometry at 440 nm and transformed to Pt mg/L⁻¹ using the equation of Cuthberg and Del Giorgio (1992).

Statistics

Differences of total Hg and MeHg concentrations in insects between systems (lakes and groups of lakes), periods of time (year and season) and taxa were assessed using analysis of variance (ANOVA) and Student's t-test. Pearson's correlation was used to study the influence of water (pH, colour, conductivity, DOC, etc.) and sediment characteristics (eH, pH, carbon content, water content, etc.) on total Hg and MeHg contents of insects. To normalize the data and reduce heteroscedasticity the data were transformed to log values. Only Quebec data were included in all analyses.

Results

Total Hg and MeHg Concentrations in Lake Sediments

Total Hg concentrations in surface sediments of the Quebec lakes ranged from 41 ng Hg g⁻¹ dw in Koury Lake to 351 ng Hg g⁻¹ in Laporte Lake, with a mean of 82 ng Hg g⁻¹ (Table 1). Sediment MeHg concentrations averaged 0.5 ng Hg g⁻¹, ranging from 0.2 ng Hg g⁻¹ in Koury Lake to 1.1 ng Hg g⁻¹ in Evans Lake. The proportion of MeHg to total Hg contents of sediments was generally less than 1%, while C content varied between 2 and 19% (Table 1). Mean sediment total Hg concentrations in the Swedish lakes ranged from 160 ng Hg g⁻¹ in Blacksältsjärn to 300 ng Hg g⁻¹ in Skärhultssjön and C content from 7 to 29% (Table 1). In the Quebec lakes, sediment MeHg concentration and organic carbon content were strongly correlated (r=0.84, p<0.001).

In a study of lakes along a 1,200 km north-south transect in northern Quebec, Lucotte et al. (1995a) reported that atmospheric Hg deposition was similar over the whole study area and that sediment organic carbon contents were positively correlated with sediment Hg concentrations. Based on their sediment characteristics (organic carbon, total Hg and MeHg concentrations), Quebec lakes in our study were classified into three groups. Sediment total Hg and MeHg concentrations differed significantly between all three groups (ANOVA, p<0.05), but were similar within each group. Groups 1, 2 and 3 are characterized by sediment total Hg concentrations of 45 ± 4 ng Hg g⁻¹, 83 ± 13 ng Hg g⁻¹, and 207 ± 83 ng Hg g⁻¹ and carbon contents of 3 ± 1%, 9 ± 0.7%, and 16 ± 3%, respectively (Table 1).
Total Hg and MeHg Concentrations in Insects

In the Quebec lakes, insect total Hg concentrations ranged from <50 ng Hg·g⁻¹ in dipterans and trichopterans to >600 ng Hg·g⁻¹ in coleopterans and heteropterans (Fig. 2, Table 2). MeHg concentrations showed similar

![Graph showing total mercury and methylmercury concentrations in various insects from different lakes.](Image)

**Fig. 2.** Total mercury and methylmercury concentrations (ng Hg·g⁻¹ dw, mean, standard deviation and number of samples analyzed) in various insects from different lakes (group 1 and 2, see text) in Quebec. The letter in parenthesis at the end of the insect groups represents the stage of development (L: larvae, A: adult). General feeding habits were assigned according to Merritt and Cummins (1985). Levels 1 and 2 correspond to the defined trophic levels (see text).
Table 2. Compilation (from top to bottom) of the mean concentrations of total mercury, methylmercury (as Hg, ng g⁻¹ dw) and the mean proportion of methylmercury to total mercury (%) in insects from 11 lakes in northern Quebec sampled in 1992-95.

<table>
<thead>
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<th>Name of lake</th>
<th>Ephemeroptera</th>
<th>Odonata</th>
<th>Heteroptera</th>
<th>Trichoptera</th>
<th>Coleoptera</th>
<th>Diptera</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Leptophlebia sp.</td>
<td>Somatochlora and Cordulia</td>
<td>Gerris sp. and Sigara sp.</td>
<td>Limnephilidae</td>
<td>Gyrinus sp.</td>
<td>Chironomus</td>
</tr>
<tr>
<td>Des Voeux</td>
<td>49 (37-61)</td>
<td>121</td>
<td>147 (106-200)</td>
<td>143 (42-244)</td>
<td>65 (56-69)</td>
<td>151</td>
</tr>
<tr>
<td></td>
<td>14</td>
<td>90</td>
<td>102 (30-189)</td>
<td>32 (14-49)</td>
<td>42 (34-55)</td>
<td>34</td>
</tr>
<tr>
<td></td>
<td>38%</td>
<td>74%</td>
<td>66 (22-94)%</td>
<td>27 (20-34)%</td>
<td>65 (49-80)%</td>
<td>22%</td>
</tr>
<tr>
<td>Detchevery</td>
<td>69 (61-76)</td>
<td>167 (116-217)</td>
<td>129 (66-129)</td>
<td>59 (34-117)</td>
<td>65 (56-69)</td>
<td>105 (85-124)</td>
</tr>
<tr>
<td></td>
<td>39</td>
<td>76 (74-78)</td>
<td>92 (69-119)</td>
<td>20 (11-30)</td>
<td>42 (34-55)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>41%</td>
<td>51 (34-67)%</td>
<td>64 (58-72)%</td>
<td>36 (22-51)%</td>
<td>65 (49-80)%</td>
<td></td>
</tr>
<tr>
<td>Duncan</td>
<td>99 (31-216)</td>
<td>107 (34-171)</td>
<td>227 (67-793)</td>
<td>104 (50-178)</td>
<td>81 (22-175)</td>
<td>65 (17-196)</td>
</tr>
<tr>
<td></td>
<td>34 (12-67)</td>
<td>81 (59-127)</td>
<td>129 (59-410)</td>
<td>46 (20-102)</td>
<td>61 (35-107)</td>
<td>70 (39-88)</td>
</tr>
<tr>
<td></td>
<td>35 (10-60)%</td>
<td>73 (47-92)%</td>
<td>58 (30-74)%</td>
<td>47 (19-79)%</td>
<td>63 (44-84)%</td>
<td>43 (42-44)%</td>
</tr>
<tr>
<td>Evans area</td>
<td>241 (180-355)</td>
<td>217 (201-233)</td>
<td>405</td>
<td>68</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>196 (142-289)</td>
<td>167 (136-198)</td>
<td></td>
<td>17%</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>81 (75-86)%</td>
<td>76 (67-86)%</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Jobert</td>
<td>80</td>
<td>90 (79-100)</td>
<td>108</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>64</td>
<td>25 (16-34)</td>
<td>77</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>80%</td>
<td>28 (20-34)%</td>
<td>71%</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

(continued)
<table>
<thead>
<tr>
<th>Name of lake</th>
<th>Ephemeroptera ( \text{Leptophlebia} ) sp.</th>
<th>Odonata ( \text{Somatochloro} ) and ( \text{Cordulia} )</th>
<th>Heteroptera ( \text{Gerris} ) sp. and ( \text{Sigara} ) sp.</th>
<th>Trichoptera ( \text{Limnephilidae} )</th>
<th>Coleoptera ( \text{Gyrinus} ) sp.</th>
<th>Diptera ( \text{Chironomus} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lake 136</td>
<td>84 (65-102)</td>
<td>207 (98-359)</td>
<td>132 (28-248)</td>
<td>106 (42-335)</td>
<td>56</td>
<td></td>
</tr>
<tr>
<td></td>
<td>54 (34-74)</td>
<td>137 (80-176)</td>
<td>70 (6-210)</td>
<td>41 (36-49)</td>
<td>27</td>
<td></td>
</tr>
<tr>
<td></td>
<td>62 (52-72)%</td>
<td>70 (57-84)%</td>
<td>57 (22-84)%</td>
<td>85 (72-96)%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lake 150</td>
<td>178</td>
<td>331 (233-405)</td>
<td>141 (30-219)</td>
<td>104 (86-122)</td>
<td>166 (147-184)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>144</td>
<td>280 (198-334)</td>
<td>43 (10-101)</td>
<td>74 (54-93)</td>
<td>56</td>
<td></td>
</tr>
<tr>
<td></td>
<td>84%</td>
<td>84 (74-95)%</td>
<td>46 (10-58)%</td>
<td>70 (63-76)%</td>
<td>31%</td>
<td></td>
</tr>
<tr>
<td>Laporte</td>
<td>217</td>
<td>217 (147-276)</td>
<td>277 (275-279)</td>
<td>133</td>
<td>137 (112-162)</td>
<td></td>
</tr>
<tr>
<td>Matagami</td>
<td>55</td>
<td>151</td>
<td>45</td>
<td>192 (79-281)</td>
<td>106</td>
<td></td>
</tr>
<tr>
<td></td>
<td>23</td>
<td>112</td>
<td>9</td>
<td>210 (168-251)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>43%</td>
<td>74%</td>
<td>20%</td>
<td>84 (78-90)%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Opinaca</td>
<td>164</td>
<td>149</td>
<td>151 (136-166)</td>
<td>129 (93-164)</td>
<td>95</td>
<td></td>
</tr>
<tr>
<td></td>
<td>89</td>
<td>117 (93-140)</td>
<td>88</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>54%</td>
<td>76 (68-85)%</td>
<td>93%</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*Corresponding range of values is shown in parentheses. A missing range indicates that only one pooled insect sample was analyzed.*
trends for the same insect groups with a range from <25 ng Hg g^{-1} dw to >500 ng Hg g^{-1} dw. The proportions of MeHg to total Hg ranged 30–45% in detritivores (dipterans, ephemeropterans), 35–50% in detritivores-grazers (trichopterans), 65–70% in grazers-predators (heteropterans, coleopterans), and 75–95% in predators (odonates). Similar taxonomic patterns were found for total Hg and MeHg contents of insects of the Swedish lakes (Table 3), with the exception of dipterans which were the most contaminated order in the profundal zone.

Table 3. Compilation (from top to bottom) of the mean concentrations of total mercury, methylmercury (ng Hg g^{-1} dw) and the mean proportion of MeHg to total Hg (%) in invertebrates from 8 Swedish forest lakes sampled in 1985–86.

<table>
<thead>
<tr>
<th>Lake name</th>
<th>Odonata</th>
<th>Trichoptera</th>
<th>Diptera</th>
<th>Diptera</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>linnephilidae</td>
<td>chironomidae</td>
<td>Chaoborus</td>
</tr>
<tr>
<td>Bottentjärn</td>
<td>501</td>
<td>163</td>
<td>218 (211–225)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>316</td>
<td>88</td>
<td>79 (58–100)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>63%</td>
<td>54%</td>
<td>35 (27–43)%</td>
<td></td>
</tr>
<tr>
<td>Skärhultssjön</td>
<td>423</td>
<td>209 (56–443)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>352</td>
<td>54 (25–66)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>83%</td>
<td>38 (15–55)%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Blacksåstjärn</td>
<td>358 (201–446)</td>
<td>299 (124–372)</td>
<td>78 (62–84)%</td>
<td></td>
</tr>
<tr>
<td>Löjesjön</td>
<td>337</td>
<td>109</td>
<td>60</td>
<td></td>
</tr>
<tr>
<td></td>
<td>234</td>
<td>62</td>
<td>39</td>
<td></td>
</tr>
<tr>
<td></td>
<td>69%</td>
<td>56%</td>
<td>66%</td>
<td></td>
</tr>
<tr>
<td>Loppesjön</td>
<td>152</td>
<td>93</td>
<td>33</td>
<td></td>
</tr>
<tr>
<td></td>
<td>104</td>
<td>45</td>
<td>9.5</td>
<td></td>
</tr>
<tr>
<td></td>
<td>68%</td>
<td>48%</td>
<td>29%</td>
<td></td>
</tr>
<tr>
<td>Gårdsjön</td>
<td>371</td>
<td>114</td>
<td>380 (311–427)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>296</td>
<td>27</td>
<td>21 (16–27)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>80%</td>
<td>24%</td>
<td>12 (4–9)%</td>
<td></td>
</tr>
<tr>
<td>Stensjön</td>
<td>123</td>
<td>386 (165–667)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>38</td>
<td>55 (38–67)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>31%</td>
<td>19 (6–35)%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Holmeshultasjön</td>
<td>299</td>
<td>252</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>217</td>
<td>24</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>73%</td>
<td>10%</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*Corresponding range of values is shown in parentheses. A missing range indicate that only one pooled insect sample was analyzed.
Systematic differences of Hg concentrations in insects were found between both lakes and between insect orders (ANOVA, Table 4). The influences of insect order and the lake on both total Hg and MeHg concentrations in insects were highly significant: the models (model 6, Table 4) explained 57 and 79%, respectively, of the total variance when all order are considered (Hg: n=235, p<0.0001, r²=0.57, MeHg: n=166, p<0.0001, r²=0.79). Within-lake variability of MeHg concentrations between feeding guilds was high, with predators showing 3- to 4-fold higher mean values than detritivores-grazers (T-test, all p <0.05). The geometric range (max/min) within each order was fairly constant both within and among lakes (2- to 3-fold), as were the ratios of mean total Hg or MeHg concentrations between given order across the lakes. The concentration of MeHg in predators was not related to individual age or size since the ranges of MeHg concentration in small, medium or large *Somatochlora* and *Cordulia* were similar (t-test, all p<0.05, n=32).

Total Hg concentrations in insects increased over the growing season: mean values for detritivores-grazers increased from 60–80 ng Hg g⁻¹ in the spring to 125–175 ng Hg g⁻¹ in the fall, and from 88–120 ng Hg g⁻¹ to 180–200 ng Hg g⁻¹ for predators. Insect MeHg concentrations showed a similar pattern. The proportion of MeHg to total Hg remained constant from spring to fall in the detritivores-grazers, whereas it increased slightly in the predators. Significant correlations were found between water temperature and MeHg concentration in chironomids (r=0.99, p<0.05, n=18) and odonates (r=0.64, p<0.006, n=32). When all insect order were considered, there is a weak influence of year or season on the Hg and MeHg concentrations in insects.

### Table 4. ANOVA of log (total Hg) and log (MeHg) in insects (ng Hg g⁻¹ dw) with selected variables for 11 Quebec lakes

<table>
<thead>
<tr>
<th>No.</th>
<th>Var. 1</th>
<th>Var. 2</th>
<th>Total Hg</th>
<th>MeHg</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>n</td>
<td>r²</td>
<td>p</td>
<td>n</td>
</tr>
<tr>
<td>1</td>
<td>Insect order</td>
<td>235</td>
<td>0.23</td>
<td>0.0001</td>
</tr>
<tr>
<td>2</td>
<td>Lake</td>
<td>235</td>
<td>0.26</td>
<td>0.0001</td>
</tr>
<tr>
<td>3</td>
<td>Season⁻ᵇ</td>
<td>235</td>
<td>0.09</td>
<td>0.0001</td>
</tr>
<tr>
<td>4</td>
<td>Year⁻ᶜ</td>
<td>235</td>
<td>0.06</td>
<td>0.0001</td>
</tr>
<tr>
<td>5</td>
<td>Lake group⁻ᵈ</td>
<td>222</td>
<td>0.03</td>
<td>0.0003</td>
</tr>
<tr>
<td>6</td>
<td>Insect order</td>
<td>Season</td>
<td>235</td>
<td>0.57</td>
</tr>
<tr>
<td>7</td>
<td>Insect order</td>
<td>Lake</td>
<td>234</td>
<td>0.33</td>
</tr>
<tr>
<td>8</td>
<td>Insect order</td>
<td>Year</td>
<td>235</td>
<td>0.32</td>
</tr>
<tr>
<td>9</td>
<td>Insect order</td>
<td>Group</td>
<td>222</td>
<td>0.29</td>
</tr>
</tbody>
</table>

⁻ᵇIn multivariate models, p<0.0001 for all variables except where indicated.
⁻ᶜSpring, summer and fall.
⁻²1 or 2, classified according to lake sediment characteristics.
MeHg concentrations in insects: models 3 and 4 which explained only 6–11% of the variation in single variable ANOVAs. Adding the variables year or season as a second variable only slightly improved the insect orders and the lakes influences (Table 4, models 6, 7, and 8).

**Sediment as a Source of MeHg**

In the Quebec lakes, total Hg concentrations in odonates were significantly correlated with those in sediments \( (r=0.55, p<0.001, n=32) \) and with sediment total Hg/C ratios \( (r=0.46, p<0.001, n=32) \). Significant correlations were found between MeHg concentrations in sediments on the one hand and those in odonates \( (r=0.62, p<0.001, n=32) \) and in chironomids \( (r=0.78, p<0.005, n=18) \) on the other.

Student's t-test was used to assess the differences of mean total Hg and MeHg concentrations in given insect orders between lake groups 1 and 2 (group 3 was excluded from the analysis because of small sample size). Although mean total Hg and MeHg contents of sediments differed \( (t\text{-test, } p<0.05) \) by 40 and 50%, respectively, between the two lake groups, values for both detritivores and grazers were not significantly different between lake groups \( (p>0.05) \). Only predatory insect orders showed significantly higher total Hg and MeHg levels \( (p<0.05) \) in group 2 lakes (coleopterans and odonates for total Hg; coleopterans, heteropterans and odonates for MeHg) than the ones from group 1 (Fig. 2).

As a rule, organisms have an organic carbon content of about 50–52%, which agrees closely with the results of this study 48–52%. In detritivores however, organic content varied between 38 to 50% with a mean of 46%, indicating a dilution of 2 to 24% (mean of 12%) of the animal carbon content by ingested inorganic sediment particles. Since total Hg concentrations in lake sediment are lower than those in insects (Tables 1, 2 and 3, Fig. 2), sediment ingestion may result in a dilution of total Hg in the animals and lead to an underestimation of their contamination levels. This dilution effect is probably stronger in the case of MeHg because MeHg:total Hg ratios of lake sediments are <1%.

**Discussion**

Total Hg concentrations in insects from 19 Quebec and Swedish lakes remote from known point sources of Hg were comparable to those reported in the literature (Huckabee et al. 1979; Surma-Aho et al. 1986; Jackson 1988; Parkman and Meili 1993; Rask et al. 1994; Tremblay et al. 1996). Our values were similar to those reported by Tremblay et al. (1996) for various insect species in a natural lake of northern Quebec as well as to those measured by Surma-Aho et al. (1986) for mixed zoobenthos (trichopterans and odonates) in two Finnish lakes. Our results show that the proportions of MeHg to total Hg concentrations in the various insect taxa analyzed varied from 20 to 95% (Fig. 2 and Tables 2 and 3), in agreement with the findings of Surma-Aho et al. (1986) and Tremblay et al. (1996).
Sediment as a Source of MeHg

Although most aquatic insects grow and feed in or on sediments, total Hg concentrations in the animals and in the sediments they inhabit are generally poorly correlated (this study; Bissonnette 1975; Jackson 1988; Parkman and Meili 1993). Since MeHg is more efficiently bioaccumulated, we obtained a significant correlation between chironomids or odonates and sediment MeHg levels. Although the total Hg content of sediments may, to some extent, reflect the degree of contamination in a lake, the Hg content of the organic fraction of the sediment is probably a better indicator of the exposure of non-selective detritivores or detritivores-grazers to Hg. Langston (1982) found a positive correlation between the Hg concentration in two bivalves and the sediment Hg/organic matter content ratio, whereas Jackson (1988) reported that Hg concentration in chironomids decreased with increasing organic C content of sediments ($r=0.97$, $p<0.001$). Parkman and Meili (1993) observed a weak negative relationship between the Hg contents of chironomids and the sediment Hg/C ratio. However, in the same study, the Hg concentration in Anisoptera (Odonata) was positively correlated with the sediment Hg/C ratio. Similarly, we found a positive correlation between Hg in odonates and the Hg/C ratio in sediments. Odonates are predators, and therefore the observed trends are probably a result of either trophic interactions or a causal relationship, this would be explained by sediment chemistry and the general exposure of the animals to total Hg and MeHg rather than direct interactions between odonates and sediment (Parkman and Meili 1993).

The weak relationships observed between total Hg or MeHg concentrations in the insects and those in the sediments suggest that mercury accumulation by benthic insects may be determined to a greater extent by environmental and biological processes than by the sediment total Hg or MeHg concentration. Moreover, these patterns emphasize the importance of considering both carbon content and nutritional quality of sediments in studies of MeHg accumulation in animals at lower trophic levels (primary consumers). Low food quality requires animals to increase their ingestion rates in order to achieve growth, resulting in their greater exposure to Hg (Parkman and Meili 1993; Tremblay et al. 1996; Plourde et al. 1996). In agreement with the findings of Parkman and Meili (1993) and Rask et al. (1995) we observed similar total Hg concentrations in organisms (from detritivore taxa to predator taxa) having different feeding habits. These results support the conclusions of Tremblay et al. (1996) who attributed the high total Hg concentrations observed in detritivores to their greater exposure to inorganic Hg as a result of feeding on sediments of low nutritional value.

Further evidence for the importance of the nature of the ingested food with respect to Hg exposure is provided by the high total Hg values measured in the dipterans from the profundal zone of two Swedish lakes (Table 3). As many studies have shown anoxia to enhance the net methylation of Hg (e.g., Korthals and Winfrey 1987), thus increasing its bioavailability, it has been suggested that the high concentrations of total Hg in
benthic animals from profundal zones may be due to the higher degree of oxygen depletion (Parkman and Meili 1993). However, while the highest insect total Hg concentrations in this study were observed in the profundal zone dipterans from Gårdsjön and Stensjön lakes, MeHg concentrations in these organisms were among the lowest of all insect samples. This suggests that the accumulation of total Hg by profundal detritivores resulted from their high exposure to inorganic Hg in their low quality food rather than to methylated Hg.

Biomagnification of MeHg Along Food Chain

Since methylated Hg is the predominant form in which Hg is transferred from one trophic level to another, a small difference of sediment MeHg concentrations between lakes should be amplified along the food web. Thus, when MeHg concentrations in given feeding guilds are compared between lakes, the largest difference is expected to be observed for predators (at the highest trophic level). This pattern of increasing MeHg concentrations up the food chain is illustrated in Fig. 2: the mean feeding guild-specific MeHg ratio between lake groups (MeHg group 2/ MeHg group 1) increased from 1.2 for detritivores to 2.4 for predators. The mean MeHg concentration was significantly higher in the predators from group 2 lakes than in those from group 1 lakes (t-test, p<0.05), while no significant difference was found for detritivores (t-test, p>0.05), in spite of the large differences of total Hg and MeHg concentrations, as well as C content between the two lake groups (t-test, all p<0.05) (Table 1). These results indicate that a small difference in MeHg bioavailability between lakes may not be obvious in animals of the first trophic level (detritivores) because it is masked by a greater variability of MeHg concentrations among animals of that trophic level. However, this difference is increasing with the trophic level of the organisms and becomes significant with the top predator.

Several studies have shown a positive relationship between Hg concentrations in fish and both the age of the animals and their position in the food web (Rogers and Beamish 1983; Wren et al. 1991; Meili 1991a; Cabana et al. 1994). In our study, however, no relationship was found between size and MeHg concentration in odonates. Parkman and Meili (1993), in a study of 8 Swedish lakes, found no significant relationship between total Hg contents and body size of predatory invertebrates, despite a 100-fold variation in body weight. This supports the hypothesis that Hg concentrations in many animals are essentially unaffected by exposure time, thus suggesting a dynamic equilibrium (Meili 1991a). The absence of a size or weight effect on MeHg accumulation in insects confirms that the increase up the food chain of the MeHg concentration in insect larvae, observed in this study and by Tremblay et al. (1996), is a food web effect. This conclusion agrees with that of Cabana et al. (1994) who compared lakes with and without Mysis and forage fish and showed that Hg accumulation in lake trout increases with the length of the food chain.

The trophic levels established by Tremblay et al. (1996) were arbi-
trarily defined on the basis of literature reports of insect feeding habits (Merritt and Cummins 1985). Based on the C contents of insects from 11 Quebec lakes, their MeHg concentrations, as well as their MeHg/total Hg ratios, we propose a benthic food web consisting of two true trophic levels. This classification modifies the previous one (Tremblay et al. 1996) by combining insect taxa of similar trophic level and Hg concentration (detritivores and detritivores-grazers; grazers-predators and predators). The first trophic level consists of dipterans, ephemeropterans and some trichopterans. In these animals, the C content ranged from 38 to 50%, MeHg concentrations were <100 ng Hg g⁻¹ dw and MeHg/total Hg ratios <60%. The frequently but not consistently low C content suggests that these organisms tend to ingest sediment and may be considered as detritivores-grazers. The second level consists of typical predators such as coleopterans, heteropterans, odonates and some trichopterans, with C contents >48%, MeHg levels >100 ng Hg g⁻¹ dw and MeHg/total Hg ratios >60%. Some samples of Phryganeidae (trichoptera) may have included animals from both level since different species are known to vary greatly with respect to their diet (Merritt and Cummins 1985). This might explain, at least in part, the large variations in Hg concentrations observed for this taxon (Fig. 2). The MeHg biomagnification factor between detritivores-grazers (level 1) and predators (level 2) was about 3, which agrees with the data from a comprehensive food chain study of Swedish lakes (Meili 1991a, 1991b). The assumption of the existence of only two true trophic levels in the insect food web is justified by the high probability that omnivory (feeding simultaneously at several trophic levels) leads to comparatively small differences in Hg concentration between insects. This is supported by the results of Lucotte et al. (1995b) who, for lakes Duncan and Detcheverry, observed a difference between detritivores-grazers and predators with respect to their nitrogen isotopic composition (δ¹⁵N=2.7-3.2‰), which corresponds to about one trophic level (δ¹⁵N:3.0-3.5‰). The threefold difference in MeHg concentrations between trophic levels also agrees with the data from a comprehensive food chain study of Swedish lakes (Meili 1991a; Meili et al. 1993).

Geographic Patterns of Insects Hg Accumulation

The accumulation patterns of both total Hg and MeHg in the insects are very similar in all lakes in this study, as evidenced by the constancy of both geometric ranges among taxa and ratios of mean total Hg or MeHg concentrations between given taxa (e.g., odonates/heteropterans, heteropterans/coleopterans, odonates/trichopterans, etc.). Biotic factors account for most of the total variability of insect total Hg and MeHg contents within and between lakes, while differences between lakes contributes very little to the observed differences (Table 4). For benthic invertebrates of Swedish lakes, Parkman and Meili (1993) reported similar models (ANOVAs), in which biotic factors accounted for most of the total variability of invertebrate contamination by Hg. Since our data covers numerous lakes of varying latitude, located on 2 continents and with a wide range of Hg deposi-
tion rates, the observed patterns of total Hg and MeHg accumulation in
the food web are probably representative of boreal lakes in general.

In order to illustrate the wide applicability of the patterns of Hg accu-
mulation in insects across Quebec and Swedish lakes, we have normalized
the total Hg concentration in insects for differences among taxa within
lakes. For this purpose, a reference total Hg concentration was calculated
for each lake from the median of the observed values of the odonates and
the weighted odonate/heteropteran, odonate/coleopteran and odonate/
detritivore ratios. This way to normalized the Hg values in odonates allows
odonate total Hg concentrations to be estimated for lakes where no
odonates were sampled, since the ratios between odonates and others taxa
were constant among lakes. Odonates were chosen as a reference because
they are common in most lakes, are easily distinguished from the other
animals, have comparatively high total Hg concentrations and proportion-
ally high MeHg concentrations, and show little variability of their
MeHg/total Hg ratios. Although a threefold range of sediment total Hg/C
ratios was observed for oligotrophic lakes, the mean normalized total Hg
concentrations in odonates are similar in all these lakes, whether in Sweden
or in Quebec (Fig. 3). For lakes of a given trophic status, no differences
of the odonate total Hg concentrations were observed between central

Fig. 3. Normalized total mercury concentrations in odonates (ng Hg g\(^{-1}\) dw) in
relation to sediment weight ratio of Hg/C (x10\(^7\)) for 11 Quebec and 8 Swedish
lakes. The normalized total Hg concentration was calculated for each lake from
the median of the observed values of the odonates and the weighted odonate/het-
eropteran, odonate/coleopteran and odonate/detritivore ratios (see text for more
details).
and southern Sweden, regions which show a twofold difference in their atmospheric Hg deposition rates (Meili 1991c). In general, an increase in lake trophic status is associated with an increase in nutrient concentrations and microbial productivity (Wetzel 1983), leading to an expected increase in methylation (Wright and Hamilton 1982; Winfrey and Rudd 1990; Jackson 1988; Jackson 1991; Miskimmin et al. 1992). Thus, the observed differences of Hg concentrations in odonates among lakes of different trophic status may reflect a higher degree of bioavailability and greater accumulation of Hg in the zoobenthos in productive lakes.

In Quebec lakes, we observed an increase in insect Hg concentrations from spring to fall, but despite a 2-3 fold seasonal increase in water temperature during this period, the microbial methylation and the nature of food ingested would better explained the rise in Hg levels in the insects than the temperature itself. These results suggest that abiotic factors, such as temperature, oxygen concentration, atmospheric deposition and the organic content of the sediment, have important effects on the bioavailability of MeHg to animals at low trophic levels. A similar interpretation was made by Jackson (1988) and Parkman and Meili (1993). This is consistent with the findings of Tremblay et al. (1996), who concluded that the bioavailability of MeHg to organisms at lower trophic levels controls the uptake of Hg by the predators at the upper end of the food chain.

Conclusions

Our results show that the proportion of MeHg to total Hg in aquatic insects is controlled by their feeding behaviour, and increases from detritivores to predators. This effect is due to biomagnification in the food web rather than to body size or age. Whereas the MeHg concentrations of predatory animals are partly governed by the trophic structure and dynamics of the food web, MeHg concentrations in aquatic insects at low trophic levels are more dependent upon abiotic and microbial processes. Food quality and microbial Hg methylation appear to be the most important factors controlling the transfer of MeHg from the sediments to insects. Since the biomagnification of MeHg from one trophic level to the next is around 3 (this study; Meili 1991a; Tremblay et al. 1996), an apparently minor difference in either food quality or microbial methylation rates may lead to a significant difference in the contamination of predators. This applies not only to invertebrates, but also to the fish community for which invertebrates usually constitute the most important food source.

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