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Tracking the Limnoecological History of Lake Hiidenvesi (Southern Finland) Using the Paleolimnological Approach

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1   **Tracking the limnoecological history of Lake Hiidenvesi (southern Finland)**
2   **using the paleolimnological approach**

3

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21

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24   Helsinki. We are grateful for the two journal reviewers for constructive criticism that helped to
25   improve the manuscript.

26   **Abstract**

27

28   We examined a sediment record from Lake Hiidenvesi in southern Finland using paleolimnological
29   methods to trace its limnoecological history. In our record, beginning from the 1940's, chironomid
30   (Diptera) assemblages shifted from typical boreal taxa towards mesotrophic community
31   assemblages at ~1960-1980 CE being finally replaced by eutrophic taxa from the 1990's onward.
32   The diatom (Bacillariophyceae) assemblages reflected relatively nutrient rich conditions throughout
33   the record showing a further increase in eutrophic taxa from the 1970's onward. A chironomid-
34   based reconstruction of late-winter hypolimnetic dissolved oxygen (DO) conditions suggested
35   anoxic conditions already in the 1950's, probably reflecting increased inlake production due to
36   allochthonous nutrient inputs and related increase in biological oxygen consumption. However, the
37   reconstruction also indicated large variability in long-term oxygen conditions that appear typical for
38   the basin. With regard to nutrient status, chironomid- and diatom-based reconstructions of total
39   phosphorus (TP) showed a similar trend throughout the record, although, chironomids indicated a
40   more straightforward eutrophication process in the benthic habitat and seemed to reflect the
41   intensified human activities in the catchment more strongly than diatoms. The DO and TP
42   reconstructions were mostly similar in trends compared to the measured data available since the
43   1970's/1980's. However, the increase in TP during the most recent years in both reconstructions
44   was not visible in the monitored data. The results of our multiproxy study emphasize the
45   significance of including both epilimnetic and hypolimnetic systems in water quality assessments
46   and provide important long-term limnoecological information that will be useful in the future when
47   setting targets for restoration.

48

49   *Keywords:* *Chaoborus*; chironomids; diatoms; hypolimnetic oxygen; nutrient enrichment;
50   phosphorus

51

52 **Introduction**

53

54 Assessments of long-term limnoecological dynamics extending beyond the observational period are
55 essential for the successful implementation of lake management acts. Paleolimnology examines the
56 environmental history of lakes and their catchments using sedimentary archives that preserve
57 physical, chemical, and biological proxy information (Smol 2009). Paleolimnology has proven to be
58 very useful in assessments of limnological reference conditions that allow the evaluation of natural
59 dynamics, timing of change, and targets of restoration (Bennion et al. 2011). The most common
60 biological proxy sources in assessments of reference state include diatom (Bacillariophyceae) algae
61 and chironomid (Diptera: Chironomidae) insect larvae, of which remains preserve well in sediments
62 and are identifiable to species or generic level (Dixit et al. 1992; Hofmann 1988). Diatoms and their
63 fossil communities often readily reflect the nutrient development of the water column (Anderson
64 1997; Kauppila and Valpola 2003), whereas fossil chironomid midge assemblages tend to reflect
65 changes in the bottom water, such as in the hypolimnetic oxygen concentrations (Brodersen and
66 Quinlan 2006; Francis 2001) or deep-water nutrients (Vanni 2002).

67 In addition to ecological dynamics, fossil communities can be used to quantitatively
68 reconstruct changes in limnology via the calibration set approach. In such reconstructions, the
69 modern species optima in a training set are utilized in a sediment downcore using a transfer
70 function, which connects the modern species optima with the past fossil communities producing a
71 quantitative reconstruction of a particular variable. Diatoms are commonly used to quantitatively
72 reconstruct long-term changes in total phosphorus (TP) (Kauppila et al. 2002) and pH (Battarbee et
73 al. 2010), whereas chironomids are often used to reconstruct TP (Brooks et al. 2001) and
74 hypolimnetic dissolved oxygen (DO) (Quinlan and Smol 2001). It is also possible to estimate the

75 concentration of deep-water oxygen by using the ratio between chaoborids (Diptera: Chaoboridae)
76 and chironomids as an indicator of anoxia (Quinlan and Smol 2010).

77 Our study site, Hiidenvesi, is a naturally clay-turbid and currently eutrophic lake in
78 southern Finland. A recently initiated Hiidenvesi restoration project (2016-2021) aims to reduce the
79 load of suspended solids and nutrients as well as to promote conditions for recreation. The long-
80 term objective for the restoration work is to improve the ecological state of Hiidenvesi and diminish
81 the signs of eutrophication. Lake restoration activities, such as the management of fish stock and the
82 establishment of sedimentation basins in the catchment, have been performed since 1995 (Repka
83 2005), albeit without consistent effectiveness monitoring.

84 In this study, we examine the long-term ecological and limnological development of
85 the lake using fossil diatom and chironomid analyses combined with quantitative paleolimnological
86 modeling. The objective is to reconstruct changes in the planktonic and benthic communities and in
87 the surface-water nutrient and deep-water oxygen levels of the basin in high resolution since the
88 initiation of intensified human activity around the lake at the turn of the 1950s'. This knowledge
89 will be useful when setting targets for lake restoration, especially in the case of reducing surface
90 water nutrients and in evaluating the usefulness of artificial bottom-water oxygenation. The results
91 of this study will also improve understanding of lake development under increasing anthropogenic
92 pressure.

93

94 **Materials and methods**

95

96 *Study site*

97

98 Hiidenvesi (60°22'N, 23°11'E; 32 m a.s.l.) is a clay-turbid lake located in southern Finland (Fig. 1).
99 It is one of the largest lakes in the area (30 km²), also having a wide catchment area (935 km²). The

lake is located between the city of Lohja and municipality of Vihti and it drains southwest via the Vänteenjoki River into Lake Lohjanjärvi. Lake water quality varies notably between the basins of Hiidenvesi, in general, the larger basins having better limnological status than the small and shallow basins. The study site Kiihkelyksenselkä is the main basin of Hiidenvesi having a surface area of 10.5 km² and a maximum depth of 33 m. Adjacent to the metropolitan area of Helsinki, the lake provides significant ecosystem services. However, the lake suffers from serious nutrient loading derived from agriculture, forestry and other sources of diffuse loading. Currently, the autumnal epilimnetic TP varies in the Kiihkelyksenselkä basin between ~30 and 40 µg l⁻¹, total nitrogen (TN) between 800 and 1400 µg l⁻¹, chlorophyll-a between ~10 and 20 µg l⁻¹, pH between 7.0 and 7.8, and the hypolimnetic DO between ~4 and 6 mg l⁻¹. Hypolimnetic DO measurements (minimum oxygen during late summer) from the examined Kiihkelyksenselkä basin are available since 1981 CE and epilimnetic autumn TP since 1973 CE (Finnish Environment Institute).

Sediments

An 18-cm sediment profile was collected in June 2015 from the Kiihkelyksenselkä basin at a water depth of 14 m using a Limnos gravity corer (Kansanen et al. 1991). The sediments were subsampled in the field into small plastic bags at 1 cm intervals. The sediment profile consisted of generally homogenous grey-brown clayey gyttja (6-12% organic matter, Mörner 1982) (Fig. 2). The samples were stored in a cold room (+4 °C) for later preparation for the paleolimnological analyses. Loss on ignition (LOI) was used to assess the organic content of the sediments and was determined first to avoid degradation of organic material. For the LOI, samples were first dried at 105 °C for 12 h and then ignited in an oven at 550 °C for 4 h (Heiri et al. 2001).

Midge analysis

125

126 Volumetric sediment samples of 5 cm³ were prepared using standard methodology for subfossil
127 chironomid analysis (Brooks et al. 2007). Sediments were sieved through a 100-µm mesh and the
128 residue was examined in a Bogorov sorting tray under a binocular microscope for extraction of
129 subfossil head capsules using fine forceps. All specimens (typically the 4th instar larvae) were
130 permanently mounted in Euparal® on microscope slides and identified under a light microscope at
131 100 to 400-times magnification. A minimum count size of 50 individuals was set (Larocque 2001).
132 Chironomids were identified using Brooks et al. (2007). From the same samples, chaoborids and
133 ceratopogonids (Diptera: Ceratopogonidae) were also identified based on Finnish fossil specimens
134 (Luoto 2009; Luoto and Nevalainen 2009).

135

136 *Diatom analysis*

137

138 Samples for diatom analysis were prepared following standard procedures (Battarbee et al. 2001).
139 Organic matter was removed by oxidizing sediment samples with hydrogen peroxide solution (30%
140 H₂O₂), after which a few drops of hydrochloric acid (37% HCl) were added to remove carbonate
141 minerals. Coarse minerogenic matter was removed physically by swirling the sample solution in a
142 beaker and decanting the diatom suspension. The remaining sample residue was checked for
143 absence of diatom valves before disposal. Samples were dried on coverslips and mounted with
144 Naphrax® (Brunel Microscopes Ltd, Wiltshire, U.K.). Diatoms were enumerated under a light
145 microscope at 1000x magnification, setting the minimum counting sum at 300 diatom valves.
146 Taxonomic determination was mainly based on the flora of Krammer and Lange-Bertalot
147 (1986–1991), with nomenclature updated where relevant due to taxonomic refinements (Suppl. 1).

148

149 *Statistical analyses and paleolimnological modeling*

150

151 Sample-specific diversity for midges and diatoms was calculated using the Hill's (1973) N2 index,
152 which represents the effective number of occurrences. Principal components analysis (PCA) was
153 used to detect the direction of the main midge and diatom community variance in ordination space.
154 The PCAs were run using square-root transformed relative abundances. Subsequently, segmented
155 regression analysis was used to identify statistically significant breakpoints in the PCA scores
156 applying a minimum confidence level of 95%. The selection of the best breakpoint and function
157 type was based on maximizing the statistical coefficient of explanation, and performing tests of
158 significance using the program SegReg (Oosterbaan 2011).

159 Past variability in minimum hypolimnetic DO (i.e. late-winter in the training set) was
160 reconstructed using a 30-lake chironomid-based calibration model for southern Finland ranging
161 from anoxic to hypersaturated sites (Luoto and Nevalainen 2011; Luoto and Salonen 2010). The
162 weighted averaging partial least squares (WA-PLS) model using one WA-PLS component has a
163 cross-validated (leave-one-out) coefficient of determination (r^2_{jack}) of 0.72 and a root mean squared
164 error of prediction (RMSEP) of 2.4 mg l⁻¹. In addition to DO, chironomid assemblages were used to
165 reconstruct past changes in TP. The TP model (Luoto 2011) uses 51 lakes across Finland ranging
166 from oligotrophic to hypertrophic sites (TP=1.5-105 µg l⁻¹). The chironomid-based autumnal
167 epilimnetic TP inference model uses WA-PLS technique with four calibration regression
168 components and it has an r^2_{jack} of 0.92 and RMSEP of 6.7 µg l⁻¹. The diatom-based epilimnetic TP
169 reconstructions used a 47-lake calibration set from eastern Finland covering a TP gradient of 7-122
170 µg l⁻¹. The two-component WA-PLS model with leave-one-out cross-validation has an r^2_{jack} of 0.82
171 and RMSEP of 0.15 log µg l⁻¹ (Tammelin and Kauppila 2015). All reconstructions were performed
172 using the program C2 (Juggins, 2007). The reconstructions were validated for their reliability by
173 comparing the reconstructed values against limnological measurements. LOESS smoothing was
174 applied to standardize chronological differences between the reconstructed and measured values.

175

176 *Sediment dating*

177

178 Chronological determinations were performed using ^{210}Pb and ^{137}Cs analysis at the
179 Radiochronology Laboratory of the Centre for Northern Studies, Laval, Québec (Canada). The age-
180 depth model was established using a constant rate of unsupported ^{210}Pb supply (CRS) model
181 (Appleby 2001). The ^{210}Pb and ^{137}Cs concentrations remained low due to high sediment
182 accumulation rate, yet high enough for the construction of a tentative chronology (Fig. 3).

183

184 **Results**

185

186 According to the LOI analysis (Fig. 2), the sediment profile was mostly inorganic corresponding to
187 clayey gyttja (5.8–9.1% of organic matter). Between 17–13 cm, the LOI varied between 7 and 9%
188 followed by a decrease to the record minimum at 10 cm. Thereafter, the LOI progressively
189 increased showing the highest values at the topmost sediment layers.

190 Owing to the low ^{210}Pb and ^{137}Cs concentrations, we were able to construct only a
191 tentative age-depth model (Fig. 3). Based on the CRS model, the core extends ~70 years back in
192 time representing a bottom age that dates to the late 1940's. However, as the model represents large
193 estimation errors, the chronology should be considered with caution. Nonetheless, the initiation of
194 the ^{137}Cs peak at 8 cm that corresponds to the Chernobyl accident in 1986 fits well with the ^{210}Pb
195 chronology. In lakes in southern Finland, Chernobyl fallout typically marks the only clear ^{137}Cs
196 peak (Ojala et al. 2017), hence, suggesting that the age-depth model is realistic. Linear time-depth
197 relationship provides a high sediment accumulation rate of 2.5 mm per year, which explains the low
198 ^{210}Pb and ^{137}Cs concentrations.

199   The midge assemblages in the sediment core consisted mostly of chironomids and
200 chaoborids (Fig. 4). A total of 29 chironomid taxa were identified from the samples. In general, the
201 chironomid flux (head capsules per volumetric sample) increased towards the present. Of the non-
202 chironomid midges, *Chaoborus flavicans* was abundant throughout the core, whereas *Bezzia*-type
203 ceratopogonids occurred only in the surface sediment. Of the chironomids, *Tanytarsus glabrescens*-
204 type was abundant in the lower part of the core (~1945-1970 CE). *Sergentia* was common in the
205 1960's and 1970's, when also *T. mendax*-type had its maximum abundances. In the later part of the
206 core, *Procladius* thrived from the 1990's until 2000, after which *T. glabrescens*-type again
207 increased in abundance and *Chironomus plumosus*-type appeared in the record. Midge diversity,
208 measured as N2, showed an increasing trend throughout the record with the highest diversity
209 reached at the most recent sample (Fig. 4).

210   In all, 146 different diatom taxa from 32 genera were identified from the samples
211 (Suppl. 1). Planktonic taxa dominated the diatom assemblages (Fig. 5), with high abundance of
212 *Aulacoseira granulata*, *A. ambigua*, and *A. subarctica*. *A. subarctica* type II (lower mantle
213 height/valve diameter ratio) was the most common taxon in the lower part of the sediment profile
214 (~1945-1985 CE) but began to decline thereafter, and was largely replaced by a more slender
215 morphotype in the upper part of the core. *A. ambigua*, *A. islandica*, and *Fragilaria crotonensis*
216 displayed a slight increase from the 1970's onwards, and *Stephanodiscus medius* and *Asterionella*
217 *formosa* showed their highest abundances since the 1980's. The benthic community was rich in
218 species but low in numbers, with species of *Fragilaria* sensu lato (e.g., *Staurosirella pinnata*,
219 *Pseudostaurosira brevistriata*) as the most abundant. Planktonic diatom diversity was slightly
220 elevated between the 1960's and 2000 CE, with the lowest diversity recorded in the most recent
221 sample (Fig. 5). In the benthic community, diatom diversity declined gradually since the 1960's.

222   The midge PCA axis 1 scores (Fig. 6) were negative in the bottom and top parts of the
223 sediment sequence and mostly positive in between. Highest axis 2 scores occurred around the

224 1980's. The diatom PCA axis 1 scores (Fig. 6) remained negative until the 1980's but shifted
225 thereafter into positive scores showing a clear directional succession. The highest diatom axis 1
226 score occurred in the surface sediment sample. According to the segmented regression analysis, a
227 significant breakpoint in the midge PCA axis 1 scores occurred at 1963 CE and in the axis 2 scores
228 at 1976 CE. No significant breakpoint was found in the diatom axis 1 scores but in the axis 2 scores
229 a breakpoint occurred at 1991 CE.

230   The chironomid-based hypolimnetic DO reconstruction varied from anoxic to well-
231 oxygenated conditions (Fig. 7). The highest DO (8.3 mg l^{-1}) was reached already at the lowermost
232 sediments but the conditions turned into oxygen deficiency and anoxia during the 1950-60's. In the
233 1960's the oxygen conditions improved and remained elevated until the 1980's. In the 1990's the
234 oxygen state again deteriorated with anoxia occurring in the first half of the 1990's. The 21st
235 century was characterized by consecutive increases and decreases in hypolimnetic DO. When
236 comparing the trends between the DO reconstruction and the measured DO since the 1980's (Fig.
237 7), they show rather similar features despite representing different seasons (late winter vs. late
238 summer).

239   The chironomid-based reconstruction of TP (Fig. 8) showed a general development
240 from oligo-mesotrophic conditions between ~1945 and 1975 CE to mesotrophy between ~1980 and
241 2010 CE, finally reaching eutrophy at the present. The diatom-TP inferences did not show a clear
242 eutrophication process. Nevertheless, the trend is otherwise very similar to the chironomid-based
243 reconstruction with elevated values in the oldest and most recent samples as well as during the
244 1980's. Despite the differences, there was a significant correlation ($R=0.55$, $r^2=0.30$, $p<0.019$)
245 between the chironomid- and diatom-based TP reconstructions. In comparison to the measured data
246 available since the 1970's (Fig. 8), the chironomid- and diatom-based TP trends showed close
247 correspondence, with the exception that the measured TP did not record a recent increase that was
248 particularly clear in the chironomid-based reconstruction.

249

250 **Discussion**

251

252 *Ecological dynamics*

253

254 The fossil chironomid assemblages (Fig. 4) in Hiidenvesi were rather typical for a clay-turbid
255 nutrient-rich lake in the area (Luoto and Ojala 2014, 2017; Luoto and Raunio 2011; Salonen et al.
256 1993). In addition to chironomids, *Chaoborus flavicans*, which prefers turbid and productive lakes
257 (Liljendahl-Nurminen et al. 2002), was common throughout the sediment profile. Subsequently, the
258 chaoborus:chironomid-ratio, which indicates the presence of anoxia (Quinlan and Smol 2010),
259 provided evidence that hypolimnetic oxygen deficiency has occurred in the basin since the 1940's.
260 To thrive, *Chaoborus* requires an anoxic lake bottom, where it can hide during the day avoiding
261 visual predation by fish and, when the night falls, it rises up the water column to feed on
262 zooplankton (Liljendahl-Nurminen 2006).

263   The most distinct change in the chironomid communities was the increase in
264 mesotrophic chironomid taxa, such as *Procladius*, *Tanytarsus mendax*-type and *Sergentia*, at the
265 mid-part of the stratigraphy (1960–2000 CE). In the more recent period, the most significant change
266 was the appearance of the typical eutrophy indicating species *Chironomus plumosus*-type
267 (Kansanen 1985; Salonen et al. 1993), which also tolerates oxygen deficiency, into the stratigraphy
268 in the 1990's. A distinct diversity threshold was also crossed in the midge communities during the
269 1990's displayed as a sudden increase in diversity (Fig. 4). This is a typical development in a
270 eutrophication process, as the number of benthic invertebrate species increases alongside nutrient
271 enrichment due to increased habitat availability (Wiederholm 1980). However, when lakes become
272 hypertrophic and permanently anoxic, the diversity naturally decreases (Bryce and Hobart 1972).

273   The diatom diversity showed a decrease in benthic diatom life forms and a
274 simultaneous increase in the planktonic diversity since the 1970's (Fig. 5). This shift in the diatom
275 communities could indicate increased turbidity in the water column related to increased
276 phytoplankton production and sediment flux from the catchment, reducing light availability to
277 benthic growth. Overall, the diatom communities (Fig. 5) of the basin have been dominated by
278 planktonic taxa, which require water column turbulence to linger in the euphotic zone. The
279 abundant *Aulacoseira granulata* and *Aulacoseira ambigua* are typical for eutrophic lakes (Lotter
280 2001; Meriläinen et al. 2003; Miettinen 2003), and *Aulacoseira subarctica* is commonly affiliated
281 with mesotrophic waters (Gibson et al. 2003). The presence of eutrophic *Stephanodiscaceae* species
282 (e.g. *Cyclostephanos dubius*) provides further indication for high productivity (Miettinen 2003;
283 Punning et al. 2008), whereas the small fragilarioids of the benthic community tolerate unstable
284 environmental conditions and reduced light availability (Anderson 2000; Luoto et al. 2012), hence
285 reflecting the turbid waters of Hiidenvesi.

286   The changes related to the eutrophication process were relatively small in scale and
287 less clear-cut in diatoms in comparison to the development in the chironomid communities. Unlike
288 in a previous paleolimnological assessment from the shallow Kirkkojärvenselkä basin of Hiidenvesi
289 (Weckström et al. 2011), we found no evidence of a recent increase in small-sized eutrophy-
290 preferring cyclotelloid species in the deeper *Aulacoseira*-dominated Kiihtelyksenselkä basin, most
291 probably due to the differences in the depths of the basins and associated divergence in the physical
292 characteristics of the water column. The success of planktonic diatom taxa is strongly dependent on
293 changes in thermal stratification and mixing regimes that are tightly coupled to external nutrient
294 fluxes, and further regulate internal nutrient cycling in lakes. The high abundance of heavy
295 *Aulacoseira* taxa and low numbers of small cyclotelloids, such as *Cyclotella stelligera*, in the upper
296 parts of the studied sediment profile hence suggests efficient convective mixing in the
297 Kiihkelyksenselkä basin of Hiidenvesi over the past decades.

298   According to the PCAs, it appears that chironomids have responded, in addition to the
299 primary environmental driver (axis 1), to secondary environmental gradients (axis 2), whereas the
300 secondary gradients have had only a minute influence on the diatom communities (Fig. 6). Based on
301 the analysis, chironomids appear to have returned in the 2000's to a previous ecological state that
302 prevailed during the 1940–50's, i.e. in the initial part of the record. Yet, the species composition is
303 rather different, possibly suggesting an alternative stable state (cf. Hobbs et al. 2012). This
304 community shift is probably due to the lake restoration efforts during the recent years that have
305 improved the hypolimnetic conditions of the basin (measured DO in Fig. 7), while no clear declines
306 in nutrient concentrations have occurred (Fig. 8). Consequently, the diatom communities show a
307 distinct progressive succession towards a new ecological state. This is also verified by the
308 breakpoint analysis, which did not identify a significant threshold for the diatom PCA axis 1 scores.
309 The significant breakpoint in the primary midge PCA axis scores occurred at 1963 CE when several
310 nutrient-preferring chironomids, such as *Tanytarsus mendax*-type (Ekrem et al. 1999), increased in
311 the assemblages. Although midge responses to oxygen and nutrients have independent signals
312 owing to taxa-specific environmental requirements (Brodersen et al. 2008; Eggermont and Heiri
313 2012), they also covariate as taxa preferring low oxygen conditions tend to prefer increased nutrient
314 conditions (Brodersen and Quinlan 2006). Nonetheless, the current results can separate the
315 development of the ecological lake status between hypolimnetic and epilimnetic waters and suggest
316 that in future assessments of ecological lake status both surface and bottom water habitats need to
317 be examined.

318

319 *Limnological development*

320

321 The chironomid-based reconstruction of hypolimnetic DO showed low-oxygen conditions already
322 between ~1950–1975 CE (Fig. 7). This suggests that agricultural activities, even before the

323 initiation of intensified farming (Hietala-Koivu 2002), had caused bottom water oxygen deficiency
324 and anoxia due to the increased transport of nutrients and their effects on biological oxygen
325 consumption following increased catchment erosion (forest clearance for cultivation). In
326 conjunction with the present results, chironomid fauna in the very shallow Kirkkojärvenselkä basin,
327 examined in a previous paleolimnological survey (Weckström et al. 2011), suggested deteriorated
328 oxygen conditions since the 1950's. In agreement with the measured minimum DO, the
329 reconstruction showed improved oxygen conditions in the basin during the 1980's that was
330 followed by significant oscillations in the values from the 1990's onwards. Although the
331 reconstructed and measured trends were similar, there were differences in the values. This is most
332 likely due to seasonal differences, since the oxygen calibration model is based on late-winter
333 measurements, whereas the instrumentally measured minimum DO at the basin occurs during the
334 late-summer (August).

335   Both the reconstructed and observed conditions at the present ($O_2 \sim 6 \text{ mg l}^{-1}$) suggest
336 that there has been improvement in the oxygen state since the poor conditions of the 1990's. The
337 current oxygen concentrations are rather typical for a baseline condition of a clay-turbid lake with
338 intermediate human influence in the catchment (Luoto and Nevalainen 2011). The overall large
339 variability in DO throughout the record and the apparent lack of a connection with the variations in
340 the pelagic nutrient concentrations underscores the importance of other environmental controls,
341 such as yearly variation in water column mixing, on hypolimnetic oxygen status. The impacts of the
342 ongoing climate change may also affect the oxygen state through increased catchment erosion,
343 longer ice-free period and higher biological productivity. Generally, increased erosion and
344 biological production may have a deteriorating, while the diminished ice-cover an improving
345 impact on oxygen state (Adrian et al. 2009; Foley et al. 2012).

346   Although the chironomid- and diatom-based TP reconstructions had similar trends and
347 the values showed significant correlation, the changes were larger in the chironomid record

348 compared to diatoms (Fig. 8). Regardless that both calibration models are based on epilimnetic TP,
349 the differences in the model outputs could be due to habitat characteristics, since as benthic
350 invertebrates, chironomids utilize bottom water phosphorus for growth and development (Aagaard
351 1982). Typically, there is more phosphorus available at the hypolimnion compared to the
352 epilimnion (Salonen et al. 1984), which could explain the higher values in the chironomid-based
353 reconstruction in the most recent part of the record.

354   In contrast to the diatom-based epilimnetic TP values that indicate mesotrophy already
355 during the 1940's, the chironomid-based TP reconstruction showed oligo-mesotrophic conditions
356 and a slightly decreasing trend in the initial part of the record with minimum values in the mid
357 1970's. The minimum TP is also reflected in the measured data representing the water quality
358 conditions of the basin in the summer of 1974 CE. During the 1980's the basin shifted to a
359 mesotrophic state, however, with temporarily lower summer nutrient conditions during the early
360 1990's. According to the chironomid-based reconstruction, there has been a rapid recent increase
361 towards more nutrient-rich conditions. Although visible also in the diatom-based reconstruction,
362 this recent nutrient enrichment was not, however, seen in the measured data, probably owing to the
363 fact that it represents a snapshot in time (single measurement) compared to the longer integrated
364 period in the proxy-based data.

365   Microbial activity and degradation processes of settled material in upper sediment
366 layers are typically more intensive in surface sediments than in deeper (historical) sediments
367 (Wetzel 2001) that could potentially influence paleolimnological interpretations. However, the
368 sediment profile consisted of mostly inorganic homogenous material and no distinct difference was
369 observed in the sediment quality that could indicate possible problems. Generally, the best means to
370 verify paleolimnological reconstructions is to compare them against instrumental data (Battarbee et
371 al. 2012). In our study, the reconstructions appear realistic, not only based on the trends but also
372 according to the inferred values. For example, the chironomid-inferred DO for the surface sample

373 was 5.7 mg l⁻¹, whereas the measured was 5.5 mg l⁻¹ fitting well within the models RMSEP. In the
374 diatom-based TP reconstruction, the reconstructed value for the present was 33 µg l⁻¹, whereas the
375 measured epilimnetic TP value was 39 µg l⁻¹, also showing good correspondence. However, the
376 chironomid-based TP of 53 µg l⁻¹ is closer to the modern measured hypolimnetic TP of 59 µg l⁻¹
377 than the epilimnetic measurement, further suggesting that our interpretation on the influence of
378 habitat characteristics on the inferences are correct. Although it is clear that chironomids and
379 chaoborids respond to both nutrients and oxygen (Lencioni et al. 2008; Small et al. 2011), it can be
380 spurious to simultaneously reconstruct both variables using the transfer function approach since it
381 may not be clear how the chironomid-environment relationships change in time. In this study, the
382 results demonstrate that both chironomid-based reconstructions were logical and realistic, at least
383 during the observational period during which the instrumental verification of the reconstructions
384 was possible.

385

386 **Conclusions**

387

388 The results of this paleolimnological study show consistent changes in the development of the
389 nutrient and oxygen status of Hiidenvesi that were mostly comparable to the measured limnological
390 data of the observational period. The lake benthos has changed since the 1940's first into a
391 mesotrophic community in the 1960's and later in the 1990's into a eutrophic community.
392 Similarly, the diatom communities show a clear directional shift with increases in the abundances of
393 species typically related to the eutrophication process since the 1970's. In general, the basin appears
394 to have remained relatively mildly nutrient stressed for a turbid lake in the early part of the record,
395 although the diatom-based TP reconstruction suggested mesotrophic epilimnion already during the
396 1940's. From the end of the 1970's until the late 1980's and again since the mid-1990's the lake has
397 developed into a more productive system, the most recent years reflecting a significant increase in

398 nutrient conditions especially in the benthic habitat. The presence of *Chaoborus* throughout the
399 record provides indications that a persistent low-oxygen refugia has prevailed in the hypolimnion.
400 The chironomid-based reconstruction of hypolimnetic DO displayed cyclic fluctuations over the
401 study period, largely irrespective of the nutrient development.

402   Although this study shows signs of recent eutrophication, it can also be seen from the
403 results that, in comparison to a pristine boreal lake, the lake has been elevated in nutrients already
404 since the beginning of the record at the 1940's. Similarly, it is also evidenced by the results that the
405 basin has suffered from anoxia during the entire studied period. This research cannot define the
406 actual reference state of the lake, since the record does not extend back in time before human
407 disturbances in the ecosystem. The results of this study can, however, act as applicable guidelines
408 for future preservation, conservation and restoration efforts following that the lake and catchment
409 conditions during the 1940's, prior to intensified farming, most probably represent a more realistic
410 target state than conditions prior to any anthropogenic influence. This study also underlines the
411 importance of separating the epilimnetic and hypolimnetic water bodies in long-term
412 limnoecological assessments.

413

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Figure captions

Fig. 1 Location of Lake Hiidenvesi in southern Finland and the sampling site at the Kiihkelyksenselkä basin

Fig. 2 Lithology, water content and organic matter content (measured as loss on ignition) of the sediment profile from Hiidenvesi

Fig. 3 Total specific activity of ^{210}Pb and ^{226}Ra (daughters) and accumulation of ^{137}Cs in the sediment core from Hiidenvesi. The age-depth model is based on constant rate of unsupported ^{210}Pb supply model (CRS). The peak in ^{137}Cs results from the Chernobyl accident fallout in 1986

668 **Fig. 4** Midge stratigraphy from Hiidenvesi including the absolute and relative abundances of
669 chironomids and chaoborids. The chaoborid:chironomid-ratio indicates severity of anoxia and N2
670 diversity index represents the effective number of occurrences

671

672 **Fig. 5** Relative (%) abundances of the most common ($\max \geq 2\%$) diatom taxa in the sediment
673 profile from Hiidenvesi. The N2 diversity index represents the effective number of occurrences

674

675 **Fig. 6** Principal component analysis (PCA) plot for midge ($\lambda_1=0.23$, $\lambda_2=0.17$) and diatom ($\lambda_1=0.28$,
676 $\lambda_2=0.09$) assemblages in the Hiidenvesi sediment record

677

678 **Fig. 7** Chironomid-inferred hypolimnetic dissolved oxygen (DO) from the Hiidenvesi sediment
679 profile compared against measured DO since the 1980's. The trend lines use LOESS smoothing
680 (span 0.4)

681

682 **Fig. 8** Chironomid- and diatom-inferred total phosphorus (TP) from the Hiidenvesi sediment profile
683 compared against measured TP since the 1970's. The trend lines use LOESS smoothing (span 0.4)

684

685 **Electronic Supplementary Material**

686

687 **Suppl. 1** List of diatom species with their habitat preferences and occurrences in the Hiidenvesi
688 sediment core. Updates in nomenclature are primarily based on Porter (2008)