

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

Tomi P. Luoto · Marttiina V. Rantala ·
Mira H. Tammelin

Received: 28 June 2017 / Accepted: 25 October 2017 / Published online: 24 November 2017
© Springer International Publishing AG, part of Springer Nature 2017

Abstract We examined a sediment record from Lake Hiidenvesi in southern Finland using paleolimnological methods to trace its limnoecological history. In our record, beginning from the 1940s, chironomid (Diptera) assemblages shifted from typical boreal taxa towards mesotrophic community assemblages at ~ 1960–1980 CE being finally replaced by eutrophic taxa from the 1990s onward. The diatom (Bacillariophyceae) assemblages reflected relatively nutrient rich conditions throughout the record showing a further increase in eutrophic taxa from the 1970s onward. A chironomid-based reconstruction of late-winter hypolimnetic dissolved oxygen (DO) conditions suggested anoxic conditions already in the 1950s, probably reflecting increased inflake production due to allochthonous nutrient inputs and related increase in biological oxygen consumption. However, the reconstruction also indicated large variability in long-term oxygen conditions that

appear typical for the basin. With regard to nutrient status, chironomid- and diatom-based reconstructions of total phosphorus (TP) showed a similar trend throughout the record, although, chironomids indicated a more straightforward eutrophication process in the benthic habitat and seemed to reflect the intensified human activities in the catchment more strongly than diatoms. The DO and TP reconstructions were mostly similar in trends compared to the measured data available since the 1970s/1980s. However, the increase in TP during the most recent years in both reconstructions was not visible in the monitored data. The results of our multiproxy study emphasize the significance of including both epilimnetic and hypolimnetic systems in water quality assessments and provide important long-term limnoecological information that will be useful in the future when setting targets for restoration.

Electronic supplementary material The online version of this article (<https://doi.org/10.1007/s11270-017-3622-z>) contains supplementary material, which is available to authorized users.

T. P. Luoto (✉)
Department of Environmental Sciences, University of Helsinki,
Niemenkatu 73, FI-15140 Lahti, Finland
e-mail: tomi.luoto@helsinki.fi

M. V. Rantala
Department of Geosciences and Geography, University of
Helsinki, P.O. Box 64, FI-00014 Helsinki, Finland

M. H. Tammelin
Department of Geography and Geology, University of Turku,
FI-20014 Turku, Finland

Keywords *Chaoborus* · Chironomids · Diatoms ·
Hypolimnetic oxygen · Nutrient enrichment ·
Phosphorus

1 Introduction

Assessments of long-term limnoecological dynamics extending beyond the observational period are essential for the successful implementation of lake management acts. Paleolimnology examines the environmental history of lakes and their catchments using sedimentary archives that preserve physical, chemical, and biological proxy information (Smol 2009). Paleolimnology has

proven to be very useful in assessments of limnological reference conditions that allow the evaluation of natural dynamics, timing of change, and targets of restoration (Bennion et al. 2011). The most common biological proxy sources in assessments of reference state include diatom (Bacillariophyceae) algae and chironomid (Diptera: Chironomidae) insect larvae, of which remains preserve well in sediments and are identifiable to species or generic level (Dixit et al. 1992; Hofmann 1988). Diatoms and their fossil communities often readily reflect the nutrient development of the water column (Anderson 1997; Kauppila and Valpola 2003), whereas fossil chironomid midge assemblages tend to reflect changes in the bottom water, such as in the hypolimnetic oxygen concentrations (Brodersen and Quinlan 2006; Francis 2001) or deep-water nutrients (Vanni 2002).

In addition to ecological dynamics, fossil communities can be used to quantitatively reconstruct changes in limnology via the calibration set approach. In such reconstructions, the modern species optima in a training set are utilized in a sediment downcore using a transfer function, which connects the modern species optima with the past fossil communities producing a quantitative reconstruction of a particular variable. Diatoms are commonly used to quantitatively reconstruct long-term changes in total phosphorus (TP) (Kauppila et al. 2002) and pH (Battarbee et al. 2010), whereas chironomids are often used to reconstruct TP (Brooks et al. 2001) and hypolimnetic dissolved oxygen (DO) (Quinlan and Smol 2001). It is also possible to estimate the concentration of deep-water oxygen by using the ratio between chaoborids (Diptera: Chaoboridae) and chironomids as an indicator of anoxia (Quinlan and Smol 2010).

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

In this study, we examine the long-term ecological and limnological development of the lake using fossil diatom and chironomid analyses combined with quantitative paleolimnological modeling. The objective is to

reconstruct changes in the planktonic and benthic communities and in the surface-water nutrient and deep-water oxygen levels of the basin in high resolution since the initiation of intensified human activity around the lake at the turn of the 1950s. This knowledge will be useful when setting targets for lake restoration, especially in the case of reducing surface water nutrients and in evaluating the usefulness of artificial bottom-water oxygenation. The results of this study will also improve understanding of lake development under increasing anthropogenic pressure.

2 Materials and Methods

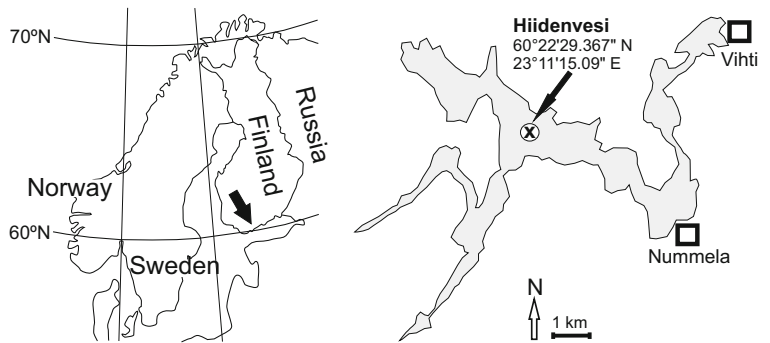
2.1 Study Site

Hiidenvesi (60° 22' N, 23° 11' E; 32 m a.s.l.) is a clay-turbid lake located in southern Finland (Fig. 1). 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 the 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).

2.2 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.

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



1991). The sediments were subsampled in the field into small plastic bags at 1 cm intervals. The sediment profile consisted of generally homogenous gray-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).

2.3 Midge Analysis

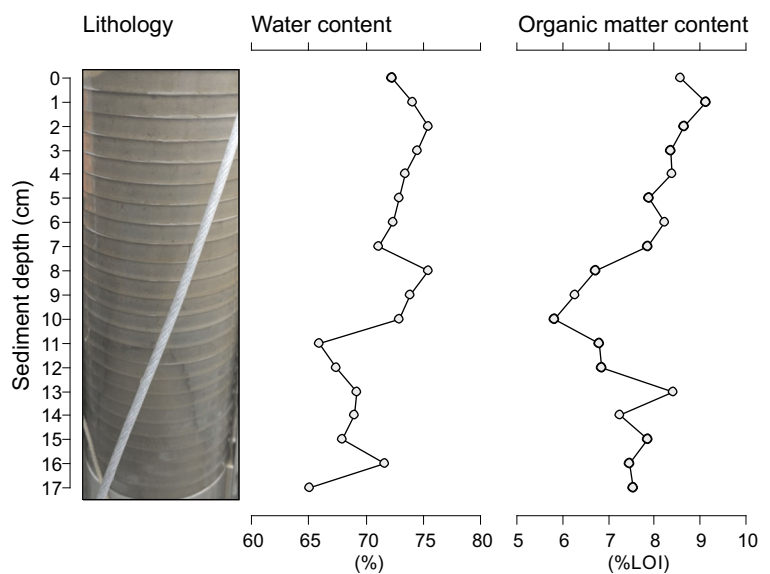
Volumetric sediment samples of 5 cm³ were prepared using standard methodology for subfossil chironomid analysis (Brooks et al. 2007). Sediments were sieved through a 100-µm mesh and the residue was examined in a Bogorov sorting tray under a binocular microscope

for extraction of subfossil head capsules using fine forceps. All specimens (typically the fourth instar larvae) were permanently mounted in Euparal® on microscope slides and identified under a light microscope at × 100 to × 400 magnification. A minimum count size of 50 individuals was set (Larocque 2001). Chironomids were identified using Brooks et al. (2007). From the same samples, chaoborids and ceratopogonids (Diptera: Ceratopogonidae) were also identified based on Finnish fossil specimens (Luoto 2009; Luoto and Nevalainen 2009).

2.4 Diatom Analysis

Samples for diatom analysis were prepared following standard procedures (Battarbee et al. 2001). Organic matter was removed by oxidizing sediment samples with hydrogen peroxide solution (30% H₂O₂), after which a few drops of hydrochloric acid (37% HCl) were

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



added to remove carbonate minerals. Coarse minerogenic matter was removed physically by swirling the sample solution in a beaker and decanting the diatom suspension. The remaining sample residue was checked for absence of diatom valves before disposal. Samples were dried on coverslips and mounted with Naphrax® (Brunel Microscopes Ltd., Wiltshire, UK). Diatoms were enumerated under a light microscope at $\times 1000$ magnification, setting the minimum counting sum at 300 diatom valves. Taxonomic determination was mainly based on the flora of Krammer and Lange-Bertalot (1986, 1988, 1991a, b), with nomenclature updated where relevant due to taxonomic refinements (Suppl. 1).

2.5 Statistical Analyses and Paleolimnological Modeling

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

Past variability in minimum hypolimnetic DO (i.e., late-winter in the training set) was reconstructed using a 30-lake chironomid-based calibration model for southern Finland ranging from anoxic to hypersaturated sites (Luoto and Nevalainen 2011; Luoto and Salonen 2010). The weighted averaging partial least squares (WA-PLS) model using one WA-PLS component has a cross-validated (leave-one-out) coefficient of determination (r^2_{jack}) of 0.72 and a root mean squared error of prediction (RMSEP) of 2.4 mg l^{-1} . In addition to DO, chironomid assemblages were used to reconstruct past changes in TP. The TP model (Luoto 2011) uses 51 lakes across Finland ranging from oligotrophic to hypertrophic sites ($\text{TP} = 1.5\text{--}105 \text{ } \mu\text{g l}^{-1}$). The chironomid-based autumnal epilimnetic TP inference model uses WA-PLS technique with four calibration regression components, and it has an r^2_{jack} of 0.92 and RMSEP of $6.7 \text{ } \mu\text{g l}^{-1}$. The diatom-based epilimnetic TP reconstructions used a 47-lake

calibration set from eastern Finland covering a TP gradient of $7\text{--}122 \text{ } \mu\text{g l}^{-1}$. The two-component WA-PLS model with leave-one-out cross-validation has an r^2_{jack} of 0.82 and RMSEP of $0.15 \text{ log } \mu\text{g l}^{-1}$ (Tammelin and Kauppi 2015). All reconstructions were performed using the program C2 (Juggins 2007). The reconstructions were validated for their reliability by comparing the reconstructed values against limnological measurements. Locally weighted smoothing (LOESS) was applied to standardize chronological differences between the reconstructed and measured values.

2.6 Sediment Dating

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

3 Results

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

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

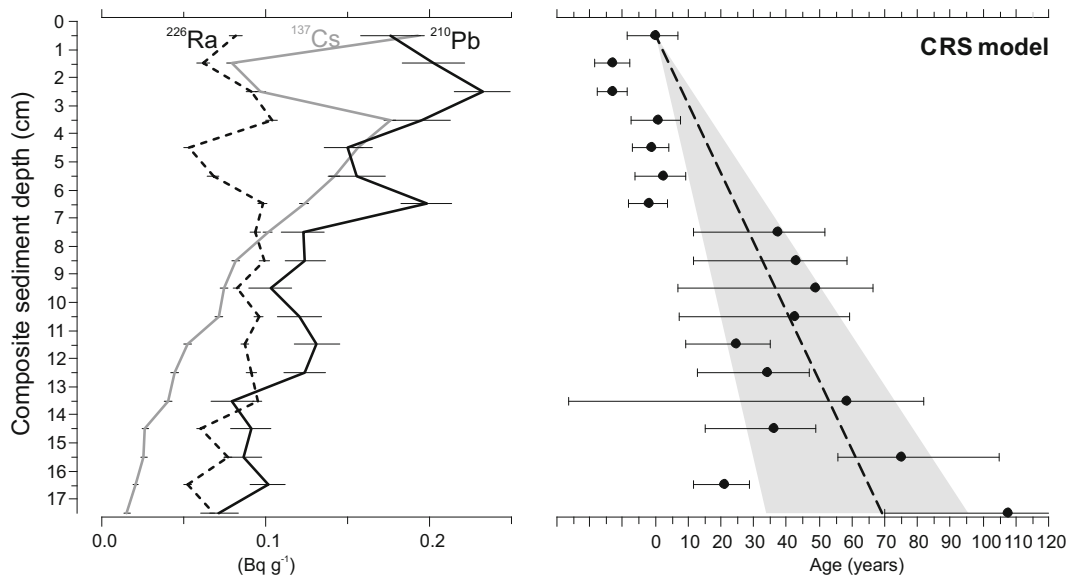


Fig. 3 Total specific activity of ^{210}Pb and ^{226}Ra (daughters) and accumulation of ^{137}Cs in the sediment core from Hiidenvesi. The age-depth model is based on constant rate of unsupported ^{210}Pb

supply model (CRS). The peak in ^{137}Cs results from the Chernobyl accident fallout in 1986

The midge assemblages in the sediment core consisted mostly of chironomids and chaoborids (Fig. 4). A total of 29 chironomid taxa were identified from the samples. In general, the chironomid flux (head capsules per volumetric sample) increased towards the present. Of the non-chironomid midges, *Chaoborus flavicans* was abundant throughout the core, whereas *Bezzia*-type ceratopogonids occurred only in the surface sediment. Of the chironomids, *Tanytarsus glabrescens*-type was abundant in the lower part of the core (~1945–1970 CE). *Sergentia* was common in the 1960s and 1970s, when also *T. mendax*-type had its maximum

abundances. In the later part of the core, *Procladius* thrived from the 1990s to 2000, after which *T. glabrescens*-type again increased in abundance and *Chironomus plumosus*-type appeared in the record. Midge diversity, measured as N2, showed an increasing trend throughout the record with the highest diversity reached at the most recent sample (Fig. 4).

In all, 146 different diatom taxa from 32 genera were identified from the samples (Suppl. 1). Planktonic taxa dominated the diatom assemblages (Fig. 5), with high abundance of *Aulacoseira granulata*, *Aulacoseira ambigua*, and *Aulacoseira subarctica*. *A. subarctica*-

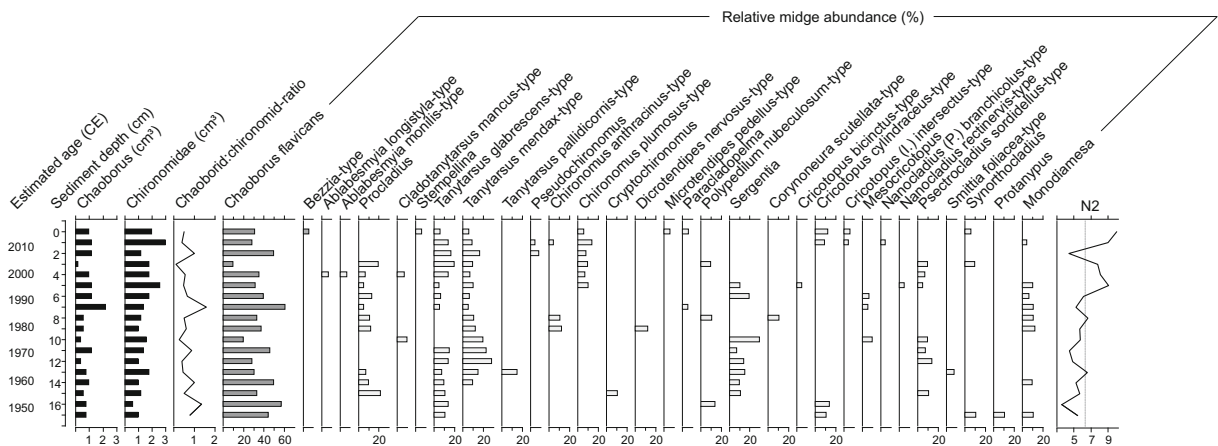


Fig. 4 Midge stratigraphy from Hiidenvesi including the absolute and relative abundances of chironomids and chaoborids. The chaoborid/chironomid ratio indicates severity of anoxia and N2 diversity index represents the effective number of occurrences

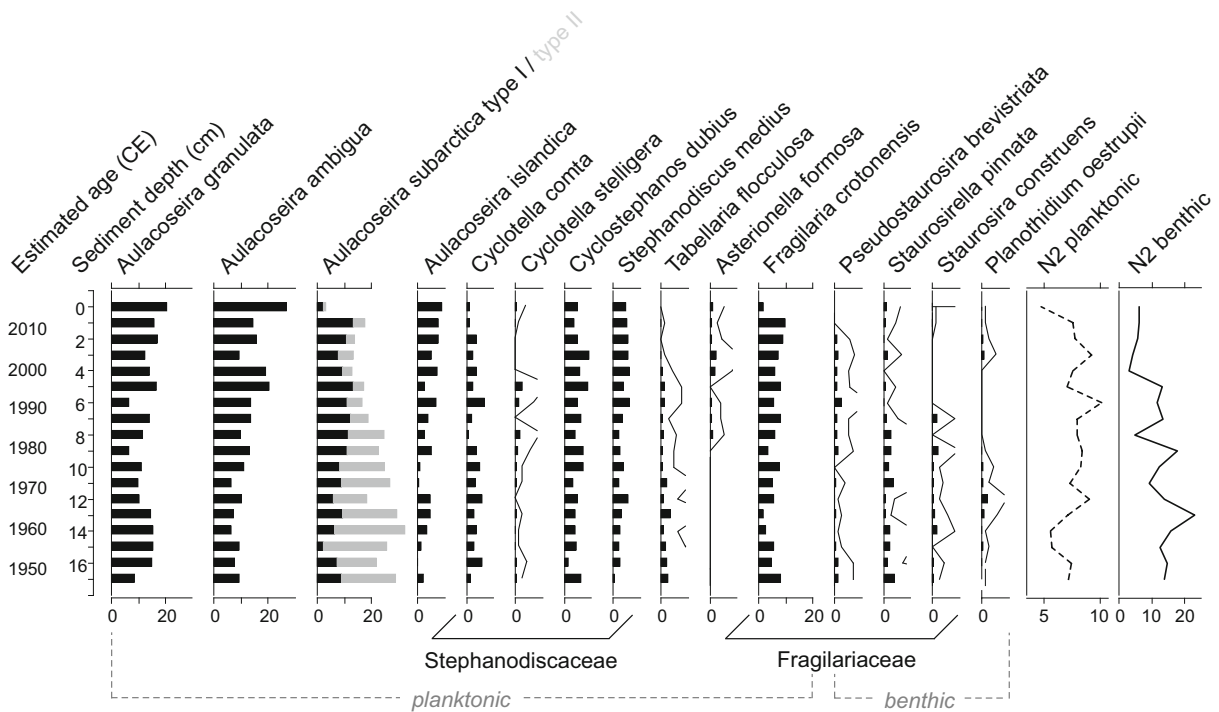


Fig. 5 Relative (%) abundances of the most common (max $\geq 2\%$) diatom taxa in the sediment profile from Hiidenvesi. The N2 diversity index represents the effective number of occurrences

type II (lower mantle height/valve diameter ratio) was the most common taxon in the lower part of the sediment profile (~ 1945 – 1985 CE) but began to decline, thereafter, and was largely replaced by a more slender morphotype in the upper part of the core. *A. ambigua*, *Aulacoseira islandica*, and *Fragilaria crotonensis* displayed a slight increase from the 1970s onwards, and *Stephanodiscus medius* and *Asterionella formosa* showed their highest abundances since the 1980s. The benthic community was rich in species but low in numbers, with species of *Fragilaria* sensu lato (e.g., *Staurosirella pinnata*, *Pseudostaurosira brevistriata*) as the most abundant. Planktonic diatom diversity was slightly elevated between the 1960s and 2000 CE, with the lowest diversity recorded in the most recent sample (Fig. 5). In the benthic community, diatom diversity declined gradually since the 1960s.

The midge PCA axis 1 scores (Fig. 6) were negative in the bottom and top parts of the sediment sequence and mostly positive in between. Highest axis 2 scores occurred around the 1980s. The diatom PCA axis 1 scores (Fig. 6) remained negative until the 1980s but shifted thereafter into positive scores showing a clear directional succession. The highest diatom axis 1 score occurred in the surface sediment sample. According to the

segmented regression analysis, a significant breakpoint in the midge PCA axis 1 scores occurred at 1963 CE and in the axis 2 scores at 1976 CE. No significant breakpoint was found in the diatom axis 1 scores but in the axis 2 scores, a breakpoint occurred at 1991 CE.

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

The chironomid-based reconstruction of TP (Fig. 8) showed a general development from oligo-mesotrophic conditions between ~ 1945 and 1975 CE to mesotrophy between ~ 1980 and 2010 CE, finally reaching eutrophy at the present. The diatom-TP inferences did not show a

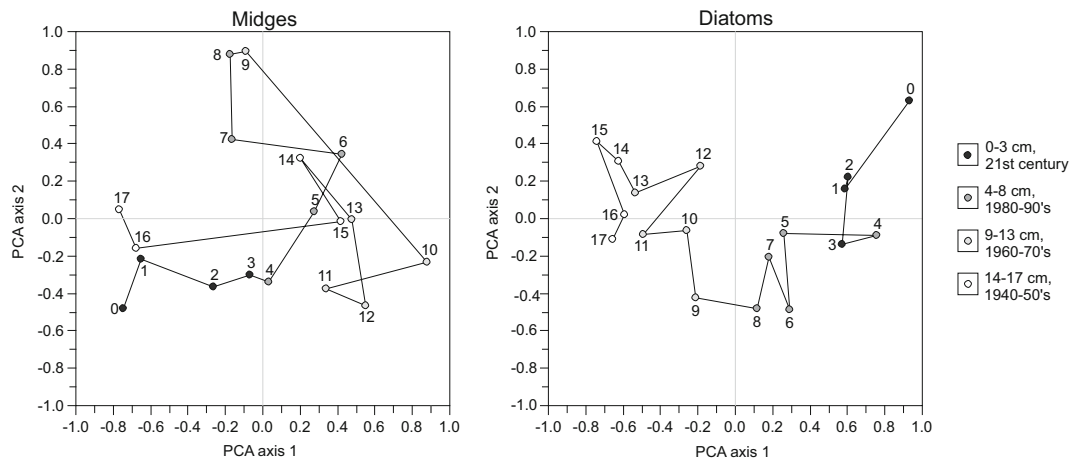


Fig. 6 Principal component analysis (PCA) plot for midge ($\lambda_1 = 0.23, \lambda_2 = 0.17$) and diatom ($\lambda_1 = 0.28, \lambda_2 = 0.09$) assemblages in the Hiidenvesi sediment record

clear eutrophication process. Nevertheless, the trend is otherwise very similar to the chironomid-based reconstruction with elevated values in the oldest and most recent samples as well as during the 1980s. Despite the differences, there was a significant correlation ($R = 0.55, r^2 = 0.30, p < 0.019$) between the chironomid- and diatom-based TP reconstructions. In comparison to the measured data available since the 1970s (Fig. 8), the chironomid- and diatom-based TP trends showed close correspondence, with the exception that the measured

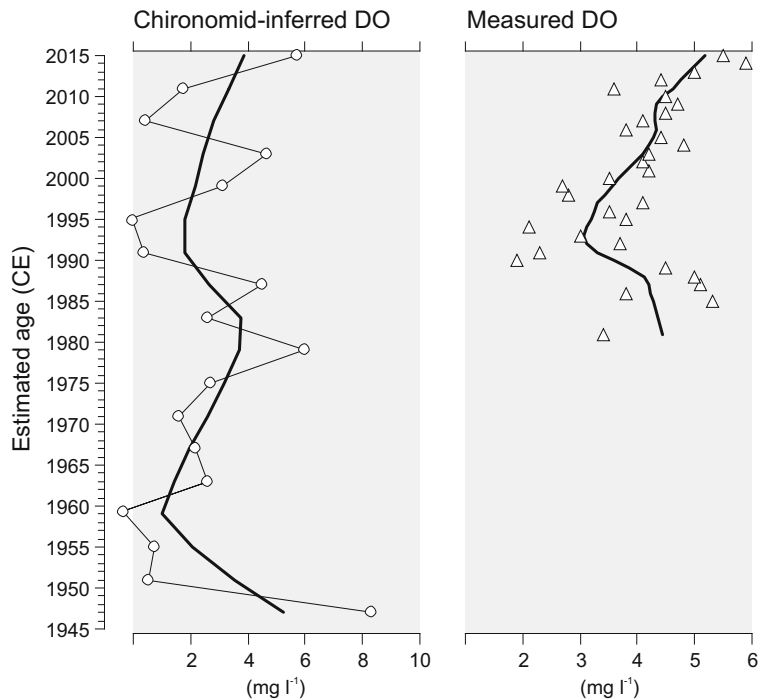
TP did not record a recent increase that was particularly clear in the chironomid-based reconstruction.

4 Discussion

4.1 Ecological Dynamics

The fossil chironomid assemblages (Fig. 4) in Hiidenvesi were rather typical for a clay-turbid

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



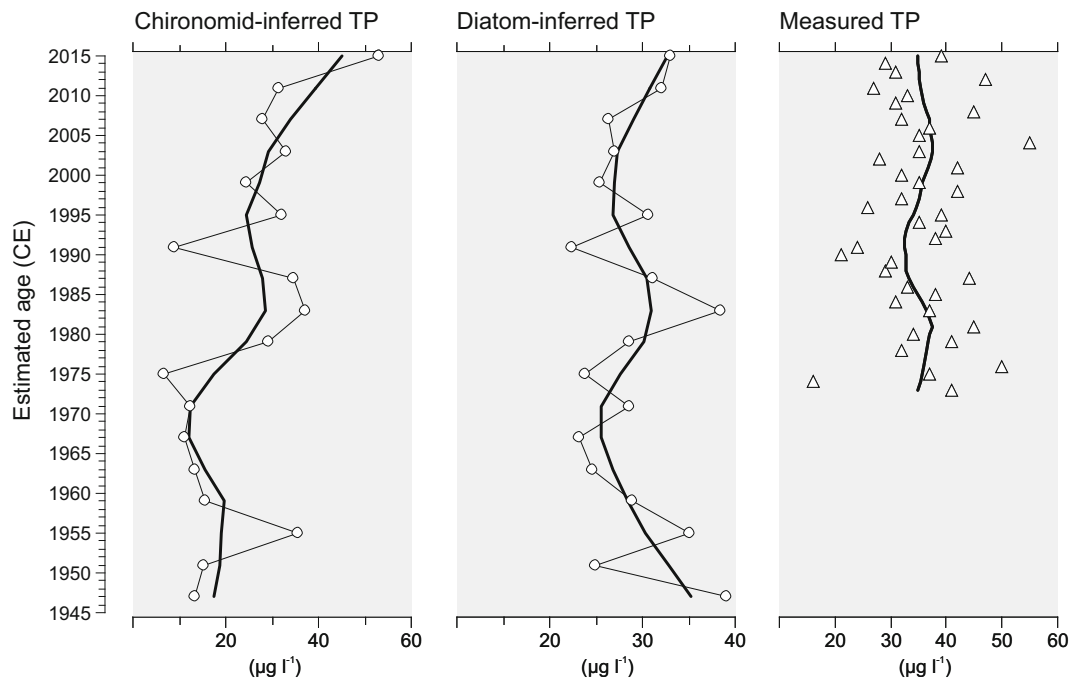


Fig. 8 Chironomid- and diatom-inferred total phosphorus (TP) from the Hiidenvesi sediment profile compared against measured TP since the 1970s. The trend lines use LOESS smoothing (span 0.4)

nutrient-rich lake in the area (Luoto and Ojala 2014, 2017; Luoto and Raunio 2011; Salonen et al. 1993). In addition to chironomids, *Chaoborus flavicans*, which prefers turbid and productive lakes (Liljendahl-Nurminen et al. 2002), was common throughout the sediment profile. Subsequently, the chaoborus/chironomid ratio, which indicates the presence of anoxia (Quinlan and Smol 2010), provided evidence that hypolimnetic oxygen deficiency has occurred in the basin since the 1940s. To thrive, *Chaoborus* requires an anoxic lake bottom, where it can hide during the day avoiding visual predation by fish and, when the night falls, it rises up the water column to feed on zooplankton (Liljendahl-Nurminen 2006).

The most distinct change in the chironomid communities was the increase in mesotrophic chironomid taxa, such as *Procladius*, *Tanytarsus mendax*-type, and *Sergentia*, at the mid-part of the stratigraphy (1960–2000 CE). In the more recent period, the most significant change was the appearance of the typical eutrophy indicating species *Chironomus plumosus*-type (Kansanen 1985; Salonen et al. 1993), which also tolerates oxygen deficiency, into the stratigraphy in the 1990s. A distinct diversity threshold was also crossed in the midge communities during the 1990s displayed as

a sudden increase in diversity (Fig. 4). This is a typical development in a eutrophication process, as the number of benthic invertebrate species increases alongside nutrient enrichment due to increased habitat availability (Wiederholm 1980). However, when lakes become hypertrophic and permanently anoxic, the diversity naturally decreases (Bryce and Hobart 1972).

The diatom diversity showed a decrease in benthic diatom life forms and a simultaneous increase in the planktonic diversity since the 1970s (Fig. 5). This shift in the diatom communities could indicate increased turbidity in the water column related to increased phytoplankton production and sediment flux from the catchment, reducing light availability to benthic growth. Overall, the diatom communities (Fig. 5) of the basin have been dominated by planktonic taxa, which require water column turbulence to linger in the euphotic zone. The abundant *Aulacoseira granulata* and *Aulacoseira ambigua* are typical for eutrophic lakes (Lotter 2001; Meriläinen et al. 2003; Miettinen 2003), and *Aulacoseira subarctica* is commonly affiliated with mesotrophic waters (Gibson et al. 2003). The presence of eutrophic *Stephanodiscaceae* species (e.g., *Cyclostephanos dubius*) provides further indication for high productivity (Miettinen 2003; Punning et al. 2008),

whereas the small fragilarioids of the benthic community tolerate unstable environmental conditions and reduced light availability (Anderson 2000; Luoto et al. 2012), hence reflecting the turbid waters of Hiidenvesi.

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

According to the PCAs, it appears that chironomids have responded, in addition to the primary environmental driver (axis 1), to secondary environmental gradients (axis 2), whereas the secondary gradients have had only a minute influence on the diatom communities (Fig. 6). Based on the analysis, chironomids appear to have returned in the 2000s to a previous ecological state that prevailed during the 1940–1950s, i.e., in the initial part of the record. Yet, the species composition is rather different, possibly suggesting an alternative stable state (cf. Hobbs et al. 2012). This community shift is probably due to the lake restoration efforts during the recent years that have improved the hypolimnetic conditions of the basin (measured DO in Fig. 7), while no clear declines in nutrient concentrations have occurred (Fig. 8). Consequently, the diatom communities show a distinct progressive succession towards a new ecological state. This is also verified by the breakpoint analysis, which did not identify a significant threshold for the diatom PCA axis 1 scores. The significant breakpoint in the primary midge PCA axis scores occurred at 1963 CE when several nutrient-preferring chironomids, such as *Tanytarsus mendax*-type (Ekrem et al. 1999), increased in the assemblages. Although midge responses to

oxygen and nutrients have independent signals owing to taxa-specific environmental requirements (Brodersen et al. 2008; Eggermont and Heiri 2012), they also covariate as taxa preferring low oxygen conditions tend to prefer increased nutrient conditions (Brodersen and Quinlan 2006). Nonetheless, the current results can separate the development of the ecological lake status between hypolimnetic and epilimnetic waters and suggest that in future assessments of ecological lake status, both surface and bottom water habitats need to be examined.

4.2 Limnological Development

The chironomid-based reconstruction of hypolimnetic DO showed low-oxygen conditions already between ~1950–1975 CE (Fig. 7). This suggests that agricultural activities, even before the initiation of intensified farming (Hietala-Koivu 2002), had caused bottom water oxygen deficiency and anoxia due to the increased transport of nutrients and their effects on biological oxygen consumption following increased catchment erosion (forest clearance for cultivation). In conjunction with the present results, chironomid fauna in the very shallow Kirkkojärvenselkä basin, examined in a previous paleolimnological survey (Weckström et al. 2011), suggested deteriorated oxygen conditions since the 1950s. In agreement with the measured minimum DO, the reconstruction showed improved oxygen conditions in the basin during the 1980s that was followed by significant oscillations in the values from the 1990s onwards. Although the reconstructed and measured trends were similar, there were differences in the values. This is most likely due to seasonal differences, since the oxygen calibration model is based on late-winter measurements, whereas the instrumentally measured minimum DO at the basin occurs during the late-summer (August).

Both the reconstructed and observed conditions at the present ($O_2 \sim 6 \text{ mg l}^{-1}$) suggest that there has been improvement in the oxygen state since the poor conditions of the 1990s. The current oxygen concentrations are rather typical for a baseline condition of a clay-turbid lake with intermediate human influence in the catchment (Luoto and Nevalainen 2011). The overall large variability in DO throughout the record and the apparent lack of a connection with the variations in the pelagic nutrient concentrations underscores the importance of other environmental controls, such as yearly variation in

water column mixing, on hypolimnetic oxygen status. The impacts of the ongoing climate change may also affect the oxygen state through increased catchment erosion, longer ice-free period, and higher biological productivity. Generally, increased erosion and biological production may have a deteriorating, while the diminished ice-cover an improving, impact on oxygen state (Adrian et al. 2009; Foley et al. 2012).

Although the chironomid- and diatom-based TP reconstructions had similar trends and the values showed significant correlation, the changes were larger in the chironomid record compared to diatoms (Fig. 8). Regardless that both calibration models are based on epilimnetic TP, the differences in the model outputs could be due to habitat characteristics, since as benthic invertebrates, chironomids utilize bottom water phosphorus for growth and development (Aagaard 1982). Typically, there is more phosphorus available at the hypolimnion compared to the epilimnion (Salonen et al. 1984), which could explain the higher values in the chironomid-based reconstruction in the most recent part of the record.

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

Microbial activity and degradation processes of settled material in upper sediment layers are typically more intensive in surface sediments than in deeper (historical) sediments (Wetzel 2001) that could potentially influence paleolimnological interpretations. However, the sediment profile consisted of mostly inorganic homogenic material and no distinct difference was observed in the sediment quality that could indicate possible problems. Generally, the best means to verify paleolimnological

reconstructions is to compare them against instrumental data (Battarbee et al. 2012). In our study, the reconstructions appear realistic, not only based on the trends but also according to the inferred values. For example, the chironomid-inferred DO for the surface sample was 5.7 mg l^{-1} , whereas the measured was 5.5 mg l^{-1} fitting well within the models RMSEP. In the diatom-based TP reconstruction, the reconstructed value for the present was $33 \text{ } \mu\text{g l}^{-1}$, whereas the measured epilimnetic TP value was $39 \text{ } \mu\text{g l}^{-1}$, also showing good correspondence. However, the chironomid-based TP of $53 \text{ } \mu\text{g l}^{-1}$ is closer to the modern measured hypolimnetic TP of $59 \text{ } \mu\text{g l}^{-1}$ than the epilimnetic measurement, further suggesting that our interpretation on the influence of habitat characteristics on the inferences is correct. Although it is clear that chironomids and chaoborids respond to both nutrients and oxygen (Lencioni et al. 2008; Small et al. 2011), it can be spurious to simultaneously reconstruct both variables using the transfer function approach since it may not be clear how the chironomid-environment relationships change in time. In this study, the results demonstrate that both chironomid-based reconstructions were logical and realistic, at least during the observational period during which the instrumental verification of the reconstructions was possible.

5 Conclusions

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

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

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

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

Funding Information Funding for this research was provided by the Hiidenvesi Restoration Project, the Emil Aaltonen Foundation (grant nos. 160156, 170161), and the Doctoral Program in Geosciences of the University of Helsinki.

References

- Aagaard, K. (1982). Profundal chironomid populations during a fertilization experiment in Langvatn, Norway. *Ecography*, *5*, 325–331.
- Adrian, R., O'Reilly, C. M., Zagarese, H., Baines, S. B., Hessen, D. O., Keller, W., Livingstone, D. M., Sommaruga, R., Straile, D., Van Donk, E., Weyhenmeyer, G. A., & Winder, M. (2009). Lakes as sentinels of climate change. *Limnology and Oceanography*, *54*, 2283–2297.
- Anderson, N. J. (1997). Historical changes in epilimnetic phosphorus concentrations in six rural lakes in Northern Ireland. *Freshwater Biology*, *38*, 427–440.
- Anderson, N. J. (2000). Miniview: diatoms, temperature and climatic changes. *European Journal of Phycology*, *35*, 307–314.
- Appleby, P. G. (2001). Chronostratigraphic techniques in recent sediments. In W. M. Last & J. P. Smol (Eds.), *Basin analysis, coring, and chronological techniques, tracking environmental change using lake sediments, vol. 1* (pp. 171–203). Dordrecht: Springer.
- Battarbee, R. W., Jones, V. J., Flower, R. J., Cameron, N. C., Bennion, H., Carvalho, L., & Juggins, S. (2001). Diatoms. In J. P. Smol, H. J. B. Birks, & W. M. Last (Eds.), *Tracking environmental change using lake sediments, terrestrial, algal, and siliceous indicators, vol. 3* (pp. 155–202). Dordrecht: Kluwer Academic Publishers.
- Battarbee, R. W., Charles, D. F., Bigler, C., Cumming, B. F., & Renberg, I. (2010). Diatoms as indicators of surface-water acidity. In J. P. Smol & E. F. Stoermer (Eds.), *The diatoms: applications for the environmental and earth sciences* (2nd ed., pp. 98–121). Cambridge: Cambridge University Press.
- Battarbee, R. W., Anderson, N. J., Bennion, H., & Simpson, G. L. (2012). Combining limnological and palaeolimnological data to disentangle the effects of nutrient pollution and climate change on lake ecosystems: problems and potential. *Freshwater Biology*, *57*, 2091–2106.
- Bennion, H., Battarbee, R. W., Sayer, C. D., Simpson, G. L., & Davidson, T. A. (2011). Defining reference conditions and restoration targets for lake ecosystems using palaeolimnology: a synthesis. *Journal of Paleolimnology*, *45*, 533–544.
- Brodersen, K. P., & Quinlan, R. (2006). Midges as palaeoindicators of lake productivity, eutrophication and hypolimnetic oxygen. *Quaternary Science Reviews*, *25*, 1995–2012.
- Brodersen, K. P., Pedersen, O. L. E., Walker, I. R., & Jensen, M. T. (2008). Respiration of midges (Diptera; Chironomidae) in British Columbian lakes: oxy-regulation, temperature and their role as palaeo-indicators. *Freshwater Biology*, *53*, 593–602.
- Brooks, S. J., Bennion, H., & Birks, H. J. B. (2001). Tracing lake trophic history with a chironomid-total phosphorus inference model. *Freshwater Biology*, *46*, 513–533.
- Brooks, S. J., Langdon, P. G., & Heiri, O. (2007). *The identification and use of palaeoarctic Chironomidae larvae in palaeoecology. QRA technical guide no. 10*. London: Quaternary Research Association.
- Bryce, D., & Hobart, A. (1972). The biology and identification of the larvae of the Chironomidae (Diptera). *Entomological Gazette*, *23*, 175–217.
- Dixit, S. S., Smol, J. P., Kingston, J. C., & Charles, D. F. (1992). Diatoms: powerful indicators of environmental change. *Environmental Science and Technology*, *26*, 22–33.
- Eggermont, H., & Heiri, O. (2012). The chironomid-temperature relationship: expression in nature and palaeoenvironmental implications. *Biological Reviews*, *87*, 430–456.
- Ekrem, T., Reiss, F., & Langton, P. H. (1999). *Tanytarsus mancospinosus* sp. n. (Diptera, Chironomidae) from eutrophic lakes in Europe. *Norwegian Journal of Entomology*, *46*, 79–88.
- Foley, B., Jones, I. D., Maberly, S. C., & Rippey, B. (2012). Long-term changes in oxygen depletion in a small temperate lake: effects of climate change and eutrophication. *Freshwater Biology*, *57*, 278–289.
- Francis, D. R. (2001). A record of hypolimnetic oxygen conditions in a temperate multi-depression lake from chemical evidence and chironomid remains. *Journal of Paleolimnology*, *25*, 351–365.

- Gibson, C. E., Anderson, N. J., & Haworth, E. Y. (2003). *Aulacoseira subarctica*: taxonomy, physiology, ecology and palaeoecology. *European Journal of Phycology*, 38, 83–101.
- Heiri, O., Lotter, A. F., & Lemcke, G. (2001). Loss on ignition as a method for estimating organic carbon content in sediments: reproducibility and comparability of results. *Journal of Paleolimnology*, 25, 101–110.
- Hietala-Koivu, R. (2002). Landscape and modernizing agriculture: a case study of three areas in Finland in 1954–1998. *Agriculture, Ecosystems and Environment*, 91, 273–281.
- Hill, M. O. (1973). Diversity and evenness: a unifying notation and its consequences. *Ecology*, 54, 427–432.
- Hobbs, W. O., Hobbs, J. M. R., LaFrançois, T., Zimmer, K. D., Theissen, K. M., Edlund, M. B., Michelutti, N., Butler, M. G., Hanson, M. A., & Carlson, T. J. (2012). A 200-year perspective on alternative stable state theory and lake management from a biomanipulated shallow lake. *Ecological Applications*, 22, 1483–1496.
- Hofmann, W. (1988). The significance of chironomid analysis (Insecta: Diptera) for paleolimnological research. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 62, 501–509.
- Juggins, S. (2007). *C2 version 1.5 user guide. Software for ecological and palaeoecological data analysis and visualisation*. Newcastle upon Tyne: University of Newcastle.
- Kansanen, P. H. (1985). Assessment of pollution history from recent sediments in Lake Vanajavesi, southern Finland. II. Changes in the Chironomidae, Chaoboridae and Ceratopogonidae (Diptera) fauna. *Annales Zoologici Fennici*, 22, 57–90.
- Kansanen, P. H., Jaakkola, T., Kulmala, S., & Suutarinen, R. (1991). Sedimentation and distribution of gamma-emitting radionuclides in bottom sediments of southern Lake Päijänne, Finland, after the Chernobyl accident. *Hydrobiologia*, 222, 121–140.
- Kauppi, T., & Valpola, S. E. (2003). Response of a shallow boreal lake to recent nutrient enrichment—implications for diatom-based phosphorus reconstructions. *Hydrobiologia*, 495, 47–58.
- Kauppi, T., Moisio, T., & Salonen, V. P. (2002). A diatom-based inference model for autumn epilimnetic total phosphorus concentration and its application to a presently eutrophic boreal lake. *Journal of Paleolimnology*, 27, 261–273.
- Krammer, K., & Lange-Bertalot, H. (1986). Bacillariophyceae. 1. Teil: Naviculaceae. In H. Ettl, J. Gerloff, H. Heynig, & D. Mollenhauer (Eds.), *Süßwasserflora von Mitteleuropa. Band 2/1*. Stuttgart: Gustav Fischer Verlag 875 pp.
- Krammer, K., & Lange-Bertalot, H. (1988). Bacillariophyceae. 2. Teil: Bacillariaceae, Epithemiaceae, Surirellaceae. In H. Ettl, J. Gerloff, H. Heynig, & D. Mollenhauer (Eds.), *Süßwasserflora von Mitteleuropa. Band 2/2*. Stuttgart: Gustav Fischer Verlag 596 pp.
- Krammer, K., & Lange-Bertalot, H. (1991a). Bacillariophyceae. 3. Teil: Centrales, Fragilariaceae, Eunotiaceae. In H. Ettl, J. Gerloff, H. Heynig, & D. Mollenhauer (Eds.), *Süßwasserflora von Mitteleuropa. Band 2/3*. Stuttgart: Gustav Fischer Verlag 576 pp.
- Krammer, K., & Lange-Bertalot, H. (1991b). Bacillariophyceae. 4. Teil: Achnantheaceae, Kritische Ergänzungen zu Navicula (Lineolatae) und Gomphonema, Gesamtliteraturverzeichnis. In H. Ettl, G. Gärtner, J. Gerloff, H. Heynig, & D. Mollenhauer (Eds.), *Süßwasserflora von Mitteleuropa. Band 2/4*. Stuttgart: Gustav Fischer Verlag 437 pp.
- Larocque, I. (2001). How many chironomid head capsules are enough? A statistical approach to determine sample size for palaeoclimatic reconstructions. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 172, 133–142.
- Lencioni, V., Bernabò, P., Vanin, S., Di Muro, P., & Beltrami, M. (2008). Respiration rate and oxy-regulatory capacity in cold stenothermal chironomids. *Journal of Insect Physiology*, 54, 1337–1342.
- Liljendahl-Nurminen, A. (2006). Invertebrate predation and trophic cascades in a pelagic food web—the multiple roles of *Chaoborus flavicans* (Meigen) in a clay-turbid lake. PhD thesis, University of Helsinki, s. 35.
- Liljendahl-Nurminen, A., Horppila, J., Eloranta, P., Malinen, T., & Uusitalo, L. (2002). The seasonal dynamics and distribution of *Chaoborus flavicans* larvae in adjacent lake basins of different morphometry and degree of eutrophication. *Freshwater Biology*, 47, 1283–1295.
- Lotter, A. F. (2001). The effect of eutrophication on diatom diversity: examples from six Swiss lakes. In R. Jahn, J. P. Kociolek, A. Witkowski, & P. Compère (Eds.), *Lange-Bertalot-Festschrift, Studies on diatoms* (pp. 417–432). Ruggell: A.R.G. Gantner Verlag K.G..
- Luoto, T. P. (2009). An assessment of lentic ceratopogonids, ephemeropterans, trichopterans and oribatid mites as indicators of past environmental change in Finland. *Annales Zoologici Fennici*, 46, 259–270.
- Luoto, T. P. (2011). The relationship between water quality and chironomid distribution in Finland—a new assemblage-based tool for assessments of long-term nutrient dynamics. *Ecological Indicators*, 11, 255–262.
- Luoto, T. P., & Nevalainen, L. (2009). Larval chaoborid mandibles in surface sediments of small shallow lakes in Finland—implications for palaeolimnology. *Hydrobiologia*, 631, 185–195.
- Luoto, T. P., & Nevalainen, L. (2011). Inferring reference conditions of hypolimnetic oxygen for deteriorated Lake Mallusjärvi in the cultural landscape of Mallusjoki, southern Finland using fossil midge assemblages. *Water, Air, & Soil Pollution*, 217, 663–675.
- Luoto, T. P., & Ojala, A. E. K. (2014). Paleolimnological assessment of ecological integrity and eutrophication history for Lake Tiiläänjärvi (Askola, Finland). *Journal of Paleolimnology*, 51, 455–468.
- Luoto, T. P., & Ojala, A. E. K. (2017). Meteorological validation of chironomids as a paleotemperature proxy using varved lake sediments. *The Holocene*, 27, 870–878.
- Luoto, T. P., & Raunio, J. (2011). A comparison of chironomid-based total phosphorus training sets developed from contemporary pupal exuviae and sedimentary larval head capsules to infer lake trophic history. *Fundamental and Applied Limnology*, 179, 93–102.
- Luoto, T. P., & Salonen, V.-P. (2010). Fossil midge larvae (Diptera: Chironomidae) as quantitative indicators of late-winter hypolimnetic oxygen in southern Finland: a calibration model, case studies and potentialities. *Boreal Environment Research*, 15, 1–18.
- Luoto, T. P., Nevalainen, L., Kauppi, T., Tammelin, M., & Sarmaja-Korjonen, K. (2012). Diatom-inferred total phosphorus from dystrophic Lake Arapisto, Finland, in relation

- to Holocene paleoclimate. *Quaternary Research*, 78, 248–255.
- Meriläinen, J. J., Hynynen, J., Palomäki, A., Mäntykoski, K., & Witick, A. (2003). Environmental history of an urban lake: a palaeolimnological study of Lake Jyväsjärvi, Finland. *Journal of Paleolimnology*, 30, 387–406.
- Miettinen, J. O. (2003). A diatom-total phosphorus transfer function for freshwater lakes in southeastern Finland, including cross-validation with independent test lakes. *Boreal Environment Research*, 8, 215–228.
- Mörner, N. A. (1982). Gytja. In: *Beaches and coastal geology*, pp. 456–457. Springer US.
- Ojala, A. E. K., Luoto, T. P., & Virtasalo, J. J. (2017). Establishing a high-resolution surface sediment chronology with multiple dating methods—testing ^{137}Cs determination with Nurmijärvi clastic-biogenic varves. *Quaternary Geochronology*, 37, 32–41.
- Oosterbaan, R. J. (2011). SegReg: segmented linear regression with breakpoint and confidence intervals.
- Porter, S. D. (2008). *Algal attributes: an autecological classification of algal taxa collected by the National Water-Quality Assessment Program*. US Geological Survey Data Series 329.
- Punning, J.-M., Kapanen, G., Hang, T., Davydova, N., & Kangus, M. (2008). Changes in the water level of Lake Peipsi and their reflection in a sediment core. *Hydrobiologia*, 599, 97–104.
- Quinlan, R., & Smol, J. P. (2001). Chironomid-based inference models for estimating end-of-summer hypolimnetic oxygen from south-central Ontario shield lakes. *Freshwater Biology*, 46, 1529–1551.
- Quinlan, R., & Smol, J. P. (2010). Use of subfossil *Chaoborus* mandibles in models for inferring past hypolimnetic oxygen. *Journal of Paleolimnology*, 44, 43–50.
- Repka, S. (2005). Lake Hiidenvesi—studies on a clay-turbid and eutrophic multi-basin lake. *Advances in Limnology*, 59, 1–232.
- Salonen, K., Jones, R. I., & Arvola, L. (1984). Hypolimnetic phosphorus retrieval by diel vertical migrations of lake phytoplankton. *Freshwater Biology*, 14, 431–438.
- Salonen, V.P., Alhonen, P., Itkonen, A., Olander, H. (1993). The trophic history of Enäjärvi, SW Finland, with special reference to its restoration problems. *Hydrobiologia*, 268, 147–162.
- Small, G. E., Wares, J. P., & Pringle, C. M. (2011). Differences in phosphorus demand among detritivorous chironomid larvae reflect intraspecific adaptations to differences in food resource stoichiometry across lowland tropical streams. *Limnology and Oceanography*, 56, 268–278.
- Smol, J. P. (2009). *Pollution of lakes and rivers: a paleoenvironmental perspective*. New Jersey: John Wiley & Sons.
- Tammelin, M., & Kauppila, T. (2015). Iisalmen reitin luontainen rehevyys. *Vesitalous*, 2, 41–44.
- Vanni, M. J. (2002). Nutrient cycling by animals in freshwater ecosystems. *Annual Review of Ecology and Systematics*, 33, 341–370.
- Weckström, J., Väiliranta, M., Kaukolehto, M., & Weckström, K. (2011). *Kurkistus Hiidenveden menneisyyteen—paleolimnologinen selvitys Kirkkojärveltä ja Mustionselältä*. Lohja: Länsi-Uudenmaan vesi- ja ympäristö ry.
- Wetzel, R. G. (2001). *Limnology: lake and river ecosystems*. Houston: Gulf Professional Publishing.
- Wiederholm, T. (1980). Use of benthos in lake monitoring. *Water Pollution Control Federation*, 52, 537–547.